Quantum Optics and Photonics Division
Fachverband Quantenoptik und Photonik (Q)

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Overview of Invited Talks and Sessions

(Lecture halls Q-H10, Q-H11, Q-H12, Q-H13, Q-H14, and Q-H15; Poster P)

Invited Talks

Q 2.1	Mon	14:00–14:30	Q-H10	**Matter-wave microscope for sub-lattice-resolved imaging of 3D quantum systems** — •Christof Weitenberg
Q 6.1	Mon	14:00–14:30	Q-H14	**Quantum Cooperativity: from ideal quantum emitters to molecules** — •Claudiu Genes
Q 9.1	Mon	16:30–17:00	Q-H11	**Rotation sensors for planet Earth: Introducing ring laser gyroscopes** — •Simon Stellmer, Oliver Heckl, Ulrich Schreiber
Q 11.1	Mon	16:30–17:00	Q-H13	**Quantum-state engineering with optically-trapped neutral atoms** — •Vladimir M. Stojanovic, Gernot Alber, Thorsten Haase, Sascha H. Hauck
Q 15.1	Tue	10:30–11:00	Q-H12	**A hybrid quantum classical learning agent** — •Sabine Wölk
Q 17.1	Tue	10:30–11:00	Q-H14	**Superradiant lasing in presence of atomic motion** — •Simon B. Jäger, Haonan Liu, John Cooper, Murray J. Holland
Q 27.1	Wed	10:30–11:00	Q-H11	**Searching for physics beyond the Standard Model with isotope shift spectroscopy** — •Elina Fuchs
Q 29.1	Wed	10:30–11:00	Q-H13	**Quantum rotations of levitated nanoparticles** — •Benjamin A. Stickler
Q 30.1	Wed	10:30–11:00	Q-H14	**Optical properties of porous crystalline nanomaterials modeled across all length scales** — •Marjan Krstić
Q 37.1	Wed	14:00–14:30	Q-H14	**Nanophotonic structure-mediated free-electron acceleration and manipulation in the classical and quantum regimes** — •Roy Shiloh
Q 46.1	Thu	10:30–11:00	Q-H11	**Nanoscale heat radiation in non-reciprocal and topological many-body systems** — •Svend-Age Biehs
Q 52.1	Thu	14:00–14:30	Q-H10	**Self-bound Dipolar Droplets and Supersolids in Molecular Bose-Einstein Condensates** — •Tim Langen

Invited talks of the joint PhD symposium Solid-state Quantum Emitters Coupled to Optical Microcavities (SYPD)

See SYPD for the full program of the symposium.

SYPD 1.1	Mon	16:30–17:00	AKjDPG-H17	**Fiber-based microcavities for efficient spin-photon interfaces** — •David Hunger
SYPD 1.2	Mon	17:00–17:30	AKjDPG-H17	**A fast and bright source of coherent single-photons using a quantum dot in an open microcavity** — •Richard J. Warburton
SYPD 1.3	Mon	17:30–18:00	AKjDPG-H17	**New host materials for individually addressed rare-earth ions** — •Sebastian Horvath, Salim Ourari, Lukasz Dusanowski, Christopher Phenicie, Isaiah Gray, Paul Stevenson, Nathalie de Leon, Jeff Thompson
SYPD 1.4	Mon	18:00–18:30	AKjDPG-H17	**A multi-node quantum network of remote solid-state qubits** — •Ronald Hanson

Invited talks of the joint symposium SAMOP Dissertation Prize 2022 (SYAD)

See SYAD for the full program of the symposium.

SYAD 1.1	Tue	14:00–14:30	Audimax	**New insights into the Fermi-Hubbard model in and out-of equilibrium** — •Annabelle Bohrdt
SYAD 1.2	Tue	14:30–15:00	Audimax	**Searches for New Physics with Yb^+ Optical Clocks** — •Richard Lange
SYAD 1.3	Tue	15:00–15:30	Audimax	**Machine Learning Methodologies for Quantum Information** — •Hendrik Poulsen Nautrup
SYAD 1.4	Tue	15:30–16:00	Audimax	**Precision Mass Measurement of the Deuteron's Atomic Mass** — •Sascha Rau

Invited talks of the joint symposium Rydberg Physics in Single-Atom Trap Arrays (SYRY)

See SYRY for the full program of the symposium.

SYRY 2.1	Wed	10:30–11:00	Audimax	**Many-body physics with arrays of Rydberg atoms in resonant interaction** — •Antoine Browaeys
SYRY 2.2	Wed	11:00–11:30	Audimax	**Optimization and sampling algorithms with Rydberg atom arrays** — •Hannes Pichler
SYRY 2.3	Wed	11:30–12:00	Audimax	**Slow dynamics due to constraints, classical and quantum** — •Juan P. Garrahan
SYRY 3.3	Wed	14:30–15:00	Audimax	**New frontiers in quantum simulation and computation with neutral atom arrays** — •Giulia Semeghini
SYRY 3.4	Wed	15:00–15:30	Audimax	**New frontiers in atom arrays using alkaline-earth atoms** — •Adam Kaufman
SYRY 3.5	Wed	15:30–16:00	Audimax	**Spin squeezing with finite range spin-exchange interactions** — •Ana Maria Rey

Invited talks of the joint symposium Quantum Cooperativity of Light and Matter (SYQC)

See SYQC for the full program of the symposium.

SYQC 1.1	Thu	10:30–11:00	Audimax	**Super- and subradiant states of an ensemble of cold atoms coupled to a nanophotonic waveguide** — •Arno Rauschenbeutel
SYQC 1.6	Thu	12:00–12:30	Audimax	**Cooperative Effects in Pigment-Protein Complexes: Vibronic Renormalisation of System Parameters in Complex Vibrational Environments** — •Susana F. Huelga
SYQC 2.1	Thu	14:00–14:30	Audimax	**Quantum simulation with coherent engineering of synthetic dimensions** — •Paola Cappellaro
SYQC 2.6	Thu	15:30–16:00	Audimax	**Quantum Fractals** — •Cristiane Morais-Smith

Sessions

Q 1.1–1.2	Mon	11:00–13:00	AKjDPG-H17	**Tutorial Rydberg Physics (joint session AKjDPG/SYRY/Q)**
Q 2.1–2.7	Mon	14:00–16:00	Q-H10	**Quantum Gases (Bosons) I**
Q 3.1–3.8	Mon	14:00–16:00	Q-H11	**Precision Measurements and Metrology I**
Q 4.1–4.8	Mon	14:00–16:00	Q-H12	**Quantum Information (Concepts and Methods) I**
Q 5.1–5.8	Mon	14:00–16:00	Q-H13	**Quantum Technologies I**
Q 6.1–6.7	Mon	14:00–16:00	Q-H14	**Quantum Optics (Miscellaneous) I**
Q 7.1–7.6	Mon	14:00–15:30	A-H2	**Precision spectroscopy of atoms and ions I (joint session A/Q)**
Q 8.1–8.8	Mon	16:30–18:30	Q-H10	**Quantum Gases (Bosons) II**
Q 9.1–9.6	Mon	16:30–18:15	Q-H11	**Precision Measurements and Metrology II**
Q 10.1–10.5	Mon	16:30–17:45	Q-H12	**Quantum Information (Concepts and Methods) II**
Q 11.1–11.5	Mon	16:30–18:00	Q-H13	**Quantum Technologies II**
Q 12.1–12.6	Mon	16:30–18:00	Q-H14	**Quantum Optics (Miscellaneous) II**
Q 13.1–13.8	Tue	10:30–12:30	Q-H10	**Quantum Gases (Bosons) III**
Q 14.1–14.7	Tue	10:30–12:15	Q-H11	**Precision Measurements and Metrology III**

Q 15.1–15.7	Tue	10:30–12:30	Q-H12	**Quantum Information (Quantum Computing and Simulation)**
Q 16.1–16.10	Tue	10:30–13:00	Q-H13	**Quantum Effects I**
Q 17.1–17.7	Tue	10:30–12:30	Q-H14	**Quantum Optics (Miscellaneous) III**
Q 18.1–18.6	Tue	10:30–12:00	Q-H15	**Laser and Laser Applications**
Q 19.1–19.7	Tue	10:30–12:15	A-H2	**Ultra-cold atoms, ions and BEC I (joint session A/Q)**
Q 20.1–20.11	Tue	16:30–18:30	P	**Quantum Gases I**
Q 21.1–21.15	Tue	16:30–18:30	P	**Ultracold Atoms and Plasmas (joint session Q/A)**
Q 22.1–22.15	Tue	16:30–18:30	P	**Precision Measurements and Metrology I (joint session Q/A)**
Q 23.1–23.17	Tue	16:30–18:30	P	**Quantum Information I**
Q 24.1–24.16	Tue	16:30–18:30	P	**Quantum Effects**
Q 25.1–25.4	Tue	16:30–18:30	P	**Ultra-cold plasmas and Rydberg systems (joint session A/Q)**
Q 26.1–26.8	Wed	10:30–12:30	Q-H10	**Quantum Gases (Fermions)**
Q 27.1–27.7	Wed	10:30–12:30	Q-H11	**Precision Measurements and Metrology IV (joint session Q/A)**
Q 28.1–28.8	Wed	10:30–12:30	Q-H12	**Quantum Information (Quantum Communication) I**
Q 29.1–29.7	Wed	10:30–12:30	Q-H13	**Optomechanics I**
Q 30.1–30.7	Wed	10:30–12:30	Q-H14	**Quantum Optics (Miscellaneous) IV**
Q 31.1–31.8	Wed	10:30–12:30	Q-H15	**Photonics I**
Q 32.1–32.7	Wed	10:30–12:15	A-H2	**Ultra-cold atoms, ions and BEC II (joint session A/Q)**
Q 33.1–33.6	Wed	14:00–15:30	Q-H10	**Quantum Gases**
Q 34.1–34.6	Wed	14:00–15:30	Q-H11	**Precision Measurements and Metrology V (joint session Q/A)**
Q 35.1–35.8	Wed	14:00–16:00	Q-H12	**Quantum Information (Quantum Communication) II**
Q 36.1–36.5	Wed	14:00–15:15	Q-H13	**Optomechanics II**
Q 37.1–37.7	Wed	14:00–16:00	Q-H14	**Quantum Optics (Miscellaneous) V**
Q 38.1–38.5	Wed	14:00–15:15	Q-H15	**Photonics II**
Q 39.1–39.5	Wed	14:00–15:15	A-H2	**Precision spectroscopy of atoms and ions II (joint session A/Q)**
Q 40.1–40.13	Wed	16:30–18:30	P	**Optomechanics and Photonics**
Q 41.1–41.17	Wed	16:30–18:30	P	**Nano-Optics**
Q 42.1–42.12	Wed	16:30–18:30	P	**Laser and Laser Applications**
Q 43.1–43.9	Wed	16:30–18:30	P	**Quantum Technologies**
Q 44.1–44.21	Wed	16:30–18:30	P	**Precision spectroscopy of atoms and ions (joint session A/Q)**
Q 45.1–45.8	Thu	10:30–12:30	Q-H10	**Ultracold Atoms and Molecules I (joint session Q/A)**
Q 46.1–46.7	Thu	10:30–12:30	Q-H11	**Nano-Optics I**
Q 47.1–47.7	Thu	10:30–12:15	Q-H12	**Quantum Information (Quantum Communication and Quantum Repeater)**
Q 48.1–48.8	Thu	10:30–12:30	Q-H13	**Quantum Effects II**
Q 49.1–49.6	Thu	10:30–12:15	A-H2	**Ultra-cold atoms, ions and BEC III (joint session A/Q)**
Q 50.1–50.6	Thu	10:30–12:15	A-H3	**Precision spectroscopy of atoms and ions III (joint session A/Q)**
Q 51	Thu	13:00–14:00	Q-MV	**General Assembly of the Quantum Optics and Photonics Division**
Q 52.1–52.5	Thu	14:00–15:30	Q-H10	**Ultracold Atoms and Molecules II (joint session Q/A)**
Q 53.1–53.9	Thu	14:00–16:15	Q-H11	**Nano-Optics II**
Q 54.1–54.7	Thu	14:00–15:45	Q-H12	**Quantum Information (Quantum Repeater)**
Q 55.1–55.6	Thu	14:00–15:30	Q-H13	**Quantum Effects III**
Q 56.1–56.7	Thu	14:00–15:45	A-H1	**Ultra-cold plasmas and Rydberg systems (joint session A/Q)**
Q 57.1–57.10	Thu	16:30–18:30	P	**Quantum Gases II**
Q 58.1–58.10	Thu	16:30–18:30	P	**Matter Wave Optics**
Q 59.1–59.16	Thu	16:30–18:30	P	**Precision Measurements and Metrology II (joint session Q/A)**
Q 60.1–60.23	Thu	16:30–18:30	P	**Quantum Information II**
Q 61.1–61.18	Thu	16:30–18:30	P	**Quantum Optics (Miscellaneous)**
Q 62.1–62.22	Thu	16:30–18:30	P	**Ultra-cold atoms, ions and BEC (joint session A/Q)**
Q 63.1–63.8	Fri	10:30–12:30	Q-H10	**Matter Wave Optics**

Q 64.1–64.8	Fri	10:30–12:30	Q-H11	**Nano-Optics III**
Q 65.1–65.7	Fri	10:30–12:15	Q-H12	**Quantum Information (Miscellaneous)**
Q 66.1–66.7	Fri	10:30–12:15	Q-H13	**Quantum Effects IV**
Q 67.1–67.5	Fri	10:30–11:45	Q-H14	**Rydberg Systems (joint session Q/A)**
Q 68.1–68.8	Fri	10:30–12:30	Q-H15	**Quantum Cooperativity (joint session Q/SYQC)**
Q 69.1–69.6	Fri	10:30–12:15	A-H1	**Ultra-cold atoms, ions and BEC IV (joint session A/Q)**
Q 70.1–70.5	Fri	10:30–12:00	A-H2	**Precision spectroscopy of atoms and ions IV (joint session A/Q)**

Annual General Meeting of the Quantum Optics and Photonics Division

Thursday 13:00–14:00 Q-MV

Q 1: Tutorial Rydberg Physics (joint session AKjDPG/SYRY/Q)

Time: Monday 11:00–13:00 Location: AKjDPG-H17

Tutorial Q 1.1 Mon 11:00 AKjDPG-H17
From the Rydberg Formula to Rydberg arrays — •Jan Michael Rost — Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

Covering milestones in the development of Rydberg physics, the tutorial will introduce the properties of Rydberg atoms and major elements for a theoretical description. Milestones include hydrogen in a magnetic field and doubly excited states of atoms with their connection to classical chaos and periodic orbits through the semiclassical nature of Rydberg electrons. With ultracold environments and traps ultra long-range Rydberg molecules as seeds for Rydberg chemistry have been realized as well as ultracold plasmas. Fundamental phenomena such as the interaction blockade and Rydberg dressing have been identified as major tools to establish and control correlation in Rydberg dynamics on the way to quantum computation with Rydberg arrays which will be the covered in the second tuturial.

Tutorial Q 1.2 Mon 12:00 AKjDPG-H17
Quantum simulation and quantum computation with Rydberg atom arrays — •Johannes Zeiher — Max Planck Institute of Quantum Optics, 85748 Garching, Germany — Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

Understanding quantum mechanical systems of many particles at a microscopic level is one of the grand challenges of modern physics. In 1982, Feynman addressed this issue by formulating his vision that one can use well-controlled quantum systems to simulate and understand other quantum systems. Single atoms trapped in individual optical traps coupled to Rydberg states have recently emerged as a versatile experimental platform geared towards realizing Feynman's vision. In this tutorial, I will focus on the basics of this platform. First, I will describe how individual atoms are loaded, detected, and manipulated in optical tweezers. Afterwards, I will explain how strong, switchable interactions between highly excited atomic Rydberg states emerge, and how they can be induced and controlled by lasers. This will set the stage for highlighting the accessible many-body models for quantum simulation and the potential of the platform for quantum computation, followed by a brief discussion of recent experimental breakthroughs in the field.

Q 2: Quantum Gases (Bosons) I

Time: Monday 14:00–16:00 Location: Q-H10

Invited Talk Q 2.1 Mon 14:00 Q-H10
Matter-wave microscope for sub-lattice-resolved imaging of 3D quantum systems — •Christof Weitenberg — Institut für Laserphysik, Luruper Chaussee 149, 22761 Hamburg

Imaging is central to gaining microscopic insight into physical systems, and new microscopy methods have always led to the discovery of new phenomena and a deeper understanding of them. Ultracold atoms in optical lattices provide a quantum simulation platform, featuring a variety of advanced detection tools including direct optical imaging while pinning the atoms in the lattice. However, this approach suffers from the diffraction limit, high optical density and small depth of focus, limiting it to two-dimensional (2D) systems.

In this talk, I will present our new imaging approach where matter-wave optics magnifies the density distribution before optical imaging, allowing 2D sub-lattice-spacing resolution in three-dimensional (3D) systems. The method opens the path for spatially resolved studies of new quantum many-body regimes and paves the way for single-atom-resolved imaging of atomic species, where efficient laser cooling or deep optical traps are not available, but which substantially enrich the toolbox of quantum simulation of many-body systems.

Q 2.2 Mon 14:30 Q-H10
Observation of a dissipative time crystal — •Hans Kessler[1], Phatthamon Kongkhambut[1], Jim Skulte[1], Ludwig Mathey[1,2], Jayson G. Cosme[3], and Andreas Hemmerich[1,2] — [1]Institut für Laser-Physik, Universität Hamburg — [2]The Hamburg Center for Ultrafast Imaging — [3]National Institute of Physics, University of the Philippines

We are experimentally exploring the light-matter interaction of a Bose-Einstein condensate (BEC) with a single light mode of an ultra-high finesse optical cavity. The key feature of our cavity is the small field decay rate ($\kappa/2\pi$=4.5kHz), which is in the order of the recoil frequency (ωrec/2π=3.6kHz). This leads to a unique situation where cavity field evolves with the same timescale as the atomic distribution. If the system is pumped transversally with a steady state light field, red detuned with respect to the atomic resonance, the Hepp-Lieb superradiant phase transition of the open Dicke is realized. Starting in this self-ordered density wave phase and modulating the amplitude of the pump field, we observe a dissipative discrete time crystal, whose signature is a robust subharmonic oscillation between two symmetrybroken states [1]. For a blue-detuned pump light with respect to the atomic resonance, we propose an experimental realization of limit cycles. Since the model describing the system is time-independent, the emergence of a limit cycle phase heralds the breaking of continuous time-translation symmetry [2]. References [1] H. Keßler et al., PRL 127, 043602 (2021). [2] H. Keßler et al., PRA 99, 053605 (2019).

Q 2.3 Mon 14:45 Q-H10
Realization of a periodically driven open three-level Dicke model — •Phatthamon Kongkhambut[1], Hans Kessler[1], Jim Skulte[1,2], Ludwig Mathey[1,2], Jayson G. Cosme[3], and Andreas Hemmerich[1,2] — [1]Institut für Laser-Physik, Universität Hamburg — [2]The Hamburg Center for Ultrafast Imaging — [3]National Institute of Physics, University of the Philippines

A periodically driven open three-level Dicke model is realized by resonantly shaking the pump* field in an atom-cavity system. As an unambiguous signature, we demonstrate the emergence of a dynamical phase, in which the atoms periodically localize between the antinodes of the pump lattice, associated with an oscillating net momentum along the pump axis. We observe this dynamical phase through the periodic switching of the relative phase between the pump and cavity fields at a small fraction of the driving frequency, suggesting that it exhibits a time crystalline character.

[1] P. Kongkhambut et al., arXiv:2108.11113 (2021). [2] J. Skulte et al., arXiv:2108.10877 (2021).

Q 2.4 Mon 15:00 Q-H10
Extended Bose-Hubbard models with Rydberg macrodimer dressing — •Mathieu Barbier[1], Simon Hollerith[2], and Walter Hofstetter[1] — [1]Institut für theoretische Physik, Goethe Universität, 60438 Frankfurt am Main — [2]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

We propose dressing bosonic quantum gases dressed with macrodimer states - molecular bound states in Rydberg interaction potentials - as a promising approach for experimental observation of novel quantum phases such as supersolids. We investigate the scaling laws of the dressed interaction strength and the scattering rate with respect to the effective principal quantum number and trapping frequency of the ground state atoms for the molecular potentials of Rubidium and Potassium. Additionally, we propose a two-color excitation scheme which significantly increases the dressed interaction and cancels otherwise limiting AC Stark shifts. Furthermore, we study the corresponding extended Bose-Hubbard model within the Cluster Gutzwiller approach and compute the equilibrium phase diagram. By means of time-evolution simulations in the presence of realistic dissipation we investigate the possible preparation of supersolid phases and suggest a parameter regime for which, through ramping up to coupling to the macrodimer states, supersolid phases could be experimentally observable.

Q 2.5 Mon 15:15 Q-H10
Supersolid phases of ultracold bosons trapped in optical lattices dressed with Rydberg p-states — •Mathieu Barbier, Hen-

rik Lütjeharms, and Walter Hofstetter — Institut für theoretische Physik, Goethe Universität, 60438 Frankfurt am Main, Germany

In recent years Rydberg-excited bosonic quantum gases have emerged as a promising platform for realizing quantum phases with broken lattice translational symmetry, such as density wave and lattice supersolid phases. Although numerous theoretical works on trapped gases dressed with Rydberg s-states have predicted these phases, their experimental observation proves to be difficult due to challenges such as scattering processes and the limited experimentally achievable coupling strength. On the other hand, the less investigated case of Rydberg p-state dressing possesses advantages in this respect. We therefore study the quantum phases of an ultracold bosonic quantum gas trapped in a square optical lattice and dressed with Rydberg p-states, going both beyond the weak-dressing regime and the frozen regime. We consider an extended Bose-Hubbard model and compute its ground state phase diagram within Gutzwiller mean-field theory. We obtain Mott insulating, superfluid, density wave and supersolid regimes within the parameter space considered. Furthermore, through comparison with the ground state phases of bosons dressed with Rydberg s-states, we find the anisotropy of the long-range interaction to be beneficial for the coexistence of a condensate and spontaneously broken lattice translational symmetry, which is promising for realizing supersolid phases.

Q 2.6 Mon 15:30 Q-H10

Complex Langevin simulation of Bose-Einstein condensates

— •Philipp Heinen and Thomas Gasenzer — Kirchhoff-Institut für Physik, Heidelberg

Complex Langevin (CL) is an approach to the solution of the sign problem, which arises when trying to numerically compute path integrals for complex-valued actions with standard Monte Carlo techniques. The idea behind the method is to rewrite the path integral as a stochastic Langevin equation. The latter can be straightforwardly generalized to the case of a complex action, leading to a stochastic evolution in a complexified field manifold. Whereas the application of CL has a long-standing tradition in high energy physics, in particular in the simulation of quantum chromodynamics at finite chemical potential, it is less established so far in the field of ultracold atomic gases. We present results of CL simulations for multi-component Bose-Einstein condensates.

Q 2.7 Mon 15:45 Q-H10

Spectroscopy of heteronuclear xenon-noble gas mixtures - Towards Bose-Einstein condensation of vacuum-ultraviolet photons

— •Thilo vom Hövel, Eric Boltersdorf, Frank Vewinger, and Martin Weitz — Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, 53115 Bonn

In the vacuum-ultraviolet regime (VUV, 100 - 200 nm), realizing lasers is difficult, as excited state lifetimes scale as $1/\omega^3$, resulting in the need of high pump powers to achieve population inversion in active media. We propose an experimental approach for the realization of a coherent light source in the VUV based on Bose-Einstein condensation of photons. In our group, Bose-Einstein condensation of visible photons is investigated using liquid dye solutions as thermalization media in wavelength-sized optical microcavities, the latter providing a non-trivial low-energy ground state the photons condense into.

Conveying these principles into the VUV, a suitable thermalization medium has to be found. For this, we here consider heteronuclear mixtures of xenon and another noble gas atom as a potential candidate, with absorption re-emission cycles on the transition from the atomic ground state ($5p^6$) to the lowest electronically excited state ($5p^5 6s$) and emission from a lightly bound heteronuclear excimer state for thermalization. We report on the results of current spectroscopic measurements, investigating VUV line profiles of samples containing xenon and different noble gases. Also, the data is tested for the validity of the Kennard-Stepanov relation, a fundamental prerequisite for the suitability of a medium as thermalization mediator in the scheme.

Q 3: Precision Measurements and Metrology I

Time: Monday 14:00–16:00 Location: Q-H11

Q 3.1 Mon 14:00 Q-H11

Quantum Hybridized accelerometer for Inertial Navigation

— •Mouine Abidi[1], Philipp Barbey[1], Yueyang Zou[1], Ashwin Rajagopalan[1], Christian Schubert[1,2], Matthias Gersemann[1], Dennis Schlippert[1], Sven Abend[1], and Ernst.M Rasel[1] — [1]Institut für Quantenoptik - Leibniz Universität, Hannover, Germany — [2]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik, Germany

Today, precise inertial navigation and positioning systems are the basis for controlling vehicles such as aircrafts, ships, or satellites. However classical inertial sensors suffer from device-dependent drifts and require GNSS corrections that themselves rely on the availability of the signal broadcasted by the satellites. This leads to the non-usability of classical sensors in some environments like in-between buildings, underground, or space.

Hybrid quantum navigation, based on the combination of classical Inertial Measurement Units with quantum sensors based on atom interferometry, is a serious candidate for a new technology that meets the demand of our time requirements for inertial navigation.

Atom interferometers have proven to measure drift-free at very high sensitivities. The main challenge is to transfer a complex laboratory-based device to a robust and compact measurement unit that can be used regardless of their small bandwidth and dynamic range to subtract the drifts of the classical devices. We present the current status of our teststand for a quantum accelerometer employed on a gyro-stabilized platform.

Q 3.2 Mon 14:15 Q-H11

Gravitational Redshift Tests with Atomic Clocks and Atom Interferometers

— •Fabio Di Pumpo[1], Christian Ufrecht[1], Alexander Friedrich[1], Enno Giese[2], Wolfgang P. Schleich[1,3], and William G. Unruh[4] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ$^{\mathrm{ST}}$), Universität Ulm — [2]Institut für Angewandte Physik, Technische Universität Darmstadt — [3]Institute of Quantum Technologies, German Aerospace Center (DLR) — [4]Department of Physics and Astronomy, University of British Columbia

Atomic interference experiments test the universality of the coupling between matter-energy and gravity at different spacetime points, thus probing possible violations of the universality of the gravitational redshift (UGR). In this contribution, we introduce a UGR violation model and then discuss UGR tests performed by atomic clocks and atom interferometers on the same footing. Consequently, we present a large class of atom-interferometer geometries which are sensitive to violations of UGR, and identify their underlying mechanisms leading to such tests [see PRX Quantum **2**, 040333 (2021)].

The project “Metrology with interfering Unruh-DeWitt detectors” (MIUnD) is funded by the Carl Zeiss Foundation (Carl-Zeiss-Stiftung) through IQ$^{\mathrm{ST}}$. The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) due to an enactment of the German Bundestag under grant DLR 50WM1956 (QUANTUS V).

Q 3.3 Mon 14:30 Q-H11

Atom interferometry aboard an Earth-orbiting research lab

— •Matthias Meister[1], Naceur Gaaloul[2], Nicholas P. Bigelow[3], and the CUAS team[1,2,3,4] — [1]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany — [2]Leibniz University Hannover, Institute of Quantum Optics, QUEST-Leibniz Research School, Hanover, Germany — [3]Department of Physics and Astronomy, University of Rochester, Rochester, NY, USA — [4]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology IQ$^{\mathrm{ST}}$, Ulm University, Ulm, Germany

Atom interferometers based on Bose-Einstein condensates are exquisite systems for quantum sensing applications such as Earth observation, relativistic geodesy, and tests of fundamental physical concepts. The sensitivity of these devices depends on the free fall time of the quantum gas and, therefore, can be strongly improved by working in a microgravity environment. Here we report on a series of experiments performed with NASA's Cold Atom Lab aboard the ISS demonstrating atom interferometers with different geometries in orbit. By employing Mach-Zehnder-type interferometers we have realized atomic magnetometers and successfully compared their outcome to complementary non-interferometric measurements. Our results pave the way towards future precision measurements with atom interferometers in space.

This project is supported by NASA/JPL through RSA No. 1616833 and the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under the grant numbers 50WP1705 and 50WM1861-1862.

Q 3.4 Mon 14:45 Q-H11

Effective Models for Atom-interferometry with Center-of-mass Motion in Quantized Electromagnetic Fields — •Alexander Friedrich[1], Nikolija Momčilović[1], Sabrina Hartmann[1], and Wolfgang P. Schleich[1,2] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, 89069 Ulm, Germany — [2]Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt, Söflinger Str. 100, 89077 Ulm, Germany

Entanglement enhanced metrology promises to boost the sensitivity of quantum devices beyond the classical limit. Future atom interferometric gravitational wave detectors, tests of the equivalence principle or inertial sensors are already envisioned to employ these techniques to reach their full projected potential. However, proper characterization of the dynamic entanglement transfer between parts of the system due to the atom-light interaction requires a quantized description of the light field as well as the atomic degrees of freedom. Starting with a few-mode model of the light-field, coupled to a few-level atom with second quantized motional degrees of freedom we show: (i) how effective Jaynes-Cummings-Paul like multi-mode Rabi models can be derived for multi-photon interactions, and (ii) our approach and the resulting models are not limited to atom interferometry configurations but have possible applications ranging from cavity optomechanics to ion traps.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50WM1956.

Q 3.5 Mon 15:00 Q-H11

Mitigation of spurious effects in double Bragg diffraction — •Jens Jenewein[1], Sabrina Hartmann[1], Albert Roura[2], and Enno Giese[1,3,4] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm — [2]Institut für Quantentechnologien, DLR — [3]Institut für Angewandte Physik, TU Darmstadt — [4]Institut für Quantenoptik, Leibniz Universität Hannover

The Mach-Zehnder interference signal of single and double Bragg diffraction is influenced by the multiport nature of the diffraction process [1]. Under appropriate conditions, higher-order path contributions can be neglected and just two or three paths are respectively relevant for single and double diffraction. Although the central path can contribute significantly to the exit-port population for double diffraction, the coherent overlap with the resonant paths is only small due to velocity selectivity effects. Even when the two resonant paths are dominant for double Bragg diffraction, the interference signal due to a phase shift exhibits that the outer ports are shifted to each other. For three paths, we additionally observe a beating. By summing over the two outer exit ports, one can define an effective port that is insensitive to these effects. We analyze how this feature changes under gravity which cannot be completely compensated by frequency chirping in this case. The QUANTUS project is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Energy (BMWi) under grant number 50WM1956 (QUANTUS V).

[1] Phys. Rev. A **101**, 053610 (2020)

Q 3.6 Mon 15:15 Q-H11

Modelling the Impact of Wavefront Aberrations on the Phase of a Precision Mach-Zehnder Light-Pulse Atom Interferometer — •Stefan Seckmeyer[1], Florian Fitzek[1], Tim Kovachy[2], Yiping Wang[2], Ernst M. Rasel[1], and Naceur Gaaloul[1] — [1]Leibniz Universität Hannover, Hannover, Germany — [2]Northwestern University, Chicago, United States

Wavefront aberrations are one of the leading systematics in current state-of-the-art atom interferometry experiments. We compare the impact of wavefront aberrations on the final phase of a $2\hbar k$ Mach-Zehnder geometry between two models. One is derived in the limit of infinitely short atom light interactions where the atoms follow classical paths based on Feynman's path integral method. The other recently developed one models the wavefunction as a complex function in position and momentum space to include among others effects from finite atom-light interaction and coherent diffraction.

Q 3.7 Mon 15:30 Q-H11

Space-borne Atom Interferometry for Tests of General Relativity — •Christian Struckmann[1], Ernst M. Rasel[1], Peter Wolf[2], and Naceur Gaaloul[1] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany — [2]LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université 61 avenue de l'Observatoire, 75014 Paris, France

Quantum sensors based on the interference of matter waves provide an exceptional access to test the postulates of general relativity by comparing the free-fall acceleration of matter waves of different composition. Space-borne quantum tests of the universality of free fall (UFF) promise to exploit the full potential of these sensors due to long free-fall times, and to reach unprecedented performance beyond current limits set by classical experiments.

In this contribution, we present a dedicated satellite mission to test the UFF with ultra-cold atoms to 10-17 as proposed to the ESA Voyage 2050 initiative [Battelier et al., Exploring the foundations of the physical universe with space tests of the equivalence principle, Experimental Astronomy (2021)]. To this end, we highlight our model for suppressing spurious error terms [Loriani et al., PRD 102, 124043 (2020)] and outline our work on a dedicated simulator for satellite-based atom interferometry, which will be an indispensable tool for the detailed analysis of future space mission scenarios.

Q 3.8 Mon 15:45 Q-H11

Dynamic Time-Averaged Optical Potentials for Atom Interferometry — •Henning Albers[1], Alexander Herbst[1], Vera Vollenkemper[1], Ernst M. Rasel[1], Dennis Schlippert[1], and The PRIMUS-Team[2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]ZARM, Universität Bremen

Optical dipole traps are a commonly used tool for trapping and cooling neutral atoms. However, typical dipole traps are disadvantaged compared to magnetic traps for example implemented on atom chip traps, due to their small trapping volume and lower evaporation speed. The modulation of the center-position of dipole trap beams helps to overcome these limitations by creating large-volume time-averaged potentials with nearly arbitrary shape. The properties of these kind of atom traps can be changed dynamically and allow for faster evaporative cooling as well as atom-optical elements like matter-wave lenses. We use time-averaged optical potentials to generate Bose-Einstein condensates with up to 2×10^5 condensed ^{87}Rb atoms after 3s of evaporative cooling. Subsequently we apply an all-optical matter-wave lens by rapid decompression of the trap. This change in trap confinement induces oscillations of the ensemble, that we stop by turning off the trap, when the size is at a maximum, which reduces the further expansion of the free falling cloud. By means of this matter-wave lens we reduce the expansion temperature to 3nK in the horizontal directions. We present the results of the matter-wave lens and discuss the impact of this technique when used as the source an inertial sensitive free fall atom interferometer.

Q 4: Quantum Information (Concepts and Methods) I

Time: Monday 14:00–16:00 Location: Q-H12

Q 4.1 Mon 14:00 Q-H12

Electromagnetic Modelling of a Surface-Electrode Ion Trap for High Fidelity Microwave Quantum Simulations — •Axel Hoffmann[1], Florian Ungerechts[2], Rodrigo Munoz[2], Teresa Meiners[2], Brigitte Kaune[2], Dirk Manteuffel[1], and Christian Ospelkaus[2] — [1]Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover, Appelstr. 9A, 30167 Hannover, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Surface-electrode ion traps with integrated microwave conductors for near-field quantum control are a promissing approach for scaleable quantum computers. The goal of the QVLS-Q1 Project is to realize the first scalable 50-qubit quantum computer based on surface-electrode ion traps. Designing a multi-layer ion trap with surface-electrodes for electromagntic near-field operations comes with high demands on the design of the electrical components, such as impedance matching of the surface electrodes to the microwave and radio frequency sources. The near field had to be designed considering the necessary conditions to trap $^{9}Be^{+}$- Ions in a multi layer trap. This process will be presented in this talk, emphasising on the constraints of the electrically small chip size compared to the length of the applied electromagnetic waves. In electromagnetic full-wave simulations we can show that a properly desinged electrode combined with an efficient impedance matching accounts for a significant decrease of electrical losses. The design of the meander-like microwave guide will be discussed including the simulation methods and approaches.

Q 4.2 Mon 14:15 Q-H12

Distinguishability and mixedness in multiphoton interference — •Shreya Kumar[2], Alex E Jones[1], Simone D'Aurelio[2], Matthias Bayerbach[2], Adrian Menssen[3], and Stefanie Barz[2] — [1]QET Labs, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, Bristol BS8 1FD, UK — [2]Institute for Functional Matter and Quantum Technologies & IQST, University of Stuttgart, 70569 Stuttgart, Germany — [3]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Quantum interference of photons is central to many applications in quantum technologies such as generating entangled states, quantum metrology, quantum imaging and photonic quantum computing. One of the fundamental prerequisites for these applications is that the photons are indistinguishable and have high purity. The visibility of the Hong-Ou-Mandel (HOM) interference dip is usually used to deduce the nature of the photons. In case of two photons, this visibility is reduced by distinguishability, and by mixedness in the same way. However, here, we show that that when scaling up to three photons, despite having similar HOM interference visibilities, one can differentiate between distinguishability and mixedness of the photons by observing the count statistics after interference at a tritter. This shows that the visibility alone is inadequate to discriminate between distinguishability and mixedness of the photons and that it becomes important to characterize photon state purity, in order to study interference effects at larger scales.

Q 4.3 Mon 14:30 Q-H12

Quantum Frames and Distance Measures — •Moritz Ferdinand Richter and Heinz-Peter Breuer — Institute of Physics, University of Freiburg, Hermann-Herder-Straße 3, D-79104, Germany

Based on Informationally Complete Positive Operator Valued Measures (IC-POVM) the poster will introduce a decomposition of generally mixed quantum states - given by their density operators - in a fixed set of pure quantum states, i.e. rank-one projection operators (quantum frame). This decomposition allows a vector like representation for arbitrary quantum states which can be linearly connected to the probability distribution generated by the IC-POVM - underlying the quantum frame - applied to the quantum state at hand. Both the probability distribution and the quantum frame decomposition can be used to define certain distance measures for quantum states which provide a lower and upper bound for the trace distance between quantum states.

Q 4.4 Mon 14:45 Q-H12

Exact approach to strong-coupling quantum thermodynamics in open systems — •Alessandra Colla[1] and Heinz-Peter Breuer[1,2] — [1]Institute of Physics, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

The formulation of a solid and consistent thermodynamic theory in the quantum regime has proven to be extremely challenging. Particularly in the case of strong system-reservoir interactions, agreement on how to properly define thermodynamic quantities such as work, heat, and entropy production has yet to be reached. Using the exact time-local quantum master equation for the reduced open system states, we develop an exact theory describing the thermodynamical behavior of open quantum systems coupled to thermal baths [1]. We define an effective energy operator for the reduced system using a recent principle of minimal dissipation, which gives a unique prescription for decomposing the master equation into a Hamiltonian part (coherent evolution) and a dissipator part (decoherence). From this, we derive the first two laws of thermodynamics and investigate the relationship between violations of the second law and quantum non-Markovianity.

[1] A. Colla and H.-P. Breuer, arXiv:2109.11893 [quant-ph] (2021)

Q 4.5 Mon 15:00 Q-H12

Thermomajorization in Quantum Control — •Frederik vom Ende[1,2], Gunther Dirr[3], and Thomas Schulte-Herbrüggen[1,2] — [1]Department of Chemistry, Technische Universität München, Garching, 85737, Germany — [2]Munich Centre for Quantum Science and Technology & Munich Quantum Valley, Schellingstr. 4, 80799 München, Germany — [3]Department of Mathematics, University of Würzburg, Würzburg, 97074, Germany

Based on the recent description of thermomajorization – known in the mathematics literature as d- or relative q-majorization – as a convex polytope (arXiv:1911.01061) we visualize the constraints coming from thermomajorization for a qutrit as a parameter of the temperature. It is known that one of the extreme points of this polytope majorizes every element from the polytope clasically; this extreme point is of particular interest in quantum control systems where one of the controls is to couple the system to a bath of finite temperature (arXiv:2003.06018). Thus this graphical approach allows us to highlight some critical temperatures for when this maximal extreme point changes its behaviour. Finally, we point to a recently drawn connection to Markovian thermal operations (arXiv:2111.12130) and its possible implications for control systems of the above type.

Q 4.6 Mon 15:15 Q-H12

Quantum simulations in a linear Paul trap and a 2D array — •Florian Hasse, Deviprasath Palani, Apurba Das, Lennart Guth, Ingolf Kaufmann, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, University of Freiburg

Trapped ions present a promising platform for quantum simulations [1]. In our laboratory in Freiburg, we are performing experiments on multiple ions trapped in a linear or a surface RF-trap. In our linear Paul trap, we switch the trapping potential sufficiently fast to induce a non-adiabatic change of the ions' motional mode frequencies. Thereby, we prepare the ions in a squeezed state of motion. This process is accompanied by the formation of entanglement in the ions' motional degree of freedom and can be interpreted as an experimental analogue to the particle pair creation during cosmic inflation in the early universe [2]. Furthermore, we will transfer entanglement of the motional degree of freedom to the external degree of freedom. In our basic triangular array of individually trapped ions with 40 um inter-site distance, we realize the coupling between ions at different sites via their Coulomb interactions. We demonstrate its tuning in real-time and show interference of coherent states of currently large amplitudes [3]. In addition, we employ the individual control for local modulation of the trapping potential to realize Floquet-engineered coupling of adjacent sites [4].

[1] T. Schaetz et al., New J. Phys. 15, 085009 (2013).
[2] M. Wittemer et al., Phys. Rev. Lett. 123, 180502 (2019).
[3] F. Hakelberg et al., Phys. Rev. Lett. 123, 100504 (2019).
[4] P. Kiefer et al., Phys. Rev. Lett. 123, 213605 (2019).

Q 4.7 Mon 15:30 Q-H12

Broadband detection of a 200 MHz squeezing comb — •Dennis Wilken[1,2], Jonas Junker[1,2], and Michèle Heurs[1,2] — [1]Institut für Gravitationsphysik, Leibniz Universität Hannover, Germany — [2]Max-Planck Institut für Gravitationsphysik, Hannover, Germany

Non-classical continuous-variable states such as squeezed vacua are promising resources in the field of quantum information. One common technique to generate such states relies on optical parametric oscillators, which produce squeezed states in a frequency comb structure. These combs usually have two limitations: first, the tooth separation (free-spectral range) is often larger than GHz, strongly limiting the number of accessible sidebands. Second, only one frequency can be measured at a given time. Here, we present a broadband measurement of our 200 MHz squeezing comb allowing simultaneous access to 18 sidebands. We have detected more than 9 dB of squeezing at a frequency of 3.6 GHz. To achieve this, we have designed a GHz photodetector with close to unity quantum efficiency. It turned out that a balanced detection scheme was not feasible. Therefore, our homodyne detection is based on a 99:1 beam splitter. Our method significantly simplifies the detection process and allows the simultaneous measurement of multiple squeezed states at different frequencies. This flexibility makes our approach an ideal cornerstone on the way to quantum computation with frequency encoded continuous-variable cluster states.

Q 4.8 Mon 15:45 Q-H12

Joint measurability in non-equilibrium quantum thermodynamics — •Konstantin Beyer[1], Roope Uola[2], Kimmo Luoma[3], and Walter Strunz[1] — [1]TU Dresden, Dresden, Germany — [2]University of Geneva, Geneva, Switzerland — [3]University of Turku, Turku, Finland

Quantum work and fluctuation theorems are mostly discussed in the framework of projective two-point measurement (TPM) schemes. According to a well known no-go theorem, there is no work observable which satisfies both (i) an average work condition and (ii) the TPM statistics for diagonal input states.

Projective measurements are an idealization and difficult to implement in experiments. We generalize the TPM scenario to arbitrary measurements and ask if the no-go theorem still holds. The answer is twofold. If the initial and the final measurement are incompatible for at least some intermediate unitary evolution, a work observable cannot be constructed. However, if the measurements in the TPM scheme are jointly measurable for any unitary, the no-go theorem does not hold anymore. Then, a (noisy) work observable that satisfies (i) and (ii) can exist.

Q 5: Quantum Technologies I

Time: Monday 14:00–16:00 Location: Q-H13

Q 5.1 Mon 14:00 Q-H13

Monolithic double resonant Bragg-Cavities for efficient Second Harmonic Generation in MoS2 and WS2 — •Heiko Knopf[1,2,3], Sai Shradha[1], Fatemeh Alsadat Abtahi[1], Gia Quyet Ngo[1], Emad Najafidehaghani[4], Antony George[4], Ulrike Schulz[2], Sven Schröder[2], and Falk Eilenberger[1,2,3] — [1]Institute of Applied Physics, Abbe-Center of Photonics, Friedrich-Schiller-University, Albert-Einstein-Straße 15, 07745 Jena — [2]Fraunhofer-Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Straße 7, 07745 Jena — [3]Max Planck School of Photonics, Albert-Einstein-Straße 7, 07745 Jena — [4]Institute of Physical Chemistry, Friedrich Schiller University Jena, Lessingstraße 10, 07743 Jena

Transition metal dichalcogenides (TMDCs) are semiconducting 2D-materials with a strong second-order nonlinearity per unit thickness, making them interesting for nonlinear light-conversion devices. Due to their small thickness, an interaction enhancement is, however, required for efficient operation. Considering the dispersion of real optical layers, double-resonant monolithic Fabry-Perot systems with integrated MoS2 monolayers are designed that provide the required efficiency enhancement through resonances for both fundamental and SHG modes at λ_"FW" =800 "nm" and λ_"SHG" =400 "nm" respectively. We then report on the fabrication of such cavities, with an ion-assisted deposition process. We demonstrate enhanced second-harmonic generation and discuss possible generalization schemes.

Q 5.2 Mon 14:15 Q-H13

Maximising qubit per node in a quantum memory node using silicon vacancy color center and isotope nuclear spin in 4H-SiC — •Shravan Kumar Parthasarathy[1], Roland Nagy[2], Berwian Patrick[1], and Birgit Kallinger[1] — [1]Fraunhofer IISB — [2]FAU Erlangen

The silicon vacancy color center (V_{Si}^{-}) in 4H-SiC is examined to be a potential candidate for quantum technology applications. The experimental feasibility of realizing a quantum memory node is probed into currently by coupling the spin of VSi- in a 4H-SiC sample which is composed of electrons with that of the isotope nuclear spin (^{13}C or ^{29}Si) in the lattice. The coupling of the isotope with the color center can be utilized using a controlled rotation (CROT) pulse sequence to achieve maximal entanglement between the corresponding spins. Maximizing the isotope nuclear spin qubits entangled within one node would prove to be beneficial to the construction of a distributed quantum computing network. It is hence important to analyze how many such nuclear spins could be identified to achieve maximal entanglement. A numerical model that makes use of a protocol to identify the nuclear spin is hence constructed. The sample parameters like the concentration of the isotope and that of the experimental parameters of the microwave pulse sequence which plays a vital role are fed into the simulation and a statistical analysis is performed to understand their corresponding influence. The simulation is aimed at providing a direction on how to adjust the sample and experimental parameters to optimise the control over maximal number of qubits within one quantum memory node.

Q 5.3 Mon 14:30 Q-H13

Successful nanophotonic integration of silicon vacancy colour centres in silicon carbide — •Florian Kaiser[1], Charles Babin[1], Rainer Stöhr[1], Naoya Morioka[1,2], Tobias Linkewitz[1], Timo Steidl[1], Raphael Wörnle[1], Di Liu[1], Erik Hesselmeier[1], Vadim Vorobyov[1], Andrej Denisenko[1], Mario Hentschel[1], Christian Gobert[3], Patrick Berwian[3], Georgy V Astakhov[4], Wolfgang Knolle[5], Sridhar Majety[6], Saha Pranta[6], Marina Radulaski[6], Nguyen T Son[7], Jawad Ul-Hassan[7], and Jörg Wrachtrup[1] — [1]Universität Stuttgart — [2]Kyoto University — [3]IISB Erlangen — [4]HDZI Dresden — [5]IOM Leipzig — [6]Davis University — [7]Linköping University

We nanofabricate silicon vacancy (VSi) centres in silicon carbide (SiC) without degrading their good spin-optical properties. We show nearly lifetime limited optical lines and record spin coherence times for single defects generated via ion implantation and in SiC waveguides.

We show further controlled coupling to nearby nuclear spin qubits with fidelities of 95%. In this regard, VSi centres are unique central spins due to their high operation temperature (T=20 K). The high cooling powers of cryogenic equipment at these temperatures make it possible to directly control nuclear spins via radiofrequency drive.

This shows that VSi centres are prime candidates for developing next-generation quantum networks based on integrated quantum computational clusters with efficient spin-photon interfaces. We will also highlight how the electrical control capabilities offered by the semiconductor SiC platform will play a major role towards scalability.

Q 5.4 Mon 14:45 Q-H13

Fiber-coupled plug-and-play heralded single-photon source based on Ti:LiNbO3 and polymer technology — •Christian Kiessler[1], Harald Herrmann[1], Hauke Conradi[2], Moritz Kleinert[2], and Christine Silberhorn[1] — [1]Paderborn University, Integrated QuantumOptics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn — [2]Fraunhofer HHI, Einsteinufer 37, 10587 Berlin

The large amount of research in quantum technology has led to much progress in this field. Nevertheless, many of the experimental setups in the laboratories are very large, expensive and not robust. In order for quantum technology to take the next step and follow a success story like microelectronics, it is necessary to convert these complex meter-sized systems into millimeter-sized chips. This transition reduces size and cost, improves robustness and reproducibility and opens up the possibilty for future commercialization.
Here, we present the first chip-size plug-and-play heralded single photon source (HSPS) module based on Ti:LiNbO3 and Polymer technology. A SPDC process in a periodicly-poled Ti:LiNbO3 waveguide with a pump wavelength of 532 nm leads to signal and idler of 810 nm and 1550 nm. The chip has a size of $2 \times 1\,\mathrm{cm}^2$ and is fully fibercoupled with one pump input fiber and two output fibers for seperated signal and idler. Additional components like optical filters and heaters are integrated within the module. For $1\,\mu$W pump power we can achieve a heralded second-order correlation function of $g_h^{(2)}(0) < 0.07$ with a heralding efficiency of $\eta_h = 4\,\%$.

Q 5.5 Mon 15:00 Q-H13

Engineering of Quantum Light with Space-Time Correlations — •Fabian Schlue, Marcello Massaro, Jano Gil López, Benjamin Brecht, Harald Herrmann, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Straße 100, 33098 Paderborn, Germany

Deterministic single photon sources are necessary for numerous quantum applications, e.g., quantum communication, quantum metrology, and quantum computing. To approximate a deterministic single photon source with probabilistic sources, source-multiplexing can be used. Examples are spatial multiplexing and frequency multiplexing, which both have challenges: the former requires a large resource overhead, the latter relies on fast and efficient frequency shifting of single photons, which is still an outstanding goal.

Here, we demonstrate a time-frequency multiplexing scheme. Different sources are encoded in the frequency of one photon and, simultaneously, the timing of the partner photon. Frequency-resolved detection reads out the source and low-loss electro-optic time shifting realises the routing. This requires a specially designed source. We utilize our in-house design and production capabilities to fabricate a dispersion-engineered photon-pair source. We combine this with techniques from ultrafast pulse shaping and demonstrate the operation of a tuneable, user-chosen number of multiplexed sources. This demonstration brings us one step closer to a deterministic single photon source based on multiplexing.

Q 5.6 Mon 15:15 Q-H13

Coupling function from bath density of states — •Somayyeh Nemati[1], Carsten Henkel[1], and Janet Anders[1,2] — [1]University of Potsdam, Institut für Physik und Astronomie, 14476 Potsdam, Germany. — [2]Department of Physics and Astronomy, University of Exeter, Stocker Road, Exeter EX4 4QL, UK.

Quantum technologies face many challenges, often arising due to the unavoidable coupling of any system to its environment. Modelling of such open quantum systems requires parameters and the functional form of this coupling, which critically affects the system dynamics [1,2]. However, beyond relaxation rates, realistic parameters for specific environments or materials are rarely known.

Here [3] we present a method of inferring the coupling function between a generic system and its bosonic (e.g., phononic) environment from the experimentally measurable density of states (DOS). The DOS of the well-known Debye model for three-dimensional solids is shown to be equivalent to an Ohmic bath. We further match a real phonon DOS to a series of Lorentzian coupling functions, and determine parameters for gold, yttrium iron garnet (YIG) and iron. The results also illustrate the functional shape of memory kernels. The proposed method may predict more accurately the relaxation of spin systems that are damped by coupling to the crystal lattice.

[1] Zou H. M., Liu R., Long D., Yang J., Lin D., Phys. Scr. **95**, 085105 (2020).
[2] Anders J., Sait C. R. J., Horsley S. A. R., arXiv:2009.00600.
[3] Nemati S., Henkel C., Anders J., arXiv:2112.04001.

Q 5.7 Mon 15:30 Q-H13

Quantum science and technology with small satellites — •Tobias Vogl[1,2], Sebastian Ritter[1], Josefine Krause[1], Mostafa Abasifard[1], Heiko Knopf[1,3], and Falk Eilenberger[1,3] — [1]Institute of Applied Physics, Friedrich-Schiller-University Jena, Germany — [2]Cavendish Laboratory, University of Cambridge, United Kingdom — [3]Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Germany

The maximal transmission distance of quantum states in telecom fibers is limited due to absorption. Global quantum communication therefore requires to link metropolitan fiber networks with satellites. In space-to-ground scenarios, these satellites need to be equipped with efficient and space-compatible single photon sources. Quantum emitters hosted by hexagonal boron nitride (hBN) have been proven to be a suitable candidate for single photon quantum communication, due to their high intrinsic quantum efficiency and photon purity.

Here, we present the QUICK3 space mission, where we combine a quantum emitter in hBN with integrated optics. The optical circuit is based on a laser-written waveguide, that provides the necessary compact footprint for implementation on our 3U CubeSat. The satellite verifies the full functionality of the quantum light source in orbit. Moreover, the satellite has also a quantum interferometer on board, which allows us to test certain quantum gravity models - thereby searching for physics beyond the standard model. To route the photons to the different experiments, we use active Mach-Zehnder switches in the waveguide.

Q 5.8 Mon 15:45 Q-H13

Near-infrared single photon detector with μHz dark count rate — Katharina-Sophie Isleif and •ALPS Collaboration — Deutsches-Elektronen Synchrotron DESY, Hamburg, Germany

On behalf of the ALPS Collaboration we present the use of near-infrared photon-counting technology with μHz dark count rate in the Any Light Particle Search (ALPS II) at DESY. ALPS II is a laboratory-based light shining through a wall experiment that searches for axion-like particles (ALPs). It will utilize a superconducting transition edge sensor (TES) to detect single photons at a wavelength of 1064 nm, which are converted from axion-like particles about once per day assuming an axion-photon coupling strength of $g_{a\gamma\gamma} \approx 2 \times 10^{-11}\,\mathrm{GeV}^{-1}$. To detect this weak signal, a low dark count rate, a high detection efficiency and a good energy resolution are required. We present the experimental setup of the TES and how we reach an intrinsic dark count rate of μHz by using analysis routines in the time and frequency domain. Connecting an optical fiber increases the rate by three orders of magnitude, which can be explained by blackbody radiation and can be decreased by improving the detector's energy resolution and other measures. Additionally, we present the setup for characterizing system detection efficiency using a calibrated single photon source.

Q 6: Quantum Optics (Miscellaneous) I

Time: Monday 14:00–16:00 Location: Q-H14

Invited Talk Q 6.1 Mon 14:00 Q-H14

Quantum Cooperativity: from ideal quantum emitters to molecules — •Claudiu Genes — Max Planck Institute for the Science of Light, Erlangen, Germany

Light-matter platforms provide an optimal playground for the observation and exploitation of quantum cooperative effects. Quantum light, either multimode, as naturally arising in the quantum electromagnetic vacuum or single mode, as confined in the small volume of an optical resonator, can induce strong interactions among quantum emitters. At the level of ideal quantum emitters, recent proposals employing cooperativity aim at the design of extremely thin atom-thick metasurfaces with applications in nonlinear quantum optics or nano-optomechanics or acting as platforms for the study of topological quantum optics effects. For more complex quantum emitters, such as molecules, recent experiments hint towards strong modifications of material properties such as chemical reactivity, charge conductivity and energy transfer. In this talk, I will introduce the basic concepts of quantum cooperativity with emphasis on light-molecule platforms. Aside from a quick introduction into the physics of electron-vibron interactions, I will present recent results on cavity quantum electrodynamics with systems ranging from single molecules to mesoscopic ensembles.

Q 6.2 Mon 14:30 Q-H14

A Quantum Optical Microphone in the Audio Band — •Raphael Nold[1,2], Charles Babin[1,2], Joel Schmidt[1,2], Tobias Linkewitz[1,2], Mariá T. Pérez Zaballos[3], Rainer Stöhr[1,2], Roman Kolesov[1,2], Vadim Vorobyov[1,2], Daniil M. Lukin[4], Rüdiger Boppert[5], Stefanie Barz[2,6], Jelena Vučković[4], Christof M. Gebhardt[2,7], Florian Kaiser[1,2], and Jörg Wrachtrup[1,2] — [1]3rd Institute of Physics, University of Stuttgart, Stuttgart, Germany — [2]Center for Integrated Quantum Science and Technology (IQST), Germany — [3]The Old Schools, Cambridge CB2 1TN, Reino Unido , UK — [4]Ginzton Laboratory, Stanford University, Stanford, CA, USA — [5]Department of Pediatric Audiology and Neurotology, Olgahospital, Stuttgart, Germany — [6]Institute for Functional Matter and Quantum Technologies, University of Stuttgart, Stuttgart, Germany — [7]Institute of Biophysics, Ulm University, Ulm, Germany

We introduce a easy-to-use nonlinear interferometer, that infers optical phase shifts through intensity measurements and sampling rates up to 100 kHz, while still maintaining a quantum advantage in the measurement precision. Capitalising on this, we present an application as a quantum microphone in the audio band. Recordings of both, the quantum sensor and an equivalent classical counterpart are benchmarked with a medically-approved speech recognition test. The results show that the quantum sensor leads to a by $0.57\,\mathrm{dB_{SPL}}$ reduced speech recognition threshold. These results open the door towards applications in quantum nonlinear interferometry, and additionally show that quantum phenomena can be experienced by humans.

Q 6.3 Mon 14:45 Q-H14

Many-particle coherence and higher-order interference — •Marc-Oliver Pleinert[1], Eric Lutz[2], and Joachim von Zanthier[1] — [1]Institut für Optik, Information und Photonik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany — [2]Institute for Theoretical Physics I, University of Stuttgart, 70550 Stuttgart, Germany

Quantum mechanics is based on a set of only a few postulates, which can be separated into two parts: one part governing the ‘inner' structure, i.e., the definition and dynamics of the state space, the wave function and the observables; and one part making the connection to experiments. The latter is known as Born's rule, which - simply put - relates detection probabilities to the modulus square of the wave function. The resulting structure of quantum theory permits interference of indistinguishable paths; but, at the same time, limits such interference to certain interference orders. In general, quantum mechanics allows for interference up to order $2M$ in M-particle correlations. Depending on the mutual coherence of the particles, however, the related interference hierarchy can terminate earlier. Here, we show that mutually coherent particles can exhibit interference of the highest orders allowed. We further demonstrate that interference of mutually incoherent particles truncates already at order $M+1$ although interference of the latter is principally more multifaceted due to a significantly higher number of different final states. Finally, we demonstrate the disparate vanishing of such higher-order interference terms as a function of coherence in experiments with mutually coherent and incoherent sources.

Q 6.4 Mon 15:00 Q-H14

Information Extraction in Photon Counting Experiments — •Timon Schapeler and Tim Bartley — Mesoscopic Quantum Optics, Department of Physics, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany

How much information out of the total available Hilbert space can be extracted with a certain detection architecture in photon-counting experiments? The answer to this question can quantify the photon-number resolution of the detector under test. We use quantum detector tomography, which yields a quantum mechanical description of a detector in terms of its positive operator valued measures (POVMs), to compare the quality of five different multiplexed detectors. Quantum detector tomography yields the conditional probabilities of different detection outcomes occurring given a certain number of incident photons, which can directly be used to determine figures of merit such as efficiency, dark counts and cross-talk. These measures provide an intuition of the quality of the detector; however, it may be unclear how they combine to determine the utility of certain detection outcomes. Here, the concept of information is much more useful. From the POVMs we can calculate the amount of information that can be extracted out of the Hilbert space by certain detection outcomes.

Q 6.5 Mon 15:15 Q-H14

Parametrically driven dissipative three-level Dicke Model — •Jim Skulte[1,2], Phatthamon Kongkhambut[1], Hans Kessler[1], Andreas Hemmerich[1,2], Ludwig Mathey[1,2], and Jayson G. Cosme[3] — [1]Zentrum für Optische Quantentechnologie and Institut für Laser-Physik, University of Hamburg, Hamburg, Germany — [2]The Hamburg Center for Ultrafast Imaging, University of Hamburg, Hamburg, Germany — [3]National Institute of Physics, University of the Philippines, Diliman, Philippines

In this talk, we discuss the three-level Dicke model, which describes a fundamental class of light-matter systems. We determine the phase diagram in the presence of dissipation, which we assume to derive from photon loss. Utilizing both analytical and numerical methods we characterize the incommensurate time crystalline, light-induced, and light-enhanced superradiant states in the phase diagram for the parametrically driven system. As a primary application, we demonstrate that a shaken atom-cavity system is naturally approximated via a parametrically driven dissipative three-level Dicke model.

Q 6.6 Mon 15:30 Q-H14

N-photon Subtractor Using a 1D Rydberg Superatom Chain — •Nina Stiesdal[1], Lukas Ahlheit[1], Hannes Busche[1], Kevin Kleinbeck[2], Jan Kumlin[2], Hans-Peter Büchler[2], and Sebastian Hofferberth[1] — [1]Institute for Applied Physics, University of Bonn — [2]Institute for Theoretical Physics III, University of Stuttgart

Here we present our experiments with a 1D chain of Rydberg superatoms coupled to a few-photon probe field. Our Rydberg superatoms consist of thousands of atoms collectively acting as a single two-level system because of the Rydberg blockade.

Due to the collective nature of the excitation, we reach very high coupling between the light field and our superatoms and strongly directional emission back into the initial probe mode. Thus, our system resembles a system of emitters coupled to a single-mode waveguide - but in free space.

We discuss how this waveguide description can lead to insights into the internal dymanics of the Rydberg superatom, and show how we can use our cascaded system to realize a N-photon subtractor.

Q 6.7 Mon 15:45 Q-H14

Transient dipolar interactions in a thin thermal vapor — •Felix Moumtsilis[1], Max Mäusezahl[1], Florian Christaller[1], Hadiseh Alaeian[2], Harald Kübler[1], Robert Löw[1], and Tilman Pfau[1] — [1]5. Physikalisches Institut and Center for Integrated Quantum Science and Technology IQST, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — [2]Departments of Electrical & Computer Engineering and Physics & Astronomy, Purdue University, West Lafayette, IN 47907, USA

Micrometer-sized cells for atomic vapors are powerful devices in the realm of fundamental research and applied quantum technology. The effect of light-induced atomic desorption (LIAD) is exploited to produce high atomic densities (n $\gg k^3$) in a rubidium vapor cell. An intense off-resonant laser is pulsed on a micrometer-sized sapphire-coated cell, which results in the desorption of atomic clouds from both internal surfaces. The resulting transient (LIAD-induced) atomic densities are investigated by time-resolved absorption spectroscopy for the D1 and D2 line respectively [1]. This time dependent broadening and line shift is attributed to dipole-dipole interactions. As this timescale is much faster than the natural atomic lifetime, the experiment probes the dipolar interaction in a non-equilibrium situation beyond the usual steady-state, assumed in the derivation of the Lorentz-Lorenz shift. This fast switching of the atomic density and dipolar interactions could be the basis for future quantum devices based on the excitation blockade.

[1] Christaller et al., arXiv:2110.00437 (2021)

Q 7: Precision spectroscopy of atoms and ions I (joint session A/Q)

Time: Monday 14:00–15:30 Location: A-H2

Q 7.1 Mon 14:00 A-H2

Sympathetic cooling of macroscopically separated ions via image-current coupling — •Christian Will[1], Matthew Bohman[1,2], Markus Wiesinger[1,2], Fatma Abbass[4], Jack Devlin[2,7], Stefan Erlewein[2,7], Markus Fleck[2,8], Julia Jäger[1,7], Barbara Latacz[2], Peter Micke[7], Andreas Mooser[1], Daniel Popper[4], Elise Wursten[1,2,7], Klaus Blaum[1], Yasuyuki Matsuda[8], Christian Ospelkaus[5,6], Wolfgang Quint[9], Jochen Walz[3,4], Christian Smorra[2,4], and Stefan Ulmer[2] — [1]Max-Planck-Institut für Kernphysik — [2]RIKEN — [3]Helmholtz-Institut Mainz — [4]Johannes Gutenberg-Universität Mainz — [5]Leibniz Universität Hannover — [6]Physikalisch-Technische Bundesanstalt — [7]CERN — [8]University of Tokyo — [9]GSI Helmholtzzentrum für Schwerionenforschung GmbH

A general-purpose cooling technique that achieves mK-temperatures for species without suitable laser transitions is of interest for a wide range of AMO experiments with trapped charged particles. We present recently published results on sympathetically cooling a single proton in a Penning trap with laser-cooled beryllium ions located in a different trap (Bohman et al., Nature, 2021). Coupling is achieved via image currents induced in adjacent trap electrodes, allowing a macroscopic separation between the two species. This techniques allows cooling of any trapped charged particle, with a particular focus on exotic species such as antimatter or highly-charged ions.

This talk will cover the most recent experimental results as well as future prospects based on simulation work.

Q 7.2 Mon 14:15 A-H2

Implementing Sympathetic Laser Cooling and a Josephson Junctions based Voltage Source for the Measurement of the Nuclear Magnetic Moment of ^{3}He^{2+} — •Annabelle Kaiser[1], Antonia Schneider[1], Andreas Mooser[1], Stefan Dickopf[1], Marius Müller[1], Alexander Rischka[1], Stefan Ulmer[2], Jochen Walz[3], and Klaus Blaum[1] — [1]Max-Planck Institute for Nuclear Physics, Heidelberg, Germany — [2]RIKEN, Wako, Japan — [3]Johannes Gutenberg-University and Helmholtz-Institute, Mainz, Germany

The Heidelberg 3He-experiment is aiming at the first direct high-precision measurement of the nuclear magnetic moment of ^{3}He^{2+}, with a relative uncertainty on the 10^{-9} level. The helion nuclear magnetic moment is an important parameter for the development of hyperpolarized 3He-NMR-probes for absolute magnetometry.

The measurement is performed using a cryogenic four Penning-trap setup, with techniques presented in [1]. To achieve the mandatory frequency stability for spin-state detection, a single ^{3}He^{2+} ion will be prepared at temperatures of a few mK via sympathetic laser cooling with ^{9}Be$^+$. To further improve the stability, the noise generated by the voltage sources applied to the trap electrodes can be reduced by implementing Josephson junctions as a voltage source. The tuning will be achieved by switching a low-noise DAC in series to the Josephson junctions, aiming at an absolute voltage stability better than 70nV over two minutes. The setup and status of the project will be presented.

[1] Mooser et al, J. Phys.: Conf. Ser. 1138 012004 (2018)

Q 7.3 Mon 14:30 A-H2

High-precision measurement of the hyperfine structure of ^{3}He$^+$ in a Penning trap — •Antonia Schneider[1], Bastian Sikora[1], Stefan Dickopf[1], Marius Müller[1], Natalia S. Oreshkina[1], Alexander Rischka[1], Igor Valuev[1], Stefan Ulmer[2], Jochen Walz[3,4], Zoltan Harman[1], Christoph H. Keitel[1], Andreas Mooser[1], and Klaus Blaum[1] — [1]Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117, Heidelberg, Germany — [2]RIKEN, Ulmer Fundamental Symmetries Laboratory, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan — [3]Institute for Physics, Johannes Gutenberg-University Mainz, Staudinger Weg 7, D-55099 Mainz, Germany — [4]Helmholtz Institute Mainz, Staudingerweg 18, D-55128 Mainz, Germany

We investigated the ground-state hyperfine structure of a single ^{3}He$^+$ ion in a Penning trap to directly measure the zero-field hyperfine splitting, the bound electron g-factor and the nuclear g-factor with a relative precision of $3 \cdot 10^{-11}$, $2 \cdot 10^{-10}$ and $8 \cdot 10^{-10}$, respectively. The latter allows for the determination of the g-factor of the bare nucleus with a relative precision of $8 \cdot 10^{-10}$ via our accurate calculation of the diamagnetic shielding constant. This constitutes the first direct calibration for ^{3}He nuclear magnetic resonance (NMR) probes and an improvement of the precision by one order of magnitude compared to previous indirect results [1]. The measured zero-field hyperfine splitting allows us to determine the Zemach radius, which characterizes the electric and magnetic form factors, with a relative precision of $7 \cdot 10^{-3}$.

[1] Y. I. Neronov and N. N. Seregin, Metrologia, **51** (2014) 54.

Q 7.4 Mon 14:45 A-H2

Optimal laser cooling of a single ion in a radiofrequency trap — •Daniel Vadlejch[1], André Kulosa[1], Henning Fürst[1,2], Oleg Prudnikov[3], and Tanja Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [3]Institute of Laser Physics, 630090, Novosibirsk, Russia

We present a systematic study of quench cooling of a single ion trapped in a linear radiofrequency (RF) Paul trap. In our experiments, a narrow electronic quadrupole transition near 411 nm in ^{172}Yb$^+$ is used for resolved sideband cooling [1]. The cooling transition is effectively quench-broadened by means of a laser at 1650 nm, coupling the excited state of the transition to a higher-lying, fastly decaying state. We control the broadening via the intensity of the quenching field and distinguish different regimes of laser cooling. We show optimum cooling parameters for rapid cooling towards the motional ground state of the trap and discuss their impact on the population distribution of Fock states during the cooling process. The presented work builds the fundament for further multi-ion experiments, e.g, using large mixed-species crystals with different cooling properties for optical clocks [2].

[1] D. Kalincev et al., *Quantum Sci. Technol.* **6**, 034033 (2021).
[2] J. Keller et al., *Phys. Rev. A* **99**, 013405 (2019).

Q 7.5 Mon 15:00 A-H2

Hyperfine Spectroscopy of Single Molecular Hydrogen Ions in a Penning Trap at Alphatrap — •C. M. König[1], F. Heisse[1], J. Morgner[1], T. Sailer[1], B. Tu[1,2], K. Blaum[1], S. Schiller[3], and S. Sturm[1] — [1]Max-Planck-Institut für Kernphysik, 69117 Heidelberg — [2]Institute of Modern Physics, Fudan University, Shanghai 200433 — [3]Institut für Experimentalphysik, Univ. Düsseldorf, 40225 Düsseldorf

As the simplest molecules, molecular hydrogen ions (MHI) are an excellent system for testing QED. We plan to perform high-precision spectroscopy on single MHI in the Penning-trap setup of Alphatrap [1], initially focusing on the hyperfine structure of HD$^+$. This will allow extracting the bound g factors of the constituent particles and coefficients of the hyperfine hamiltonian. The latter can be compared with high-precision ab initio theory [2] and are important for a better understanding of rovibrational spectroscopy performed on this ion.
In the future, we aim to extend our methods to single-ion rovibrational laser spectroscopy of H_2^+ enabling the ultra precise determination of fundamental constants, such as $m_\mathrm{p}/m_\mathrm{e}$ [3]. The development of the required techniques will be an important step towards spectroscopy of an antimatter $\overline{H}_2^-$ ion [4]. In this contribution, I will present an overview of the experimental setup and first measurement results of the hyperfine structure of HD$^+$.

[1] S. Sturm *et al.*, Eur. Phys. J. Spec. Top. **227**, 1425-1491 (2019)
[2] J.-Ph. Karr, *et al.* Phys. Rev. A **102**, 052827 (2020)
[3] J.-Ph. Karr, *et al.*, Phys. Rev. A **94**, 050501(R) (2016)
[4] E. Myers, Phys. Rev. A **98**, 010101(R) (2018)

Q 7.6 Mon 15:15 A-H2

Enhanced Dipolar Interactions — •Artur Skljarow[1], Benyamin Shnirman[1], Xiaoyu Cheng[1], Charles S. Adams[2], Tilman Pfau[1], Robert Löw[1], and Hadiseh Alaeian[3] — [1]5. Physikalisches Institut and IQST, Universität Stuttgart, Pfaffenwaldring 57, Stuttgart, Germany — [2]JQC Durham-Newcastle, Department of Physics, Durham University, South Road, Durham, United Kingdom — [3]Department of Physics & Astronomy, Purdue Quantum Science & Engineering Institute, Purdue University, West Lafayette, IN, USA

The interest in nonlinear quantum optics based on strong photon-photon interactions continuously grows with time as it might lead to an all-optical quantum network.

Atoms aligned in a 1D chain or 2D lattice show stronger interactions than in an arbitrary 3D arrangement as they exchange photons in a favored direction. A wide variety of ultracold experiments makes use of this fact by trapping individual atoms in 1D or 2D optical traps or tweezers and probing their interaction with a free-space laser beam. In contrast to the ultracold experiments, here we create confined 1D light fields, well below the diffraction limit, with engineered nanophotonic devices and immerse them in a thermal cloud of atoms. As a result, we observe the first realization of repulsive blue-shifted dipole-dipole interactions in a thermal vapor. Additionally, we demonstrate the power of nanophotonics by boosting those interactions by almost one order of magnitude via a Purcell modification hence, creating a highly nonlinear medium.

Q 8: Quantum Gases (Bosons) II

Time: Monday 16:30–18:30 Location: Q-H10

Q 8.1 Mon 16:30 Q-H10

Floquet-heating-induced non-equilibrium Bose condensation in a dissipative optical lattice — •Alexander Schnell[1], Ling-Na Wu[1], Artur Widera[2], and André Eckardt[1] — [1]Technische Universität Berlin, Institut für Theoretische Physik, 10623 Berlin, Germany — [2]Department of Physics and State Research Center OPTIMAS, University of Kaiserslautern, 67663 Kaiserslautern, Germany

We investigate theoretically a mixture of two weakly interacting species of bosonic quantum gases, where the parameters are such that an open-system description in terms of a Floquet-Born-Markov master equation applies. One component, the system, is a non-interacting gas in a one-dimensional optical lattice potential, the other component, the bath, is a three-dimensional weakly-interacting BEC. Interestingly, by additionally time-periodically driving the system at one lattice site, a nonequilibrium steady state that features Bose condensation can be induced in the system. Condensation can occur at bath temperatures well above equilibrium condensation temperature as well as in excited single-particle states. An intuitive explanation is that the Floquet drive induces a large inflow of heat that can be avoided by the system by condensing in a mode that decouples from the driving site. The model should be realizable with state of the art quantum gas experiments.

Q 8.2 Mon 16:45 Q-H10

Driving a 1D Bose Gas into Non-Equilibrium by Particle Losses — Anja Seegebrecht and •Carsten Henkel — Universität Potsdam, Institut für Physik und Astronomie

Low-dimensional Bose gases form a model system where comparison to a portfolio of theories (Lieb-Liniger, Luttinger liquid, stochastic Gross-Pitaevskii equation [1]) is possible. Being a nearly integrable system, long-lived non-equilibrium states appear while particles are lost [2]. We perform stochastic simulations for loss processes also involving 2-, or 3-body collisions. The thermometers we developed give different readings as the system evolves, that can be given heuristic interpretations and compared to experiments. Particular large discrepancies appear due to the “shot noise” that arises from the information gain due to particle loss [3].

[1] N. Proukakis, S. Gardiner, M. Davis, and M. Szymańska, *Quantum Gases: Finite Temperature and Non-Equilibrium Dynamics*, Series Cold Atoms vol. 1 (Imperial College Press 2013).
[2] A. Johnson, S. Szigeti, M. Schemmer, and I. Bouchoule, “ Long-lived non-thermal states realized by atom losses in one-dimensional quasi-condensates,” Phys. Rev. A **96** (2017) 013623.
[3] P. Grišins, B. Rauer, T. Langen, J. Schmiedmayer, and I. E. Mazets, “Degenerate Bose gases with uniform loss,” Phys. Rev. A **93** (2016) 033634; I. Bouchoule, M. Schemmer, and C. Henkel, “Cooling phonon modes of a Bose condensate with uniform few body losses,” SciPost Phys. **5** (2018) 043.

Q 8.3 Mon 17:00 Q-H10

Experimental realization of a 3D random hopping model — •Patrick Mischke, Carsten Lippe, Jana Bender, Tanita Klas, Thomas Niederprüm, and Herwig Ott — Department of Physics and research center OPTIMAS, Technische Universität Kaiserslautern, Germany

We present experimental results from a Rydberg system described by the XY-model Hamiltionian with random couplings.

While systems with disordered potentials have already been studied in detail, experimental investigations on systems with disordered hopping are still rare. Small amounts of disorder can dramatically change the transport properties of a system compared to the underlying simple model. We present an experimental study of a dipole–dipole-interacting three-dimensional Rydberg system described by the XY transport model for spin-$\frac{1}{2}$ particles $\hat{H}_{XY} = \sum \frac{J_{ij}}{2}\left(\hat{\sigma}_i^x\hat{\sigma}_j^x + \hat{\sigma}_i^y\hat{\sigma}_j^y\right) + \sum \varepsilon_i \hat{\sigma}_i^z$. We observe spectroscopic agreement with theoretical models and discuss emerging localization phenomena.

The presented Rydberg platform allows for high control over the microscopic parameters and will allow to further study transport processes and localization phenomena in random hopping models.

Q 8.4 Mon 17:15 Q-H10

Experimental characterization of a dissipative phase transition in a multi-mode system — •Marvin Röhrle, Jens Benary, Christian Baals, Erik Bernhart, Jian Jiang, and Herwig Ott — Department of Physics and Research Center OPTIMAS, Erwin-Schrödinger-Straße 46, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

We experimentally investigate the behavior of a driven-dissipative Bose-Einstein condensate of weakly interacting ^{87}Rb atoms in a 1-D optical lattice. The dissipation is induced by a scanning electron microscope setup, which allows us to observe a single site time resolved. Tunneling from the neighboring sites makes up the driving force.

By changing the tunnel coupling J of the lattice, a dissipative phase transition from a coherent super fluid phase to an incoherent phase can be seen. In the vicinity of the phase transition, both branches coexist in a meta stable region depending on the initial state. Measuring the relaxation rates between the two states allows us to approximate the adiabatic decay rate and find the critical point. In every individual realization of the experiment, the filling of the site shows a digital behavior, which is visible as pronounced jumps in the site occupation. We find that the switching between both states takes only a few tunneling times despite hundreds of atoms tunneling. Furthermore, starting from an initially filled site, the losses induce a super fluid current which keeps the site filled. This complete extinction of a matter wave within a medium indicates the onset of coherent perfect absorption.

Q 8.5 Mon 17:30 Q-H10

High signal to noise imaging of potassium at high magnetic fields — •Maurus Hans, Celia Viermann, Marius Sparn, Nikolas Liebster, Helmut Strobel, and Markus K. Oberthaler — Kirchhoff-Institut für Physik, Universität Heidelberg, Deutschland

In 39K a broad Feshbach resonance at 560G allows for the tuning of the atomic interaction over a wide range. To detect the in-situ atomic density with high spatial resolution, direct imaging at this field is necessary. However, for the F=1 ground state manifold a closed optical transistion does not exist. In this talk, we present an imaging scheme that utilises four atomic levels and two laser frequencies to get an approximately closed optical cycle [1]. It allows for a drastic enhancement of the number of scattered photons. We demonstrate the extraction of the atomic column density of a 39K Bose-Einstein condensate with absorption imaging and show the suitability of the scheme for fluorescence imaging of few atoms per detection volume.

[1] Hans, M. et al., Rev. Sci. Instrum. 92, 023203 (2021)

Q 8.6 Mon 17:45 Q-H10

Disorder in topological Floquet engineered systems. — •Christoph Braun[1,2,3], Raphaël Saint-Jalm[1,2], Alexander Hesse[1,2], Monika Aidelsburger[1,2], and Immanuel Bloch[1,2,3] — [1]Ludwig-Maximilians-Universität München, München, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), München, Germany — [3]Max-Planck-Institut für Quantenoptik, Garching, Germany

Floquet engineering, i.e. periodic modulation of the systems parameters, has proven as a powerful experimental tool for the realization of quantum systems with exotic propertiest that are otherwise not accessible in static realizations. Our experimental system consists of bosonic atoms in a periodically driven honeycomb lattice. Depending on the driving parameters several topological phases can be realized, including genuine out-of-equilibrium topological phases without any static analog [1]. Recently, we have added a random optical potential to study localization in topological bands. To this end we are investigating the real-space evolution of an initially localized wavepacket after release from a tightly-focused optical tweezer. In general, disorder will drive a transition to a topologically trivial phase. The interplay between topology and disorder in driven systems, however, was further predicted to give rise to exotic disorder-induced topological phases, such as the anomalous Floquet Anderson insulator.

Q 8.7 Mon 18:00 Q-H10

A Kapitza Pendulum for Ultracold Atoms — •Erik Bernhart, Jian Jiang, Marvin Röhrle, Jens Benary, Marvin Beck, Christian Baals, and Herwig Ott — Department of Physics and Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany

We present the experimental realization of a Kapitza pendulum for ultracold ^{87}Rb atoms.

Our experiment shows how a periodic modulation of the potential can lead to dynamical stabilization of the atomic motion in an otherwise unstable potential. While the time average of the modulated potential vanishes, the corresponding Floquet Hamiltonian results in an effective time independent potential, which traps the atoms.

In our experiment we create the Kapitza pendulum by two time modulated Gaussian shaped laser beams, which generate an attractive and repulsive potential. We analyze the lifetime and the stability of the trap, depending on the driving frequency of the potentials.

Q 8.8 Mon 18:15 Q-H10

Quantum phases of a dipolar gas of bosons in an one-dimensional optical lattice — •Rebecca Kraus[1], Titas Chanda[2,3], Jakub Zakrzewski[2,4], and Giovanna Morigi[1] — [1]Theoretical Physics, Saarland University, Saarbrücken, Germany — [2]Institute of Theoretical Physics, Jagiellonian University, Kraków, Poland — [3]ICTP, Trieste, Italy — [4]Mark Kac Complex Systems Research Center, Jagiellonian University, Kraków, Poland

We present a theoretical analysis of the phase diagram of ultracold bosons in a lattice and interacting with long-range forces decaying with the inter-particle distance. The theoretical model is an extended Bose-Hubbard model and describes the dynamics of ultracold atoms in optical lattices realised in present experimental platforms. We determine the ground state in one dimension using numerical programs based on tensor networks. We focus in particular on parameters for which quantum fluctuations compete with the interaction-induced correlated hopping between lattice sites. We analyse the phases emerging from the competition of these two mechanisms. For larger densities we identify the parameters where correlated hopping and quantum fluctuations destructively interfere. This quantum interference leads to insulating phases at relatively large kinetic energies, where one would otherwise expect superfluidity. For unit density our results predict that correlated tunnelling can significantly modify the parameter range where the topological phase is found. At vanishing values of the onsite interactions, moreover, correlated tunnelling promotes here the onset of a phase separation.

Q 9: Precision Measurements and Metrology II

Time: Monday 16:30–18:15 Location: Q-H11

Invited Talk Q 9.1 Mon 16:30 Q-H11

Rotation sensors for planet Earth: Introducing ring laser gyroscopes — •Simon Stellmer[1], Oliver Heckl[2], and Ulrich Schreiber[3,4,5] — [1]Rheinische Friedrich-Wilhelms-Universität Bonn, Germany — [2]Universität Wien, Austria — [3]Technische Universität München, Germany — [4]University of Canterbury, Christchurch, New Zealand — [5]Fundamentalstation Wettzell, Bad Kötzting, Germany

The rotation rate of Earth is not as constant as it may seem: in fact, it is perturbed by various effects, ranging from astronomical and atmospheric phenomena all the way to anthropogenic climate change.

Very-long baseline interferometry (VLBI) is a well-established and highly precise method to access the rotation of Earth, but VLBI is not well-suited for continuous monitoring at high temporal resolution. This is where ring laser gyroscopes enter the stage.

In this presentation, we will introduce the working principle of ring lasers and their application in geodetic observations. We will present the latest developments and future concepts that will allow for continuous tracking of sub-daily variations in the Earth rotation rate. Such observations are in high demand in the fields of radioastronomy, geodesy, and geophysics.

Q 9.2 Mon 17:00 Q-H11

Precision and readout algorithms of DFM-interferometry — •Tobias Eckhardt — Universität Hamburg, Hamburg, Germany

We present our work on the readout of compact displacement sensors based on deep-frequency modulation interferometry. We aim to use such sensors for the local readout of test-masses in future gravitational wave detectors. We show the results of a readout noise analysis for such sensors where we derive their limitations by computing the Cramer-Rao lower bound of their phase estimator in the presence of common noise sources. Additionally we discuss a new algorithm to extract the interferometric phase in deep-frequency-modulation interferometry in a fast and non-recursive way. Finally, we present the status of implementing such an algorithm using real-time FPGA processing.

Q 9.3 Mon 17:15 Q-H11

Investigation of Photoelastic Noise in Einstein Telescope — •Jan Meyer[1,2], Stefanie Kroker[1,2,3], Mika Gaedtke[2,4], and Johannes Dickmann[1,2,3] — [1]TU Braunschweig, Institut für Halbleiterphysik, Germany — [2]LENA Laboratory for Emerging Nanometrology, Braunschweig, Germany — [3]Physikalisch-Technische Bundesanstalt, Braunschweig — [4]Leibniz Universität Hannover, Hannover, Germany

Since the first direct detection of gravitational waves in 2015, the research in the field of interferometric gravitational wave detectors underwent a decisive progress. The second generation of the Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) and Advanced VIRGO utilizes pioneering noise reduction techniques like squeezing of light to reach sensitivities of better than 1E-23. The most critical noise sources limiting this precision are driven by thermal fluctuations in the optical components. To ensure that future gravitational wave detectors can reach their best possible sensitivity, all noise sources have to be investigated. In this contribution, we quantify photoelastic fluctuations in solids as a noise source in Einstein Telescope (ET). The local variations of the stress caused by thermal fluctuations lead to fluctuations of the refractive index due to the photoelastic material property. We present calculations of the photoelastic noise in the beam splitter and the input test mass of the ET. We show that the amplitude of the photoelastic noise in the ET low-frequency detector is about four orders of magnitude below the maximum design sensitivity and five orders of magnitude below that of the ET high-frequency detector.

Q 9.4 Mon 17:30 Q-H11

High-reflective Si metamaterial coating for 1550 nm — •Mariia Matiushechkina[1], Andrey Evlyukhin[2], Boris Chichkov[2], and Michèle Heurs[1] — [1]Institute for Gravitational Physics, Leibniz Universität Hannover, Callinstr. 36, 30167 Hannover, Germany — [2]Institute of Quantum Optics, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

Modern quantum experiments require systems with unique mechanical and optical properties that would be able to operate at the quantum regime. One particular possible implementation is a high-reflective at the wavelength 1550 nm substrate that will be kept at cryogenic temperature for the purpose to increase sensitivity in the future gravitational wave detectors. We suggest a design of a system that exposes not only high mechanical properties but also high-reflectivity due to the metamaterial surface on the top. The metasurface is made from periodically arranged silicon nano-spheres placed on a sapphire substrate that coming into the Mie-resonance with the incident light. We theoretically and numerically investigate the functionality of such metasurface and study the influence of structural and dimensional imperfections on the optical properties.

Q 9.5 Mon 17:45 Q-H11

Frequency-Dependent Squeezing from a Squeezer — •Jonas Junker[1,2,3], Nived Johny[1,2,3], Dennis Wilken[1,2,3], and Michèle Heurs[1,2,3] — [1]Max Planck Institute for Gravitational Physics, and Institute for Gravitational Physics, Germany — [2]QuantumFrontiers — [3]PhoenixD

In opto-mechanical force measurements, quantum back-action noise fundamentally limits the measurement sensitivity at low frequencies. To reduce or even evade back-action noise, several techniques have been proposed, e.g. the injection of squeezed light. When the squeezed sidebands have a frequency-dependent phase difference the noise can be likewise reduced in a broad frequency band. However, for a full back-action evasion, an inversely input squeezed state [1] serving as an effective negative mass oscillator can be used [2]. This state calls not only for a frequency-dependent squeezing phase but also for a frequency-dependent squeezing factor. In our talk, we present the idea of using a detuned optical-parametric oscillator (OPO) to generate this needed state. We briefly show how we have realized and experimentally controlled our detuned OPO. We reconstruct the output state of this squeezer with quantum tomography for different measurement frequencies. This allows to even visually demonstrate and analyze the frequency-dependent state rotation. Our system seems to be applicable as a non-ideal, but very simple effective-negative mass oscillator applicable in opto-mechanical force measurements limited by back-action noise. [1] Kimble et al. Phys. Rev. D65, 022002 (2001) [2] Wimmer, Steinmeyer, Hammerer, and Heurs, Phys. Rev. A89,053836 (2014)

Q 9.6 Mon 18:00 Q-H11

Suitable optomechanical oscillators for an all optical coherent quantum noise cancellation epxeriment — •Bernd Schulte[1,2], Roman Kossak[1,2], Nived Johny[1,2], Mariia Matiushechkina[1,2,3], and Michèle Heurs[1,2,3] — [1]Max Planck Institute for Gravitational Physics and Institute for Gravitational Physics, Hannover, Germany — [2]Quantum Frontiers — [3]PhoenixD

Optomechanical detectors have reached the standard quantum limit in position and force sensing where backaction noise, caused by radiation pressure noise, starts to be the limiting factor for sensitivity. One strategy to circumvent measurement backaction, and surpass the standard quantum limit, has been suggested by M. Tsang and C. Caves [1] and is called Coherent Quantum Noise Cancellation (CQNC). This scheme can be viewed as coupling a second oscillator with an effectively negative mass (see J. Junker) to the one subject to quantum radiation pressure noise and thus realizing a quantum non-demolition measurement. After an introduction of the idea and the requirements for CQNC this talk will be focused on the oscillator susceptible to quantum radiation pressure noise. We discuss and show the measurement principles intended to determine mechanical and optical properties of our devices (membrane-in-the-middle vs. membrane-at-the-end setup). These setups could also be used to shift the mechanical properties via the optical spring effect to satisfy CQNC requirements.

[1] M. Tsang and C. Caves, Phys. Rev. Lett. 105 ,123601, 2010.

Q 10: Quantum Information (Concepts and Methods) II

Time: Monday 16:30–17:45 Location: Q-H12

Q 10.1 Mon 16:30 Q-H12

Initial state dependence in the dynamics of open systems — •Sebastian Wenderoth and Michael Thoss — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

Intuitively, an open system coupled to an environment relaxes to a well-defined and unique equilibrium state, which is determined by macroscopic properties of the environment like the temperature or the chemical potential only. In the long-time limit, the state of the open system is thus expected to be independent of its initial state.

In this contribution we present a concept which allows us to characterize the influence of the initial state on the dynamics of an open system. Our approach is based on the reduced system propagator, the latter being a linear map on the open system's state space. Using properties of the reduced system propagator we quantify the influence of the initial state on expectation values of observables of the open system. Additionally, we provide necessary and sufficient conditions under which the long-time dynamics of an open system is independent of its initial state. We demonstrate our concepts for different long-time behaviors of the spin-boson model.

Q 10.2 Mon 16:45 Q-H12

Bohmian Trajectories in a Double Slit Experiment — •Carlotta Versmold[1,2,3], Jan Diewior[1,2,3], Lukas Knips[1,2,3], Florian Huber[1,2,3], Jasmin Meinecke[1,2,3], and Harald Weinfurter[1,2,3] — [1]Department für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany

Bohmian mechanics (BM) is one of many alternative interpretations of quantum mechanics (QM). Attributing a definite position to particles at all times it allows the introduction of particle trajectories, which are forbidden in standard QM. Necessary for this is the introduction of nonlocal effects into the theory, which can cause instantaneous reordering of trajectories. In order to investigate this non-locality one photon of an entangled photon pair is sent through a double slit apparatus where its average Bohmian trajectory is observed via weak measurement. Employing the entanglement in the photon's polarization degree of freedom enables to analyze different cases of which-way-information as the evolution of the interfering photon depends on the observation of the second photon. By varying the point in time of the polarization-measurement of the second photon, delayed choice measurements of the corresponding trajectories can be performed.

Average trajectories have already been measured in experiments and are shown to correspond with those calculated in BM. Nevertheless, the meaning of average trajectories and BM is much discussed. This experiment will contribute to a better understanding of the theory.

Q 10.3 Mon 17:00 Q-H12

Markovian Quantum Systems with Full and Fast Hamiltonian Control — •Emanuel Malvetti[1,2], Frederik vom Ende[1,2], Thomas Schulte-Herbrüggen[1,2], and Gunther Dirr[3] — [1]Dept. Chem., TU-München (TUM) — [2]Munich Centre for Quantum Science and Technology (MCQST) and Munich Quantum Valley (MQV) — [3]Institute of Mathematics, Universität Würzburg

Markovian quantum systems with full and fast Hamiltonian control can be reduced to an equivalent control system on the eigenvalues of the density matrix describing the state. First we consider the case of a single qubit, presenting explicit solutions of the optimal control problem for a large family of Lindblad operators. For the cases where analytic solutions seem out of reach, we can still efficiently compute numerical solutions. Second we consider quantum systems of arbitrary finite dimension. While analytic solutions to optimal control problems do not exist in the general case, the reduced control system on the eigenvalues is still a powerful tool. As an example, we derive necessary and sufficient conditions for a Markovian quantum system to be coolable.

Q 10.4 Mon 17:15 Q-H12

Bohmian Trajectories of Quantum Walks — •Florian Huber[1,2,3], Carlotta Versmold[1,2,3], Jan Dziewior[1,2,3], Lukas Knips[1,2,3], Harald Weinfurter[1,2,3], and Jasmin Meinecke[1,2,3] — [1]Department für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MC-QST), Munich, Germany

Quantum walks are the quantum mechanical equivalent to the classical random walk and ,in standard quantum mechanics (QM), describes the coherent propagation of a quantum particle in a discrete environment, which cannot be represented with trajectories, as it would be possible in the classical case. However, certain interpretations of QM, as for example Bohmian mechanics, a non-local hidden variable theory, attribute definite positions and momenta to particles and therefore allow particle trajectories. In classical electrodynamics energy flow lines of photons, given by the Poynting vectors, correspond to these Bohmian trajectories. Here we report on the simulation and how to observe energy flow lines of a quantum walk, realized in an integrated waveguide array written into fused silica substrate. The curvature of the phase front, corresponding to the Poynting vector is reconstructed via weak measurements. To this end, the curvature is first weakly coupled to the polarization of the photons. Subsequently, a strong polarization measurement, behind a phase front preserving magnification optics, gives the desired information on the phase front curvature and thus makes a reconstruction of the Bohmian trajectories possible.

Q 10.5 Mon 17:30 Q-H12

On Quantum Cats and How to Control Them — •Matthias G. Krauss[1,2], Daniel M. Reich[1,2], and Christiane P. Koch[1,2] — [1]Universität Kassel, Kassel, Germany — [2]Freie Universität, Berlin, Germany

Schrödinger cat states are non-classical superposition states that are useful in quantum information science, for example for computing or sensing. Optimal control theory provides a set of powerful tools for preparing such superposition states, for example in experiments with superconducting qubits [Ofek, et al. *Nature* **536**, 2016]. In general, the preparation of specific cat states is considered to be a hard problem [Kallush et al. *New J. Phys.* **16**, 2014]. Since many applications do not rely on a particular cat state, it can be beneficial to optimize towards arbitrary cat states instead. We derive optimization functionals that target the cat properties without prescribing a specific cat state. To analyze the practical performance of these functionals, we exemplify their use in conjunction with Krotov's method [Reich et al. *J. Chem. Phys.* **136**, 2012]. In particular, we analyze the quantum speed limit for generating entangled cat states in a Jaynes-Cummings model and test their robustness under dissipation.

Q 11: Quantum Technologies II

Time: Monday 16:30–18:00 Location: Q-H13

Invited Talk Q 11.1 Mon 16:30 Q-H13

Quantum-state engineering with optically-trapped neutral atoms — •Vladimir M. Stojanovic, Gernot Alber, Thorsten Haase, and Sascha H. Hauck — Institut für Angewandte Physik, Technical University of Darmstadt, Germany

Recent years have seen tremendous experimental progress in the realm of optically-trapped neutral atoms. In this talk, three theoretical proposals for quantum-state engineering in this type of systems will be presented. It will first be demonstrated that a deterministic conversion of a three-qubit W state into its Greenberger-Horne-Zeilinger counterpart can efficiently be carried out in the Rydberg-blockade regime of neutral-atom systems using a dynamical-symmetry-based approach. It will then be shown that a W-type entanglement can be engineered in arrays of neutral atoms with Rydberg-dressed resonant dipole-dipole interaction. Finally, a time-efficient control scheme for coherent single-atom transport in moving optical lattices (optical conveyor belts and double-well lattices) – based on the enhanced shortcuts-to-adiabaticity approach – will be described.

Q 11.2 Mon 17:00 Q-H13

Fabrication of NbTiN Superconducting Nanowire Single-Photon Detectors using Helium-Focused Ion Beam — •Matthias D. Kurschner, Martin A. Wolff, Lisa Sommer, Matvey Lyatti, and Carsten Schuck — Physics Institute, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany

Superconducting nanowire single-photon detectors (SNSPDs) have shown to be the detector technology of choice for single photon counting experiments as they offer high repetition rate, high quantum efficiency, low time jitter and low dark count rates [1]. However, current fabrication methods employ e-beam lithography and dry etching in order to realize nanowire geometries in a top-down approach, which limits the resolution and suffers from proximity effects. In this work, we introduce state-of-the-art focused helium ion beam (HE-FIB) milling for the fabrication of niobium titanium nitride (NbTiN) nanowires. Moreover, we use automated patterning capabilities to achieve scalable fabrication of larger numbers of devices on a chip. We assess the damage nanowires may incur when exposed to helium ions and investigate the effective width and length of the manufactured nanowires. We compare results with HI-FIB milling with more established patterning techniques using a gallium FIB. We further realize long meander-shaped wires connected in series with the photosensitive nanowire for controlling the kinetic inductance, which allows realizing SNSPDs with wider nanowire width.

[1] S. Ferrari et al., Nanophotonics, 7, 1725 (2018)

Q 11.3 Mon 17:15 Q-H13

Argon Trap Trace Analysis - an applied Quantum Technology — •Julian Robertz[1], Yannis Arck[2], David Wachs[1,2], Florian Meienburg[1,2], Werner Aeschbach[2,3], and Markus Oberthaler[1] — [1]Kirchhoff Institute for Physics, Heidelberg, Germany — [2]Institute of Environmental Physics, Heidelberg, Germany — [3]Heidelberg Center for the Environment, Heidelberg, Germany

Environmental tracers serve as an important source of information in a wide range of sciences. Due to the low relative abundance of some of these tracers an ultra-sensitive detection technique is necessary. In the case of the environmental tracer ^{39}Ar the Argon Trap Trace Analysis (ArTTA) allows us to measure relative abundances in the range of 10^{-16}. The isotopic shift in the resonance frequency together with multiple resonant scattering processes grants perfect selectivity. Single atoms are captured and identified in a magneto-optical trap (MOT), while the huge background of abundant isotopes remains unaffected.

This ultra-sensitive Quantum Technology was successfully used to study groundwater, lake, ocean and ice samples. Resulting requirements on ArTTA as well as (fundamental) limits will be discussed.

Q 11.4 Mon 17:30 Q-H13

Epitaxial growth of InP-based 1.3 micrometer quantum dots — •Vinayakrishna Joshi, Sven Bauer, Vitalii Sichkovskyi, Kerstin Fuchs, and Johann Reithmaier — Technische Physik, Institute of Nanostructure Technologies and Analytics (INA), CINSaT, University of Kassel Kassel, Germany

The transmission bands for medium to long range data communication are centered at 1.3 and 1.55 micrometer. The InAs/GaAs material system is widely researched at 1.3 micrometer[1], but 1.55 micrometer is hard to accomplish. Contrary, InP and InAs have a smaller lattice mismatch, which enables emission at 1.55 microns and already has been playing a dominant role. Compared to GaAs, InP devices allows higher frequency response and also has a higher modal gain. Therefore, to cover also the 1.3 micrometer regime, a strongly modified growth process is needed.

The structures were grown on S-doped InP (100) substrates, starting with a thick InP buffer layer, followed by InAlGaAs barrier layer. The active layer of 3 ML thick InAs QDs was grown. This was capped by another InAlGaAs layer. To achieve lasing at 1.3 microns, the QDs were grown on a nucleation layer which enables in creating more nucleation points for the QDs. This new type of QD gain material processed into broad area and ridge waveguide lasers. Static characterization data showed a high modal gain of about 15 cm-1 per quantum dot layer similar to 1.55 micrometer high-performance QD lasers [2]. [1]*M. Suguwara, et al., Journal of Applied Physics 97 (2005) [2]*S. Bauer et al., IEEE Nanotechnology Magazine 23 (2021)

Q 11.5 Mon 17:45 Q-H13

Cryogenic Fiber-based Fabry-Pérot Microcavities — •Timon Eichhorn[1], Maximilian Pallmann[1], Thomas Hümmer[2], and David Hunger[1] — [1]Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]Qlibri Projekt, Fakultät für Physik, Ludwig-Maximilians-Universität München, Germany

One of the fundamental challenges in realizing optical quantum technologies is to have an efficient light-matter interface. A promising approach therefore is to use fiber-based Fabry-Pérot microcavities due to their high cooperativities and large coupling efficiencies into single-mode optical fibers [1]. For the sake of good coherence properties of the quantum emitters, systems have to be cooled down to cryogenic temperatures. During the past decade, much effort was put into the development of cryo-compatible microcavity stages. The noisy environment in closed-cycle cryostats poses the biggest challenge to operate such fully tunable open microcavities. Here, we present our achievements regarding the operation of high-finesse scanning cavities with cavity length stabilities of down to 1pm rms and full 3-axis tunability at cryogenic temperatures in closed-cycle and flow cryostats. [1] New J. Phys. **12** (2010) 065038

Q 12: Quantum Optics (Miscellaneous) II

Time: Monday 16:30–18:00 Location: Q-H14

Q 12.1 Mon 16:30 Q-H14

Two-Mode Photon-Number Correlations Created by Measurement-Induced Nonlinearity — •Jan Philipp Höpker, Maximilian Protte, Christof Eigner, Christine Silberhorn, Polina Sharapova, Jan Sperling, Torsten Meier, and Tim Bartley — Department of Physics, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany

In quantum optics, a measurement can be used as a tool to manipulate a quantum state. Photon subtraction, implemented with a partial detection of a quantum state, is a pertinent example for this nonlinear manipulation. Furthermore, single-photon measurements (a particle-like phenomenon) can be directly combined with the interference of two quantum states (a wave-like phenomenon), yielding interesting features in both phase space and the photon-number basis. In this work, we explore theoretically and experimentally complex correlations in the photon numbers of two-mode quantum states using this scheme. For this, we use integrated beam-splitter networks based on titanium in-diffused lithium niobate waveguides and superconducting single-photon detectors.

Q 12.2 Mon 16:45 Q-H14

Compensating decoherence of squeezed light in cavity-enhanced quantum metrology — •Mikhail Korobko[1], Jan Südbeck[1], Sebastian Steinlechner[2], and Roman Schnabel[1] — [1]Institut für Laserphysik und Zentrum für Optische Quantentechnologien, Universität Hamburg — [2]Maastricht University, Netherlands

Quantum states of light are commonly used to enhance detection in modern sensors. For instance, quantum squeezed light allows to reach high sensitivity without using significant optical power, and thus it finds application in various metrological devices, from biological sensing to gravitational-wave detection. At the same time, quantum states are very fragile, and even a small amount of decoherence significantly impacts them. For example, decoherence due to optical loss limits the benefit from using squeezed light to enhance the sensitivity of cavity-enhanced sensors, such as gravitational-wave detectors. We propose a new approach that allows to compensate a significant part of quantum decoherence, thus increasing the sensitivity beyond the previously established decoherence-induced quantum limit. To achieve this, we use an optimally tuned quantum squeezer placed directly inside the detector cavity. We present the first experimental combination of intra-cavity and externally injected squeezing used to enhance the sensitivity. We use intra-cavity squeezing to demonstrate for the first time quantum enhancement to the sensitivity that is not affected by the increase in optical loss. Finally, we derive the new decoherence-induced quantum limit. Our approach will add the new level of flexibility to the design of quantum sensors.

Q 12.3 Mon 17:00 Q-H14

Characterization of Cryogenic Integrated Spontaneous Parametric Down-Conversion — •Nina Amelie Lange[1], Jan Philipp Höpker[1], Raimund Ricken[2], Viktor Quiring[2], Christof Eigner[2], Christine Silberhorn[2], and Tim J. Bartley[1] — [1]Mesoscopic Quantum Optics, Department of Physics, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany — [2]Integrated Quantum Optics, Department of Physics, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany

We show for the first time that spontaneous parametric down-conversion (SPDC) in nonlinear waveguides remains functional when operated at cryogenic temperatures. With this proof-of-principle experiment, we demonstrate that SPDC, a standard technology for the generation of nonclassical light under ambient conditions, is fully compatible with integrated components that require cryogenic operating conditions, such as superconducting detectors. We characterize our SPDC source at room temperature and under cryogenic conditions at 4.7 K. We measure the spectral properties, including the marginal spectra of the signal and idler photons and the joint spectral intensity. Our experimental results show very good agreement with theory, based on the temperature-dependent dispersion of the waveguide. Furthermore, we investigate the source performance metrics, which do not show a significant change compared to our results at room temperature. Although we change the operation temperature by nearly two orders of magnitude, our SPDC source remains fully operational.

Q 12.4 Mon 17:15 Q-H14

A stepwise approach to the BSV description — •Dennis Scharwald and Polina Sharapova — Paderborn University, Department of Physics, Warburger Str. 100, D-33098 Paderborn, Germany

The bright squeezed vacuum state of light (BSV) is a macroscopic state generated by unseeded parametric down-conversion (PDC). Its large photon number and strong correlations between the signal and idler photons make it an interesting candidate for applications and theoretical investigations. One of the prominent theoretical frameworks for the BSV description is the “regular” Schmidt-mode theory, which describes the BSV in terms of Schmidt modes. This provides a fully analytical description but fails to explain the broadening of the itensity spectrum with increasing gain [1]. Another purely numerical approach involves the solution of integro-differential equations in order to obtain the output state of the PDC section [2]. This approach is in good agreement with the experiment even with increasing gain.

In our work, we combine both approaches by splitting the PDC section into small segments which are connected via the input/output relations for the plane-wave operators. As a result, we can observe the evolution of the Schmidt-modes as they propagate through a nonlinear crystal, as well as the broadening in the intensity spectrum which matches the prediction of the integro-differential equation method and the experimental results.

[1] P. Sharapova *et al.*, Phys. Rev. A **91**, 043816 (2015)
[2] P. R. Sharapova *et al.*, Phys. Rev. Research **2**, 013371 (2020)

Q 12.5 Mon 17:30 Q-H14

Microwave Stimulated Raman Adiabatic Passage in the Electronic Ground State of the NV Center — •Florian Böhm[1], Niko Nikolay[1], Sascha Neinert[1], Christoph E. Nebel[2], and Oliver Benson[1] — [1]Institut für Physik IRIS Adlershof, Humboldt-Universität zu Berlin, Germany — [2]Nanomaterials Research Institute, Kanazawa University, Japan

The nitrogen-vacancy (NV) center in diamond features an electronic qutrit ground state with long coherence times even at room temperature, which can conveniently be manipulated by microwave pulses and read-out optically [1]. The NV center is well-known for offering a broad range of quantum applications, which stimulates a great interest in developing new, or adapting known control schemes.

Here we present the well-known concept of stimulated Raman transitions [2], which can be used to excite transitions between two states not directly coupled to a radiation field, applied to the NV center's triplet ground state. Depending on the two-photon microwave pulse sequence, either stimulated Raman transitions (SRT) or stimulated Raman adiabatic passage (STIRAP) could successfully be implemented in the NV center [3]. We show, that both schemes can successfully drive the dipole-forbidden $m_s = -1 \leftrightarrow m_s = +1$ transition. Furthermore we compare both mechanisms on their robustness and success of spin-swap, as well as their experimental challenges.

[1] Doherty, Marcus, et al., Physics Reports 528.1 (2013): 1-45
[2] Sola, Ignacio, et al., Adv. Mol. Opt. Phys., 67 (2018): 151-256.
[3] Böhm, Florian, et al., Phys. Rev. B, 104.3 (2021): 035201

Q 12.6 Mon 17:45 Q-H14

Fabrication of periodically poled LNOI for efficient non-linear optical processes — •Laura Bollmers[1], Peter Mackwitz[2], Laura Padberg[1], Marcello Massaro[1], Gerhard Berth[2], Christof Eigner[1], and Christine Silberhorn[1] — [1]Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany — [2]Paderborn University, Nanostructure Optoelectronics, Warburger Str. 100, 33098 Paderborn, Germany

Miniaturization of optical circuits has been a vivid field of both, research and development for several decades. Within the last years, this progress has reached the realms of integrated optics and quantum photonics. Here, LNOI has become one of the most promising materials, as it combines the excellent properties of lithium niobate with small feature sizes. In order to fully exploit the possibilities of the material platform, dispersion engineered processes can be tailored by means of quasi-phase matching, which is based on periodic poling of the crystal. For periodically poled LNOI samples, novel processes need to be developed, which makes LNOI technology challenging and demanding. On our first step we focused on the fabrication of finger electrodes for periodic poling and investigated and optimized the respective design parameters. We tested different timing schemes for periodic domain inversion to optimize switching kinetics. We demonstrate that poling lengths up to 7.5 mm are possible and show first nonlinear optical conversion analysis.

Q 13: Quantum Gases (Bosons) III

Time: Tuesday 10:30–12:30 Location: Q-H10

Q 13.1 Tue 10:30 Q-H10

Emerging Dissipative Phases in a Superradiant Quantum Gas with Tunable Decay — Francesco Ferri[1], Rodrigo Rosa-Medina[1], •Fabian Finger[1], Nishant Dogra[1], Matteo Soriente[2], Oded Zilberberg[2], Tobias Donner[1], and Tilman Esslinger[1] — [1]Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland — [2]Institute for Theoretical Physics, ETH Zürich, 8093 Zürich, Switzerland

Dissipative and coherent processes are at the core of the evolution of many-body systems. Their competition and interplay can lead to new phases of matter, instabilities, and complex non-equilibrium dynamics. However, probing these phenomena at a microscopic level in a setting of well-defined, controllable coherent and dissipative couplings often proves challenging. We realize such a system using a ^{87}Rb spinor Bose-Einstein condensate (BEC) strongly coupled to a single optical mode of a lossy cavity [1]. Two transverse laser fields incident on the BEC allow for cavity-assisted Raman transitions between different motional states of two neighboring spin levels. Adjusting the drive imbalance controls coherent dynamics and dissipation, with the appearance of a dissipation-stabilized phase and bistability. We relate the observed phases to microscopic elementary processes in the open system by characterizing the properties of the underlying polariton modes. Our findings provide prospects for studying squeezing in non-Hermitian systems, quantum jumps in superradiance, and spin-orbit coupling in a dissipative setting.

[1] F. Ferri, et al., Phys. Rev. X 11, 041046 (2021).

Q 13.2 Tue 10:45 Q-H10

Engineering dynamical tunneling in a superradiant quantum gas — •Rodrigo Rosa-Medina, Francesco Ferri, Fabian Finger, Nishant Dogra, Katrin Kroeger, Rui Lin, R. Chitra, Tobias Donner, and Tilman Esslinger — ETH Zurich, 8093 Zurich, Switzerland

Dynamic transients are a natural ingredient of non-equilibrium quantum systems. One paradigmatic example is Dicke superradiance, describing the collectively enhanced population inversion of an ensemble of two-level atoms coupled to a single mode of light. In this talk, we present a new experimental approach, which exploits superradiance in a quantum degenerate gas to engineer dynamical currents in a synthetic lattice geometry.

Our experimental implementation is based on a spinor Bose-Einstein condensate coupled to a single mode of an ultrahigh finesse optical cavity. Two transverse laser fields induce cavity-assisted Raman transitions between discrete momentum states of two spin levels, which we interpret as tunnelling in a momentum space lattice [1]. As the cavity field depends on the local density and spin configuration, the tunneling rate evolves dynamically with the atomic state. By monitoring the cavity leakage, we gain real-time access to the emerging currents and benchmark their collective nature. Our results provide prospects to explore dynamical gauge fields and transport phenomena in driven-dissipative quantum systems.

[1] Rosa-Medina, R., Ferri, F., Finger, F., Dogra, N., Kroeger, K., Lin, R., Chitra, R., Donner, T., Esslinger, T. (2021). arXiv:2108.11888

Q 13.3 Tue 11:00 Q-H10

Photon BEC with Thermo-Optic Interaction at Dimensional Crossover — •Enrico Stein and Axel Pelster — Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Erwin-Schrödinger Straße 46, 67663 Kaiserslautern, Germany

Since the advent of experiments with photon Bose-Einstein condensates in dye-filled microcavities in 2010, many investigations have focused upon the emerging effective photon-photon interaction. Despite its smallness, it can be identified to stem from two physically distinct mechanisms. On the one hand, a Kerr nonlinearity of the dye medium yields a photon-photon contact interaction. On the other hand, a heating of the dye medium leads to an additional thermo-optic interaction, which is both delayed and non-local.

In this talk, we theoretically analyse how the effective photon-photon interaction increases when the system dimension is reduced from 2D to 1D. To this end, we consider an anisotropic harmonic trapping potential and determine how the properties of the photon Bose-Einstein condensate in general, and both aforementioned interaction mechanisms in particular, change with increasing anisotropy. We find that the thermo-optic interaction strength increases at first linearly with the trap aspect ratio and lateron saturates at a certain value of the trap aspect ratio. Furthermore, in the strong 1D limit the roles of both interactions get reversed as the thermo-optic interaction remains saturated and the contact Kerr interaction becomes the leading interaction mechanism.

Q 13.4 Tue 11:15 Q-H10

Observation of curvature and particle production in expanding space-time geometries — Celia Viermann[1], Tobias Haas[2], Maurus Hans[1], Elinor Kath[1], Nikolas Liebster[1], Álvaro Parra-López[2], Natalia Sánchez-Kuntz[2], •Marius Sparn[1], Helmut Strobel[1], Mireia Tolosa-Simeón[2], Stefan Floerchinger[2], and Markus Oberthaler[1] — [1]Kirchhoff Institute for Physics, University of Heidelberg, Germany — [2]Institute for Theoretical Physics, University of Heidelberg, Germany

The traces of particle production in the very early instances of our universe can today be found in the cosmic microwave background. The modern view on this inflation stage suggests, that the initial particle production starting from a quantum vacuum state is caused by rapid expansion of space. However, inferring the precise expansion history from the structure of the traces is a formidable task. Here, we present an experimental implementation of an effective expanding space-time for phonons in a potassium Bose-Einstein condensate. We show the resulting excitation structure from density measurements of the ultracold gas and observe a clear dependence on the expansion history. Furthermore, we realize and observe curvature of space in the form of an FLRW metric in the system.

Q 13.5 Tue 11:30 Q-H10

Compressibility and the Equation of State of an Optical Quantum Gas in a Box — •Erik Busley, Leon Espert, Andreas Redmann, Kirankumar Umesh, Martin Weitz, and Julian Schmitt — Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, D-53115 Bonn

The compressibility of a medium, quantifying its response to mechanical perturbations, is a fundamental quantity determined by the equation of state. For gases of material particles, studies of the mechanical response are well established, in fields from classical thermodynamics to cold atomic quantum gases. Here we demonstrate a measurement of the compressibility of a two-dimensional quantum gas of light in a box potential and obtain the equation of state of the optical medium. The experiment is carried out in a nanostructured dye-filled optical microcavity. Upon reaching quantum degeneracy we observe signatures of Bose-Einstein condensation in the finite-size system, and strikingly, the measured density response to an external force sharply increases, hinting at the peculiar prediction of an infinite compressibility of a Bose gas condensate [1].

[1] E. Busley et al., Science (accepted for publication)

Q 13.6 Tue 11:45 Q-H10

Bose Einstein Condensate and Cold Atom Laboratory (BECCAL) — •Lisa Wörner[1], Christian Schubert[2,3], Jens Grosse[4], and The BECCAL Collaboration[1,2,3,4,5,6,7,8,9,10,11] — [1]DLR-QT — [2]DLR-SI — [3]LUH — [4]ZARM — [5]DLR-SC — [6]FBH — [7]HUB — [8]JGU — [9]OHB — [10]UHH — [11]UUlm

BECCAL (Bose Einstein Condensate and Cold Atom Laboratory) is a

joint mission between NASA and DLR. The payload will be installed to the international space station (ISS) to enable research on cold and condensed atoms in the unique microgravity environment.
To create a design baseline, six main areas of research for BECCAL were defined by the science definition team: Atom Interferometry, Coherent Atom Optics, Scalar Bose Einstein Condensates, Spinor Bose Einstein Condensates and Quantum Gas Mixtures, Strongly Interacting Gases and Molecules, and Quantum Information.
With those areas as a baseline, BECCAL offers researchers several possibilities to work with cold and condensed atoms using magnetic and optical fields. BECCAL operates with Rubidium and Potassium, also enabling the study of mixtures.
In this talk, we will give an overview over the payload and the possibilities offered by the mission.

Q 13.7 Tue 12:00 Q-H10

Thermalization dynamics of a gauge theory on a quantum simulator — •Guo-Xian Su[1], Zhao-Yu Zhou[1], Jad Halimeh[2], Robert Ott[3], Hui Sun[1], Philipp Hauke[2], Bing Yang[4], Zhen-Sheng Yuan[1], Jürgen Berges[3], and Jian-Wei Pan[1] — [1]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany — [2]INO-CNR BEC Center and Department of Physics, University of Trento, Trento, Italy — [3]Institute for Theoretical Physics, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany — [4]Department of Physics, Southern University of Science and Technology, Shenzhen, China

Gauge theories form the foundation of modern physics, with applications ranging from elementary particle physics to early-universe cosmology. We demonstrate emergent irreversible behavior, such as the approach to thermal equilibrium, by quantum simulating the fundamental unitary dynamics of a U(1) symmetric gauge field theory. This is made possible through the experimental implementation of a large-scale cold atomic system in an optical lattice. The highly constrained gauge theory dynamics is encoded in a one-dimensional Bose–Hubbard simulator, which couples fermionic matter fields through dynamical gauge fields. We investigate global quantum quenches and the equilibration to a steady state well approximated by a thermal ensemble. Our work establishes a new realm for the investigation of elusive phenomena and paves the way for more complex higher-dimensional gauge theories on quantum synthetic matter devices.

Q 13.8 Tue 12:15 Q-H10

Non-equilibrium steady states of driven dissipative quantum gases beyond ultraweak coupling — •Adrian Köhler — TU Berlin, Berlin, Deutschland

The microscopic description of ideal quantum gases in presence of a finite coupling to a heat bath poses a theoretical challenge. Even though the system itself is non-interacting, the system-bath coupling is cubic in the field operators making the problem interacting. As a first step, we study the mean-field dynamics of the single-particle density matrix under the Redfield quantum master equation. We find that typical steady-state solvers converge only in a very limited parameter regime, forcing one to rely on numerically more costly time-integration. We also discuss approaches to overcome this problem using perturbation theory in the coupling strength. We apply our approach to a Bose gas coupled to two baths of different temperature, for which in the regime of ultraweak coupling Bose condensation is predicted also in cases, where both bath temperatures lie well above the equilibrium crtitical temperature [PRL 119, 140602].

Q 14: Precision Measurements and Metrology III

Time: Tuesday 10:30–12:15 Location: Q-H11

Q 14.1 Tue 10:30 Q-H11

Atom interferometry in the presence of quadratic potentials — •Matthias Zimmermann — Institute of Quantum Technologies, German Aerospace Center (DLR), 89081 Ulm, Germany

Matter-wave interferometers employing trapped atoms are promising candidates to enhance the achievable interferometer time. These compact devices could, for instance, be employed for precision measurements of accelerations and rotations.

This talk will address several fundamental issues that arise for atom interferometry in the presence of quadratic potentials. In particular, we distinguish classical and quantum closing conditions which have a crucial influence on the contrast and thus the signal of the interferometer. Moreover, we present modifications [1] of existing devices that allow their operation within compact geometries. As a particular example, we demonstrate a modified version of the T^3 interferometer [2,3] in the presence of quadratic potentials. We analyze advantages and potential drawbacks of this device, and suggest measures to overcome the latter.

[1] M. Zimmermann, *Interference of Matter Waves - Branch-dependent dynamics, the Kennard phase, and T^3 Stern-Gerlach interferometry*, Ph.D. thesis, Ulm University (2021).
[2] M. Zimmermann et al., *T^3 interferometer for atoms*, Appl. Phys. B **123**, 102 (2017).
[3] O. Amit et al., *T^3 Stern-Gerlach Matter-Wave Interferometer*, Phys. Rev. Lett. **123**, 083601 (2019).

Q 14.2 Tue 10:45 Q-H11

3D Simulations of Guided BEC Interferometers — •Rui Li[1], Simon Kanthak[2], and Naceur Gaaloul[1] — [1]Leibniz Universität Hannover, Institute of Quantum Optics, Hannover, Germany — [2]Humboldt-Universität zu Berlin, Institut für Physik, Berlin, Germany

Atom interferometry has grown into an extremely successful tool for precision measurements since the pioneering works of Mark Kasevich and Steve Chu [1, 2]. Experiments with record-breaking precision have been performed in the fields of inertial sensing and tests of the foundations of physics. These high precision measurements are achieved either by large momentum transfer (LMT) or long interrogation times (LIT). Bose-Einstein Condensates (BECs) can be used to further enhance precision atom interferometry due to its high coherence and narrow momentum width. In this talk, we use numerical methods to study BEC interferometers in an optical guide by time-evolving 3D Gross-Pitaevskii equation (GPE). We specifically investigate the double-Bragg diffraction (DBD) of BEC pulsed by two retroretlecting laser beams and its momentum distribution after time of flight (ToF) in the guide, which is provided by the dipole trap of the red-detuned Gaussian laser beam.

[1] Kasevich M. and Chu S., Phys. Rev. Lett., 67 (1991) 181.
[2] Kasevich M. and Chu S., Appl. Phys. B, 54 (1992) 321.

Q 14.3 Tue 11:00 Q-H11

Simulations of Integrated Laser-Guided Atom Interferometers — •Matthew Glaysher, Hannah Paltzer, Ernst Maria Rasel, and Naceur Gaaloul — Leibniz Universität Hannover, Institute of Quantum Optics, Germany

Atom interferometry provides a highly accurate measurement tool, its applications ranging from inertial sensing and navigation to tests of fundamental physics. High precision interferometry is achieved either by Large Momentum Transfer or long interrogation times. Whereas the more common light pulse interferometer schemes can produce the necessary momentum transfer, guided interferometers can achieve long interrogation times. For guided ensembles it is essential to understand the internal interactions, as well as the continuous interactions with a light field, to realize a phase-sensitive interferometer. For this purpose we combine the computation of the dynamics of Bose-Einstein Condensates (BECs) by numerically solving the Gross-Pitaevskii-Equation (GPE) and classical n-particle simulation. We specifically investigate beam-splitting mechanisms and the phase evolution of BECs in a guided system, in which the guide is realized by dynamically shaped cavity modes or painted potentials.

Q 14.4 Tue 11:15 Q-H11

Analytic theory for Bloch-oscillation-based LMT atom interferometry — •Florian Fitzek[1,2], Jan-Niclas Siemss[1,2], Naceur Gaaloul[2], and Klemens Hammerer[1] — [1]Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Germany

Light-pulse atom interferometers are quantum sensors that enable a wide range of high-precision measurements such as the determination of inertial and electromagnetic forces or the fine-structure constant. Increased sensitivities can be achieved by implementing large momentum transfer (LMT) techniques. A well-known method to increase the momentum separation between the two arms of the interferometer are Bloch oscillations. Despite operating in the adiabatic regime, finite lattice ramping times will eventually lead to non-adiabatic corrections.

We develop an analytic model that describes non-adiabatic corrections to excited Bloch bands and verify our model by comparing to an exact numerical integration of the Schrödinger equation [Fitzek et al., Sci Rep 10, 22120 (2020)]. Furthermore, we characterize losses to excited Bloch bands as well as losses to the continuum to discuss their role for the realization of LMT atom interferometry.

This work is supported through the Deutsche Forschungsgemeinschaft (DFG) under EXC 2123 QuantumFrontiers, Project-ID 390837967 and under the CRC1227 within Project No. A05 as well as by the VDI with funds provided by the BMBF under Grant No. VDI 13N14838 (TAIOL).

Q 14.5 Tue 11:30 Q-H11

QUANTUS - Theory in the Ulm group — •Richard Lopp[1], Alexander Friedrich[1], Enno Giese[3], Wolfgang P. Schleich[1,2], and the QUANTUS Team[1] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm — [2]Institute of Quantum Technologies, German Aerospace Center (DLR) — [3]Institut für Angewandte Physik, Technische Universität Darmstadt

Atom interferometry provides a unique opportunity not only for probing the foundations of physics at the interplay of relativity and quantum theory, but also for devising diverse, compact applications like sensors. In this spirit, the long-standing and fruitful QUANTUS collaboration investigates the dynamics of Bose-Einstein condensates under microgravity conditions and its application to atom interferometry. In particular, the QUANTUS theory group in Ulm focuses on a fundamental modelling of the light-matter dynamics, its impact on interferometric experiments, as well as potential setups to improve sensitivitity in the test of relativistic physics and fundamental principles. In this contribution, we will present an overview of the current, diverse work of the QUANTUS theory group in Ulm, and provide a perspective on upcoming projects of the newly starting QUANTUS+ collaboration.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) due to an enactment of the German Bundestag under grant DLR 50WM1956 (QUANTUS V).

Q 14.6 Tue 11:45 Q-H11

Probing Physics beyond the Standard Model with ultracold Mercury — Thorsten Groh, •Felix Affeld, Quentin Lavigne, and Simon Stellmer — Physikalische Institut, Universität Bonn, Germany

The standard model of physics is a well-established theory, yet it fails to capture a number of experimental observations. Related topics include the search for cold dark matter candidates, the origin of the cosmological baryon asymmetry, and finite neutrino masses.

In our experiment, we aim to investigate physics beyond the standard model using ultracold gases of mercury. Mercury's high mass, its low sensitivity to blackbody radiation, and the availability of seven stable isotopes make it a unique candidate for such studies.

We report on the measurement of the isotope shifts of various transitions in mercury. Emerging nonlinearities in this measurement could hint towards a fifth force mediated by a new boson Φ that would couple neutrons and electrons.

Q 14.7 Tue 12:00 Q-H11

Analyse von thermischen Einzelionenwellenpaketen durch Flugzeitmessungen — •Felix Stopp, Henri Lehec, Luis Ortiz-Gutiérrez und Ferdinand Schmidt-Kaler — QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Wir kontrollieren die Eigenschaften von Einzelionen-Wellenpaketen außerhalb einer Paulfalle: Dafür wird ein $^{40}Ca^{+}$-Ion im harmonischen Fallenpotential eingeschlossen und durch Laserkühlung präpariert. Nach anschließender Extraktion propagiert das Ion zu einem 0.27m entfernten Detektor. Die Auswertung der Ankunftszeitverteilung erlaubt direkte Rückschlüsse auf die Breite des vorher in der Falle präparierten thermischen, bzw kohärent-angeregten Wellenpaketes [1]. Weiterhin wird der erste deterministische Ionenspringbrunnen präsentiert, bei dem einzelne Ionen aus der Falle in den freien Raum extrahiert und nach dem Flug reflektiert werden, um sie mit einer Einfangrate von >95.1 % im Fallenpotential wieder zu fangen [2]. Als Anwendungen dieser Methoden sehen wir neuartige Ionen-Interferometer bzw. die Verbindung von Ionenfallen Quantenprozessor-Knoten.

[1] F. Stopp et al., New J. Phys. **23** 063002 (2021)
[2] F. Stopp et al., arXiv:2108.06948 (2021)

Q 15: Quantum Information (Quantum Computing and Simulation)

Time: Tuesday 10:30–12:30 Location: Q-H12

Invited Talk Q 15.1 Tue 10:30 Q-H12

A hybrid quantum classical learning agent — •Sabine Wölk — Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

Machine learning and quantum information become more and more important in our digital world. An important paradigm within machine learning is reinforcement learning. Here, a decision-making entity called agent solves a task by interacting with its environment. The agent updates its behaviour, and thus learns, by using the obtained feedback it receives from the environment. We can speed up the learning if the agent and its environment can be transformed into corresponding quantum systems interacting with each other.

We have developed a hybrid quantum classical learning agent which combines quantum exploration of the environment with classical behavior updates [1,2]. In this way, we can achieve a quadratic speedup in learning. In this talk, I will explain the main features of this hybrid learning agent and discuss possible applications as well as first proof-of-principle experiments.

[1] A. Hamann and S. Wölk, Performance analysis of a hybrid agent for quantum-accessible reinforcement learning, arXiv: 2107.14001.

[2] V. Saggio, B. Asenbeck, A. Hamann, T. Strömberg, P. Schiansky, V. Dunjko, N. Friis, N. C. Harris, M. Hochberg, D. Englund, S. Wölk, H. J. Briegel, and P. Walther, Experimental quantum speed-up in reinforcement learning agents, Nature 591, 229 (2021).

Q 15.2 Tue 11:00 Q-H12

Numerical optimization and demonstration of amplitude-modulatedpulses for microwave-driven entanglement-gates — •Markus Duwe[1,2], Nicolas Pulido-Mateo[1,2], Hardik Mendpara[1,2], Giorgio Zarantonello[3], Ludwig Krinner[1,2], Amado Bautista-Salvador[1,2], Klemens Hammerer[4], Reinhard Werner[4], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]PTB, Bundesallee 100, 38116 Braunschweig — [3]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA — [4]Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstrasse 2, 30167 Hannover, Germany

A universal set of quantum gates requires entangling operations with infidelities below the fault-tolerance threshold [1]. Trapped ions are one of the leading platforms approaching the required gate fidelities [2]. For trap-integrated microwave gate mechanisms, amplitude modulation of the gate drive has shown an increased of the resilience of two-qubit entangling operations against motional mode drifts [3]. Here we discuss the numerical optimization and experimental realization of pulse envelopes for the Mølmer-Sørensen entangling gate. The method allows the trajectory in phase space to be insensitive to chosen errors, such as trap and pulse parameters. We report infidelities approaching 10^{-3} with faster operation than previously shown in our experiment.

[1] E. Knill, Nature **434**, 39 (2005)
[2] J. Gaebler *et al.*, Phys. Rev. Lett. **117**, 060505 (2016)
[3] G. Zarantonello *et al.*, Phys. Rev. Lett. **123**, 260503 (2019)

Q 15.3 Tue 11:15 Q-H12

Non-classical features of a multiparticle bosonic state propa-

gating in an integrated network — •federico pegoraro, philip held, syamsundar de, sonja barkhofen, jan sperling, benjamin brecht, and christine silberhorn — Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098, Paderborn, Germany

According to Schrödinger equation, the evolution of a quantum system is governed by a unitary transformation. In light of this premise, the development of new protocols and platforms capable of probing the properties of unitary operations has a key role in a large range of fields from physics to information science. Among all the possible evolutions, Quantum Walks (QWs) have been proved to be a powerful tool within the framework of quantum information and computation. In particular, inhomogeneous and noisy QWs have been largely investigated. Our contribution finds itself along this direction: it is in fact our aim to exploit a fully reconfigurable integrated photonic network, capable to generate and probe a large variety of unitary operations in a reliable and efficient way, in order to implement QW evolutions with a certain degree of inhomogeneities and probe the properties of non-classical correlation of a bosonic multi-particle quantum state that propagates in our network.

Q 15.4 Tue 11:30 Q-H12

Mimimal number of couplings and local controls for universal quantum computing — •Fernando Gago Encinas, Monika Leibscher, David Pohl, Daniel Basilewitsch, and Christiane Koch — Freie Universität Berlin

Universal quantum computing requires evolution-operator controllability on the circuits used as a platform to perform every possible quantum logic gate. Since we know how to decide for a given system whether it is controllable or not, we can ask how many local controls and 2-qubit couplings are needed. This information is key for building larger and larger devices because these controls and couplings are very expensive in terms of the physical space in the circuit and the calibrations required. We analyze different schemes for a controllable qubit array that minimize these couplings and controls using a special controllability test derived from graph theory. We find that some specific couplings yield better results for controllability and identify some possible candidates to design a scalable modular circuit.

Q 15.5 Tue 11:45 Q-H12

Towards Measurement-Based Variational Quantum Simulation of the Multi-Flavor Schwinger Model — •Stephan Schuster[1], Stefan Kühn[2], Tobias Hartung[2,3], Lena Funcke[4], Marc-Oliver Pleinert[1], Joachim von Zanthier[1], and Karl Jansen[5] — [1]Friedrich-Alexander University Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen, Germany — [2]Computation-Based Science and Technology Research Center, The Cyprus Institute, 20 Kavafi Street, 2121 Nicosia Cyprus — [3]Department of Mathematical Sciences, University of Bath, Bath BA2 7AY, United Kingdom — [4]Center for Theoretical Physics, MIT Department of Physics, 77 Massachusetts Avenue, Cambridge MA 02139 USA — [5]NIC, Desy Zeuthen, Platanenallee 6, 15738 Zeuthen, Germany

Recently, the first measurement-based variational quantum simulation has been proposed, which employs a one-way quantum computation instead of a quantum circuit for the simulation. This shifts the experimental challenge of complex gate realizations to the generation of a entangled cluster state which is then locally measured. In our work, we developed a variational one-way quantum computing simulation protocol for the multi-flavor lattice Schwinger model with a flavor-dependent chemical potential, considering model-specific symmetries in our quantum algorithm. The flavor-dependent chemical potential increases the model complexity but also allows us to investigate first-order energy phase transitions in dependence of the chemical potential. First classical simulation results of our protocol look very promising and allowed us to determine several critical points in the phase diagram.

Q 15.6 Tue 12:00 Q-H12

Fehlertolerante Paritätsauslese auf einem Quantenprozessor mit Ionenkristallen — •Janine Hilder, Daniel Pijn, Oleksiy Onishchenko, Alexander Stahl, Maximilian Orth, Björn Lekitsch, Ulrich Poschinger und Ferdinand Schmidt-Kaler — QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany

Quantenprozessoren basierend auf gefangenen Ionen sind einer der vielversprechendsten Kandidaten für die Realisierung eines skalierbaren Quantenprozessors. Um eine fehlertolerante Quanteninformationsverarbeitung zu realisieren, ist es von entscheidender Bedeutung, Quantenfehlerkorrektur durchführen zu können. Ein wesentlicher Baustein ist die Erkennung von Fehlern durch Stabilisatormessungen, ohne den Quantenzustand der Datenbits zu zerstören [1,2]. Diese wurde kürzlich auf shuttlingbasierten Quantenprozessoren experimentell demonstriert [3,4]. Wir erreichen eine Verbesserung der Paritätsauslesegüte von 92.3(2)% auf 93.2(2)% bei Selektierung aufgrund des Flag-Qubits, welches Datenqubit kompromittierende Fehler während der Stabilisatormessung anzeigt. Zusätzlich zeigen wir die Erzeugung von Verschränkung auf allen Ionen, die an dieser fehlertoleranten Paritätsauslese beteiligt sind.

[1] A. Bermudez et al., Phys. Rev. X 7, 041061 (2017)
[2] A. Rodriguez-Blanco et al., PRX Quantum 2, 020304 (2021)
[3] J. Hilder et al., arXiv:2107.06368 (2021)
[4] C. Ryan-Anderson et al., arXiv:2107.07505 (2021)

Q 15.7 Tue 12:15 Q-H12

Compiler zur Register-Rekonfiguration eines Ionenfallen-Quantencomputers — •Janis Wagner[1], Janine Hilder[1], Christian Melzer[1], Björn Lektisch[1], Ulrich Poschinger[1], André Brinkmann[2] und Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany — [2]Zentrum für Datenverarbeitung, Universität Mainz, Anselm-Franz-von-Bentzel-Weg 12, 55128 Mainz, Germany

Ionenfallen mit laserbasierten Gattern sind aufgrund ihrer hohen Operationsgüte ein möglicher Kandidat für Quantencomputer. Die Architektur einer segmentierten Paul-Falle mit mehreren Speicher- und Prozessorregionen, zwischen denen die Ionen mittels zeitabhängiger Spannungsrampen bewegt werden können, erlaubt eine Rekonfigurierbarkeit der Register und damit eine Skalierung jenseits der reinen Kristallvergrößerung. Um eine Gattersequenz effizient auf einer solchen Architektur ausführen zu können, muss aus dieser eine sinnvolle Startkonfiguration der Ionen ermittelt werden, sowie eine Rekonfigurationssequenz berechnet werden. Der vorgestellte Shuttling-Compiler implementiert einen Algorithmus, der dies in polynomieller Abhängigkeit für Anzahl der Qubits und Gatter bewerkstelligt.

Q 16: Quantum Effects I

Time: Tuesday 10:30–13:00 Location: Q-H13

Q 16.1 Tue 10:30 Q-H13

A Quantum Klystron - Controlling Quantum Systems with Modulated Electron Beams — •Dennis Rätzel[1], Daniel Hartley[2], Osip Schwartz[3], and Philipp Haslinger[2] — [1]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin, Germany — [2]Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria — [3]Dept. of Physics of Complex Systems, Weizmann Institute of Science, Rehovot, Israel

Coherent control of quantum transitions - indispensable in quantum technology - generally relies on the interaction of quantum systems with electromagnetic radiation. Here, we theoretically demonstrate that the non-radiative electromagnetic near-field of a temporally modulated free-space electron beam can be utilized for coherent control of quantum systems. We show that such manipulation can be performed with only classical control over the electron beam itself, and is readily realizable with current technology. This approach may provide a pathway towards spectrally selective quantum control with nano-scale spatial resolution, harnessing the small de Broglie wavelength of electrons.

Q 16.2 Tue 10:45 Q-H13

Quantum friction near nonreciprocal media — •Omar Jesús Franca Santiago and Stefan Yoshi Buhmann — Institute of Physics, University of Kassel, Germany

We investigate how the quantum friction experienced by a polarisable charged particle moving with constant velocity parallel to a planar interface is modified when the latter consists of nonreciprocal media, with special focus on topological insulators. We use macroscopic quantum electrodynamics to obtain the Casimir–Polder frequency shift, decay rate and force for the atom. These results are a generalization of the respective quantities to matter with time-reversal symmetry breaking which violates the Lorentz reciprocity principle.

Q 16.3 Tue 11:00 Q-H13

Quantum pulses in non-Markovian waveguide QED — •Kisa Barkemeyer, Andreas Knorr, and Alexander Carmele — Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstr. 36, 10623 Berlin

Waveguide quantum electrodynamics (QED) systems, where emitters interact with the electromagnetic field confined to a one-dimensional geometry, are a promising platform for the implementation of quantum networks. If memory effects cannot be neglected, non-Markovian approaches have to be employed. In this regime, coherent time-delayed feedback allows controlling the system dynamics while preserving quantum coherence, and characteristic features such as the formation of bound states in the continuum can be observed.

In this talk, we discuss the strongly entangled system-reservoir state in waveguide QED systems with coherent time-delayed feedback. Thereby, we focus on the role of quantum pulses to describe the transmission of quantum information in a fully quantized manner. We employ different methods, an approach based on the time evolution with matrix product states [1,2] and a Heisenberg-picture approach [3], which complement each other and allow an in-depth study of various aspects of non-Markovian waveguide QED with multiphoton pulses.

[1] K. Barkemeyer, A. Knorr, and A. Carmele, *Phys. Rev. A* **103**, 033704 (2021).
[2] S. Arranz Regidor, G. Crowder, H. Carmichael, and S. Hughes, *Phys. Rev. Research* **3**, 023030 (2021).
[3] K. Barkemeyer, A. Knorr, and A. Carmele, arXiv:2111.02816.

Q 16.4 Tue 11:15 Q-H13

Ginzburg effect in a dielectric medium with dispersion and dissipation — •Sascha Lang[1,2], Roland Sauerbrey[1,3,4], Ralf Schützhold[1,5,2], and William G. Unruh[6,7] — [1]Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany — [2]Fakultät für Physik, Universität Duisburg-Essen, Duisburg, Germany — [3]Institut für Angewandte Physik, Technische Universität Dresden, Dresden, Germany — [4]Center for Advanced Systems Understanding (CASUS), Görlitz, Germany — [5]Institut für Theoretische Physik, Technische Universität Dresden, Dresden, Germany — [6]Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada — [7]Institute for Quantum Science and Engineering, Texas A&M University, College Station, Texas, United States

As a quantum analog of Cherenkov radiation, an inertial photon detector moving through a medium with constant refractive index n may perceive the electromagnetic quantum fluctuations as real photons if its velocity v exceeds the medium speed of light c/n. For dispersive Hopfield type media, we find this Ginzburg effect to extend to much lower v because the phase velocity of light is very small near the medium resonance. In this regime, however, dissipation effects become important. Via an extended Hopfield model, we present a consistent treatment of quantum fluctuations in dispersive and dissipative media and derive the Ginzburg effect in such systems. Finally, we propose an experimental test.

Q 16.5 Tue 11:30 Q-H13

Resonances and radiation features of a quantum free-electron laser — •Peter Kling[1], Enno Giese[2], C. Moritz Carmesin[3], Roland Sauerbrey[4], and Wolfgang P. Schleich[3,1] — [1]Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Ulm — [2]Institut für Angewandte Physik, Technische Universität Darmstadt — [3]Institut für Quantenphysik, Universität Ulm — [4]Helmholtz-Zentrum Dresden-Rossendorf e.V.

In the quantum regime of a free-electron laser (FEL) the quantum mechanical recoil, an electron experiences during the scattering from photons, dominates the dynamics of the electron-light system. Energy-momentum conservation combined with the discreteness of the recoil lead to narrow resonances for the electron momentum. We investigate the time scales of the dynamics as well as the features of the emitted radiation from such a Quantum FEL for different resonant momenta.

Q 16.6 Tue 11:45 Q-H13

Observation of coherent coupling between super- and subradiant states of an ensemble of cold atoms collectively coupled to a single propagating optical mode — •Riccardo Pennetta, Daniel Lechner, Martin Blaha, Arno Rauschenbeutel, Philipp Schneeweiss, and Jürgen Volz — Department of Physics, Humboldt Universität zu Berlin, 12489 Berlin, Germany

We discuss the evolution of the quantum state of an ensemble of atoms that are coupled via a single propagating optical mode. We theoretically show that the quantum state of N atoms, which are initially prepared in the timed Dicke state, evolves through all the N-1 states that are subradiant with respect to the propagating mode. We predict this process to occur for any atom number and any atom-light coupling strength. These findings are supported by measurements performed with cold cesium atoms coupled to the evanescent field of an optical nanofiber. We experimentally observe the evolution of the state of the ensemble passing through the first two subradiant states, leading to sudden, temporary switch-offs of the optical power emitted into the nanofiber. Our results contribute to the fundamental understanding of collective atom-light interaction and apply to all physical systems, whose description involves timed Dicke states.

Q 16.7 Tue 12:00 Q-H13

Investigating the Casimir-Polder force in nonplanar geometries — •Bettina Beverungen[1], Kurt Busch[1,2], and Francesco Intravaia[1] — [1]Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik & Photonik, Newtonstr. 15, 12489 Berlin, Germany — [2]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2A, 12489 Berlin, Germany

Quantum and thermal fluctuations of the electromagnetic field are responsible for many nontrivial effects such as dispersion forces. One example is the Casimir-Polder force, which describes the interaction between an atom and a macroscopic, electrically neutral object. At short distances, the quantum effects dominate and can be highly relevant to many nanotechnological applications. Since the interaction depends on the system's geometry, this constitutes one possible avenue to influence its behavior.

We focus our investigation on this aspect, using a Green tensor based formalism. The Green tensor characterizes the system's electromagnetic response and encodes the geometry as well as the material properties of the macroscopic object. This information allows us to identify the system's intrinsic characteristics such as relevant length scales and link them to the behavior of the interaction. We perform semi-analytical calculations for different geometries and interpret them in light of the physical system's properties. Furthermore, we perform analytical calculations of various asymptotic limiting cases in order to validate our results. At the same time, this can offer a deeper insight into the underlying physics.

Q 16.8 Tue 12:15 Q-H13

Probing the Quantum Vacuum in Space and Time — •Frieder Lindel[1], Robert Bennett[2], Francesca Fabiana Settembrini[3], Alexa Marina Herter[3], Jérôme Faist[3], and Stefan Yoshi Buhmann[4] — [1]Instiute of Mathematics and Physics, University of Freiburg, Germany — [2]School of Physics and Astronomy, University of Glasgow, United Kingdom — [3]Institute of Quantum Electronics, ETH Zürich, Switzerland — [4]Institute of Physics, University of Kassel, Germany

When quantising the electromagnetic radiation field, one of the most fascinating consequences is the existence of fluctuations associated with the ground state. These vacuum fluctuations manifest themselves indirectly through their influence on matter where they may be regarded as responsible for fundamental processes such as spontaneous emission or the Lamb shift. More recently, an alternative route to observing the quantum vacuum has been developed in electro-optic sampling experiments [1,2].

In my talk, I will show how vacuum correlations between individually chosen space-time regions can be accessed in electro-optics sampling experiments. I will argue that this makes it possible to observe retardation effects, cavity-induced changes and correlations between causally separated regions of the quantum vacuum.

[1] C. Riek et al., Science 350, 420 (2015)
[2] I.-C. Benea-Chelmus et al., Nature 568, 7751 (2019)

Q 16.9 Tue 12:30 Q-H13

A Photon Pair Source from a Single Atom — •Luke Masters, Martin Cordier, Xinxin Hu, Gabriele Maron, Lucas Pache, Maximilian Schemmer, Jürgen Volz, and Arno Rauschenbeutel — Department of Physics, Humboldt Universität zu Berlin, 10099 Berlin, Germany

Photon emission from a single quantum emitter can be described as an interference phenomena between coherent and incoherently scattered light. In this picture, perfect photon anti-bunching in the light scattered by an atom arises from the complete destructive interference of the two-photon components of these two light fields.

The coherent and incoherently scattered light have distinct spectral properties, making it possible to separate them from each other by applying selective spectral filtering. In turn, this will modify the photon statistics of the emitted light, and can transform the perfect anti-bunching into strong photon-bunching.

In our experiment, we employ narrow-band spectral filtering to isolate the incoherent two-photon wavefunction from the fluorescence of a single, laser cooled Rb^{85} atom confined in an optical dipole trap. Without filtering, the measured second order correlation function shows a strong photon anti-bunching of $g^{(2)}(0) \approx 0$, while a photon bunching of $g^{(2)}(0) \gg 1$ is measured when filtering is applied. This is in agreement with our expectation that the incoherently scattered part consists purely of energy-time-entangled photon pairs.

Q 16.10 Tue 12:45 Q-H13

Multi-mode quantum optics in lossy resonators — •Dominik Lentrodt[1,2], Oliver Diekmann[2], Christoph H. Keitel[2], Stefan Rotter[3], and Jörg Evers[2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany — [3]Institute for Theoretical Physics, Vienna University of Technology (TU Wien), 1040 Vienna, Austria

Few-mode models — such as the Jaynes-Cummings model and its generalizations — have been an indispensable tool in studying the quantum dynamics of light-matter interactions in optical resonators. Recently, novel regimes featuring strong coupling in combination with large losses have attracted attention in various experimental platforms. In this context, central assumptions of these canonical quantum optical models have to be revisited. In this talk, I will discuss extensions of Jaynes-Cummings-type few-mode models and an associated class of loss-induced multi-mode effects. Besides recent theoretical progress [1-4], I will discuss implications for experiments in x-ray cavity QED with Mössbauer nuclei [5] — an emerging platform at the high-energy frontier of quantum optics, featuring lossy resonators doped with ultranarrow emitters.

[1] Lentrodt & Evers, *PRX* **10**, 011008 (2020), [2] Medina et al. *PRL* **126**, 093601 (2021), [3] Lentrodt et al. *arXiv:2107.11775 [quant-ph]*, [4] Franke et al. *PRL* **122**, 213901 (2019), [5] Lentrodt et al. *PRResearch* **2**, 023396 (2020)

Q 17: Quantum Optics (Miscellaneous) III

Time: Tuesday 10:30–12:30 Location: Q-H14

Invited Talk Q 17.1 Tue 10:30 Q-H14

Superradiant lasing in presence of atomic motion — •Simon B. Jäger[1,2], Haonan Liu[2], John Cooper[2], and Murray J. Holland[2] — [1]Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany — [2]JILA and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440, USA

Advances in time and frequency standards require the realization of extremely stable high-Q oscillators. For lasers this high-Q oscillator is usually a narrow-linewidth resonator mode while the laser linewidth is limited by fluctuations of the resonator length. Remarkably, these limitations can be softened by coupling many atoms to a rather broad-linewidth cavity mode and storing the coherence in the collective dipole of the atoms. In this superradiant regime, we discuss the effects of atomic motion resulting in inhomogeneous broadening of the emission frequencies. We show that the superradiant laser can overcome this broadening using a phase synchronization mechanism. Our theoretical analysis shows the possibility to build rugged, continuous-wave superradiant lasers based on a thermal atomic beam source. In addition, we study different superradiant phases that rely on Doppler effects where we observe polychromatic light emission and mode-hopping dynamics. We discuss the relevance of these effects for laser-based gyroscopes and sensors.

Q 17.2 Tue 11:00 Q-H14

Exploring precise loss characterization methods for LNOI waveguides — •Silia Babel, Laura Padberg, Marcello Massaro, Christof Eigner, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn

Lithium Niobate (LN) has been a groundbreaking and benchmarking material platform for numerous integrated optical devices due to its great property portfolio, e.g. its large second-order nonlineartiy and electro-optical coefficients. A miniaturization of the current devices is desirable as this reduces the footprint and allows to integrate more complex structures on a chip, to increase the efficiency and to reduce the energy consumption. Here, the novel material platform Lithium Niobate on Insulator (LNOI) allows an tremendous step towards a further significant reduction as it combines the advantages of LN with a high index contrast change of the waveguides which makes it a very promising material for integrated photonic quantum technologies. For quantum applications low-loss optical devices are indispensable. This includes an optimization of waveguide propagation losses. In literature, different methods are used for estimating the propagation losses in LNOI waveguides. Yet, the question for a profound comparison between different methods remains unanswered. In order to provide this, we explore and compare different methods for waveguide loss characterization in LNOI waveguides, such as Fabry-Pérot or ring resonator method. These different methods will later set the ground for a versatile toolbox for nano-waveguide characterization.

Q 17.3 Tue 11:15 Q-H14

Exploiting electro-optic modulators in $LiNbO_3$ for quantum-optics applications — •Felix vom Bruch, Christof Eigner, Harald Herrmann, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn

Within the last decades, research and development on quantum technologies has been a vivid field and the interest and investment in those technologies has been steadily increasing. Many of the most promising approaches are based on using and manipulating light and its properties. In many quantum optic setups, the manipulation is performed by means of bulk optic modulators. Yet, the performance limitations hinder further development in terms of data processing rates. Here, we present our latest progress in replacing bulk optic modulators by their integrated counterparts in free space setups and exploit the accompanied benefits of these novel hybrid approaches.

The used platform on which our modulators are implemented is titan-in-diffused waveguides in $LiNbO_3$. Here, different crystal cuts enable us to implement different types of modulators such as electro-optic polarization converters. Challenges that need to be overcome are spectral limitations, switching speed and electro-optic performance as well as device stability. Additionally, maintaining full applicability even on a single photon regime, requires very low optical losses. We are focusing on comparing advantages and disadvantages of different modulator architectures and further exploit their experimental implementation in quantum optic experiments.

Q 17.4 Tue 11:30 Q-H14

Superradiance in an ensemble of multilevel atoms — •Aleksei Konovalov and Giovanna Morigi — University Des Saarlandes

We derive a master equation for a superradiant medium which includes multilevel interference between the individual scatterers. The derivation relies on the Born-Markov approximation and implements the coarse-graining formalism. The master equation fulfills the Lindblad form and contains terms describing multilevel interference between parallel transitions of a single atom, multiatom interference between identical transitions, and multiatom interference between different electronic transitions with parallel dipoles. This formalism is then applied to determine the excitation spectrum of two emitters using the parameters of the hydrogen transitions 2S1/2 ? 4P1/2 and 2S1/2

? 4P3/2, where the gap between the parallel dipoles is of the order of GHz. The distortion of the signal due to the interplay of multilevel and multiemitter interference is analyzed as a function of their distance. We then derive the limit in which the atomic transitions can be described by oscillators and analyse the predictions for an ensemble of Rb87 atoms driven by a laser below saturation.

[1] Aleksei Konovalov and Giovanna Morigi Phys. Rev. A 102, 013724 (2020)

Q 17.5 Tue 11:45 Q-H14

Engineering the photon statistics by destructive and constructive two-photon interference — •Max Schemmer, Martin Cordier, Philipp Schneeweiss, Jürgen Volz, and Arno Rauschenbeutel — Department of Physics, Humboldt-Universität zu Berlin, 10099 Berlin, Germany

Interference phenomena are at the origin of for many intriguing effects in physics and in particular in the field of quantum optics (e.g., double-slit experiment). Here, we demonstrate a type of quantum interference that allows us to engineer the photon statistics of a laser light field via the interaction with an ensemble of cold atoms. When probing the ensemble with resonant light (D2 line of Cesium), entangled photon-pairs can be generated that will interfere with the two-photon components of the incoming light [1]. Here we show how the relative amplitude and phase of these entangled photon-pairs can be tuned by controlling the number of atoms and the detuning of the laser light. Using this effect, the photon-statistics can be tuned from bunching to antibunching. Our results open new routes for realizing nonclassical light sources with variable $g^{(2)}(\tau)$ based on weak, collectively enhanced nonlinearities.

[1] Prasad et al., Nature Photonics 1 (2020).

Q 17.6 Tue 12:00 Q-H14

Polarization-entangled photons from nanoscale nonlinear layers — •Vitaliy Sultanov[1,2], Tomás Santiago-Cruz[1,2], and Maria V. Chekhova[1,2] — [1]Max-Planck Institute for the Science of Light, Erlangen, Germany — [2]Friedrich-Alexander University Erlangen-Nuremberg, Erlangen, Germany

Entanglement is a crucial feature of quantum systems essential for various applications of quantum technologies. One of the most convenient platforms for quantum entanglement realization is photon pairs generated via spontaneous parametric down-conversion (SPDC). However, the phase-matching condition limits the existing bulk SPDC-based sources of entangled photons. The restrictions can be overcome by utilizing phase-matching-free SPDC in nano-scale nonlinear layers.

In this work, we demonstrate, for the first time, polarization-entangled photons from a 400 nm nonlinear layer of gallium phosphide. We achieve an unprecedented tunability of the two-photon polarization state not possible in common bulk sources of photon pairs. The polarization adjustability shown in this work gives an opportunity to easily change a degree of polarization entanglement on demand, making such sources a unique, promising platform for the realization of miniaturized quantum light generators for integrated photonics.

Q 17.7 Tue 12:15 Q-H14

A remedy to finite coupling master equations for open quantum systems — •Becker Tobias[1], Alexander Schnell[1], Juzar Thingna[2], and André Eckardt[1] — [1]Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany — [2]Center for Theoretical Physics of Complex Systems, Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea

For the description of open quantum systems master equations are used that are derived perturbatively to some order of the system-bath coupling strength. The Bloch-Redfield master equation and all other first order expansions give an adequate description only in trivial order of the coupling strength that is for almost vanishing coupling. Attempts to increase the accuracy beyond the Bloch-Redfield equation must go beyond first order perturbation theory. However, for a wide range models, rigorous higher order expansions are hardly possible. We develop a master equation for finite coupling that is easily obtained within the Bloch-Redfield formalism. We benchmark our results against the exact solution of the damped harmonic oscillator that also features non-Markovian behaviour.

Q 18: Laser and Laser Applications

Time: Tuesday 10:30–12:00 Location: Q-H15

Q 18.1 Tue 10:30 Q-H15

Spectroscopy of High Pressure Rubidium-Helium-Mixtures — •Till Ockenfels, Paško Roje, Frank Vewinger, and Martin Weitz — Institut für Angewandte Physik der Universität Bonn, Wegelerstr. 8, D-53115 Bonn

Spectroscopy of alkali-buffer gas mixtures in a regime beyond the impact limit of collisional broadening is relevant in a wide range of fields, ranging from collisional redistribution laser cooling to laboratory astrophysics [1,2]. Here we report recent spectroscopic measurements of dense rubidium-helium gas mixtures recorded in a pressure cell equipped with soldered sapphire optical viewports, where the sapphire window is bonded to a metal flange via active soldering making use of a compound intermediate structure allowing to mediate thermally induced stress [3]. In the gas cell, we have recorded rubidium absorption and emission spectra subject to 250bar helium buffer gas pressure at 500K temperature. The spectra to good accuracy fulfill the Kennard-Stepanov Boltzmann-like frequency scaling of the ratio of absorption and emission spectral profiles.

[1] U. Vogl and M. Weitz, Nature 461, (2009).
[2] F. Bouhadjar et al., J. Phys. B 47 (2014).
[3] T. Ockenfels et al., Rev. Sci. Instrum. 92, 065109 (2021).

Q 18.2 Tue 10:45 Q-H15

Argon Trap Trace Analysis: Applications on age determination in ocean science and stratified lakes — •Yannis Arck[2], Julian Robertz[1], Maximilian Schmidt[1,2], David Wachs[1,2], Florian Meienburg[1,2], Werner Aeschbach[2,3], and Markus Oberthaler[1] — [1]Kirchhoff Institute for Physics, Heidelberg, Germany — [2]Institute of Environmental Physics, Heidelberg, Germany — [3]Heidelberg Center for the Environment, Heidelberg, Germany

The radioisotope ^{39}Ar serves as an environmental tracer in natural science. It is an inert noble gas with a half-life of 269 years, thus suited for dating processes in the age range of 50 to 1000 years. Due to the relative atmospheric abundance of only 10^{-15}, a special quantum-optical technology analysis method is required, if the desired sample sizes should not exceed 10 L of water. In Heidelberg, Argon Trap Trace Analysis (ArTTA) has emerged over the last few years to provide major advances in applicability concerning this difficult tracer.

This is especially relevant for oceanographic studies. In summer 2021, ocean water samples were collected during the Synoptic Artic Survey onboard the Swedish icebreaker Oden. The aim is to investigate circulation and ventilation patterns in combination with noble gas saturation anomalies in the central Arctic Ocean to estimate the uptake of anthropogenic carbon. The most recently completed campaign was on the stratification of Lake Kivu, located in central Africa, a region strongly influenced by volcanic activity. This 450 m deep lake has several resilient stratified layers caused by subsurface groundwater and volcanic gas intrusions. Both studies will be presented in this talk.

Q 18.3 Tue 11:00 Q-H15

3D-Printed Fresnel Lenses for Terahertz Frequencies Using a Cyclic Olefin Copolymer (TOPAS) — •Konstantin Wenzel[1], Sarah Klein[2], Martin Traub[2], Jonas Merit[2], Christian Vedder[2], Martin Schell[1,3], Björn Globisch[1,3], and Lars Liebermeister[1] — [1]Fraunhofer Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin, Germany — [2]Fraunhofer-Institute for Laser Technology, Steinbachstraße 15, 52074 Aachen, Germany — [3]Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstraße 36, 10623 Berlin, Germany

In recent years, the field of terahertz (THz) technology has developed rapidly. With the improvement of transmitters and detectors, optics is in the need to catch up. Currently, off-axis parabolic mirrors or lenses are used as focusing THz optical-elements. Such lenses are usually manufactured from bulk materials as polymers or silicon, e.g. by grinding or cutting, or by compression molding of powders. With the advent of affordable and accurate 3D printers that utilize fused material deposition, a flexible and readily available method for fabricating complex terahertz optical components is now available. Here, we present two- and three-zone Fresnel lenses fabricated by a commercial 3D printer using a cyclic olefin copolymer (TOPAS). TOPAS exhibits particularly low absorption and dispersion and prints well with standard printers. We measured the frequency-dependent beam profile of lenses up to 4 THz and the effects of fabrication onto the scattering. The direct comparison with traditionally manufactured lenses of equal design demonstrates the potential of this fabrication technique.

Q 18.4 Tue 11:15 Q-H15

Integration of a DSTMS based THz emitter into a fibre-coupled THz time-domain spectroscopy system. — •Tina Hesselmann[1,2], Konstantin Wenzel1[1], Robert Kohlhaas[1], Martin Schell[1,3], Björn Globisch[1,3], and Lars Liebermeister[1] — [1]Fraunhofer Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin, Germany — [2]Berliner Hochschule für Technik, Luxemburger Str. 10, 13353 Berlin, Germany — [3]Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstraße 36, 10623 Berlin, Germany

In recent years, Terahertz (THz) time-domain spectroscopy (TDS) has gained relevance in science and is now established on the market. THz spectroscopy is particularly used in contactless and non-destructive thickness measurement of coatings. Due to their user-friendly operation, fibre-coupled THz spectrometer are commonly utilized for such applications. By combining a fs-pulse fibre laser with state-of-the-art semiconductor-based photoconductive antennas, these systems reach bandwidths up to 6.5 THz. However, a recently developed detector, based on a photoconductive membrane, accomplishes an effective bandwidth of 10 THz. A fibre coupled emitter with comparable bandwidth is still needed. An alternate approach uses non-linear optical rectification, e.g. based on DSTMS-crystals in free space excitation, which allows for a wider bandwidth. This study integrates a DSTMS crystal as a emitter into a fibre-coupled TDS system while applying the novel photoconductive antenna as receiver. We find that this setup can utilize the bandwidth of the new receiver by demonstrating a THz bandwidth up to 9.5 THz in a fibre-coupled THz TDS-system.

Q 18.5 Tue 11:30 Q-H15

Highly localized field enhancement at sputter-sharpened tungsten nanotips — •Leon Brückner[1], Timo Paschen[1,2], Mingjian Wu[3], Erdmann Spiecker[3], and Peter Hommelhoff[1] — [1]Department Physik, Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), 91058 Erlangen — [2]Korrelative Mikroskopie und Materialdaten, Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, 91301 Forchheim — [3]Department Werkstoffwissenschaften, Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

Nanotips, i.e., ultrasharp, nanometer-scale protrusions on the surface of field emitter needle tips, are known to have intriguing properties, such as highly localized field enhancement and electron emission, and a narrow transverse energy distribution through emission from surface states. We fabricated nanotips from regular tungsten needle tips via an in-situ ion sputtering technique and investigated their geometry through transmission electron microscope imaging. The field enhancement at the nanotip is probed via laser-driven electron rescattering. Extracting the near-field enhancement factor from the electron energy spectra yields an increase of more than a factor of 2 compared to a regular needle tip, i.e., 8.2 ± 0.2 as compared to 4-5. The experimental results are well reproduced by finite-difference time-domain simulations and bode well for potential applications in strong-field physics or as electron sources for ultrafast electron microscopy.

Q 18.6 Tue 11:45 Q-H15

Impact of the Raman Effect on Two-Color Compound States — •Stephanie Willms[1,2], Oliver Melchert[1,2,3], Surajit Bose[2,3], Uwe Morgner[1,2,3], Ihar Babushkin[1,2], and Ayhan Demircan[1,2,3] — [1]Cluster of Excellence PhoenixD, Wlefengarten 1, 30167 Hannover, Germany — [2]Leibniz University Hannover, Institute of Quantum Optics, Welfengarten 1, 30167, Hannover, Germany — [3]Hannover Centre for Optical Technologies, Nienburger Str. 17, 30167, Hannover, Germany

Soliton molecules usually refer to objects, consisting of two solitons with a fixed temporal separation, which propagate stably in a waveguide. Such molecule states appear, e.g., in dispersion-managed fibers. Recently, a fundamentally different kind of soliton molecule was demonstrated: Two-color compound states. They consist of subpulses at vastly separated center frequencies with similar group-velocities. Therefore, a suitable propagation constant requires at least two separate domains of anomalous dispersion. Such compound states have recently been demonstrated experimentally in a mode-locked laser cavity. Here, we demonstrate that compound states show intriguing propagation dynamics when perturbed by the Raman effect as only one of its subpulses is restrained by a zero dispersion point. Moreover, the generation of such two-color compound states is difficult, since access to two incommensurable, group-velocity matched frequencies is required. For a possible experimental realization, we propose a self-generation scheme enabled by the Raman effect. In particular, we show that a compound state can be generated with a single initial input frequency.

Q 19: Ultra-cold atoms, ions and BEC I (joint session A/Q)

Time: Tuesday 10:30–12:15 Location: A-H2

Q 19.1 Tue 10:30 A-H2

Imaging the interface of a qubit and its quantum many-body environment — Sidharth Rammohan[1], •Aritra Mishra[2], Shiva Kant Tiwari[1], Abhijit Pendse[1], Anil. K. Chauhan[3], Rejish Nath[4], Alexander Eisfeld[2], and Sebastian Wüster[1] — [1]Indian Institute of Science Education and Research, Bhopal, India — [2]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [3]Palacký University, Olomouc, Czechia — [4]Indian Institute of Science Education and Research, Pune, India

Decoherence affects all quantum systems and impedes quantum technologies. In this contribution, we theoretically demonstrate that for a Rydberg atom in a Bose-Einstein condensate, experiments can image the system environment interface that is central for decoherence [1]. High precision absorption images of the condensate can capture transient signals that show real time buildup of the mesoscopic entangled states in the environment. The tuning of the decoherence time scales is possible even from nano seconds to micro seconds using the principle quantum number. As a result, probing is possible even before other sources of decoherence kick in [2]. Finally, we discuss the case in which the system is under a constant microwave drive. This simple modification drastically changes the Hamiltonian as well as the system dynamics, making it non-Markovian, which we study using an advanced numerical technique called the Hierarchy of Pure States [3].

[1] S. Rammohan, et al., (2020), URL https://arxiv.org/abs/2011.11022
[2] S. Rammohan, et al., *Phys. Rev. A.* 103, 063307 (2021)
[3] D. Suess, et al., *Phys. Rev. Lett.* 113, 150403 (2014)

Q 19.2 Tue 10:45 A-H2

Observation of Feshbach Resonances between ^{138}Ba^{+} and ^{6}Li — •Fabian Thielemann[1], Pascal Weckesser[1,2], Joachim Welz[1], Wei Wu[2], Thomas Walker[1], and Tobias Schaetz[1] — [1]Albert-Ludwigs Universität, Freiburg — [2]Max Planck Institut für Quantenoptik, Garching

The experimental control over Feshbach resonances in ensembles of ultracold atoms has lead to breakthrough results in the field. An ion, overlapped with a cloud of ultracold atoms, exhibits a longer range interaction potential and can offer a high degree of control at the single particle level. Reaching the ultracold regime, at which Feshbach resonances emerge, in hybrid traps has so far proven difficult due to micromotion heating. In this talk we present the first observation of Feshbach resonances between ions and atoms by immersing a single ^{138}Ba^{+} ion into a cloud of ultracold ^{6}Li atoms and demonstrate tunability of the two-body and three-body scattering rate of the atom-ion system.

Q 19.3 Tue 11:00 A-H2

Observation of Hole Pairing in Mixed-Dimensional Fermi-Hubbard Ladders — •Sarah Hirthe[1,2], Thomas Chalopin[1,2], Dominik Bourgund[1,2], Petar Bojovic[1,2], Annabelle Bohrdt[3,4], Fabian Grusdt[5,2], Eugene Demler[3,6], Immanuel Bloch[1,2,5], and

Timon Hilker[1,2] — [1]Max-Planck-Institut für Quantenoptik, Garching, Germany — [2]Munich Center for Quantum Science and Technology, Munich, Germany — [3]Harvard University,Cambridge, USA — [4]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, USA — [5]Ludwig-Maximilians-Universität, Munich, Germany — [6]ETH Zurich, Zurich, Switzerland

Doping an antiferromagnet lies at the heart of many strongly correlated systems and the pairing of dopants in particular is believed to play a key role in the emergence of high-Tc superconductivity. In the talk I will discuss our recent direct observation of hole-pairing due to magnetic order in a Fermi-Hubbard type system in our Lithium quantum-gas microscope. We engineer mixed-dimensional Fermi-Hubbard ladders in which the tunneling along the rungs is suppressed, while enhanced spin exchange supports singlet formation, thus drastically increasing the binding energy. We observe pairs of holes preferably occupying the same rung of the ladder. We furthermore find indications for repulsion between pairs when there is more than one pair in the system.

Q 19.4 Tue 11:15 A-H2

Adiabatic charge pumping in bosonic Chern insulator analogs — •Isaac Tesfaye, Botao Wang, and André Eckardt — TU Berlin, Institut für Theoretische Physik, Hardenbergstr. 36, 10623 Berlin, Deutschland

Mimicking fermionic Chern insulators with bosons has drawn a lot of interest in experiments by using, for example, cold atoms [1,2] or photons [3].
Here we present a scheme to prepare and probe a bosonic Chern insulator analog by using an ensemble of randomized bosonic states.
By applying a staggered superlattice, we identify the lowest band with individual lattice sites. The delocalization over this band in quasi-momentum space is then achieved by introducing on-site disorder or local random phases.
Adiabatically turning off the superlattice then gives rise to a bosonic Chen insulator, whose topologically non-trivial property is further confirmed from the Laughlin-type quantized charge pumping.
Our protocol may provide a useful tool to realize and probe topological states of matter in quantum gases or photonic waveguides.
[1] Aidelsburger, Monika, et al. "Measuring the Chern number of Hofstadter bands with ultracold bosonic atoms." Nature Physics 11.2 (2015): 162-166.
[2] Cooper, N. R., J. Dalibard, and I. B. Spielman. "Topological bands for ultracold atoms." Reviews of modern physics 91.1 (2019): 015005.
[3] Ozawa,Tomoki, et. al. "Topological photonics." Rev. of Mod. Phys. 91.1 (2019): 015006

Q 19.5 Tue 11:30 A-H2

Machine learning universal bosonic functionals — •Benavides-Riveros Carlos L.[1], Schmidt Jonathan[2], and Fadel Matteo[3] — [1]Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden, Germany — [2]Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, 06120 Halle (Saale), Germany — [3]Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland

The one-body reduced density matrix γ plays a fundamental role in describing and predicting quantum features of bosonic systems, ultra-cold gases or Bose-Einstein condensates. The recently proposed reduced density matrix functional theory for bosonic ground states establishes the existence of a universal functional F[γ] that recovers quantum correlations exactly. Based on a novel decomposition of γ, we have developed a method to design reliable approximations for such universal functionals [1]. Our results demonstrate that for translational invariant systems the constrained search approach of functional theories can be transformed into an unconstrained problem through a parametrization of a Euclidian space. This simplification of the search approach allows us to use standard machine learning methods to perform a quite efficient computation of both F[γ] and its functional derivative. For the Bose-Hubbard model, we present a comparison between our approach and the quantum Monte Carlo method.
[1] Phys. Rev. Research 3, L032063 (2021).

Q 19.6 Tue 11:45 A-H2

Fibre cavity based quantum network node with trapped Yb ion — •Santhosh Surendra, Pascal Kobel, Ralf Berner, Moritz Breyer, and Michael Köhl — Physikalisches institute, University of Bonn, Bonn, Germany

Quantum networks are promising to revolutionise information exchange and cryptography. An important part of these networks are nodes where quantum states can be stored, and manipulated. In this work, we investigate such a quantum communication node formed by a trapped Yb ion coupled to an optical fibre cavity. Using a resonant fibre cavity for the electric dipole transition at 370nm, we are able to collect the emitted photons with high efficiency, which carry quantum information from node to node via their polarisation. We use pulsed excitation to realise a fibre coupled, deterministic single photon source, where the photons are entangled with the hyperfine states of the ion with a high fidelity of 90.1(17)%. The state of the trapped ion represents the quantum memory, which is used to realise a memory enhanced quantum key distribution protocol (BBM92), being the first step towards realising a quantum repeater node.

Q 19.7 Tue 12:00 A-H2

Pattern formation in quantum ferrofluids: From supersolids to superglasses — •Jens Hertkorn[1], Jan-Niklas Schmidt[1], Mingyang Guo[1], Fabian Böttcher[1], Kevin S. H. Ng[1], Sean D. Graham[1], Paul Uerlings[1], Tim Langen[1], Martin Zwierlein[2], and Tilman Pfau[1] — [1]5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Germany — [2]MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, and Department of Physics, Massachusetts Institute of Technology, USA

Pattern formation is a ubiquitous phenomenon observed in nonlinear and out-of-equilibrium systems. In equilibrium, ultracold dipolar quantum gases have been shown to host superfluid quantum droplet patterns, which realize a supersolid phase. Here we theoretically study the phase diagram of such quantum ferrofluids in oblate trap geometries and discover a wide range of exotic states of matter. Beyond the supersolid droplet regime, we find crystalline honeycomb and amorphous labyrinthine states with strong density connections. These patterns, combining superfluidity with a spontaneously broken spatial symmetry, are candidates for a new type of supersolid and superglass, respectively. The stabilization through quantum fluctuations allows one to find these patterns for a wide variety of trap geometries, interaction strengths, and atom numbers. Our study illuminates the origin of the various possible morphologies of quantum ferrofluids, highlights their emergent supersolid and superglass properties and shows that their occurrence is generic of strongly dipolar interacting systems.

Q 20: Quantum Gases I

Time: Tuesday 16:30–18:30 Location: P

Q 20.1 Tue 16:30 P

Dissipative time crystals in an atom-cavity system — •Phatthamon Kongkhambut[1], Hans Kessler[1], Jim Skulte[1,2], Ludwig Mathey[1,2], Jayson G. Cosme[3], and Andreas Hemmerich[1,2] — [1]Institut für Laser-Physik, Universität Hamburg — [2]The Hamburg Center for Ultrafast Imaging — [3]National Institute of Physics, University of the Philippines

We are experimentally exploring the light-matter interaction of a Bose-Einstein condensate (BEC) with a single light mode of an ultra-high finesse optical cavity. The key feature of our cavity is the small field decay rate ($\kappa/2\pi = 4.5$kHz), which is in the order of the recoil frequency (ωrec$/2\pi = 3.6$kHz). This leads to a unique situation where cavity field evolves with the same timescale as the atomic distribution. If the system is pumped with a steady state light field, red detuned with respect to the atomic resonance, the Dicke model is implemented. Starting in this self-ordered density wave phase and modulating the amplitude of the pump field, we observe a dissipative discrete time crystal, whose signature is a robust subharmonic oscillation between two symmetry-broken states [1]. Modulation of the phase of the pump field give rise to an incommensurate time crystalline behaviour [2-3]. For a blue-detuned pump light with respect to the atomic resonance, we propose an experimental realization of limit cycles. Since the model describing the system is time-independent, the emergence of a limit cycle phase heralds the breaking of continuous time-translation symmetry. [1] H. Keßler et al., PRL, 127, 043602 (2021). [2] J. G. Cosme et al., PRA 100, 053615 (2019). [3] P. Kongkhambut et al., arXiv:2108.11113.

Q 20.2 Tue 16:30 P

Far-from-equilibrium dynamics of the sine-Gordon model — •Philipp Heinen, Aleksandr Mikheev, and Thomas Gasenzer — Kirchhoff-Institut für Physik, Universität Heidelberg

The sine-Gordon (SG) model, a quantum field theory with a cosine interaction potential, has applications in numerous fields of physics. In the context of condensed-matter physics it is particularly well known because it provides a dual description to quantum vortex ensembles. We have studied the far-from-equilibrium dynamics of the SG model both analytically and numerically and show that it exhibits universal dynamics in the vicinity of a non-thermal fixed point (NTFP), which has been described previously for other models. However, we here find an anomalously small temporal and anomalously large spatial scaling exponent. We attribute these to the interaction vertices of arbitrary high order that are present in the SG action.

Q 20.3 Tue 16:30 P

Wilsonian Renormalization in the Symmetry-Broken Polar Phase of a Spin-1 Bose Gas — •Niklas Rasch, Aleksandr Mikheev, and Thomas Gasenzer — Kirchhoff-Institut für Physik, Universität Heidelberg, Germany

Wilsonian renormalization group theory (WRG) is applied to the spin-1 Bose gas both in the thermal and in the symmetry-broken polar phase. WRG is employed in a 1-loop perturbative expansion. In the thermal phase all relevant flow equations are derived and analysed for their fixed-point behaviour and critical exponents. To describe the thermal phase transition, the symmetry is broken explicitly and flow equations in the polar phase are computed including the renormalization of the condensate density. A general scheme is established for investigating the flow equations in a cut-off independent manner at fixed macroscopic density. We find cut-off independent critical temperatures as well as the decrease in condensate density towards criticality and predictions for the condensate depletion. Nevertheless, anomalous scaling is observed in most couplings impeding convergence and physical predictions. This is overcome by introducing anomalous couplings for the temporal and spatial derivatives for which additional flow equations are derived. Including them leads to the disappearance of cut-off dependencies and predictions for all couplings.

Q 20.4 Tue 16:30 P

Shell-shaped dual-component BEC mixtures — •Alexander Wolf[1], Patrick Boegel[2], Matthias Meister[1], Antun Balaž[3], Naceur Gaaloul[4], and Maxim Efremov[1,2] — [1]Institute of Quantum Technologies, German Aerospace Center (DLR), 89077 Ulm, Germany — [2]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ^{ST}), Universität Ulm, 89081 Ulm, Germany — [3]Institute of Physics Belgrade, University of Belgrade, 11080 Belgrade, Serbia — [4]Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany

Since the launch of NASA's Cold Atom Lab there have been ongoing efforts to create shell-shaped Bose-Einstein condensates (BECs) in microgravity. The experimental realization is based on radio-frequency (rf) dressing which, however, is intrinsically sensitive to typical inhomogeneities of the involved magnetic fields. A fully closed shell of Bose-Einstein condensed atoms is therefore yet to be created.

Motivated by this experimental challenge, we propose an alternative approach [1] based on dual-component BEC mixtures where one component forms a shell around the other due to a repulsive inter-component interaction. We find that the mixture shows similar signatures in its collective excitation spectrum at the transition between a filled sphere and a hollow sphere as the rf-dressed BEC but offers additional benefits such as the conservation of the shell structure during the free expansion dynamics.

[1] A. Wolf et al. arXiv 2110.15247 (2021).

Q 20.5 Tue 16:30 P

A Digital Micromirror Device setup for the simulation of spatially curved spacetimes in a two-dimensional BEC — Marius Sparn, Celia Viermann, Maurus Hans, Nikolas Liebster, •Elinor Kath, Helmut Strobel, and Markus Oberthaler — Kirchhoff Institut für Physik, University of Heidelberg, Germany

Analog quantum simulation on a cold atom platform can be used to study a wide variety of cosmological effects like Hawking or Unruh radiation in the lab [1]. We present an implementation which allows for simulation of quantum fields in arbitrarily curved spacetimes in 2+1 dimensions. In our potassium-39 Bose-Einstein condensate the mean field background density determines the spacetime for the quantum field of phononic excitations. Different spatial curvatures can be simulated by preparing the corresponding density profile. This is implemented with the help of a Digital Micromirror Device (DMD), which precisely shapes the intensity profile of a blue detuned dipole trap within the two-dimensional plane. This allows for arbitrary density profiles and their manipulation during an expansion of the metric, which is implemented by a change of the atomic interaction strength. [1] Jiazhong Hu et al., Nature 15, 785-789 (2019).

Q 20.6 Tue 16:30 P

Fluctuations effects in many body self-organization in a dissipative cavity — •Luisa Tolle[1], Catalin-Mihai Halati[2], Ameneh Sheikhan[1], and Corinna Kollath[1] — [1]PI, University of Bonn, Germany — [2]DQMP, University of Geneva, Switzerland

The complexity of open interacting many body quantum systems makes it very appealing to gain control over the quantum states to tailor the properties of the system.

We investigate many body dynamics of the self ordering phase transition present in quantum matter coupled to quantum light. Theoretically, we consider ultracold interacting fermionic atoms on a chain coupled to the field of a dissipative cavity. The model features many competing energy scales, from the atomic short-range interaction to the global coupling to the cavity mode and the interplay with an external bath through photon losses.

To study the steady states and self-ordering processes, we developed a quasi-exact numerical method based on time dependent matrix-product state methods that is able to capture the full dynamics of the complex atoms-cavity coupled system. The newly elaborated method allows to treat a short range interacting quantum many-body system coupled to a lossy bosonic mode and can potentially be adapted to a broad range of systems.

With this method, going beyond the mean field level, we are able to investigate the influence of fluctuations on the coupling between atoms and cavity field and observe the transition to a density modulated phase between mixed states at finite temperature.

Q 20.7 Tue 16:30 P

Comparing Interacting and Non-Interacting Fermions in Topological Synthetic Ladder Systems — •Marcel Diem[1,2], Koen Sponselee[1,2], Benjamin Abeln[1,2], Nejira Pintul[1,2], Tobias Petersen[1,2], Klaus Sengstock[1,2], and Christoph Becker[1,2] — [1]Center for Optical Quantum Technologies, University of Hamburg, Hamburg, Germany — [2]Institute for Laser Physics, University of Hamburg, Hamburg, Germany

Ultracold quantum gases of neutral atoms have been established as an excellent platform for quantum simulation including non-trivial topological systems due their ability to invoke artificial gauge fields and mimic the physics of charged particles in strong magnetic fields.

Here, we present experimental results on two ultracold fermionic ytterbium isotopes in topologically non-trivial lattices. One isotope, ^{171}Yb, is non-interacting, whereas the isotope ^{173}Yb interacts repulsively. We study their behavior in synthetic two-dimensional ladder systems, comprised of a 1D lattice in real space, and a synthetic dimension spanned by two m_F states coupled by Raman beams.

In these ladder systems, the Raman beams impart momentum on the atoms, which results in a coupling between the spin and orbit degrees of freedom, analogous to the effect of a real magnetic field on charged particles.

We measure chiral edge currents and compare interacting and non-interacting systems. Our work paves the way towards a better understanding of the effect of interactions in non-trivial topological systems.

This work has been supported by the DPG within SFB 925.

Q 20.8 Tue 16:30 P

FermiQP: A Fermion Quantum Processor — •Janet Qesja, Maximilian Schattauer, Immanuel Bloch, Timon Hilker, and Philipp Preiss — Max Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching

FermiQP aims to develop a quantum processor based on ultracold fermionic Lithium gas operable in two modes. The analogue quantum gas microscopy mode will be using the fermionic nature of 6Li to perform quantum simulations relevant for quantum material research. The digital mode will enable quantum computation using spin qubits manipulated by laser-driven single qubit and superlattice-based global 2-qubit gates allowing for universal programming. The demonstrator will have a single chamber design with a first 2D MOT capture stage and a second 3D MOT cooling stage. On this poster, we present the design of the vacuum system, the laser system, and the MOTs.

Q 20.9 Tue 16:30 P

A high-resolution imaging system for quantum simulation experiments — •Micha Bunjes, Tobias Hammel, Maximilian Kaiser, Philipp Preiss, Selim Jochim, and Matthias Weidemüller — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg (Germany)

Detecting ultracold Lithium-6 atoms in a new setup for quantum simulations requires a high-resolution imaging setup to resolve and manipulate single atoms, and to image versatile optical dipole traps.

For this we design a system including a high NA objective, featuring diffraction limited broadband performance, a large field of view, and an external back focal plane to retroreflect a collimated MOT beam. Characterizing this system in detail allows us to improve its performance even further and counteract aberrations.

Further we are developing a mounting structure, enabling a passive alignment relative to the imaging objective while maintaining good optical access. Additionally, the mounting around the vacuum viewports is designed to support a modular approach for any optics near the atoms, improving the flexibility of the experiment.

Q 20.10 Tue 16:30 P

Pairing in a Mesoscopic 2D Fermi Gas — •Keerthan Subramanian, Marvin Holten, Luca Bayha, Sandra Brandstetter, Carl Heintze, Philipp Lunt, Philipp Preiss, and Selim Jochim — Physikaliches Insitut, Universität Heidelberg

Pairing in fermionic systems occurs at different length scales from Nuclei to condensed matter systems to neutron stars. The behavior of such disparate systems spanning several orders of magnitude in size can be understood by considering competing energy scales in the system - Fermi energy, confinement energy and Interaction energy - and their relation. In this poster we present a pristine model system with control over each of these energy scales.

Working in the few-body limit we deterministically prepare low entropy, closed shell configurations of fermionic 6Li atoms in a 2D harmonic oscillator potential. With a Feshbach resonance we tune the interaction energy and control how it relates to the other energy scales in the system. We observe the precursor of the many-body Normal-Superfluid quantum phase transition and the associated Higgs mode with interaction modulation spectroscopy. Spin-resolved microscopy of such a system reveals the formation of Cooper pairs in momentum space as interaction energy is tuned in the system.

Future directions including microscopy of such systems in position space with a matterwave microscope and spin-imbalanced systems are presented.

Q 20.11 Tue 16:30 P

Mesoscopic Fermion Systems in Rotating Traps — •Johannes Reiter, Philipp Lunt, Paul Hill, Diana Körner, Philipp Preiss, and Selim Jochim — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Ultracold atomic gases in rotating traps enable the study of integer and fractional quantum Hall physics with unprecedented control of the systems′ properties [1].

In order to access the microscopic level of strongly correlated quantum Hall states we build on our previously established experimental methods - the deterministic preparation of ultracold ^{6}Li few Fermion systems in low dimensions [2,3], as well as local observation of their correlation and entanglement properties on the single atom level [4].

Here, we present current experimental progress and theoretical simulations on the adiabatic preparation of mesoscopic Fermion systems in rapidly rotating optical potentials. Experimentally, we achieve rotation by interference of a Gaussian and Laguerre-Gaussian mode via a spatial light modulator. Theoretically, we utilize efficient diagonalization methods to study few strongly interacting Fermionic atoms where analytical solutions are unfeasible and statistical methods are not yet applicable. In particular, we showcase the elaborate optical setup with first experimental results and present the numerical calculations.

[1] Palm et al. New J. Phys. 22 083037 (2020) [2] Serwane et al. Science 332 (6027), 336-338 (2011) [3] Bayha et al. Nature 587, 583-587 (2020) [4] Bergschneider et al. Nat. Phys. 15, 640-644 (2019)

Q 21: Ultracold Atoms and Plasmas (joint session Q/A)

Time: Tuesday 16:30–18:30 Location: P

Q 21.1 Tue 16:30 P

Controlling multipole moments of magnetic chip traps — •Tobias Liebmann and Reinhold Walser — Institute of Applied Physics, TU Darmstadt, Hochschulstr. 4a, 64289 Darmstadt, Germany

Magnetic chip traps are a standard tool for trapping atoms [1, 2]. These are robust devices with multiple fields of use ranging from fundamental physics experiments [3] to applications of inertial sensing [2]. While magnetic traps do provide good confinement potentials, they are not perfectly harmonic. In particular, they do exhibit cubic anharmonicities. In this contribution, we discuss a method for designing printable two-dimensional wire guides which compensate unfavorable multipole moments. Parametrizing a wire shape with suitable basis functions allows us to calculate the magnetic induction field using the Biot-Savart law from Magnetostatics. This enables us to control the multipole moments in proximity to the trap minimum.

[1] J. Reichel, and V. Vuletic, eds. *Atom chips* (John Wiley & Sons, Weinheim, 2011).
[2] M. Keil, et al., *Fifteen years of cold matter on the atom chip: promise, realizations, and prospects*, Journal of Modern Optics **63**, 1840 (2016).
[3] D. Becker, et al., *Space-borne Bose-Einstein condensation for precision interferometry*, Nature **562**, 391 (2018).

Q 21.2 Tue 16:30 P

Optical zerodur bench system for the BECCAL ISS quantum gas experiment — •Faruk Alexander Sellami[1], Jean Pierre Marburger[1], Esther del Pino Rosendo[1], André Wenzlawski[1], Ortwin Hellmig[2], Klaus Sengstock[2], Patrick Windpassinger[1], and THE BECCAL TEAM[1,3,4,5,6,7,8,9,10,11] — [1]Inst. für Physik, JGU Mainz — [2]ILP, UHH — [3]Inst. für Physik, HUB — [4]FBH, Berlin — [5]IQ & IMS, LUH — [6]ZARM, Bremen — [7]Inst. für Quantenoptik, Univ. Ulm — [8]DPG-SC — [9]DPG-SI — [10]DPG-QT — [11]OHB

BECCAL is a NASA-DLR collaboration, which will be a facility for the study of Bose Einstein Condensates consisting of potassium and rubidium atoms in the microgravity environment of the International Space Station (ISS). An essential component of the apparatus is the optical system, which takes over laser light distribution and frequency stabilization for several light fields. To ensure this, all system components must for instance be able to cope with vibrations during rocket launch and temperature fluctuations during the campaign. To this end, we are using and extending a toolkit based on the glass-ceramic Zerodur, that has already successfully been used on numerous space missions, like FOKUS, KALEXUS or MAIUS. This poster discusses the optical modules developed for BECCAL. Our work is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50 WP 1433, 50 WP 1703 and 50 WP 2103.

Q 21.3 Tue 16:30 P

Improved Laser System for Optical Trapping of Neutral Mercury — •Rudolf Homm, Tatjana Beynsberger, and Thomas Walther — Technische Universität Darmstadt, Institut für Angewandte Physik, Laser und Quantenoptik, Schlossgartenstraße 7, 64289 Darmstadt

Cold Hg-atoms in a magneto-optical trap offer opportunities for various experiments. The two stable fermionic isotopes are interesting with regard to a new time standard based on an optical lattice clock employing the $^1S_0$ - $^3P_0$ transition at 265.6 nm. The five stable bosonic isotopes can be used to form ultra cold Hg-dimers through photo-association in connection with vibrational cooling by applying a specific excitation scheme.

The laser system consists of an MOFA-Setup at 1014.8 nm followed by two consecutive frequency-doubling stages. Due to a new high-power diode and a 50 W-pump laser at 976 nm the fundamental power was amplified up to 12 W. This results in up to 5 W at 507.4 nm after the first frequency-doubling cavity.

The limiting factor in generating high power at 253.7 nm so far, was the degradation of the non-linear BBO-crystal used in the second frequency-doubling stage. To avoid this problem, we developed and tested a cavity with elliptical focusing [1,2]. This new cavity produces over 700 mW at 253.7 nm without a sign of degradation. We will report on the status of the experiments.

[1] Preißler, D., *et al.*, *Applied Physics B* **125** (2019): 220
[2] Kiefer, D., *et al.*, *Laser Physics Letters* **16** (2019): 075403

Q 21.4 Tue 16:30 P

Generation of time-averaged potentials using acusto-optical deflectors — •Vera Vollenkemper, Henning Albers, Sebastian Bode, Alexander Herbst, Knut Stolzenberg, Ernst M. Rasel, and Dennis Schlippert — Institute of Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167, Hannover, Germany

The production of degenerated quantum gases in optical dipole traps is a cornerstone of many modern experiments in atomic physics. To achieve ultracold temperatures evaporative cooling is commonly used. However, the long timescales of a few seconds for conventional evaporative cooling represent a bottleneck for many applications like inertial sensors, where high repetition rates are essential. Time-averaged optical potentials are a technique to shorten these timescales and therefore significantly increasing the repetition rate. Among other methods, these potentials can be implemented using an 2D acusto-optical deflector (AOD) modulating the trapping laser beam. Due to the nonlinearity of the AOD the input frequency ramps are not exactly imprinted on the beam and therefore the exact form of the potential in the trap is unknown. To investigate the resulting shape of the trapping potential a test stand was set up. We test the influence of different RF-sources, lens systems and modulation techniques. The generated trap geometries are analyzed using a large beam profiling camera. We compare the measured potentials and frequency ramps imprinted on the laser beam to the theoretically expected ones.

Q 21.5 Tue 16:30 P

A first two-dimensional magneto-optical trap for dysprosium — •Jianshun Gao, Christian Gölzhäuser, Karthik Chandrashekara, Joschka Schöner, Valentina Salazar Silva, Lennart Hooenen, Shuwei Jin, and Lauriane Chomaz — Physikalisches Institut der Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Ultracold atoms offer an ideal platform to explore new quantum phenomena due to their great experimental controllability and a high degree of isolation. Being the most magnetic element, dysprosium presents not only a tunable short-range contact interaction but also a competing isotropic long-range dipole-dipole interaction. Making use of this competition, novel many-body quantum states were discovered, including liquid-like droplets, droplet crystals, and most recently supersolids. Our new group, Quantum Fluids, at Heidelberg University is designing a novel compact experimental set-up which will be based on the first two-dimensional magneto-optical trap (2D-MOT) to produce a high-flux beam of slow dysprosium atoms, instead of the more standard Zeeman slower design. Additionally, combining a crossed-optical dipole trap, a tuneable accordion lattice optical trap, a tailorable in-plane trap, and a tunable magnetic environment, will give us a great opportunity to investigate many-body phenomena occurring in dipolar gases confined in two-dimensional spaces. At the Erlangen 22 conference, I would like to present the design and implementation of our 2D-MOT.

Q 21.6 Tue 16:30 P

A modular optics approach for a new quantum simulation apparatus — •Vivienne Leidel[1], Malaika Göritz[1], Marlene Matzke[1], Tobias Hammel[1], Maximilian Kaiser[1], Philipp Preiss[2], Selim Jochim[1], and Matthias Weidemüller[1] — [1]Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg (Germany) — [2]Max Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching (Germany)

In order to conduct quantum simulation with ultracold trapped Lithium-6 atoms, a multitude of optical elements is needed. By dividing our setup into modules that can be easily moved and exchanged, we hope to become more efficient both in implementing new setups and tweaking existing ones. Additionally, reducing degrees of freedom as much as possible will yield more stable alignments.

Examples for this passive stability are our double pass modules for acousto-optic modulators, which are used to detune a cooling and a repumping beam.

The first cooling stage of the experiment is a 2D-MOT. As available laser power is crucial for a fast loading rate, we use a bowtie configuration and prepare flat-top beam profile using an optical diffuser. We use a high-power TA-SHG laser system providing 1W of laser power.

This Laser is locked to the Lithium-6 D2 transition using a modulation transfer scheme to ensure minimal drifts in frequency.

Q 21.7 Tue 16:30 P

Erbium-Lithium: Towards a new mixture experiment — •Florian Kiesel, Alexandre De Martino, and Christian Gross — Eberhard Karls Universität Tübingen, Physikalisches Institut, Auf der Morgenstelle 14, 72076 Tübingen

Ultra cold fermions can not be cooled below 10% of the Fermi temperature efficiently. Sympathetic cooling with a classical gas as an entropy reservoir may provide a new direction to overcome the current limit. Testing this approach, we are building a new two species ultra cold quantum gas experiment. Its goal is to overlap fermionic lithium and bosonic erbium using a dipole trap at a tune-out wavelength. Doing this, we are planning to trap and cool both species separately. Transporting the atoms into the science chamber will be done optically, but aided by magnetic levitation. In the course of this, a transport distance of up to 1 m has to be demonstrated. The following sympathetic cooling by an intentionally kept classical erbium gas of the lithium cloud, enables to overcome the limiting factor of exponentially rising thermalization time of spin-mixture cooling. There, the great mass imbalance does not only help to cool lithium more efficiently, but it also gives rise to the chance of exploring polaron and impurity physics. In the future using the interspecies Feshbach resonances, this mixture could allow to exhibit in process cooling of qubits to stabilize long sequences of gate operations.

Q 21.8 Tue 16:30 P

Simulating atom dynamics in grating magneto-optical trap — •Aaditya Mishra[1], Hendrik Heine[1], Joseph Muchovo[1], Waldemar Herr[1,2], Christian Schubert[1,2], and Ernst M. Rasel[1] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR), Institut für Satellitengeodäsie und Intertialsensorik, c/o Leibniz Universität Hannover, DLR-SI, Callinstr. 36, D-30167 Hannover, Germany

Ultracold atoms provide exciting opportunities in precision measurements using atom interferometers, quantum information and testing fundamental physics. Grating magneto-optical traps (gMOTs) in conjunction with atom chips provide an efficient and compact source of cold atoms. However, experimentally tuning the gMOT parameters for trapping maximum number of atoms is rather challenging, given the laborious installation of several microfabricated test gratings and re-establishing the ultra-high vacuum required for trapping.

In this poster, I will present a computational simulation of atom dynamics emerging from atom-light interactions, as well as gMOT parameter optimization for atom cooling and trapping. This is useful for quick analysis of various design techniques for gMOTs and atom chips.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) due to the enactment of the German Bundestag under grant number DLR 50WM1947 (KACTUS-II), DLR 50RK1978 (QCHIP) and by the German Science Foundation (DFG) under Germany's Excellence Strategy (EXC 2123) "QuantumFrontiers".

Q 21.9 Tue 16:30 P

Point-spread-function engineering for 3D atom microscopy — •Tangi Legrand[1], Carrie Ann Weidner[2], Brian Bernard[3], Gautam Ramola[1], Richard Winkelmann[1], Dieter Meschede[1], and Andrea Alberti[1] — [1]Institut für Angewandte Physik der Universität Bonn, Bonn, Germany — [2]Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark — [3]École normale supérieure Paris-Saclay, Gif-sur-Yvette, France

Quantum gas microscopes can resolve atoms trapped in a 3D optical lattice down to the single site in the horizontal plane. Along the line of sight, however, a much lower resolution is achieved when the position in this direction is inferred from the defocus. It is shown how phase-front engineering can be used to detect atoms' positions with submicrometer resolution in the three dimensions using a single image acquisition. By means of a spatial light modulator, we imprint a phase modulation in the Fourier plane of the imaging system, resulting in a superposition of Laguerre-Gaussian modes at the camera. As a result, the so-called point spread function of the imaging system exhibits a spiraling intensity distribution along the line of sight. The angle of the spiraling distribution encodes the position in the third dimension. As a proof of concept, we set up an optical experiment reproducing the conditions of a quantum gas microscope. The choice and optimization of the mode superposition and an implementation scheme for Bonn's quantum walk setup is discussed. This method can find applications in other quantum gas experiments to extend the domain of quantum simulation from two to three dimensions.

Q 21.10 Tue 16:30 P

Development of a laser system for Hg-photoassociation — •Tatjana Beynsberger, Rudolf Homm, and Thomas Walther — Technische Universität Darmstadt, Institut für Angewandte Physik, Laser und Quantenoptik, Schlossgartenstraße 7, 64289 Darmstadt

The trapping of cold Hg-atoms in magneto-optical traps in combination with the fact that Hg consists of stable fermionic and bosonic isotopes provides the opportunity for a number of different experiments. For the two fermionic isotopes the $^1S_0 - {}^3P_0$ transition could prove valuable for defining a new time standard based on an optical lattice clock. A matter of particular interest for the bosonic isotopes is the formation of ultra cold Hg-dimers via photoassociation, where two colliding atoms absorb a photon to form an excited molecule, and subsequent vibrational cooling employing a specific excitation scheme. A laser system to be used for photoassociation needs to fulfill certain requirements, namely a narrow line width and sufficient power while also being tunable. The photoassociation laser system, when finished, consists of an interference filter-stabilized external cavity diode laser with an emission at 1016.4 nm, a tapered amplifier, and two consecutive frequency-doubling stages, the latter includes a cavity with elliptical focus designed to reduce crystal degradation. Our goal is to achieve several tens of milliwatt for the frequency-quadrupled light. We will report on the current status of the laser system.

Q 21.11 Tue 16:30 P

A Compact Optical Lattice Quantum Simulator for Random Unitary Observables — •Naman Jain and Philipp Preiss — Max Planck Institute of Quantum Optics, Garching, Germany

The recent advances in probing complex quantum many-body systems at the level of single constituents allow us to pose incisive questions regarding the dynamics of such systems. Combining approaches from quantum information theory with state-of-the-art quantum simulation techniques may lead to new ways of characterizing itinerant quantum systems more generally. We pursue this in our project UniRand by realizing a new, widely applicable approach to measuring global quantum state properties in a system of ultracold atoms in an optical lattice - using random unitary operations. The strategy promises an entirely new toolbox for state characterization and device verification. To this end, we are developing a new, compact apparatus for the preparation of small-scale fermionic quantum gases in optical lattices with short cycle times. The design features a 2D MOT atomic source, a nanocoated glass cell and high-resolution imaging. Here, we report on the progress of this new experimental setup.

Q 21.12 Tue 16:30 P

Towards hybrid quantum systems of ultracold Rydberg atoms, photonic and microwave circuits at 4 K — •Cedric Wind, Julia Gamper, Hannes Busche, and Sebastian Hofferberth — Institut für Angewandte Physik, Universität Bonn, Germany

The strong interactions of ultracold Rydberg atoms can be exploited not only for neutral atom quantum computing and simulation, but also to implement a growing toolbox of nonlinear single photon devices in Rydberg quantum optics (RQO). Following demonstrations of e.g. single photon sources, optical transistors, or quantum gates, it is our goal to bring RQO closer to practical applications by realizing networks of such devices "on-a-chip". Moreover, as Rydberg atoms couple strongly to microwaves, RQO provides a promising route towards optical read-out of superconducting qubits, e.g. in combination with electromechanical oscillators. However, unlike most experiments with ultracold Rydberg atoms to date, all these applications require cryogenic temperatures to suppress thermal noise.

Here, we present our progress towards a closed-cycle cryogenic ultracold atom apparatus that will allow us to trap and manipulate atoms near integrated photonic chips and microwave circuits. Besides reduced thermal noise, we also expect that the improved vacuum due to cryopumping eliminates the need to bake the system and allows for a rapid sample exchange. The cryogenic environment should also suppress blackbody-induced decay of Rydberg excitations, a major limitation in quantum simulation and information processing applications.

Q 21.13 Tue 16:30 P

Autler-Townes spectroscopy of Rydberg ions in coherent motion — •Alexander Schulze-Makuch[1], Jonas Vogel[1], Marie Niederländer[1], Bastien Gely[1,2], Arezoo Mokhberi[1], and Ferdinand Schmidt-Kaler[1,3] — [1]QUANTUM, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany — [2]ENS Paris-Saclay, 91190 Gif-sur-Yvette, France — [3]Helmholtz-Institut Mainz, D-55128 Mainz, Germany

The exaggerated polarizability of Rydberg atoms and ions has led to significant interest in the cold atom and ion community. Due to their enhanced electric field sensitivity, electric kicks on a Rydberg ion result in large state dependent forces which can be used to generate entanglement in a multi-ion crystal in the sub-μs timescale [1]. We use electric kicks to excite a Rydberg ion into a coherent motional state. Observing now the Stark shift in the Rydberg spectrum allows for the determination of the state polarizability. By microwave-coupling Rydberg nS and mP states, with opposite sign of polarizability, we aim for dressing the state and engineering the polarizability. We present Autler-Townes spectroscopy measurements with a single trapped ion probing thermal and coherent motional excitations in the trapping fields, and eventually the engineering of the effective polarizability, important for gate operations [2].

[1] Vogel et al., *Phys. Rev. Lett.* **123**, 153603 (2019) [2] Zhang et al., *Nature* **580**, 7803 (2020)

Q 21.14 Tue 16:30 P

Towards the formation of ultracold ion-pair-state molecules — •Martin Trautmann, Anna Selzer, Lukas Müller, Michael Peper, and Johannes Deiglmayr — Leipzig University, Department of Physics and Geosciences, 04103 Leipzig, Germany

Recently it was proposed that a gas of long-range Rydberg molecules (LRM) may be converted into a gas of ultracold molecules in ion-pair states (UMIPS) by stimulated deexcitation [1,2]. UMIPS may facilitate the creation of a strongly correlated plasma with equal-mass charges [3], a system hitherto unavailable for laboratory studies, and provide a source of ultracold anions, *e.g.* for the sympathetic cooling of anti-protons [4]. To explore the proposed route towards the creation of UMIPS, we first create a gas of Cs_2 LRMs using photoassociation (PA). By referencing the PA laser to an atomic spectroscopy via an electronic-sideband-locked transfer cavity, we can stabilize the PA lasers frequency to arbitrary molecular resonances with frequency fluctuations of less than 0.3 MHz per day. To drive the transition towards UMIPS, we have set up a pulsed Mid-IR laser with pulse energies around 1 mJ and a transform-limited bandwidth of 130 MHz. This improved spectroscopic setup will be presented together with the current status of our experiments.

[1] M. Peper, J. Deiglmayr, J. Phys. B 53, 064001 (2020) [2] F. Hummel *et al.*, New J. Phys. 22, 063060 (2020) [3] F. Robicheaux *et al.*, J. Phys. B 47, 245701 (2014) [4] C. Cerchiari *et al.*, Phys. Rev. Lett. 120, 133205 (2018)

Q 21.15 Tue 16:30 P

Towards a photonic phase gate using stationary light polaritons — •Lorenz Luger[1], Annika Tebben[1], Eduard J. Braun[1], Titus Franz[1], Maximilian Müllenbach[1], André Salzinger[1], Sebastian Geier[1], Clement Hainaut[1,2], Gerhard Zürn[1], and Matthias Weidemüller[1] — [1]Physikalisches Institut, Im Neuenheimer Feld 226 — [2]Université Lille, CNRS, UMR 8523 -PhLAM-Physique des Lasers, Atomes et Molécules, Lille, France

We work towards a photonic phase gate where a target photon experiences a phase shift of pi depending on the presence of a control photon. By using quantum states, a superposition of atomic coherences and electromagnetic light fields, we take advantage of the long storage times of atomic coherences and the fast transport properties of light fields. The light fields couple an atomic ground state to a long-lived Rydberg state where the fields are chosen such that no short-lived excited states are populated. These quantum states are called dark state polaritons and we incorporate a so-called stationary light polariton where these dark state polaritons are coupled. We aim to achieve a mode coupling like that of a Bragg grating with sharp transmission resonances by finding particular field parameters. In presence of a Rydberg excitation, called Rydberg impurity, the coupling is modified, leading to reflection of an incoming target probe field. By using a Sagnac interferometer this switch between transmission and reflection is transformed in a photonic pi phase gate.

Q 22: Precision Measurements and Metrology I (joint session Q/A)

Time: Tuesday 16:30–18:30 Location: P

Q 22.1 Tue 16:30 P

Towards dual species interferometry in space: MAIUS-B laser system — •Pawel Arciszewski[1], Klaus Döringshoff[1], Achim Peters[1], and The MAIUS Team[1,2,3,4,5] — [1]Institut für Physik, Humboldt-Universität zu Berlin — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin — [3]ZARM, Zentrum für Angewandte Raumfahrttechnologie und Mikrogravitation, Bremen — [4]Institut für Physik, JGU Mainz — [5]IQO, Leibniz Universität Hannover

The first production of a space-borne BEC carried out during the MAIUS-1 sounding rocket mission in January 2017 paved the way for more advanced experiments with an ultra-cold matter in space. The goal of upcoming MAIUS-2 and MAIUS-3 missions is to perform dual-species interferometry onboard a sounding rocket to investigate the weak equivalence principle.

To make that possible a new laser system was developed. The designed equipment can provide the light needed for simultaneous laser cooling of rubidium and potassium and further stages used in atom interferometry experiments. Moreover, the system has to be robust and reliable to meet the demands of a sounding rocket mission.

We report on the current status of the system, its assembly process, and used technologies as well, as tests carried out to assure the equipment can face the present needs of the mission.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50WP1432.

Q 22.2 Tue 16:30 P

Third-order atomic Raman diffraction in microgravity — •Sabrina Hartmann[1], Jens Jenewein[1], Sven Abend[4], Albert Roura[2], and Enno Giese[1,3,4] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm — [2]Institut für Quantentechnologien, DLR — [3]Institut Angewandte Physik, TU Darmstadt — [4]Institut für Quantenoptik, Leibniz Universität Hannover

Large-momentum-transfer (LMT) applications such as sequential pulses, higher-order Bragg diffraction and Bloch oscillations are essential tools to increase the enclosed area of an atom interferometer and thus, its sensitivity. However up to now only sequential pulses have routinely been employed with Raman diffraction.

We show theoretically [1] that double Raman diffraction [2,3] enables third order diffraction. We compare the process to a sequence of first-order pulses with the same total momentum transfer and demonstrate that third-order diffraction gives higher diffraction efficiencies for ultracold atoms. Hence, it is a competitive tool for atom interferometry with BECs in microgravity which increases the momentum transfer by a factor of six. Moreover, it allows us to reduce the complexity of the experimental setup and the total duration of the diffraction process.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry of Economics and Energy (BMWi) under grant number 50WM1956 (QUANTUS V).

[1] *PRA* **102**, 063326 (2020). [3] *PRL* **103**, 080405 (2009).
[2] *PRA* **101**, 053610 (2020).

Q 22.3 Tue 16:30 P

Towards high-precision Bragg atom interferometry using rubidium Bose-Einstein condensates — •Dorothee Tell[1], Christian Meiners[1], Henning Albers[1], Ann Sabu[1,2], Klaus H. Zipfel[1], Ernst M. Rasel[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Deutschland — [2]Cochin University of Science and Technology (CUSAT), Kerala, India

The Very Long Baseline Atom Interferometry (VLBAI) facility at the university of Hannover aims for high precision measurements of inertial quantities. Goals span from contributions to absolute geodesy as well as fundamental physics at the interface between quantum mechanics and general relativity. The VLBAI facility makes use of a freely falling ensemble of ultracold atoms as a probe for inertial forces, interrogating the atoms in an interferometer scheme using near-resonant light pulses.

Here we present details of the fast, all-optical preparation of rubidium Bose-Einstein condensates in time-averaged dynamic optical dipole traps. We will show first proof-of-principle Bragg beam splitting and interferometry in a reduced baseline of up to 30 cm. Prospects and challenges of extending the free fall distance to more than 10 m in the frame of the VLBAI facility will be discussed.

We acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Project-ID 434617780 - SFB 1464 as well as CRC 1227 (DQ-mat), project B07. The VLBAI facility is a major research equipment funded by the DFG.

Q 22.4 Tue 16:30 P

Second-quantized effective models for Raman diffraction with center-of-mass motion — •Nikolija Momčilović[1], Alexander Friedrich[1], and Wolfgang P. Schleich[1,2] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm — [2]Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt

Two-photon Raman transitions are commonly used to facilitate $\pi/2$- and π-pulses in atom interferometry, and are the analogue of beam splitters and mirrors in optical interferometers. In practice, these transitions are driven by laser light which can be described semi-classically as quasi-coherent states. Thus quantization effects are averaged out due to the broad photon distribution in typical beams. However, technological progress moves towards the use of optical cavities due to their superior optical properties. Theoretical modeling of such configurations demands a second-quantized description of the light fields which we pursue based on the light-matter interaction of two second-quantized single-mode light fields and an effective two-level atom. In our contribution we derive and investigate a two-photon Rabi model with center-of-mass motion including intensity-dependent operator-valued couplings between the light field and the center-of-mass motion. We show, that under certain approximations we obtain an effective Jaynes-Cummings model with a center-of-mass dependent detuning.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50WM1956.

Q 22.5 Tue 16:30 P

Light-pulse atom interferometry with quantized light fields — •Tobias Assmann[1], Fabio Di Pumpo[1], Katharina Soukup[1], Enno Giese[2], and Wolfgang P. Schleich[1,3] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm — [2]Institut für Angewandte Physik, Technische Universität Darmstadt — [3]Institute of Quantum Technologies, German Aerospace Center (DLR)

The analogues of optical elements in light-pulse atom interferometers are generated from the interaction of matter waves with light, where the latter is usually treated as a classical field. Nonetheless, light fields are inherently quantum, which has fundamental implications for atom interferometry.

In particular, *quantized* light fields lead to a reduced visibility in the observed interference [J. Chem. Phys. **154**, 164310 (2021)]. This loss is a consequence of the encoded which-way information about the atom's path. However, the quantum nature of the atom-optical elements also offers possibilities to mitigate such effects: We demonstrate that involving superpositions in every light field yields an improved visibility, and an infinitely-strong coherent state recovers full visibility. Moreover, entanglement between all light fields can erase information about the atom's path and by that partially recovers the visibility.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry of Economics and

Technology (BMWi) due to an enactment of the German Bundestag under grant DLR 50WM1956 (QUANTUS V).

Q 22.6 Tue 16:30 P

Hybridized atom interferometer with an opto-mechanical resonator — •Ashwin Rajagopalan[1], Lee Kumanchik[2,3], Claus Braxmaier[2,3], Felipe Guzmán[4], Ernst M. Rasel[1], Sven Abend[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Hannover — [2]DLR - Institute of Space Systems, Bremen — [3]University of Bremen - Center of Applied Space Technology and Microgravity (ZARM),Bremen — [4]Department of Aerospace Engineering & Physics, Texas A&M University, College Station, TX 77843, USA

Vibrational noise coupling through the inertial reference mirror hinders the atom interferometer (AI) performance, so we use a novel opto-mechanical resonator (OMR) in order to suppress it. We have utilized the OMR signal to resolve a T = 10 ms AI fringe, which would have otherwise been obscured by an average ambient vibrational noise of 3.2 mm/s^2 in our laboratory. By incorporating the OMR in our AI we could demonstrate operation in a noisy environment without the use of bulky vibration isolation equipment, therefore paving a way for miniaturization of the AI sensor head. We show our sensor fusion concept and discuss prospects for tailored setups by design and implementation of customized OMRs.

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers - 390837967. This work is supported by the DLR with funds provided by the BMWi under grant no. DLR 50RK1957 (QGyro) and DLR 50NA2106 (QGyro+).

Q 22.7 Tue 16:30 P

Multi-axis quantum gyroscope with multi loop atomic Sagnac interferometry — •Yueyang Zou[1], Mouine Abidi[1], Philipp Barbey[1], Ashwin Rajagopalan[1], Christian Schubert[1,2], Matthias Gersemann[1], Dennis Schlippert[1], Sven Abend[1], and Ernst M. Rasel[1] — [1]Institut für Quantenoptik - Leibniz Universität, Welfgarten 1, 30167 Hannover — [2]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik, Germany

The interferometric Sagnac phase shift can be used for rotation detection in inertial navigation. We are designing a transportable demonstrator aiming at a multi-axis inertial sensor, not only for the precise measurement of rotations but also for accelerations. This poster will give an overview of the multi-loop atomic Sagnac interferometry theory, and present a preliminary system design for the demonstrator with Bose-Einstein condensates (BECs) of 87Rb atoms.

We acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy - EXC-2123 QuantumFrontiers - 390837967 and through the CRC 1227 (DQ-mat), as well as support from DLR with funds provided by the BMWi under grant no. DLR 50RK1957 (QGyro) and DLR 50NA2106 (QGyro+).

Q 22.8 Tue 16:30 P

Single-photon transitions in atom interferometry — •Alexander Bott[1], Fabio Di Pumpo[1], Enno Giese[2], and Wolfgang P. Schleich[1,3] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany — [2]Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstr. 7, Darmstadt D-64289, Germany — [3]Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt, Söflinger Str. 100, D-89077 Ulm, Germany

Differential measurements with atom interferometers have been employed for the measurement of gravity gradients and are promising for the detection of gravitational waves. By using only a single laser to create atom interferometers in a differential setup, phase noise from secondary laser beams cannot influence the measurement. However, with a single laser two-photon transitions are no longer possible. Instead, single-photon transitions have to be employed to create the interferometers. In our contribution we perform a detailed discussion of possible types of single-photon transitions and investigate their advantages and draw-backs for atom interferometers. Specifically, we focus on the effects of the coupling induced by the dispersion relation of the laser driving the single-photon transitions in earth-bound experiments.

The QUANTUS project is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50WM1956 (QUANTUS V).

Q 22.9 Tue 16:30 P

Absolute light-shift compensated laser system for a twin-lattice atom interferometry — •Mikhail Cheredinov[1], Matthias Gersemann[1], Martina Gebbe[2], Ekim T. Hanimeli[2], Simon Kanthak[3], Sven Abend[1], Ernst M. Rasel[1], and the QUANTUS team[1,2,3,4,5,6] — [1]Institut für Quantenoptik, LU Hannover — [2]ZARM, Uni Bremen — [3]Institut für Physik, HU zu Berlin — [4]Institut für Quantenphysik, Uni Ulm — [5]Institut für Angewandte Physik, TU Darmstadt — [6]Institut für Physik, JGU Mainz

Twin-lattice interferometry is a method to form symmetric interferometers featuring matter waves with large relative momentum by employing two counterpropagating optical lattices. A limiting factor here is loss of contrast, linked to the AC-Stark effect from far detuned light. This contribution presents the realisation of an absolute light-shift compensation and its potential to increase the interferometric contrast. The optical setup utilizes two independent frequency doubling stages. Key features are beam overlap on an interference filter with low power loss and coupling of high optical power in a photonic crystal fiber, opening up possibilities for new records in momentum transfer.

This work is supported by the DLR with funds provided by the BMWi under grant no. DLR 50WM1952-1957 (Q-V-Ft), DLR 50RK1957 (QGyro) and DLR 50NA2106 (QGyro+), the VDI with funds provided by the BMBF under grant no. VDI 13N14838 (TAIOL) and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy EXC-2123 QuantumFrontiers 390837967.

Q 22.10 Tue 16:30 P

An ytterbium setup for gravity measurements at VLBAI — •Ali Lezeik[1], Abhishek Purohit[1], Klaus Zipfel[1], Christian Schubert[1,2], Ernst M. Rasel[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover - Institut für Quantenoptik — [2]Institute for Satellite Geodesy and Inertial Sensing - German Aerospace Center (DLR)

Atoms such as strontium (Sr) and ytterbium (Yb) have no magnetic moments in their spin-singlet ground state making them nearly insensitive to external magnetic fields and hence appealing for precision measurements through atomic interferometry. Furthermore, Yb's high mass and hence low expansion rate in addition to its narrow clock transition in the optical frequency range creates an ideal candidate for gravity measurements tests.

We present the Yb-174 setup for producing a robust, high-flux source of laser-cooled ytterbium atoms for the Very Large Baseline Atomic Interferometry (VLBAI) facility [1,2]. We present the laser system, the cooling sequence, the transfer cavity for frequency stabilization of the cooling beams, and a clock cavity for the 1156nm clock transition beam. We outline possible implementations of this system for atom-interferometric tests of the universality of gravitational redshift [3].

[1] É. Wodey et al., J. Phys. B: At. Mol. Opt. Phys. 54 035301 (2021)

[2] D. Schlippert et al., arXiv:1909.08524 (2019)

[3] C. Ufrecht, ..., C. Schubert, D. Schlippert, E. M. Rasel, E. Giese, arxiv:2001.09754 (2020)

Q 22.11 Tue 16:30 P

An overview of Very Long Baseline Atom Interferometry facility — •Abhishek Purohit[1], Klaus H. Zipfel[1], Ali Lezeik[1], Dorothee Tell[1], Christian Meiners[1], Christian Schubert[1,2], Ernst M. Rasel[1], and Dennis Schlippert[1] — [1]Leibniz Universität Hannover, Institut für Quantenoptik, Germany — [2]German Aerospace Center (DLR), Institute for Satellite Geodesy and Inertial Sensing, Hannover, Germany

Our Very Long Baseline Atom Interferometry (VLBAI) facility aims for a complementary method to the state-of-the-art gradiometers and gravimeters when operated with a single atomic species, and for quantum tests of the universality of free fall at levels comparable to the best classical tests and beyond in a mode with two atomic species.

We discuss the main components of the Hannover VLBAI facility: the sources for ultra-cold atom samples, a magnetically shielded interferometry zone, state-of-the-art vibration isolation and gravity gradient mapping and modeling with an uncertainty below the 10 nm/s^2 level. We also show the design and target performance for applications in geodesy and tests of fundamental physics.

The VLBAI facility is a major research equipment funded by the DFG. We acknowledge support from the CRCs 1128 *geo-Q* and 1227 *DQ-mat*

Q 22.12 Tue 16:30 P

Testing trapped atom interferometry with time-averaged optical potentials — •Knut Stolzenberg, Sebastian Bode, Alexander Herbst, Henning Albers, and Dennis Schlippert — Institute of Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany

Time-averaged optical potentials can be used to realise flexible quantum sensors, for example by exploiting the tunnel effect for beam splitters and recombiners.
We use an acousto-optical deflector (AOD) to diffract the laserlight of a 55 W MOPA with a wavelength of 1064 nm to create dynamic time-averaged traps such as harmonic and double well potentials.
We demonstrate creation of a ^{87}Rb BEC in a crossed optical dipole trap and our first results on coherent beam splitting by momentum driven tunneling, showing stable interference patterns 37 ms after the BEC is split at a potential barrier.

Q 22.13 Tue 16:30 P

Analytic Theory for Diffraction Phases in Bragg Interferometry — •Jan-Niclas Siemss[1,2], Florian Fitzek[1,2], Ernst M. Rasel[2], Naceur Gaaloul[2], and Klemens Hammerer[1] — [1]Institut für Theoretische Physik, Leibniz Universität Hannover, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Germany

High-fidelity Bragg pulses operate in the quasi-Bragg regime. While such pulses enable an efficient population transfer essential for state-of-the-art atom interferometers, the diffraction phase and its dependence on the pulse parameters are currently not well characterized despite playing a key role in the systematics of these interferometers. We demonstrate that the diffraction phase when measuring relative atom numbers originates from the fact that quasi-Bragg beam splitters and mirrors are fundamentally multi-port operations governed by Landau-Zener physics (Siemß et al., Phys. Rev. A 102, 033709).

We develop a multi-port scattering matrix representation of the popular Mach-Zehnder atom interferometer and discuss the connection between its phase estimation properties and the parameters of the Bragg pulses. Furthermore, our model includes the effects of linear Doppler shifts applicable to narrow atomic velocity distributions on the scale of the photon recoil of the optical lattice.

This work is supported through the Deutsche Forschungsgemeinschaft (DFG) under EXC 2123 QuantumFrontiers, Project-ID 390837967 and under the CRC1227 within Project No. A05 as well as by the VDI with funds provided by the BMBF under Grant No. VDI 13N14838 (TAIOL).

Q 22.14 Tue 16:30 P

Systematic Approach To Phaseshifts of Matter Wave Interferometers in Weekly Curved Spacetimes — •Michael Werner and Klemens Hammerer — Institut für theoretische Physik, Leibniz Universität Hannover, Germany

We present a systematic approach to calculate all relativistic phase-shift effects in matter wave interferometer (MWI) experiments up to (and including) order c^{-2}, placed in a weak gravitational field. The whole analysis is derived from first principles and even admits test of General Relativity (GR) apart from the usual Einstein Equivalence Principle (EEP) tests, consisting of universality of free fall (UFF) and local position invariance (LPI) deviations, by using the more general 'parametrized post-Newtonian' (PPN) formalism. We collect general phase-shift formulas for a variety of well-known MWI schemes and calculate how modern experimental setups could measure PPN induced deviations from GR without the use of macroscopic test masses. This procedure should be seen as a way to easily calculate certain phase contributions, without having to redo all relativistic calculations in new MWI setups.

Q 22.15 Tue 16:30 P

Universal atom interferometer simulator — •Gabriel Müller, Christian Struckmann, Stefan Seckmeyer, Florian Fitzek, and Naceur Gaaloul — Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover

The simulation of matter-wave light-pulse interaction is crucial for designing and understanding atom interferometry (AI) experiments. However, the usual approach of solving the associated system of ordinary differential equations is limited by a quadratic scaling with the number of coupling states. Here, the universal atom interferometer simulator (UATIS) [1] overcomes this limitation with log-linear scaling while solving the problem of atom-light diffraction in the elastic case for all regimes. By interpreting a light-pulse beam as an external potential, UATIS achieves high numerical accuracy while maintaining great flexibility. We propose intuitive methods for assembling various atom-light interactions into AI sequences. We expect UATIS to lead to a straightforward modelling of experiments and to be promoted to a widely used tool.

[1] Fitzek et al. Universal atom interferometer simulation of elastic scattering processes. Sci Rep 10, 22120 (2020).

Q 23: Quantum Information I

Time: Tuesday 16:30–18:30 Location: P

Q 23.1 Tue 16:30 P

Continuous vs. discrete truncated Wigner approximation for driven, dissipative spin systems — •Christopher D. Mink[1], David Petrosyan[2], and Michael Fleischhauer[1] — [1]Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, 67663 Kaiserslautern, Germany — [2]Institute of Electronic Structure and Laser, FORTH, GR-71110 Heraklion, Crete, Greece

We present an alternative derivation of the recently proposed discrete truncated Wigner approximation (DTWA) for the description of the many-body dynamics of interacting spin-1/2 systems. The DTWA is a semi-classical approach based on Monte-Carlo sampling in a discrete phase space which improves the classical treatment by accounting for lowest-order quantum fluctuations. We provide a rigorous derivation of the DTWA based on an embedding in a continuous phase space. We derive a set of operator-differential mappings that yield an exact equation of motion (EOM) for the continuous spin Wigner function. The truncation approximation is then identified as neglecting specific terms in the exact EOM, allowing for a detailed understanding of the quality of the approximation and possible systematic improvements. Furthermore, we show that the continuous TWA (CTWA) yields a straightforward extension to open spin systems. We derive exact stochastic differential equations for dephasing, decay and incoherent pump processes, which in the standard DTWA are plagued by problems such as non-positive diffusion. We illustrate the CTWA by studying the dynamics of dissipative 1D Rydberg arrays and compare it to exact results for small systems.

Q 23.2 Tue 16:30 P

Euclidean volume ratios for entanglement and detectability by Bell inequalities in bipartite quantum systems — •Alexander Sauer[1], József Zsolt Bernád[1,2], Héctor Moreno[1], and Gernot Alber[1] — [1]Institut für Angewandte Physik, Technische Universität Darmstadt — [2]Peter Grünberg Institute (PGI-8), Forschungszentrum Jülich

Euclidean volume ratios between quantum states with positive partial transpose and all quantum states in bipartite systems are investigated. These ratios allow quantitative exploration of the typicality of entanglement and of its detectability by Bell inequalities. With our numerical approach, which is based on the Peres-Horodecki criterion and the hit-and-run algorithm, we obtain reliable results for qubit-qudit and qutrit-qutrit systems [1]. With the help of the Clauser-Horne-Shimony-Holt inequality and the Collins-Gisin inequality the degree of detectability of entanglement is investigated for two-qubit quantum states.

[1] Sauer, A., et al., Journal of Physics A: Mathematical and Theoretical 54.49 (2021): 495302.

Q 23.3 Tue 16:30 P

Towards EIT ground-state cooling of a lattice of individually

trapped atoms — •Apurba Das, Deviprasath Palani, Florian Hasse, Lennart Guth, Amir Mohammadi, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, Hermann-Herder-Str. 3, 79104 Freiburg i. Br.

Customized trap architectures for single trapped atoms with suitable local and global control fields enable us to set up and tune increasingly complex quantum systems with a high level of control. For individual state control and coupling of internal and external degrees of freedom in the system, we typically implement two-photon stimulated Raman transition. In our future work, in addition to our established control features, we want to bring ground state cooling based on electromagnetically-induced transparency to enable broadband cooling of multiple modes to deterministically prepare the system to its global ground state. This will allow us to prepare our $^{25}Mg^{+}$ arrays for further quantum operations more efficiently. Here in this presentation, we give an overview of required technical developments, recent advancements and discuss important steps towards near-future applications.

Q 23.4 Tue 16:30 P

Quantum computing with Rydberg Atoms — •Christoph Rupprecht, Philipp Ilzhöfer, Christian Hoelzl, Jennifer Krauter, Tilman Pfau, and Florian Meinert — 5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart

In the race of building a quantum computer, several different platforms like superconducting circuits, trapped ions and nitrogen vacancy centers are competing in terms of scalability and fidelity. Our project 'QRydDemo' aims to develop a quantum computer demonstrator based on arrays of up to 500 Strontium Rydberg atoms in optical tweezer arrays. Exploiting a so far unexplored qubit encoded in the 3PJ fine structure levels capable of realizing 'triple-magic-wavelength' tweezer traps, we want to improve the coherence properties of the Rydberg platform by orders of magnitude aiming for up to 10 ms coherence time and ~100ns-long single- and two-qubit gate operations [1]. Our machine will be able to shift atoms within a single row of 2D trap arrays individually and fast, which will allow for rearranging the array during a computation, providing new algorithmic possibilities and advantages for realizing multi-qubit gates. We plan to benchmark our architecture by demonstrating advantages of these multi-qubit gates for the calculation of two-dimensional fermionic systems and the implementation of basic aspects for quantum error correction on the Rydberg platform.

[1] F. Meinert, T. Pfau, C. Hölzl, EU Patent Application No. EP20214187.5

Q 23.5 Tue 16:30 P

Towards benchmarking two-qubit quantum processor — •Hardik Mendpara[1,2], Nicolas Pulido-Mateo[1,2], Markus Duwe[1,2], Giorgio Zarantonello[3], Henning Hahn[4], Amado Bautista-Salvador[1,2,4], Ludwig Krinner[1,2], and Christian Ospelkaus[1,2,4] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]PTB, Bundesallee 100, 38116 Braunschweig — [3]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA — [4]QUDORA Technologies GmbH

A prerequisite for a scalable quantum computing platform is to perform elementary gates with a low rate of error. One can quantify the error per gate using randomized benchmarking schemes which are independent of the state-preparation and measurement error [1,2]. Here, we implement the elementary gates (single- and two-qubit gates) using microwaves. The control fields are generated by microwave conductors embedded directly into the trap structure. Using this fully integrated microwave approach, we obtain a preliminary infidelity of 10^{-4} for single-qubit gates and approaching 10^{-3} for two-qubit operations [3]. Further, to better characterize the performance of two-qubit entangling gates, we will report on our recent progress in benchmarking our two-qubit quantum processor in a computational context using the protocol described in [1,2].

[1] J. Gaebler *et al.*, Phys. Rev. Lett. **109**, 179902 (2012)
[2] A. Erhard *et al.*, Nat. Commun. **10**, 5347 (2019)
[3] G. Zarantonello et al., Phys. Rev. Lett. 123 260503 (2019)

Q 23.6 Tue 16:30 P

Apparatus design for three new cryogenic trapped-ion quantum computing experiments — •Lukas Kilzer, Tobias Pootz, Celeste Torkzaban, Timko Dubielzig, and Christian Ospelkaus — Institut for Quantum optics, Leibniz University Hannover

Further progress in trapped-ion quantum computing requires a dramatic increase in the number of ion qubits that can interact with each other, development of more integrated systems including optical waveguides, and sympathetic cooling provided by a secondary ion species to keep qubits cold without destroying their stored quantum state. We aim in our next generation of cryogenic trapped ion quantum computers to be able to engineer interactions between dozens of qubits, implement sympathetic cooling, and incrementally test and characterize new components necessary for further scaling. This poster will provide an overview of the design for the cryostats and elaborate on particular design challenges faced while integrating components developed by several other teams. Each cryostat will house a cryogenic inner vacuum chamber inside a room-temperature outer vacuum chamber, a socket-mounted surface RF trap, a cryogenic RF resonator, a cryogenic Schwarzschild objective for detecting ion fluorescence, a vibration isolation system protecting the experiment from vibrations of the cold head, feedthroughs for hundreds of DC lines and several high frequency lines, and extra space for the future integration of optical fibers. These experiments are being developed in collaboration with other research groups at LUH, the University of Siegen, TU Braunschweig, and PTB.

Q 23.7 Tue 16:30 P

Trapped Ion Architecture for Multi-dimensional Quantum Simulations — •Deviprasath Palani, Florian Hasse, Apurba Das, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, Hermann-Herder-Str. 3, 79104 Freiburg i. Br.

A rich and powerful toolbox for individually trapped atomic ions is available for quantum information processing, including quantum metrology and quantum simulation, demonstrating control with the highest fidelities. Building on this success, our architecture for analogue quantum simulations aims at setting up fully controlled and reconfigurable quantum lattices by individually trapped ions in multidimensional arrangements [1]. In this presentation, we give an overview of recent developments and demonstrations of prototype operations. We discuss features and limitations of our architecture and lay out crucial steps toward mid and long-term simulation applications.

[1] U. Warring, F. Hakelberg, P. Kiefer, M. Wittemer, T. Schaetz, Adv. Quantum Technol. 2020, 1900137.

Q 23.8 Tue 16:30 P

Towards high-fidelity Mølmer-Sørensen gate in a cryogenic surface-electrode ion trap — Niklas Orlowski[1], •Niels Kurz[1], Timko Dubielzig[1], Sebastian Halama[1], Chloë Allen-ede[1], Celeste Torkzaban[1], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]Physikalisch-Technische-Bundesanstalt Braunschweig, Bundesallee 100, 38116 Braunschweig

Practical scalable quantum computing requires quantum logic gate errors below 10^{-4} in order for error-correction strategies to work. The microwave near-field approach for trapped-ion quantum logic gates has the potential to be scalable and has been shown to allow entangling gates on $^{9}Be^{+}$ ions in a room temperature surface trap with infidelities approaching 10^{-3}. In an equivalent cryogenic setup based on a similar trap structure [2], we expect the infidelity contribution due to anomalous motional heating to be strongly suppressed. We describe technical improvements in our setup that aim at reducing other sources of infidelities related to the motion of the ions to similar levels. We characterize the shift of mode frequencies that occur during gate operations due to heating effects in constant duty-cycle sequences and evaluate the performance of a newly installed, galvanically coupled RF resonator with regard to the radial mode stability.

Q 23.9 Tue 16:30 P

A symmetric RF X-junction for register-based surface-electrode ion traps compatible with the near-field microwave approach — •Florian Ungerechts[1], Rodrigo Munoz[1], Axel Hoffmann[1,2], Brigitte Kaune[1], Teresa Meiners[1], and Christian Ospelkaus[1,3] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [2]Institut für Hochfrequenztechnik und Funksysteme, Leibniz Universität Hannover, Appelstraße 9a, 30167 Hannover, Germany — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Register-based ion traps are among the leading approaches for scalable quantum processors. A fundamental component of these are junctions that allow the ions to be moved between the specialized zones of the quantum processor via ion transport. We discuss the design and optimization of such a junction and further present a symmetric RF X-junction with a shallow pseudopotential barrier and a substantial trap depth that is feasible for multilayer microfabrication. Furthermore, we present a transition zone making the symmetric RF X-junction compatible with an asymmetric RF near-field microwave gate-zone. Moreover, we present time-dependent transport voltages for reliable multi-zone and through-junction ion transport of a single $^{9}Be^{+}$ ion.

Q 23.10 Tue 16:30 P

A Quantum Enhanced Learning Algorithm for Maze Problems — •Oliver Sefrin and Sabine Wölk — Institut für Quantentechnologien, Deutsches Zentrum für Luft- und Raumfahrt, 89077 Ulm, Deutschland

In reinforcement learning, a so-called agent should learn to optimally solve a given task by performing actions within an environment. As an example, we consider the grid-world, a two-dimensional maze for which the shortest way from an initial position to a given goal has to be found. The agent receives rewards for helpful actions which enables him to learn optimal solutions.

For large action spaces, a mapping of actions to a quantum setting can be beneficial in finding rewarded actions faster and thus in speeding up the learning process. A hybrid agent which alternates between classical and quantum behavior has been developed previously for deterministic and strictly epochal environments. Here, strictly epochal means that an epoch consists of a fixed number of actions, after which the environment is reset to its initial state.

We present and analyze strategies which aim at resolving the hybrid agent's current restriction of searching for action sequences with a fixed length. This is a first step towards applying the hybrid agent on environments with a generally unknown optimal action sequence length such as in the grid-world problem.

Q 23.11 Tue 16:30 P

Software-Struktur für die Internetanbindung eines Ionenfallen-Quantencomputers — •Christian Melzer[1], Janine Hilder[1], Fabian Kreppel[2], Janis Wagner[1], Björn Lektisch[1], Ulrich Poschinger[1], André Brinkmann[2] und Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, 55128 Mainz, Germany — [2]Zentrum für Datenverarbeitung, Universität Mainz, Anselm-Franz-von-Bentzel-Weg 12, 55128 Mainz, Germany

Segmentierte Ionenfallen sind ein erfolgversprechender Kandidat für skalierbare Quantencomputer mit hoher Operationsgüte. Um Algorithmen auf eine solche Architektur abbilden zu können, wird eine mehrschichtige Softwarestruktur benötigt. Diese muss beliebige Quanten-Schaltkreise auf native Gatter abbilden können, die erzeugten Gattersequenzen optimieren und anschließend die Ionenkonfigurationen über die Zeit hinweg kontrollieren. Dabei müssen Randbedingungen wie Fehleranfälligkeiten unterschiedlicher Operationen, Kohärenzzeiten, Streulicht und Inhomogenitäten des Magnetfelds berücksichtigt werden. Für eine möglichst effiziente Kontrolle über den Quantencomputer erlaubt es die entwickelte Softwarestruktur, auf drei unterschiedlichen Abstraktionsebenen zu arbeiten: universelle Quantenschaltkreise, architekturabhängige Operationssequenzen und präzise Kontrollsignale.

Q 23.12 Tue 16:30 P

Assessing the Precision of Quantum Simulation of Many-Body Effects in Atomic Systems using the Variational Quantum Eigensolver Algorithm — •Sumeet Sumeet[1,2,3], V. S. Prasannaa[3], B. P. Das[4], and B. K. Sahoo[5] — [1]Lehrstuhl fur Theoretische Physik I, Staudtstraße 7,FAU Erlangen-Nuremberg, D-91058 Erlangen, Germany — [2]Qu & Co B.V., Palestrinastraat 12H, 1071 LE Amsterdam, The Netherlands — [3]Centre for Quantum Engineering, Research and Education,TCG CREST, Salt Lake, Kolkata 700091, India — [4]Department of Physics, Tokyo Institute of Technology,2-12-1-H86 Ookayama, Meguro-ku, Tokyo 152-8550, Japan — [5]Atomic, Molecular and Optical Physics Division,Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India

In this pilot study, we investigate the physical effects beyond the mean-field approximation, known as electron correlation, in the ground state energies of atomic systems using the classical-quantum hybrid variational quantum eigensolver (VQE) algorithm in a quantum simulation. To this end, we consider three isoelectronic species. We employ the unitary coupled-cluster (UCC) ansatz to perform a rigorous analysis of two very important factors that could affect the precision of the simulations of electron correlation effects within a basis, namely mapping and backend simulator. When more qubits become available, our study will serve as among the first steps taken towards computing other properties of interest to various applications such as new physics beyond the Standard Model of elementary particles and atomic clocks using the VQE algorithm.

Q 23.13 Tue 16:30 P

A quantum logic gate on remote matter qubits — Severin Daiss, Stefan Langenfeld, Stephan Welte, Emanuele Distante, Philip Thomas, Lukas Hartung, •Olivier Morin, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Most quantum computing systems are currently developed in monolithic hardware architecture e.g. ions in the same trap, superconducting qubits on the same chip, Rydberg atoms in the same vacuum chamber etc. However, on the long run, a modular architecture offers a more obvious scalability when large number of qubits is required, leading to the so-called distributed quantum computing. This can typically be achieved by single qubit modules interconnected via photonic qubits travelling through a network of regular optical fibers.

Here, we present the realization of the proof of principle of this vision [1]. Our qubit modules consist of single atoms of ^{87}Rb coupled to high finesse optical cavities. While local quantum gates can easily be realized with local Raman or microwave manipulations, we show that a two-qubit gate can be mediated by a single photon successively reflected on the two cavities [2], the interface of our qubit modules. Hence, we realized a CNOT gate on two atomic qubits separated by a 60m-long optical fiber.

[1] Severin Daiss *et al.*, Science **371**, 614-617 (2021)
[2] L.-M. Duan *et al.*, Phys. Rev. A **72**, 032333 (2005)

Q 23.14 Tue 16:30 P

Ion Trap Development for Quantum Computing Applications — •Alexander Müller, Björn Lekitsch, Daniel Wessel, Robin Strohmaier, Ulrich Poschinger, and Ferdinand Schmidt-Kaler — JGU Mainz, Institute for Physics, Staudingerweg 7, 55128 Mainz, Germany

Trapped ion quantum computers are one of the leading contenders for the implementation of useful quantum algorithms. Ion traps for such systems have to meet many requirements like precise alignment of individual structures and layers, good optical access and sufficient thermal conductivity, just to name a few. But most importantly, these traps have to be fabricated in a reliable and repeatable way.

We present the fabrication of a two-layer segmented linear ion trap based on 4-inch fused silica wafers. The fabrication steps include 3D structuring using selective laser-induced etching, PVD gold-coating, electroplating, wafer dicing and μm-precision die bonding. The mounting of the ion trap will enable quick turnaround of traps and the use in different setups.

We will show a suitable setup in more detail. This experimental apparatus will include a titanium vacuum vessel intended for XHV pressures, a high-performance mu-metal shielding to suppress external magnetic fields, high NA opitcs for individual addressing of qubits in a string of 10 ions, and laser systems and compact optical components for dual species operation.

Q 23.15 Tue 16:30 P

Towards estimating molecular ground state energies on current quantum hardware — •Felix Rupprecht and Sabine Wölk — Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

Quantum simulation may achieve a quantum advantage in the near future. One immediate application is then the design of materials for energy storage systems. In the QuESt project we aim at estimating ground and exited states of relevant molecules using variational quantum eigensolvers. In order to get meaningful results on current noisy intermediate scale quantum (NISQ) computers, efficient algorithm implementation and error mitigation techniques are needed.

We present first results on running variational quantum eigensolvers with a unitary coupled cluster (UCC) ansatz on current IBM superconducting quantum processors using error mitigation methods such as zero noise extrapolation.

The QuESt project is funded by the Baden-Württemberg Ministry of Economic Affairs, Labour and Housing.

Q 23.16 Tue 16:30 P

Toward control of charge state dynamics and spin manipu-

lation in diamond NV color center for quantum information processing — •Min-Sik Kwon[1], Jonas Meinel[1,2], Qi-Chao Sun[1], Durga Dasari[1], Vadim Vorobyov[1], and Jörg Wrachtrup[1,2] — [1]3. Physikalisches Institut, University of Stuttgart, Stuttgart, Germany — [2]Max Planck Institute for Solid State Research, Stuttgart, Germany

Nitrogen-Vacancy (NV) color center is an artificial atom with optically accessible spin qubit. It is consisted of a vacancy of a missing carbon atom and substitutional nitrogen impurity in diamond crystal lattice. Due to longer electron spin relaxation (T1) and dephasing time(T2*) of negatively charged state of NV center, it is well available for coherent spin control, optical nanoscopy, charge-based memories, and electrical spin detection. For stable charged state in NV center, we studied optically induced interconversion between charge states, understanding charge state dynamics in NV color center to enhance the high fidelity measurement of spin readout. Additionally, for emergent quantum information processor and experimental quantum simulator, we designed and operated programmable quantum circuits and selectively harness the various neighbor nuclear spins by central NV electron spin to build quantum simulator to test interaction Hamiltonians at ambient condition.

Q 23.17 Tue 16:30 P

A multi-site quantum register of neutral atoms with single-site controllability — •Tilman Preuschoff, Dominik Schäffner, Lars Pause, Tobias Schreiber, Stephan Amann, Jan Lautenschläger, Malte Schlosser, and Gerhard Birkl — Institut für Angewandte Physik, TU Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt, Germany

Assembled arrays of neutral atoms offer a versatile platform for quantum technologies. As effectively non-interacting particles with identical intrinsic properties they also feature switchable interactions when excited to Rydberg states [1].

We present a micro-optical platform for defect-free assembled 2D clusters of more than 100 single-atom quantum systems [2]. Combined with a digital micromirror device (DMD), site-selective manipulation of the trapping potentials is possible while utilizing the robust architecture of microlens-based systems. We also discuss recent work with microlens arrays fabricated by femtosecond direct laser writing [3].

In addition, we present our open-source digital controllers for laser frequency and intensity stabilization [4]. Using the STEMlab (originally Red Pitaya) platform we achieve a control bandwidth of up to 1.25 MHz resulting in a laser line width of 52(1) kHz (FWHM) and intensity control to the $1 \cdot 10^{-3}$ level.

[1] M. Schlosser et. al., J. Phys. B: At. Mol. Opt. Phys **53** 144001 (2020).
[2] D. Ohl de Mello et. al., Phys. Rev. Lett. **122**, 203601 (2019).
[3] D. Schäffner et. al., Opt. Express **28**, 8640-8645 (2020).
[4] T. Preuschoff et. al., Rev. Sci. Instrum. **91**, 083001 (2020).

Q 24: Quantum Effects

Time: Tuesday 16:30–18:30 Location: P

Q 24.1 Tue 16:30 P

Towards Lasing Without Inversion in Mercury Vapor at 253.7 nm — •Daniel Preissler and Thomas Walther — TU Darmstadt, Institute for Applied Physics, Laser and Quantum Optics, Schlossgartenstr. 7, D-64289 Darmstadt

UV and VUV laser sources have a broad application range in industry and commercial use as well as in research. The development of conventional direct laser sources in the regime of small wavelengths has reached a limit, since the pump energy to obtain population inversion scales at least with the fourth power of the desired laser frequency. But if the coherent (re-)absorption of photons at the laser frequency could be suppressed, a small population of the upper laser level would be sufficient to create amplification and/or lasing. This idea is called Lasing Without Inversion (LWI) and can be achieved by use of atomic coherence effects similar to EIT and CPT.

An experimental setup of an amplification without inversion (AWI) scheme is realized in atomic mercury vapor [1]. Because of its four-level system, allowing for a Doppler free three-photon-coherence, UV LWI at 253.7 nm can be generated by two laser systems at 435.8 nm and 546.1 nm as driving fields. Through extensive simulations [2] critical parameters of the laser systems involved, in particular their powers and linewidths, were identified. In this contribution the results of those simulations as well as the overall state of the experiment will be presented.

[1] Rein et al. (2021) arXiv:2111.03023
[2] Sturm et al. (2014) doi.org/10.1364/josab.31.001964

Q 24.2 Tue 16:30 P

Stabilization schemes for a Laser System at 546.1nm used in a Lasing without Inversion experiment in Mercury — •Noah Eizenhöfer, Daniel Preissler, and Thomas Walther — TU Darmstadt, Institut für Angewandte Physik, AG Laser und Quantenoptik, Schlossgartenstr. 7, D-64289 Darmstadt

Lasing without Inversion (LWI) is an alternative concept to generate radiation in the (V)UV regime. It is based on coherent effects leading to a suppression of the absorption on the lasing transition. This overcomes the problem of conventional lasers in the UV regime since their necessary pump power scales with f^4. A LWI experiment can be realized in Mercury with possible resulting wavelengths at 185 nm and 253.7 nm. (1)
One of the most important requirements for achieving LWI in mercury is the use of two driving lasers at 435.8 nm and 546.1 nm with very narrow bandwidths. The current status of the coupling laser at 546.1 nm is presented. The system is based on the generation of the second harmonic of the radiation from an ECDL. The feasibility of different schemes for the stabilization of the system to the corresponding atomic transition, e.g. Polarization Spectroscopy and Modulation Transfer Spectroscopy, is evaluated.

(1) Fry et al.: "Four-level atomic coherence and cw VUV lasers". Optics Communications 179 (2000), 499-504

Q 24.3 Tue 16:30 P

Towards cavity-enhanced single ion spectroscopy of Yb^{3+}: Y_2O_3 — •Jannis Hessenauer[1], Diana Serrano[2], Philippe Goldner[2], and David Hunger[1] — [1]Karlsruher Institut für Technologie, Physikalisches Institut, Karlsruhe, Germany — [2]Université PSL, Chimie ParisTech, CNRS, Paris, France

Rare-earth ions are promising candidates for optically addressable spin qubits, owing to their long optical and spin coherence times in the solid state. Yb^{3+} is of special interest amongst the rare earth ions due to its simple energy level scheme, strong transition oscillator strength and excellent coherence even at low magnetic fields [1]. An efficient spin-photon interface for quantum information technology requires the coupling of single ions to a high finesse cavity to enhance the transitions via the Purcell effect.

To that goal, we integrate nanocrystals into a fiber-based Fabry-Pérot microcavity by spincoating them on a planar mirror [2]. We characterize the nanocrystal distribution on a mirror via confocal microscopy and scanning cavity microscopy. We observe that long optical lifetimes and spectral features are preserved in nanocrystals. Finally, we present first results of cavity enhanced spectroscopy of Yb^{3+}: Y_2O_3 at room temperature.

[1] Kindem, Jonathan M., et al. "Control and single-shot readout of an ion embedded in a nanophotonic cavity." Nature 580.7802 (2020): 201-204.
[2] Casabone, Bernardo, et al. "Cavity-enhanced spectroscopy of a few-ion ensemble in Eu3+: Y2O3." NJP 20.9 (2018): 095006.

Q 24.4 Tue 16:30 P

Integrating a fiber cavity along the axis of a linear ion trap — •Viktor Messerer[1], Markus Teller[1], Klemens Schüppert[1], Roberts Berkis[1], Pritom Paul[1], Dario A. Fioretto[1], Maria Galli[1], Yueyang Zou[1], Jakob Reichel[2], and Tracy E. Northup[1] — [1]Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria — [2]Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France, 24 rue Lhomond, 75005 Paris, France

Quantum networks allow for distributed quantum computation, inherently secure communication as well as enhanced quantum sensing. The nodes of a quantum network consist of multiple controllable stationary qubits and an interface to traveling qubits to interconnect distant network nodes. Trapped ions, coupled to an optical resonator mode allows for an efficient and deterministic ion-photon interface.

Recent experiments with a single trapped ion coupled to a fiber-based optical resonator have demonstrated a coherent coupling rate exceeding the atomic spontaneous-emission rate. This coherent ion-photon interaction is expected to enhance the fidelity and efficiency of quantum communication protocols.

We designed and constructed a system for strong coupling of multiple ions to a fiber cavity. The fiber mirrors are integrated along the axis of a linear Paul trap. Ions can be positioned along this axis without introducing excess micromotion. We will present the apparatus, measurements of the ion trap heating rate and micromotion, as well as first experimental results of coupling an ion to the cavity.

Q 24.5 Tue 16:30 P

Boundary Layer Model for the Reflectivity of a Metal and the Casimir Force — Mandy Hannemann and •Carsten Henkel — Universität Potsdam, Institut für Physik und Astronomie

The scattering of electromagnetic waves at a surface is a basic process in sensing and spectroscopy. It also determines dispersion forces of the van der Waals and Casimir(-Polder) type [1]. We revisit the reflectivity of a metallic surface combing a hydrodynamic model for conduction electrons with a boundary-layer theory [2]. Models based on a "no-slip" boundary condition involve a new length and time scale that characterises the near-surface response [3]. These parameters provide a framework that pushes theoretical calculations of the Casimir pressure between two planar surfaces closer to experimentally observed values. We compare the results to a recent proposal involving non-local dielectric functions [4].

[1] G. Bimonte and E. Santamato, "General theory of electromagnetic fluctuations near a homogeneous surface in terms of its reflection amplitudes," Phys. Rev. A **76** (2007) 013810.
[2] D. Bedeaux and J. Vlieger, "Optical Properties of Surfaces" (World Scientific 2004).
[3] M. Hannemann, G. Wegner, and C. Henkel, "No-Slip Boundary Conditions for Electron Hydrodynamics and the Thermal Casimir Pressure," Universe **7** (2021) 108
[4] G. L. Klimchitskaya and V. M. Mostepanenko, "An alternative response to the off-shell quantum fluctuations: A step forward in resolution of the Casimir puzzle," Eur. Phys. J. **C** 80 (2020) 900.

Q 24.6 Tue 16:30 P

Cavity-enhanced spectroscopy of molecular quantum emitters — •Evgenij Vasilenko, Weizhe Li, Senthil Kuppusamy, Mario Ruben, and David Hunger — Institute for Quantum Materials and Technologies, Kalrsruhe Institute of Technology (KIT)

Rare earth ions in solid-state hosts are a promising candidate for optically addressable spin qubits, owing to their excellent optical and spin coherence times. Recently, also rare earth ion-based molecular complexes have shown excellent optical coherence properties [1]. Due to the long optical lifetime of the optical transition $^5D_0$-$^7F_0$, an efficient spin-photon interface for quantum information processing requires the coupling of single ions to a microcavity.Open-access Fabry-Pérot fiber cavities have been demonstrated to achieve high quality factors and low mode volumes, while simultaneously offering large tunability and efficient collection of the cavity mode [2]. Since the used molecular quantum emitters require a cryogenic environment, the demands on mechanical stability of the cavity setup have a high priority. To tackle these challenges, we report on the development of a monolithic type of cavity assembly, sacrificing some lateral scanning ability for the purpose of significantly increasing the passive stability. We integrate molecules into the cavity in the form of a crystalline thin film on a macroscopic mirror and identify a sub-nanometer local surface roughness, sufficient to avoid excessive scattering loss. We report on first studies of cavity-enhanced emission spectroscopy.

[1] Serrano et al., to appear in Nature, arXiv:2105.07081
[2] Hunger et al., New J. Phys 12, 065038 (2010)

Q 24.7 Tue 16:30 P

Light-matter interaction at the transition from single-mode to multimode cavity QED — •Daniel Lechner, Riccardo Pennetta, Martin Blaha, Philipp Schneeweiss, Jürgen Volz, and Arno Rauschenbeutel — Humboldt Universität zu Berlin, Institut für Physik, Newtonstr. 15, 12489 Berlin, Germany

Cavity QED is conventionally described by the Tavis-Cummings model, where quantum emitters strongly couple to a single-mode cavity. This description implicitly assumes that the cavity roundtrip time, t_{rt}, is by far the smallest timescale of the system and, in particular, much smaller than the lifetime, τ, of the quantum emitters. Here, we present an experiment in which this condition is progressively not fulfilled. The setup consists of a fiber ring-resonator with variable length, coupled to cold cesium atoms via an optical nanofiber. Consequently, we can explore the transition from a regime close to single-mode cavity QED to multimode cavity QED with resonator lengths of 5.8 m ($t_{rt} \approx \tau$) and 45.5 m ($t_{rt} \gg \tau$). We record the response of the atom–cavity system after the sudden switch-on of resonant laser light. For the 5.8-m resonator, on top of the conventional Rabi oscillations, we observe the appearance of sharp features at multiples of the roundtrip time. For the 45.5-m long cavity, due to coupling to many resonator modes, the Rabi oscillations disappear and only the response of the atomic ensemble after each individual roundtrip remains. Our observations shed light on the interplay between the single-pass collective response of the atoms to the propagating cavity field and the ensemble–cavity dynamics.

Q 24.8 Tue 16:30 P

Time-Dependent Photon Counting Statistics Emitted from a Chiral Atom Chain — •Tom von Scheven, Igor Lesanovsky, and Beatriz Olmos — Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

We study the steady state of a laser-driven chain of two-level atoms coupled to a chiral waveguide [1]. Depending on the distance between the atoms and the laser detuning this state may be either a dark state or a mixture of a dark and a bright state. Here, we investigate the dynamical evolution of this system towards stationarity.

To do so, we introduce an imaginary counting field to the master equation that governs the dynamics of the system under consideration. This gives us access to the dynamics of not only the average photon count rate but rather the full counting statistics of the photon emission into the waveguide.

We show that, even though two systems may converge to different stationary states, their probability distributions evolve in an almost indistinguishable way for very long times.

Our results demonstrate the potential of the use of imaginary counting fields for the unravelling of the dynamics of quantum optical many-body systems.

[1] G. Buonaiuto *et al.*, New J. Phys. **21**, 113021 (2019)

Q 24.9 Tue 16:30 P

Revising cavity QED: Towards an accurate description of light-matter coupling — •Martin Blaha, Aisling Johnson, Arno Rauschenbeutel, and Jürgen Volz — HU Berlin, 12489 Berlin, Germany

The Jaynes-Cummings (JC) and Tavis-Cummings (TC) models are the standard descriptions of light-matter interaction between one or many emitters and a cavity field. In our work, we identify limits to these models, showing that they give inaccurate predictions if the emitter modifies the cavity field already significantly after a single roundtrip. This results in inaccurate predictions for the intra-cavity field, especially when investigating the case of coupling a large number of emitters to the cavity field [1].

To this end, we developed an alternative Hamiltonian by combining a waveguide approach with cavity QED, where we investigate the cascaded interaction between a propagating cavity field and each individual coupled emitter. This allows us to identify boundaries of validity of the JC and TC model. More importantly, solving our model we obtain predictions that substantially deviate from the predictions obtained from the JC and TC model, such as asymmetric vacuum-Rabi splitting, relevant for single emitters with almost perfect coupling to the cavity mode or the emergence of new resonances in the reflection spectra of resonators containing large ensembles of emitters [2].

[1] arXiv:2107.04583 (2021) [2] PRL 123 (24), 243602 (2019)

Q 24.10 Tue 16:30 P

Circular Bragg gratings for Integrated Enhancement of Quantum Emitters — •Dario Mekle, Jonas Grammel, and David Hunger — Physikalisches Institut, Karlsruher Institut für Technologie

Surface-emitting Circular Bragg gratings, forming center-disk cavities, are already successfully employed for distributed feedback lasers and quantum emitter applications based on nitrogen vacancy centers or semiconductor quantum dots. We aim to transfer this approach to achieve a better collection efficiency of rare earth ion based emitters in the form of nanocrystals or molecules. On the one hand, the collection efficiency is improved by the cavity induced Purcell enhancement and, on the other hand, by the better overlap between the far field emission pattern of the dipole emitter and the guided modes of the optical fiber being coupled into. A finite element analysis is used to perform geometric parameter optimizations of two cavity designs based on PMMA (or similar polymers) and air, where the inner resonator disk, which also contains the emitter, is once made of PMMA and the other time inverted with an air center.

The results obtained so far are very promising. In particular, it was possible to simulate a cavity geometry that leads to a Purcell factor of more than 140, which is significantly higher than previously published results.

Q 24.11 Tue 16:30 P

Sub- and superradiant modes in coupled ring-lattices — •Marcel Cech, Beatriz Olmos, and Igor Lesanovsky — Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

A hallmark of an open quantum system is its dissipative character, which means that the system loses energy and coherence due to the coupling with its environment. In a many-body system, however, collective effects - such as sub-radiance - allow to suppress excitation and energy loss [1]. We demonstrate this effect in a system of interacting four-level atoms that are coupled to the radiation field. In particular, we focus on ring-shaped lattices which we combine to create meta-structures in the three dimensional space. We consider the properties of these subradient states as a function of the number of rings and their mutual coupling strength. Our analysis shows that for lattice spacings on the order of the wavelength of the atomic transition a subspace of subradiant states emerges, which can be utilized to create lossless excitation transport.

[1] J. A. Needham *et al.*, New. J. Phys. **21** 073061 (2019)

Q 24.12 Tue 16:30 P

Collective decay in a dissipative Rydberg-gas — •Chris Nill, Federico Carollo, and Igor Lesanovsky — Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

We analyse the dynamics and the steady state of a driven open quantum spin system, which models the dynamics of a strongly interacting gas of Rydberg atoms, weakly coupled to a Markovian bath.

A common approach to describe the dissipation of such systems is to choose single-site dissipation, such as spin decay or dephasing [1]. However, the strong interaction among Rydberg atoms is expected to give rise to dissipative processes with an additional dependency on neighbouring excited atoms.

We simulate the excitation dynamics within both approaches and highlight their differences. To this end we utilise exact diagonalisation, quantum jump Monte-Carlo simulations and mean-field calculations. We identify parameter regimes in which the difference between single-site and interaction-dependent dissipation becomes most pronounced and might be tested experimentally.

[1] C. Ates *et al.*, Phys. Rev. A **85**, 043620 (2012)

Q 24.13 Tue 16:30 P

Superdecoherence of spin states — •Jérôme Denis and John Martin — Institut de Physique Nucléaire, Atomique et de Spectroscopie, CESAM, University of Liège, B-4000 Liège, Belgium

We present a detailed study of the depolarization dynamics of an individual spin with an arbitrary spin quantum number j, or, equivalently, of a system of $N = 2j$ constituent spin-1/2 initially in a symmetric state undergoing collective depolarization. In particular, we identify the most superdecoherent states. In the case of isotropic depolarization, we show that a class of maximally entangled pure states distinct from GHZ and W states, a.k.a. spin anticoherent states [1,2], display the highest decoherence rate for any number of spins. Moreover, we find that these states become absolutely separable after a time which does not depend on the number of spins. We also prove that entanglement is a necessary and sufficient condition, both for pure and mixed states, for superdecoherence to take place [3]. Finally, for anisotropic depolarization, we identify not only the states with the highest initial decoherence rate, but also the states that lose their purity most rapidly over any finite time for a few spins. [1] J. Zimba, Electron. J. Theor. Phys. 3, 143 (2006). [2] D. Baguette, T. Bastin, and J. Martin, Phys. Rev. A 90, 032314 (2014) [3] G. M. Palma, K.-A. Suominen, and A. K. Ekert, Proc. R. Soc. London, Ser. A 452, 567 (1996).

Q 24.14 Tue 16:30 P

Out-of-Time-Order Correlators in a power-law interacting Heisenberg spin chain with random positions — •Maximilian Klaus Müllenbach[1], Adrian Braemer[1], Sebastian Geier[1], Clément Hainaut[2], Martin Gärttner[1,3,4], Matthias Weidemüller[1], and Gerhard Zürn[1] — [1]Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — [2]Université de Lille, CNRS, UMR 8523, laboratoire de Physique des Lasers, Atomes et Molécules, Lille, France — [3]Kirchhoff-Institut für Physik, Universität Heidelberg, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany — [4]Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany

We use out-of-time-order correlators (OTOCs) to study the propagation of information in disordered isolated quantum systems. Specifically we study operator spreading in a 1D random-position XXZ model with power-law interactions as a function of disorder strength using numerically exact techniques. OTOCs, i.e the squared commutators, of a local Pauli operator and time-evolved originally distant Pauli operators are known to show "light cone"-like behaviour. We characterize these emerging "light cone" structures across the localization to delocalization phase transition. Furthermore we present an experimental scheme based on Floquet Hamiltonian Engineering to perform necessary echo protocols in an interacting system of Rydberg atoms and techniques to extract OTOCs experimentally from quadratic order response functions.

Q 24.15 Tue 16:30 P

Quantum scattering off a diffusive domain — •Nils Krause, Benjamin Stickler, and Klaus Hornberger — University of Duisburg-Essen, Faculty of Physics, 47048 Duisburg, Germany

We investigate the quantum scattering of massive particles in presence of spatially confined momentum diffusion. An analytical method is presented to determine the classical S-matrix, mapping incoming onto outgoing phase space distributions. We compare the results with numerical simulations and discuss how this framework can be extended to describe quantum scattering.

Q 24.16 Tue 16:30 P

Network dynamics in the presence of stochastic fluctuations — •Frederic Folz[1], Kurt Mehlhorn[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — [2]Algorithms and Complexity Group, Max-Planck-Institut für Informatik, Saarland Informatics Campus, 66123 Saarbrücken, Germany

We analyse dynamics of a classical network. The dynamics is governed by a mathematical model inspired by the food search of the slime mold Physarum polycephalum - a primitive organism that has demonstrated its ability to solve shortest path problems and to design efficient transport systems. We characterize the networks dynamics by applying measures for their robustness, transport efficiency and costs. We then add noise in the form of Langevin forces and study its effects on the network dynamics. We show that noise can favour the formation of certain network topologies yielding specifically high performance. We identify an optimal noise level to achieve the best balance between robustness, transport efficiency and costs.

Q 25: Ultra-cold plasmas and Rydberg systems (joint session A/Q)

Time: Tuesday 16:30–18:30 Location: P

Q 25.1 Tue 16:30 P

Probing Ion-Rydberg hybrid systems using a high-resolution pulsed ion microscope — •Viraatt Anasuri, Nicolas Zuber, Moritz Berngruber, Yiquan Zou, Florian Meinert, Robert Löw, and Tilman Pfau — 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Stuttgart, Germany

Here, we present our recent studies on Rydberg atom-Ion interactions and the spatial imaging of a novel type of molecular ion using a high-resolution ion microscope. The ion microscope provides an exceptional spatial and temporal resolution on a single atom level, where a highly tuneable magnification ranging from 200 to over 1500, a resolution better than 200nm and a depth of field of more than 70*m were demonstrated. A pulsed operation mode of the microscope combined with the excellent electric field compensation enables the study of highly excited Rydberg atoms and ion-Rydberg atom hybrid systems. Using the ion microscope, we observed a novel molecular ion, where the bonding mechanism is based on the interaction between the ionic charge and an induced flipping dipole of a Rydberg atom [1]. Furthermore, we could measure the vibrational spectrum and spatially resolve the bond length and the angular alignment of the molecule. The excellent time resolution of the microscope enables probing of the interaction dynamics between the Rydberg atom and the ion. [1] N. Zuber, V. S. V. Anasuri, M. Berngruber, Y.-Q. Zou, F. Meinert, R. Löw, T. Pfau, Spatial imaging of a novel type of molecular ions, arXiv preprint arXiv:2111.02680 (2021).

Q 25.2 Tue 16:30 P

Creating spin spirals with tunable wavelength in a disordered Heisenberg spin system — •Eduard Jürgen Braun[1], Titus Franz[1], Lorenz Luger[1], Maximilian Müllenbach[1], André Salzinger[1], Sebastian Geier[1], Clément Hainaut[2], Gerhard Zürn[1], and Matthias Weimüller[1] — [1]Physikalisches Instut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — [2]Université de Lille, CNRS, UMR 8523, France - PhLAM - Physique des Lasers, Atomes et Molécules

We present a novel method to create a spin spiral in a Heisenberg spin system composed of Rydberg atoms. We have designed a protocol that allows to create a spin spiral of a fixed wavevector q for an interacting spin system composed of two different angular momentum Rydberg states of Rubidium. By creating a constant electric gradient field around a fixed offset electric field one can achieve a linear detuning between the two Rydberg levels as function of position. As a consequence, after applying a $\frac{\pi}{2}$-pulse the wavelength can be tuned by the duration for which the gradient field is applied. We investigate numerically how the disorder in our system and the interaction can disturb the spiralization as well as how fast the electric fields can be ramped in order to still adiabatically follow the Rydberg states in the Stark map. The subsequent relaxation dynamics of the spirals for varying wavefector q gives insight into the mode of transport in the Heisenberg spin system. First numerical simulations with few atoms in 1D suggest that we might find a localized regime for sufficiently strong disorder in the system.

Q 25.3 Tue 16:30 P

Towards an optogalvanic flux sensor for nitric oxide based on Rydberg excitations — •Fabian Munkes[1,5], Patrick Kaspar[1,5], Yannick Schellander[2,5], Lars Baumgärtner[3,5], Philipp Neufeld[1,5], Lea Ebel[1,5], Jens Anders[3,5], Edward Grant[4], Robert Löw[1,5], Tilman Pfau[1,5], and Harald Kübler[1,5] — [1]5. Physikalisches Institut, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart — [2]Institut für Intelligente Sensorik und Theoretische Elektrotechnik, Universität Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart — [3]Institut für Großflächige Mikroelektronik, Universität Stuttgart, Allmandring 3b, 70569 Stuttgart — [4]Department of Chemistry, The University of British Columbia, 2036 Main Mall, Vancouver, BC Canada V6T 1Z1 — [5]Center for Integrated Quantum Science and Technology, Universität Stuttgart

We demonstrate the applicability of a new kind of gas sensor based on Rydberg excitations. From a gas mixture the molecule in question is excited to a Rydberg state. By succeeding collisions with all other gas components this molecule becomes ionized and the emerging electrons can be measured as a current. We investigate the excitation efficiency dependent on the used laser powers, the applied charge-extraction voltage as well as the overall gas pressure.

Q 25.4 Tue 16:30 P

Self-organization of facilitated Rydberg excitations — •Jana Bender, Patrick Mischke, Tanita Klas, Thomas Niederprüm, and Herwig Ott — Department of Physics and research center OPTIMAS, Technische Universität Kaiserslautern, Germany

We investigate the facilitation dynamics in a Rydberg system and the expected phase transition resulting from the interplay between driving strength and excitation decay.

In an off-resonantly driven cloud of atoms, the strong dipole-dipole interactions between two Rydberg states will compensate the laser detuning for a specific interatomic distance. For high enough driving strength, this results in a spreading of correlated excitations. We investigate the predicted non-equilibrium steady state phase transition between this active phase and the absorbing phase in which the spread of excitations is suppressed. The influence of disorder in our system might introduce additional, more complex phases dominated by excitation avalanches. Due to a loss of excited atoms, the system self-organizes from the acive phase towards the phase transition.

Our results show a persistant algebraic distribution of excitation cluster sizes independent of starting parameters when the system approaches the phase transition. We observe varying exponents which hint towards the influence of disorder in our system.

Q 26: Quantum Gases (Fermions)

Time: Wednesday 10:30–12:30 Location: Q-H10

Q 26.1 Wed 10:30 Q-H10

Observation of Cooper Pairs in a Mesoscopic 2D Fermi Gas — •Marvin Holten, Luca Bayha, Keerthan Subramanian, Sandra Brandstetter, Carl Heintze, Philipp Lunt, Philipp Preiss, and Selim Jochim — Physics Institute, University of Heidelberg, Germany

Pairing is the fundamental requirement for fermionic superfluidity and superconductivity. To understand the mechanism behind pair formation is an ongoing challenge in the study of many strongly correlated fermionic systems.

In this talk, I present the direct observation of Cooper pairs in our experiment [1]. We have implemented a fluorescence imaging technique that allows us to extract the full in-situ momentum distribution with single particle and spin resolution. We apply it to a mesoscopic Fermi gas, prepared deterministically in the ground state of a two-dimensional harmonic oscillator. Our ultracold gas allows us to tune freely between a completely non-interacting unpaired system and weak attractions where we find Cooper pair correlations at the Fermi surface. When increasing the interactions even further, the pair character is modified and the pairs gradually turn into tightly bound dimers. The collective behaviour that we discover in our mesoscopic system is closely related to observations in nuclear physics or metallic grains. Our method provides a new pathway to study many of the outstanding questions concerning fermionic pairing, for example in imbalanced systems or the normal phase.

[1] Arxiv Preprint: arXiv:2109.11511 (2021)

Q 26.2 Wed 10:45 Q-H10

Towards a New Experiment for Programmable Quantum Simulation using Li-6 Fermions — •Tobias Hammel[1], Maximilian Kaiser[1], Micha Bunjes[1], Philipp Preiss[2], Matthias Weidemüller[1], and Selim Jochim[1] — [1]Physics Institute, University of Heidelberg, Germany — [2]Max-Planck-Institute for Quantum

Optics, Garching, Germany

The versatility and usability of quantum simulation using ultracold atoms is often limited by the amount of data one can collect in a given time to achieve sufficiently good statistics. This is true in particular for measurements of phase diagrams or higher order correlations where many parameters are tuned simultaneously. In this new Lithium-6 experiment built at Heidelberg University this issue is addressed with the goal to reduce cycle times to below one second to make a step towards programmable quantum simulation.

In this talk, I will give an overview of the already implemented features designed to enable high cycle rates, in particular the compact vacuum system including an octagonal, nano-texture coated glass cell, versatile magnetic field coils and a 0.66 NA objective, as well as giving an outlook on the next steps including the optical dipole trap setup at 532 and 1064nm.

A very compact setup using a 2D-MOT allows to shrink the size of the vacuum apparatus to less than 50cm. The optical setup to manipulate the system has been designed in a modular way to easily update or exchange individual parts. From this we expect an increase in stability of the setup and higher fidelities, repeatability and debuggability.

Q 26.3 Wed 11:00 Q-H10

Mesoscopic Fermion systems in rotating traps — •Philipp Lunt, Paul Hill, Diana Körner, Johannes Reiter, Selim Jochim, and Philipp Preiss — Physikalisches Institut, Im Neuenheimer Feld 226, 69120 Heidelberg

The equivalence of charged particles in external magnetic fields and neutral atoms in rapidly rotating traps opens up new avenues to study quantum hall physics with ultracold atomic gases.

In order to access the microscopic level of strongly correlated states we build on our previously established experimental methods - the deterministic preparation of ultracold ^{6}Li few Fermion systems in low dimensions [1,2], as well as local observation of their correlation and entanglement properties on the single atom level [3].

Here, we present current experimental progress towards adiabatic preparation of deterministic mesoscopic fermion systems in rapidly rotating optical potentials. We showcase the optical setup, in particular the generation of interfering a Gaussian and Laguerre-Gaussian mode to achieve rotation [4]. Moreover, we show first experimental results of the new setup.

[1] Serwane et al. Science 332 (6027), 336-338 [2] Bayha et al. Nature 587, 583-587 (2020) [3] Bergschneider et al. Nat. Phys. 15, 640-644 (2019) [4] Palm et al 2020 New J. Phys. 22 083037

Q 26.4 Wed 11:15 Q-H10

Realising the Symmetry-Protected Haldane Phase in Fermi-Hubbard Ladders — •Dominik Bourgund[1], Sarah Hirthe[1], Pimonpan Sompet[1,2], Thomas Chalopin[1], Joannis Koepsell[1], Petar Bojovic[1], Guillaume Salomon[3], Julian Bibo[4], Ruben Verresen[5], Frank Pollmann[4], Christian Gross[1,6], Immanuel Bloch[1,7], and Timon A. Hilker[1] — [1]Max-Planck-Institut für Quantenoptik, Garching, Germany — [2]Research Center for Quantum Technology, Chiang Mai, Thailand — [3]Universität Hamburg, Germany — [4]Technical University of Munich, Garching, Germany — [5]Harvard University, Cambridge, MA, USA — [6]Eberhard Karls Universität, Tübingen, Germany — [7]Ludwig-Maximilians-Universität, München, Germany

The antiferromagnetic spin-1 Haldane chain with its symmetry-protected fourfold-degenerate edge states was instrumental in understanding the impact of topological properties on quantum phases of matter. Its bulk exhibits vanishing two-point correlations, gapped excitations, and a characteristic non-local order parameter. Here we report on the realisation of such a topological Haldane phase using ultracold atoms in Fermi-Hubbard ladders. Exploiting the capabilities of our quantum gas microscope, we perform single-site and spin-resolved measurements to calculate non-local correlation functions, revealing the topological order as well as localised spin-1/2 edge states. By tuning the interactions in the system, we explore the transition from the Heisenberg limit into the Hubbard regime and thus show the robustness of the phase with respect to charge fluctuations.

Q 26.5 Wed 11:30 Q-H10

Emergence of a quantum phase transition in a few-fermion system — •Keerthan Subramanian[1], Luca Bayha[1], Marvin Holten[1], Ralf Klemt[1], Johannes Bjerlin[2], Stephanie Riemann[2], Georg Bruun[3], Philipp Preiss[1], and Selim Jochim[1] — [1]Physikaliches Insitut, Universität Heidelberg — [2]Lund University — [3]Aarhus University

Phase transitions are collective macroscopic transformations that arise in many-body systems due to competing energy scales. In this talk we try to address the minimum instance where precursors of such a phase transition can be observed for as little as 6 and 12 particles.

We deterministically prepare low entropy samples of closed-shell fermionic 6Li atoms in a 2D harmonic oscillator potential. With the ability to control interactions with a Feshbach resonance, this model system is used to explore competing energy scales. The collective modes in such a system are probed with interaction modulation spectroscopy which reveals that the lowest monopole mode(s) show a non-monotonic behavior reminiscent of the Normal-Superfluid transition in the many-body limit and the associated Higgs mode. Observation that this mode(s) consists mainly of pair excitations and features an asymptotic gap closing with increasing particle number provide evidence in favor of this association to the many-body limit. The trapping potential introduces a single particle gap in the system which leads to a long lived Higgs mode precursor which is demonstrated.

Subsequent experiments on the microscopy of such and spin-imbalanced systems are alluded to.

Q 26.6 Wed 11:45 Q-H10

Matterwave microscopy of 2D few-fermion systems — •Sandra Brandstetter, Keerthan Subramanian, Carl Heintze, Marvin Holten, Philipp Preiss, and Selim Jochim — Physics Institute, University of Heidelberg, Germany

Recent advances in deterministic preparation of ultracold few-fermion systems in combination with a spin resolved time-of-flight imaging technique with single particle resolution, have led us to the first observation of Pauli crystals [2] - demonstrating correlations in a non-interacting system due to quantum statistics - and Cooper pairing between interacting atoms in different spin states [3]. However, the exploration of correlations in real space has so far remained elusive, owing to the small system size, which we cannot resolve with our optical imaging setup.

In this talk we present the addition of a matter wave microscopy scheme [4], enabling us to access the spatial distribution of our atoms. While the initial spatial distribution is too small to resolve with our imaging setup, we can easily magnify it by a factor of 30, using a combination of two T/4 evolutions in traps with different trapping frequencies. This allows us to study the spatial correlations of few fermions in the BEC-BCS crossover, as well as the nature of the normal phase and pairing in spin-imbalanced systems.

[1] L. Bayha, et al. Nature 587.7835 (2020): 583-587.
[2] M. Holten, et al. Physical Review Letters 126.2 (2021): 020401
[3] M. Holten, et al. arXiv:2109.11511 (2021).
[4] L. Asteria et al. Nature 599, 571*575 (2021).

Q 26.7 Wed 12:00 Q-H10

Many-body quantum state diffusion for non-Markovian dynamics in strongly interacting systems — Stuart Flannigan[1], •François Damanet[2], and Andrew J. Daley[1] — [1]Department of Physics and SUPA, University of Strathclyde, G4 0NG Glasgow, United Kingdom — [2]Department of Physics and CESAM, University of Liège, B-4000 Liège, Belgium.

Capturing non-Markovian dynamics of open quantum systems is generally a challenging problem, especially for strongly-interacting many-body systems. In this work, we combine recently developed non-Markovian quantum state diffusion techniques with tensor network methods to address this challenge. As a first example, we explore a Hubbard-Holstein model with dissipative phonon modes, where this new approach allows us to quantitatively assess how correlations spread in the presence of non-Markovian dissipation in a 1D many-body system. We find regimes where correlation growth can be enhanced by these effects, offering new routes for dissipatively enhancing transport and correlation spreading, relevant for both solid state and cold atom experiments.

Reference: https://arxiv.org/abs/2108.06224

Q 26.8 Wed 12:15 Q-H10

Efficient Diagonalization Methods for Mesoscopic Fermi Systems — •Paul Hill — Physikalisches Institut, Universität Heidelberg, Deutschland

Already mesoscopic systems of interacting fermions show emergent collective phenomena such as the precursor of a quantum phase transition or cooper pairing [1,2].

These strongly correlated systems are notoriously hard to describe theoretically due to the exponential scaling of their underlying Hilbert spaces. The sparsity of typical physical Hamiltonians, however, allows us to use the Lanczos algorithm, an established numerical method in the condensed matter community. At its heart, this method seeks to identify a small sub-space of the full system on which the Hamiltonian can be efficiently diagonalized without loss of the relevant physics.

Here we use the Quanty many-body code [3] to conveniently apply the Lanczos method in the language of second quantization to the problem of few ultracold atoms interacting via s-wave scattering in a two-dimensional harmonic trap. The numerical prediction of the excitation spectrum is compared to recent experimental observations [1].

[1] Luca Bayha et al. Observing the emergence of a quantum phase transition shell by shell. Nov 2020.

[2] Marvin Holten et al. Observation of cooper pairs in a mesoscopic 2d fermi gas. Sep 2021

[3] www.quanty.org, M. W. Haverkort et al. Multiplet ligand-field theory using wannier orbitals. Apr 2012.

Q 27: Precision Measurements and Metrology IV (joint session Q/A)

Time: Wednesday 10:30–12:30 Location: Q-H11

Invited Talk Q 27.1 Wed 10:30 Q-H11

Searching for physics beyond the Standard Model with isotope shift spectroscopy — •Elina Fuchs — CERN, Department for Theoretical Physics — Leibniz Universität Hannover — Physikalisch-Technische Bundesanstalt (PTB) Braunschweig

I will present searches for New Physics beyond the Standard Model using precision isotope shift spectroscopy with a focus on the King plot method and new avenues with Rydberg states.

Q 27.2 Wed 11:00 Q-H11

Metamirrors as platform for next-generation ultra-stable laser cavities — •Steffen Sauer[1,2], Johannes Dickmann[1,2], Liam Shelling Neto[1,2], and Stefanie Kroker[1,2,3] — [1]TU Braunschweig, Institute for Semiconductor Technology, Hans-Sommer-Str. 66, 38106 Braunschweig, Germany — [2]LENA Laboratory for Emergng Nanometrology, Langer Kamp 6a/b, 38106 Braunschweig — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

The key ingredients of today′s most precise quantum optics experiments are laser cavities, e.g. in interferometric gravitational wave detectors and atomic clocks. These cavities are based on two highly reflective mirrors with required reflectivities of > 99.997 %. Additionally, cavities will play a key role in future dark matter research. The currently most stable laser cavities are limited by the mirror coating noise. A highly promising approach for the reduction of thermal noise is the implementation of metamirrors. Metamirrors are formed by laterally structured optical sub-wavelength nanostructures, which are designed to manipulate the near-field of the impinging light. Thus, the reflectivity can theoretically reach 100 % with only one structured layer. In this contribution, we present the current progress in the field of metamirrors for ultra-stable laser cavities, including thermal noise computation and reflectivity measurements.

Q 27.3 Wed 11:15 Q-H11

Precision Optical Techniques in the ALPS II Experiment — •Todd Kozlowski — University of Florida, Gainesville, USA

On behalf of the ALPS Collaboration. The Any Light Particle Search II (ALPS II) is a "light-shining-through-the-wall" experiment currently in commissioning at DESY. ALPS II will search for axion-like particles (ALPs), a family of hypothetical particles outside of the Standard Model which have a feeble coupling to the electromagnetic field, motivated by exciting astrophysical hints. The experiment aims to detect light which has undergone photon-ALP and subsequent ALP-photon conversion in the presence of a magnetic field. ALPS II utilizes a pair of 122-meter long high finesse Fabry-Perot optical resonators to improve detection sensitivity. One of the resonators will store 150 kW of circulating light to improve the amplitude of the generated axion field. The second resonator, located on the other side of a light-tight (but ALP transparent) barrier, will build up the regenerated laser field to gain a factor >10,000 in signal enhancement. The resulting signal, on the order of 1 photon/day, can then either be counted by a cryogenic photon counter or detected as modulation of a reference field. The experiment requires a control scheme to allow for the two cavities to both be held simultaneously on resonance with the same frequency of light, without any light from the first resonator entering the second. I will discuss the optical technologies utilized in this experiment, including nested optical offset phase locking, heterodyne interferometric readout of ultra-low optical fields, and alignment sensing and control. I will also present updates from the in-progress experimental commissioning.

Q 27.4 Wed 11:30 Q-H11

Tailoring narrower phase-matching bandwidth with resonant quantum pulse gate — •Dana Echeverria-Oviedo, Michael Stefszky, Jano Gil-Lopez, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Warburguer Str. 100, 33098, Paderborn, Germany.

Time-frequency quantum metrology has been shown to saturate the quantum Cramér-Rao lower bound -the ultimate precision limit imposed by quantum mechanics- if temporal-mode selective measurements can be implemented. These can be realized with a so-called quantum pulse gate, a dispersion engineered sum-frequency generation between shaped pulses. In practice, the achievable resolution of such measurements is limited by the finite phase-matching bandwidth of the quantum pulse gate. It is of paramount importance to tailor narrower phase-matching bandwidths to alleviate this limitation and push technology further towards practical applications. We propose a resonant quantum pulse gate, which is comprised of two coupled waveguide cavities that reduce the phase-matching bandwidth, one of them the nonlinear cavity in which the interaction takes place, the other an additional linear cavity which helps to select only one single resonance. Our design facilitates a reduction in phase-matching bandwidth by several orders of magnitude compared to existing devices. In this talk, we report on the current progress in which our team is working with great effort.

Q 27.5 Wed 11:45 Q-H11

Integrated broadband PDC source for quantum metrology — •René Pollmann, Franz Roeder, Matteo Santandrea, Tim Wörmann, Victor Quiring, Raimund Ricken, Christof Eigner, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Straße 100, 33098 Paderborn, Germany

Broadband quantum light is a vital resource for quantum metrology applications such as quantum spectroscopy, quantum optical coherence tomography or entangled two photon absorption. To produce light suitable for these applications we implemented a broadband (10 THz) non-degenerate type-II parametric down conversion source in a 40 mm long periodically poled $LiNbO_3$ waveguide. The broadband nature of the created photon pairs yields a very short correlation time (100 fs), while the narrowband CW pump ensures strict frequency anticorrelations. This high degree of time frequency entanglement makes the created state ideal for driving two photon absorption.
Furthermore, the bandwidth of the produced biphotons can be tuned from 1 THz to 10 THz by adjusting the operating temperature of the source.
A broadband, bright source of quantum light also enables its use as an active element of so-called SU(1,1)-interferometers for applications in spectroscopy with undetected photons.

Q 27.6 Wed 12:00 Q-H11

Influence of Spontaneous Brillouin Scattering in Cascaded Fiber Brillouin Amplification for Fiber-Based Optical Frequency Dissemination — •Jaffar Kadum and Sebastian Koke — Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

The roadmap towards the redefinition of the SI Second in terms of an optical atomic clock transition demands a comparison between remote optical clocks. Ultra-stable coherent frequency dissemination via interferometric fiber links (IFLs) is currently the only available method to compare the best optical clocks at the level of their uncertainty over continental scales. Fiber Brillouin amplifiers (FBAs) are an attractive alternative to conventional Erbium-doped fiber amplifiers due to high gain and greatly reduced back-reflection sensitivity [1]. FBA exploits the stimulated Brillouin scattering (SBS) effect initiated by the nonlinear interactions of signal and counterpropagating pump wave. However, the spontaneous Brillouin scattering (SpBS) resulting from thermally excited acoustic waves [2] degrades the signal-to-noise ratio, which may become limiting for IFLs longer than currently demonstrated. To gain deeper insight into the properties of amplified SpBS in cascaded FBA and to optimize future longer FBA-based IFLs, we developed a simulation model, which will be introduced and discussed in this contribution. 1.O. Terra et al. , *Brillouin amplification in phase coherent transfer of optical frequencies over 480 km fiber,* Opt. Express 18, (2010). 2.R.W. Boyd et al., *Noise initiation of stimulated Brillouin scattering,* Phys. Rev. A, 42, (1990).

Q 27.7 Wed 12:15 Q-H11

Pertubation of trapping standards — •Martin Kernbach[1,2], Paul Oskar Sund[1], and Andreas W. Schell[1,2] — [1]Leibniz Universtity Hannover — [2]Physikalisch-Technische Bundesanstalt Braunschweig

Levitation platforms like quadrupole traps or optical tweezers are established tools for various experiments. Trapped particles are strongly isolated from their environment. This makes for example single ions accessible as individual quantum systems. Also particles up to the micrometer regime are trappable, which gives access to their even more complex properties, like internal degrees of freedom, chemical composition, or chemical reactions under well defined artificial environmental conditions.

As a first step toward a nanoparticle levitation platform we have set up a quadrupole trap with electro spray injection and in combination with a confocal microscope. The parameter range allows for trapping of nanometer to micrometer sized particles. The optical fingerprint of these particles are taken by Raman spectroscopy. As a second step we simulate trapping with respect to the driving field, atmospheric conditions or cooling. The experimental setup is designed to enable driving potentials of arbitrary waveform for particles on the micrometer scale. With these prerequisites experimental testing of promising exotic drivings can be realized. Effects on trapping speed and equilibrium temperature are expected to be confirmed.

Q 28: Quantum Information (Quantum Communication) I

Time: Wednesday 10:30–12:30 Location: Q-H12

Q 28.1 Wed 10:30 Q-H12

Propagation of orbital-angular-momentum photons across satellite-to-earth downlinks — •Jan Schreck, David Bachmann, Vyacheslav Shatokhin, and Andreas Buchleitner — Physikalisches Institut Albert-Ludwigs Universität, Hermann-Herder-Str. 3, 79104 Freiburg

Satellite-based quantum communications enable global-scale information security. Most communication systems are based on two-dimensional encoding which employs photonic spin angular momentum (SAM). Instead, photonic spatial modes endowed with orbital angular momentum (OAM) offer high-dimensional encoding, which enhances the channel capacity, and the security of quantum key distribution (QKD) protocols. However, OAM is very fragile with respect to turbulence-induced phase front distortions.

In this talk, we discuss a faithful numerical method to account for atmospheric effects on OAM beams for a broad range of turbulence conditions. We then present our simulations of beam propagation through slant atmospheric channels, and identify turbulence regimes where high-dimensional communication using OAM beams is possible.

Q 28.2 Wed 10:45 Q-H12

Nondestructive detection of photonic qubits — •Pau Farrera, Dominik Niemietz, Stefan Langenfeld, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Garching, Germany

Qubits encoded in single photons are very useful to distribute quantum information over remote locations, but at the same time are also very fragile objects. The loss of photonic qubits is actually the main limitation in the maximum reachable quantum communication distance. In this context, the nondestructive detection of photonic qubits is a great scientific challenge that can help tracking the qubit transmission and mitigate the loss problem. Such a detector is envisioned to improve loss-sensitive qubit measurements, facilitate protocols in which distributed tasks depend on the successful dissemination of photonic qubits, and also enable certain quantum key distribution attacks. We recently implemented such a detector with a single atom coupled to two crossed fiber-based optical resonators, one for qubit-insensitive atom-photon coupling and the other for atomic-state detection. We achieve a nondestructive detection efficiency of 79(3)% conditioned on the survival of the photonic qubit, a photon survival probability of 31(1)%, and we preserve the qubit information with a fidelity of 96.2(0.3)%. To illustrate the potential of our detector we show that it can provide an advantage for long-distance entanglement and quantum-state distribution, resource optimization via qubit amplification, and detection-loophole-free Bell tests.

Q 28.3 Wed 11:00 Q-H12

Improved Bell-state Measurements with Linear Optics — •Matthias Bayerbach, Simone d'Aurelio, and Stefanie Barz — Institute for Functional Matter and Quantum Technologies & IQST, University of Stuttgart, 70569 Stuttgart, Germany

Bell-state measurements play a key role in many quantum communication and computing applications like quantum repeaters or measurement-device-independent quantum key distribution. Standard Bell-state measurements using linear optics, however, can only distinguish two of the four Bell states, limiting the efficiency of all applications to 50 %. In this talk, we present the realization of a scheme [1], which can distinguish Bell states with more than 50 % success probably by utilising interference between the Bell state and an ancillary N00N state in a linear-optical circuit. Measuring the photon-number distribution of the output allows then identifying the respective Bell state.

[1] F. Ewert and P. van Loock, Phys. Rev. Lett. 113, 140403 (2014)

Q 28.4 Wed 11:15 Q-H12

Temporal mode decoding with a multi-output quantum pulse gate — •Laura Serino, Jano Gil-Lopez, Werner Ridder, Raimund Ricken, Christof Eigner, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Department of Physics, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburgerstr. 100, D-33098 Paderborn, Germany

Quantum key distribution (QKD) is a secure communication method that allows two parties to encrypt a message through a random secret key encoded in the degrees of freedom of photons. Notably, high-dimensional (HD) QKD is characterized by a higher level of security and efficiency with respect to its binary counterpart, and temporal modes (TMs) represent a convenient encoding basis.

In this work, we demonstrate a multi-output quantum pulse gate (mQPG), a device based on dispersion-engineered sum-frequency generation in periodically poled lithium niobate waveguides which can serve as a receiver for HD QKD. The mQPG allows one to project an input state at the same time onto all the elements of a HD TM basis and map the result of each projection onto a distinct output frequency.

To achieve multi-channel operation, the poling structure is engineered to generate multiple phase-matching peaks. Appropriate shaping of the pump spectrum maps each TM to one phase-matching peak and hence output frequency. A time-of-flight measurement achieves frequency-demultiplexing of the output beam, mapping the input TM to the arrival time of the photon. As proof of principle, we show a five-dimensional detector tomography obtained with this method.

Q 28.5 Wed 11:30 Q-H12

A multi-rail random-access optical memory in hot Cs with 4 μs lifetime — •Leon Messner[1,2,3], Elizabeth Robertson[2,3], Luisa Esguerra[2,3], Kathy Lüdge[4], and Janik Wolters[2,3] — [1]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany — [2]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institute of Optical Sensor Systems, Rutherfordstr. 2, 12489 Berlin, Germany — [3]Technische Universität Berlin, Institut für Optik und Atomare Physik, Str. des 17 Juni 135, 10623 Berlin, Germany — [4]Institute of Physics, Technische Universität Ilmenau, Weimarer Str. 25, 98693 Ilmenau, Germany

Random-access quantum memories (RAQMs) are considered essential in near-term quantum communication networks [1] and computing architectures. In contrast to demonstrated RAQMs in cold ensembles or single atoms, this work demonstrates an optical memory in hot Cs vapor, that is comparatively easy to miniaturize and integrate into ground and space-borne devices. Using an acousto-optic deflector (AOD) to deflect the co-propagating signal and control pulses in an EIT memory setup [2], we show a multi-rail optical memory with random access using four parallel rails in a single Cs vapor cell. Extending the number of rails is feasible with specialized AODs and a 2-dimensional lattice of rails. The 1/e lifetime of our memory was found to be 4 μs, limited by magnetic noise, and we achieved rail dependent internal memory efficiencies of between 33% and 42%.

[1] Wallnöfer, J. et al., arXiv:2110.15806 [quant-ph] (2021)
[2] Wolters, J. et al., PRL, **119**, 060502 (2017)

Q 28.6 Wed 11:45 Q-H12

Device-Independent Quantum Key Distribution between Distant Users — •Tim van Leent[1,2], Wei Zhang[1,2], Kai Redeker[1,2], Robert Garthoff[1,2], Florian Fertig[1,2], Sebastian Eppelt[1,2], Rene Schwonnek[3,4], Wenjamin Rosenfeld[1,2,7], Valerio Scarani[5,6], Charles Lim[3,5], and Harald Weinfurter[1,2,7] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Department of Electrical & Computer Engineering, National University of Singapore, Singapore — [4]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany — [5]Centre for Quantum Technologies, National University of Singapore, Singapore — [6]Department of Physics, National University of Singapore, Singapore — [7]Max-Planck-Institut für Quantenoptik, Garching, Germany

Device-independent quantum key distribution (DIQKD) is the art of establishing secure keys over untrusted channels using untrusted devices, thereby harnessing the ultimate quantum advantage for secure communications. Here we present a proof-of-concept DIQKD experiment between two users at locations 400 meters apart [1]. For this, we employ heralded entanglement between two remote single-atom quantum memories to verify the security of the generated key with a Bell-test [2]. We show that—based on asymptotic security estimates—our apparatus establishes secure keys in a fully device-independent way.

[1] W. Zhang et al., arXiv:2110.00575 (2021)
[2] W. Rosenfeld et al., Phys. Rev. Lett. **119**, 010402 (2017)

Q 28.7 Wed 12:00 Q-H12

Employing Atomically Thin Single-Photon Sources for Tests of Quantum Key Distribution — •Timm Gao[1], Martin v. Helversen[1], Carlos Anton-Solanas[2], Christian Schneider[2], and Tobias Heindel[1] — [1]Institut für Festkörperphysik, Technische Universität Berlin, 10623 Berlin, Germany — [2]Institut für Physik, Carl von Ossietzky Universität Oldenburg, 26111 Oldenburg, Germany

Quantum light sources are considered key building blocks for future quantum communication networks. In recent years, atomic monolayers of transition metal dichalcogenides (TMDCs) emerged as a promising material platform for the development of compact quantum light sources. In this work, we evaluate for the first time the performance of a single-photon source (SPS) based on a strain engineered WSe_2 monolayer [1] for applications in quantum key distribution (QKD). Employed in a QKD-testbed emulating the BB84 protocol, an antibunching of $g^{(2)}(0) = 0.127 \pm 0.001$ and a raw key rate of up to (66.95 ± 0.10)kHz make this source competitive with previous SPS based QKD experiments using quantum dot based SPSs. Furthermore, we exploit routines for the performance optimization previously applied to quantum dot based single-photon sources [2]. Our work represents an important step towards the application of TMDC-based devices in quantum technologies.

[1] L. Tripathi et al., ACS Photonics 5, 1919-1926 (2018)
[2] T. Kupko et al., npj Quantum Information 6, 29 (2020)

Q 28.8 Wed 12:15 Q-H12

A Quantum Key Distribution Testbed using a Plug&Play Telecom-Wavelength Single-Photon Source — •Timm Gao[1], Lucas Rickert[1], Felix Urban[1], Jan Grosse[1], Nicole Srocka[1], Sven Rodt[1], Anna Musiał[2], Kinga Żołnacz[3], Paweł Mergo[4], Kamil Dybka[5], Wacław Urbańczyk[3], Grzegorz Sęk[2], Sven Burger[6], Stephan Reitzenstein[1], and Tobias Heindel[1] — [1]Institute of Solid State Physics, Technical University Berlin, 10623 Berlin, Germany — [2]Department of Experimental Physics, Wrocław University of Science and Technology, 50-370 Wrocław, Poland — [3]Department of Optics and Photonics, Wrocław University of Science and Technology, 50-370 Wrocław, Poland — [4]Institute of Chemical Sciences, Maria Curie Sklodowska University, 20-031 Lublin, Poland — [5]Fibrain Sp. z o.o., 36-062 Zaczernie, Poland — [6]Zuse Institute Berlin, 14195 Berlin, Germany

We report on quantum key distribution (QKD) tests using a 19-inch benchtop single-photon source at 1321 nm based on a fiber-pigtailed quantum dot (QD) integrated into a Stirling cryocooler. Emulating the polarization-encoded BB84 protocol, we achieve an antibunching of $g^{(2)}(0) = 0.10 \pm 0.01$, a raw key rate of up to 4.72 ± 0.13 kHz. Exploiting optimized temporal filters [1] in the asymptotic limit a maximum tolerable loss of 23.19 dB can be achieved. Our study represents an important step forward in the development of fiber-based quantum-secured communication networks exploiting sub-Poissonian quantum light sources.

[1] T. Kupko et al., arXiv.2105.03473 (2021)

Q 29: Optomechanics I

Time: Wednesday 10:30–12:30 Location: Q-H13

Invited Talk Q 29.1 Wed 10:30 Q-H13

Quantum rotations of levitated nanoparticles — •Benjamin A. Stickler — Faculty of Physics, University of Duisburg-Essen, Germany

The non-linearity and anharmonicity of rigid body rotations gives rise to pronounced quantum interference effects with no analogue in the body's centre-of-mass motion [1]. This talk will briefly review two such effects, orientational quantum revivals [2] and the quantum tennis racket effect [3], and discuss how elliptic coherent scattering cooling [4] opens the door to rotational quantum experiments with nanoscale particles and rotational tests of collapse models.

[1] Stickler, Hornberger, and Kim, Nat. Rev. Phys. 3, 589 (2021).
[2] Stickler, Papendell, Kuhn, Millen, Arndt, and Hornberger, New J. Phys. 20, 122001 (2018).
[3] Ma, Khosla, Stickler, and Kim, Phys. Rev. Lett. 125, 053604 (2020).
[4] Schäfer, Rudolph, Hornberger, and Stickler, Phys. Rev. Lett. 126, 163603 (2021).

Q 29.2 Wed 11:00 Q-H13

Ultrastrong Coupling in an Optomechanical System — •Kahan Dare[1,2], Jannek Hansen[1,2], Aisling Johnson[1,2], Uros Delic[1,2], and Markus Aspelmeyer[1,2] — [1]Vienna Center for Quantum Science and Technology,Faculty of Physics, University of Vienna, Vienna, Austria — [2]Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Vienna, Austria

The ultrastrong coupling regime, where the coherent coupling rate approaches the transition energy of the system, is a rarely studied area of physics despite its vast array of novel physics such as two-mode squeezing, the dynamical Casimir effect and non-gaussian ground states. Only a handful of experiments have been recently developed to probe this regime due to the large technologically challenges associated with engineering such a system.

Here, we implement a simple scheme for reaching the ultrastrong coupling regime in an optomechanical system which can be dynamically tuned to implement a wide range of quantum control protocols. We achieve this by coupling a levitated nanoparticle to an optical cavity through coherent scattering. Together with the ability to cool the system to its motional ground state, this result opens up quantum experiments in the USC regime to simple table-top systems. Lastly, we outline how to extend this to the deep strong coupling regime and its potential for future applications.

Q 29.3 Wed 11:15 Q-H13

Non-classical mechanical states guided in a phononic waveguide — •Amirparsa Zivari, Robert Stockill, Niccolo Fiaschi, and Simon Groeblacher — Delft University of Technology, Delft, Netherlands

Quantum optics – the creation, manipulation and detection of non-classical states of light – is a fundamental cornerstone of modern physics, with many applications in basic and applied science. Achieving the same level of control over phonons, the quanta of vibrations, could have a similar impact, in particular on the fields of quantum sensing and quantum information processing. Here we demonstrate the first step towards this level of control and realize a single-mode waveguide for individual phonons in a suspended silicon micro-structure. We use a cavity-waveguide architecture, where the cavity is used as a source and detector for the mechanical excitations, while the waveguide has a free standing end in order to reflect the phonons. This enables us to observe multiple round-trips of the phonons between the source and the reflector. The long mechanical lifetime of almost 100us demonstrates the possibility of nearly lossless transmission of single phonons over, in principle, tens of centimeters. Our experiment represents the first demonstration of full on-chip control over traveling single phonons strongly confined in the directions transverse to the propagation axis and paves the way to a time-encoded multimode quantum memory at telecom wavelength and advanced quantum acoustics experiments.

Q 29.4 Wed 11:30 Q-H13

Cavity optomechanics with polymer drum resonators in fiber Fabry-Perot cavities — •Lukas Tenbrake[1], Alexander Fassbender[2], Sebastian Hofferberth[1], Stefan Linden[2], and Hannes Pfeifer[1] — [1]Institute of Applied Physics, University of Bonn, Germany — [2]Institute of Physics, University of Bonn, Germany

Cavity optomechanical experiments in micro- and nanophotonic systems have demonstrated record optomechanical coupling strenghts, but require elaborate techniques for interfacing. Their scaling towards larger systems including many mechanical and optical resonators is limited. Here, we demonstrate a directly fiber-coupled tunable and highly flexibile platform for cavity optomechanics based on polymer structures in fiber Fabry-Perot cavities (FFPCs). The polymer structures are fabricated using 3D direct laser writing. They form drum resonators with frequencies in the MHz regime. Vacuum coupling strengths exceeding 20 kHz to micron sized FFPC modes are observed. The extreme flexibility of the laser writing process allows for a direct integration of the mechanical resonator on fiber mirrors, but also for larger scale structures on macroscopic substrates. Moreover, the tolerance of FFPCs to optical power allows the observation of strong optomechanical spring effects. The ease of interfacing, the favorable scaling capabilities and the possible integration with other systems like electrodes makes it a promising platform for current challenges in cavity optomechanics.

Q 29.5 Wed 11:45 Q-H13

Synchronization of two levitated nanoparticles via direct dipole-dipole coupling — •Manuel Reisenbauer[1], Livia Egyid[1], Anton Zasedatelev[1,2], Iurie Coroli[1,2], Benjamin A. Stickler[3], Henning Rudolph[3], Markus Aspelmeyer[1,2], and Uros Delic[1,2] — [1]University of Vienna, A-1090 Vienna, Austria — [2]IQOQI, Austrian Academy of Sciences, A-1090 Vienna, Austria — [3]University of Duisburg-Essen, 47048 Duisburg, Germany

Synchronization is the phenomenon of multiple oscillators moving in unison despite their intrinsic frequencies being non-degenerate. This not only locks their frequencies/phases together, but the system also experiences lower phase noise, promising increased sensing performance over a single oscillator.

Systems up to date show only dynamics of frequencies of the coupled oscillators, neglecting phase dynamics completely. Also, separate readout of the individual oscillator position is impossible in many integrated systems, restricting the analysis to collective signatures only.

We present an experiment with two nanoparticles levitated in parallel optical tweezers, employing a direct optical dipole-dipole coupling to synchronize their motion. We present conclusive signatures of synchronization and show the transition from individual oscillators to a synchronized state. Our work shows possible applications to sensing and metrology employing the reduction of phase noise below the thermomechanical limit of each individual oscillator. Finally, we discuss the scalability of our system to large arrays of trapped particles and its operation in the quantum regime.

Q 29.6 Wed 12:00 Q-H13

Efficient optomechanical mode-shape mapping of micromechanical devices — David Hoch[1,2,3], Timo Sommer[1,2], Kevin-Jeremy Haas[1], Leopold Moller[1], Julius Röwe[1], and •Menno Poot[1,2,3] — [1]Department of Physics, Technical University of Munich, Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Institute for Advanced Study, Technical of University Munich, Garching, Germany

The rapidly growing interest in (quantum) optomechanics calls for an efficient method to map eigenmode shapes. One - very time-consuming - way to do this is to measure the driven response for every mode at different locations on the resonator. A faster approach is to drive each mode at a single frequency and record their amplitudes, but drift of the resonance frequency makes this impractical for high-Q resonators. Here, we present an efficient way of simultaneously mapping up to 6 eigenmodes. Our method is robust against drift by employing an improved phase-lock loop (PLL) that can also lock to regions with different signs of the mode shape. We demonstrate the capabilities of our technique on a square Si3N4 membrane in vacuum. The membrane is excited with a piezoelectric element and modes between 1 and 21.6 MHz are mapped accurately. Proof-of-principle measurements already shine new light on e.g. mode splitting, clamping losses, and superposition of degenerate modes. Currently ongoing experiments on crosstalk compensation and on non-flat resonators are also discussed.

Q 29.7 Wed 12:15 Q-H13

Levitodynamics in free fall — •Christian Vogt, Govindarajan Prakash, Vincent Hock, Marian Woltmann, Sven Herrmann, and Claus Lämmerzahl — Universität Bremen, ZARM (Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation

Physicists have not yet been able to unite two of the most successful theories of our time, quantum theory and relativity. One way to test the interplay between these two theories is to observe interferometers with ever heavier particles. A promising candidate for observing interferometers with "large" masses are motion-cooled silica nanoparticles. These can be optically trapped in vacuum, and due to the appropriate insulation, ground-state cooled even in an environment at room temperature.
In near-field interferometers, the required free evolution time of the particles is described by the Talbot time, which scales with mass. In the NaiS project, we will extend this time from hundreds of milliseconds to several seconds by transferring the techniques of levitated optomechanics to the weightlessness environment of the 146 m high drop tower in Bremen.
This talk will focus on the experimental setup suitable for drop tower operation and how to solve the problem of low repetition rates in weightlessness.

Q 30: Quantum Optics (Miscellaneous) IV

Time: Wednesday 10:30–12:30 Location: Q-H14

Invited Talk Q 30.1 Wed 10:30 Q-H14

Optical properties of porous crystalline nanomaterials modeled across all length scales — •Marjan Krstić — Karlsruhe Institute of Technology, Institute of Theoretical Solid State Physics, Karlsruhe, Germany

Zeolites and metal-organic frameworks have enormous application potential due to their variety and porosity. Recently, their optical properties came into the focus of attention that can be quenched or enhanced. Such control is possible by tailoring the intrinsic material properties and the photonic environment into which the molecules are placed. The enhancements of luminescence, Raman scattering, second-harmonic generation, or more general sensing are just a few examples of considered properties. To guide future developments, suitable computational tools are needed. Such tools must be interdisciplinary and should cover multiple lengths scales intrinsic to such optical devices.

Naturally, the molecular building blocks, governed by quantum effects, must be correctly described. But the molecular materials are also integrated into an advanced photonic environment, and optical simulations on macroscopic length scales must be performed. Such a setting prompts for a scale-bridging modeling approach. The theory should be used to unravel and understand complex optical processes in the nanomaterials and optimize materials and devices for selected applications. These aspects render the efficient and accurate modeling of such materials and devices a prime challenge. In my contribution, I will overview recent developments of such tools based on DFT/TD-DFT methods and explore three examples for applications of such materials.

Q 30.2 Wed 11:00 Q-H14

Nonequilibrium time-crystal quantum engine — •Federico Carollo[1], Kay Brandner[2], and Igor Lesanovsky[1] — [1]Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany — [2]School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK

Nonequilibrium many-body quantum systems can host intriguing phenomena such as transitions to exotic dynamical phases of matter. Although this emergent behaviour can nowadays be observed in experiments, its potential for technological applications is largely unexplored. Here, we propose a new type of nonequilibrium many-body quantum engine and investigate the impact of collective effects on its working principles as well as on its power output. For concreteness, we consider an optomechanical cavity setup with an interacting atomic gas as a working fluid and we demonstrate theoretically that such engines produce work under periodic driving. The stationary cycle of the working fluid features nonequilibrium phase transitions, resulting in abrupt changes of the power output. Remarkably, we find that our many-body quantum engine operates even without periodic driving. This phenomenon occurs when its working fluid enters a phase that breaks continuous time-translation symmetry: this so-called emergent time-crystalline phase can sustain the motion of a load generating mechanical work. Our findings pave the way for designing novel nonequilibrium quantum machines.

Q 30.3 Wed 11:15 Q-H14

Simulation and fabrictaion of periodically poled waveguides in KTP for quantum state preparation — •Johannes Otte, Laura Padberg, Christof Eigner, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn

Photonic quantum communication and computing require reliable and highly quality quantum state preparation. Therefore, highly efficient sources of photons with high purity and brightness are necessary. One of the materials of choice for such a photon pair source is KTP. It offers the advantages of a wide transparency range from IR to UV, high mechanical and chemical resistance, large non-linear coefficients and low refractive index change with temperature. The dispersion properties makes it unique for quantum state generation, e.g. for decorelated photon pairs at 1550 nm. Waveguides fabrication as well as period poling for quasi-phase-matching is possible in KTP, which drastically increases the efficiency of photon sources. Thus, photon sources in periodically poled KTP are highly desirable for quantum optics applications. However, the fabrication of periodocally poled waveguides in KTP is still a challenging task, which requries a profound understanding of the material behaviour. For an improvement of the fabrication of periodically poled KTP waveguides, simulations of the poling behaviour near the crystall surface leading to a better understanding of the generated domain structure. We show our recent results of the modelling for poling dynamics in rubidium exchanged waveguides.

Q 30.4 Wed 11:30 Q-H14

Single ion wave packet super-resolution imaging — •Maurizio Verde[1], Martín Drechsler[2], Milton Katz[2], Felix Stopp[1], Sebastian Wolf[1], Christian Schmiegelow[2], and Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Universität Mainz, Germany — [2]Departmento de Física, Universidad de Buenos Aires, Argentina

We present super-resolution microscopy method which enables imaging quantum wave packets of single ions in an analogous manner to STED [1]. Using hollow beams to excite single $^{40}\mathrm{Ca}^+$ ions, it has been shown recently that one can excite transitions in the beam's dark center, where the transverse gradients can drive quadrupole transitions [2]. Conversely, here we use a hollow light beam to strongly saturate a dipole-forbidden transition $|4\mathrm{S}_{1/2}, m = -1/2\rangle \leftrightarrow |3\mathrm{D}_{5/2}, m = -3/2\rangle$ of an ion except at a sub-diffraction limited area around the beam's center. This beam shelves the ion into a metastable state which does not fluoresce. Next by shining a laser resonant on a dipole-allowed transition we observe scattered photons only of ions which where in this sub-diffraction limited area. This allows us to experimentally resolve about 30 nm and sense the wave packet of a single ion either Doppler or ground state cooled [3]. The theoretical estimated resolution limit of our method is few nm, which is allowing us to explore the direct imaging of non-classical quantum mechanical matter wave Fock states.

[1] S. W. Hell and J. Wichmann, Opt. Lett. **19**, 780 (1994)
[2] C. T. Schmiegelow et al., Nat Commun **7**, 12998 (2016)
[3] M. Drechsler et al., Phys. Rev. Lett. **127**, 143602 (2021)

Q 30.5 Wed 11:45 Q-H14

Adaptive optics in Confocal microscopy and Fluorescence correlation spectroscopy — •Julius Trautmann[1], Philipp Kellner[1], Tiemo Anhut[2], Daniel Schwedt[2], and Christian Eggeling[1] — [1]Institut für Angewandte Optik und Biophysik, Friedrich-Schiller-Universität Jena, Philosophenweg 7, 07743 Jena — [2]Carl Zeiss Microscopy GmbH, Carl-Zeiß-Promenade 10, 07745 Jena

Adaptive optics has been widely used in astronomy for the last three decades. In recent years however, it has also established itself as an important feature for high resolution microscopy. The opportunity to correct for optical aberrations is particularly useful when imaging samples with inhomogeneous refractive index structures such as cells and especially cell tissue.

Adaptive optics includes elements such as deformable mirrors (DMs) and spatial light modulators (SLMs) which can dynamically correct for aberrations.

This talk will cover the basic idea of including a deformable mirror (DM) in a confocal microscope. The optical setup will be presented and the employment of fluorescence correlation spectroscopy (FCS) will be highlighted.

Q 30.6 Wed 12:00 Q-H14

Gravitational effects on time-frequency bandwidth relations in Earth-to-space telecommunications — •Mohsen Esmaeilzadeh[1,2], Roy Barzel[4], David E. Bruschi[3], Claus Lämmerzahl[4], Frank K. Wilhelm[3], and Andreas W. Schell[1,2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig — [2]Institute for Solid State Physics, Leibniz University Hannover, Appelstr. 2, 30167 Hannover — [3]Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum J*ulich, 52425 Jülich, Germany — [4]ZARM, University of Bremen, 28359 Bremen, Germany

We study the space-time curvature effects on satellite communication with single photons. We proposed a model of communication between Earth and the satellite between users using a traveling string of photon pulses. Since our quantum systems propagate in the space-time of a curved background, the propagating wave-packets are deformed because of the influence of the gravitational red-shift that also changes their time-bandwidth relation.

We provide a theoretical understanding of how the gravitational redshift affects the overlapping pulses. The antibunching behavior of them and the impact of the deformation on the intensity correlation function are studied. Moreover, we try to take the advantage of the Wigner function as a measure for quantumness to investigate the changes in the pulses after getting gravitational red-shift.

Q 30.7 Wed 12:15 Q-H14

Exploring the temporal-mode selective frequency conversion of PDC states — •Patrick Folge, Matteo Santandrea, Michael Stefszky, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Department of Physics, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Straße 100, 33098 Paderborn, Germany

Nonlinear optical elements are an essential component in many emerging quantum technologies because they can produce and probe light with non-classical features. Of central importance are parametric down-conversion (PDC) sources, which are able to generate squeezed states of light. In a multimode framework the PDC sources introduces quantum correlations between sets of field-orthogonal temporal-modes. A different non-linear element considered here is the quantum pulse gate (QPG), which is a specially engineered frequency conversion (FC) process. It allows for the temporal-mode selective conversion of light. Therefore, by applying the QPG to the squeezed light produced by a PDC source, one can transfer the squeezing properties of any mode to the output mode of the QPG. Here, we theoretically investigate which modes are best suited to transfer the squeezing properties to the output of the QPG. Further, we look at realistic scenarios and explore the limits of this scheme.

Q 31: Photonics I

Time: Wednesday 10:30–12:30 Location: Q-H15

Q 31.1 Wed 10:30 Q-H15

Wavefront characterization and simulation for high precision interferometry — •Kevin Weber, Gudrun Wanner, and Gerhard Heinzel — Albert Einstein Institut, Hannover, Niedersachsen

High precision interferometry with laser light is the foundation of many modern experiments. To further improve their incredible precision, an exact knowledge of the beam geometries involved is crucial. We present a novel means to measure and quantify beam geometries and its impact on readout signals. By combining the readout of a wavefront sensor with an in-house beamfitting algorithm, we will create a precise mathematical model of an experimental beam as a superposition of transversal electromagnetic modes. The presence of Higher-order mode contaminants are likely to negatively impact measurements. Therefore, we propose a way to study their influence in the future, namely by simulating the interferometric readout using the existing in-house C++ library IfoCAD. Insight gained on the influence of beam geometries on optical readout will contribute to the success of future geodesy and gravitational wave detector missions.

Q 31.2 Wed 10:45 Q-H15

Role of order and disorder for 2D photonic structures modelled using FDTD simulations — •David Röhlig[1], Eduard Kuhn[1], Thomas Blaudeck[2], and Angela Thränhardt[1] — [1]TU Chemnitz, Institut für Physik, Reichenhainer Str. 70, 09126 Chemnitz — [2]TU Chemnitz, Forschungszentrum MAIN, Rosenbergstraße 6, 09126 Chemnitz

Investigations of real photonic systems have so far mostly neglected fabrication imperfections and aspects of disorder [1]. Nevertheless, they always play a decisive role for function [2]: deviations from ideal crystallinity occur both in nature and artificial systems. Although in nanotechnologies the accuracy of manufacturing processes has increased, irregularities still play a role for the performance of photonic components [3]. The extent to which disorder affects photonic systems depends on the type of disorder related to various geometrical and material quantities. Using FDTD, we simulated transmission spectra of 2D optical systems introducing a controlled amount of disorder of various types. We found that increasing disorder always leads to a transmission decrease and particular spectral changes. The results were compared with spectra of amorphous photonic crystals, generated by a molecular dynamics algorithm.

[1] M. Rothammer et al. Advanced Optical Materials 9, 19, 2100787 (2021). DOI 10.1002/adom.202100787. [2] E. Kuhn, D. Röhlig et al. Nano Select 2, 12, 2461-2472 (2021). DOI 10.1002/nano.202100263. [3] D. Segura et al. Sensors and Actuators A: Physical 264, 172-179 (2017). DOI 10.1016/j.sna.2017.07.011.

Q 31.3 Wed 11:00 Q-H15

Quantum-Coherent Light-Electron Interaction in an SEM — •Tomas Chlouba, Roy Shiloh, and Peter Hommelhoff — Physics Department, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstraße 1, 91058 Erlangen, Germany

The quantum-coherent interaction of light and free electrons was shown more than a decade ago in a transmission electron microscope in the form of photon-induced near-field microscopy (PINEM). A variety of scientific demonstrations followed including attosecond quantum coherent control, free electron quantum state generation and reconstruction, attosecond pulse generation and photon statistics reconstruction. A significant drawback of the PINEM technique so far was that it required a specifically modified transmission electron microscope (TEM), mainly because high-resolution spectrometers for scanning electron microscopes (SEM) are not available. Based on a home-built, compact magnetic high resolution electron spectrometer we show the quantum coherent coupling between electrons and light in an SEM, at unprecedentedly low, sub-relativistic energies down to 10.4 keV. These microscopes not only afford the yet-unexplored energies from ~0.5 to 30 keV providing the optimum electron-light coupling efficiency, but also offer spacious and easily-configurable experimental chambers for extended, cascaded optical set-ups, potentially boasting thousands of photon-electron interaction sites. The demonstration of PINEM in an SEM opens a new avenue of electron-photon quantum interactions unfeasible in TEMs.

Q 31.4 Wed 11:15 Q-H15

Deep learning assisted design of high reflectivity metamirrors — •Liam Shelling Neto[1,2], Johannes Dickmann[1,2], and Stefanie Kroker[1,2,3] — [1]Institut für Halbleitertechnik, Braunschweig, Deutschland — [2]Laboratory for Emerging Nanometrology, Braunschweig, Deutschland — [3]Physikalisch-Technische Bundesanstalt, Braunschweig, Deutschland

Manipulating light in an ever so complex manner can be a complicated task. Metasurfaces, i.e. two-dimensional periodic nanostructures of sub-wavelength size, allow exotic applications in wavefront manipulation for the price of nonintuitive design of the surfaces building blocks. Since the mapping of a given design to the underlying electromagnetic response is highly non-linear, common approaches involve numerous simulations to optimize the device performance to given requirements. With increasing functionality of the metasurface, the parameter space that necessary to provide enough flexibility can be rather large and thus, difficult to control. When it comes to the application of metasurfaces as focusing mirrors in ultra-stable cavities or future gravitational wave detectors, those devices face unprecedented requirements such as high reflectivity, optimal phase agreement etc. Here, we utilize powerful deep learning algorithms to implement an inverse design framework that handles large parameters spaces with ease in order to design high-reflectivity metamirrors.

Q 31.5 Wed 11:30 Q-H15

Integrated Grating Outcoupler for Ion-based Quantum Computers — •Anastasiia Sorokina[1,2], Steffen Sauer[1,2], Johannes Dickmann[1,2], and Stefanie Kroker[1,2,3] — [1]Institute of Semiconductor Technology, Technische Universität Braunschweig, 38106 Braunschweig, Germany — [2]Laboratory for Emerging Nanometrology (LENA), Langer Kamp 6a/b, 38106 Braunschweig, Germany — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Trapped-ion qubits are considered a promising platform for quantum computation due to their long coherence times and high fidelity. Nevertheless, the existing requirements for the control and operation of the ions is currently accessed via conventional optics. Consequently, increasing the number of ion-trapped qubits is complex and intricate. Additionally, the sheer complexity of the optical arrangement results in vibrational noise and a decreased operational fidelity. To optically operate the multi-level transitions of the ion, we explore an integrated optical system comprising a waveguide and a grating coupler. This system delivers and focuses light to the position of the ion. In order to ensure single-mode waveguide operation, COMSOL Multiphysics FEM solver was utilized. Additionally, Lumerical FDTD solver was used to optimise the light focusing ability of the grating coupler. We present the numerical results covering the whole wavelength range of ion transitions with an optical system on a single chip.

Q 31.6 Wed 11:45 Q-H15

Aluminum nitride integration on silicon nitride photonic circuits: a new hybrid approach towards on-chip nonlinear optics — Giulio Terrasanta[1,2], •Timo Sommer[1,4], Manuel Müller[3,1], Matthias Althammer[3,1], Rudolf Gross[3,1,4], and Menno Poot[1,4,5] — [1]Department of Physics, Technical University Munich, Garching, Germany — [2]Physics Section, Swiss Federal Institute of Technology in Lausanne (EPFL), Switzerland — [3]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [4]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [5]Institute for Advanced Study, Technical University Munich, Garching, Germany

Aluminum nitride (AlN) is an emerging material for integrated quantum photonics with excellent linear and nonlinear optical properties, in particular its $\chi^{(2)}$ that allows single-photon generation. In this talk, we demonstrate the integration of AlN on silicon nitride (SiN) photonic chips. We sputtered c-axis oriented AlN on top of pre-patterned SiN microrings. We varied AlN thickness, ring radius, and waveguide width n different chips to meet the phase-matching condition for second harmonic generation or spontaneous parametric down-conversion. With XRD, optical reflectometry, SEM, and AFM, we investigated the deposited AlN films and proofed their good optical quality. This hybrid approach adds $\chi^{(2)}$ nonlinearity to the SiN platform without the challenging process of AlN etching. Therefore, the integration of single photon-pair generation depends only on reliable SiN nanofabrication.

Q 31.7 Wed 12:00 Q-H15

Tabletop setup for broadband absolute EUV reflectivity measurements from single exposures — •Johann Jakob Abel[1], Felix Wiesner[1], Florian Funke[1], Julius Reinhard[2], Martin Wünsche[2], Jan Nathanael[3], Christian Rödel[4], Silvio Fuchs[1,2], and Gerhard G. Paulus[1,2] — [1]IOQ, FSU Jena, Germany — [2]Helmholtz Institut Jena, Germany — [3]IOF, Jena, Germany — [4]TU Darmstadt, Germany

The broadband measurement of EUV reflectivity from samples is of particular interest for multilayer EUV mirror characterization [1], EUV reflection spectroscopy [2], and EUV imaging applications [3]. A tabletop setup for measurements allowing to record reference and sample spectra simultaneously with high energy resolution in a range between 40 and 100 eV is presented. The presented method provides a solution for extremely precise and robust absolute reflectivity measurements even when operating with unstable and spectrally fluctuating EUV sources. The simultaneous reference measurement improves the stability by more than one order of magnitude in comparison to a single independent reference measurement. Applications and advantages in nanoscopic three-dimensional imaging with XUV coherence tomography (XCT) [4] and reflective near-edge x-ray absorption fine structure spectroscopy (NEXAFS) are presented and discussed.

[1] J. Li, Optics Letters, 43, 16 (2018)
[2] L. Bahrenberg, Optics Express 28, 14 (2020)
[3] S. Skruszewicz, Appl. Phys. B 127, 55 (2021)
[4] S. Fuchs, Optica 4, 903-906, (2017)

Q 31.8 Wed 12:15 Q-H15

Development of a nanophotonic nonlinear unit for optical artificial neural networks — •Jan Riegelmeyer[1], Alexander Eich[1], Marlon Becker[2], Benjamin Risse[2], and Carsten Schuck[1] — [1]Institute of Physics, University of Münster, Germany — [2]Institute of Computer Science, University of Münster, Germany

Coherent nanophotonic circuit implementations of artificial neural networks (ANNs) try to mimic signal processing in biological brains and hold great potential for fast and energy efficient computing. However, the realization of nonlinear nanophotonic components, which are utilized as activation function, remains a major challenge.

In our work, we plan on employing solution-based photoresponsive molecular systems as nonlinear building blocks of optical ANNs, for which we design and fabricate nanophotonic interfaces. We perform finite difference time domain simulations of 3D waveguide-to-free-space coupling structures that create a free-space optic link on-chip, which can be filled with photoresponsive solutions realizing tunable attenuation. The corresponding structures are produced via Direct Laser Writing in photopolymer. To confine solution in-between the couplers we fabricate micrometer-sized reservoirs made from epoxy-based photoresist. Our device realizes a new platform for optically interfacing with solution-based photoresponsive systems via multiple nanophotonic channels benefitting not only ANN-implementations but integrating novel soft matter systems into nanophotonic circuits.

Q 32: Ultra-cold atoms, ions and BEC II (joint session A/Q)

Time: Wednesday 10:30–12:15 Location: A-H2

Q 32.1 Wed 10:30 A-H2

Hole-induced anomaly in the thermodynamic behavior of a 1D Bose gas — •Giulia De Rosi[1], Riccardo Rota[2], Grigori E. Astrakharchik[1], and Jordi Boronat[1] — [1]Universitat Politècnica de Catalunya, Barcelona, Spain — [2]Ecole Polytechnique Fédérale de Lausanne, Switzerland

We reveal an intriguing anomaly in the temperature dependence of the specific heat of a one-dimensional Bose gas. The observed peak holds for arbitrary interaction and remembers a superfluid transition, but phase transitions are not allowed in 1D. The presence of the anomaly signals a region of unpopulated states which behaves as an energy gap and is located below the hole branch in the excitation spectrum. The anomaly temperature is of the same order of the energy of the maximum of the hole branch. We rely on the Bethe Ansatz to obtain the specific heat exactly and provide interpretations of the analytically tractable limits. The dynamic structure factor is computed with the Path Integral Monte Carlo method for the first time. We notice that at temperatures similar to the anomaly threshold, the energy of the thermal fluctuations become comparable with the maximal hole energy. This excitation pattern experiences the breakdown of the quasiparticle description for any value of the interaction strength at the anomaly, similarly to any superfluid phase transition at the critical temperature. We provide indications for future observations and how the hole anomaly can be employed for in-situ thermometry, identifying different collisional regimes and understanding other anomalies in atomic, solid-state, electronic and spin-chain systems. [arXiv:2104.12651 (2021)].

Q 32.2 Wed 10:45 A-H2

Signatures of radial and angular rotons in a two-dimensional dipolar quantum gas — •Sean Graham[1], Jan-Niklas Schmidt[1], Jens Hertkorn[1], Mingyang Guo[1], Fabian Böttcher[1], Matthias Schmidt[1], Kevin Ng[1], Tim Langen[1], Martin Zwierlein[2], and Tilman Pfau[1] — [1]5th Institute of Physics and Center for Integrated Quantum Science and Technology IQST, University of Stuttgart, Germany — [2]MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics, and Department of Physics, Massachusetts Institute of Technology, Cambridge, USA

We observed signatures of radial and angular roton modes and their contribution to droplet formation in an oblate dipolar quantum gas. Roton modes have a finite momentum that can be significantly populated in dipolar quantum gases when dipole-dipole interactions are strong relative to hard-core interactions. For stronger dipole-dipole interactions the condensate will crystallize into droplets. Near this crystallization transition we extract the static structure factor from in-situ density fluctuations. We identify the presence of a radial roton by a peak at finite momentum in the radial structure factor that appears near the transition. Additional peaks are observed in the angular structure factor corresponding to the population of the angular roton mode. Finally, a comparison to simulated mode patterns from the extended Gross-Pitaevski equation shows good agreement with our results.

Q 32.3 Wed 11:00 A-H2

Two-body correlations in imbalanced quantum systems — •Carl Heintze[1], Keerthan Subramanian[1], Sandra Brandstetter[1], Marvin Holten[1], Philipp Preiss[1,2], and Selim Jochim[1] — [1]Physikalisches Institut, Im Neuenheimer Feld 226, 69120 Heidelberg — [2]Max Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

Superfluidity in strongly correlated systems still poses a challenging task for experimentalists and theorists. Explaining the phenomenon with pair formation enables us to tackle the problem in the limit of strongly bound particles building up molecules (BEC limit) and delocalized zero momentum pairs (BCS limit). Nevertheless, complete and verified theories of strongly correlated regimes in between are still missing. Additionally, there are ongoing discussions about the pairing mechanisms, the breakdown of superfluidity and the rich phase diagram in imbalanced systems.

Our experiment focuses on the emergence of correlations and collective behaviour in many particle systems from the few-particle limit. The apparatus enables us to prepare small quantum systems (two to twelve particles) deterministically in a two-dimensional harmonic oscillator and to image the final state with spin and single particle resolution. Therefore, we can extract the in-situ two-body correlations in momentum as well as in real space. By using spectroscopic measurements, we are also able to measure excitation spectra.

Recently we achieved to prepare imbalanced systems (3+1, 6+3, 6+1 particles) and to measure their momentum correlations.

Q 32.4 Wed 11:15 A-H2

An impurity with a resonance in the vicinity of the Fermi energy — •Mikhail Maslov, Mikhail Lemeshko, and Artem Volosniev — IST Austria, Am Campus 1, 3400 Klosterneuburg, Austria

We study an impurity with a resonance level whose energy coincides with the Fermi energy of the surrounding Fermi gas. An impurity causes a rapid variation of the scattering phase shift for fermions at the Fermi surface, introducing a new characteristic length scale into the problem. We investigate manifestations of this length scale in the self-energy of the impurity and in the density of the bath. Our calculations reveal a model-independent deformation of the density of the Fermi gas, which is determined by the width of the resonance. To provide a broader picture, we investigate time evolution of the density in quench dynamics, and study the behavior of the system at finite temperatures. Finally, we briefly discuss implications of our findings for the Fermi-polaron problem.

Q 32.5 Wed 11:30 A-H2

Dynamics of atoms within atoms — •Shiva Kant Tiwari[1], Felix Engel[2], Marcel Wagner[3,4], Richard Schmidt[3,4], Florian Meinert[2], and Sebastian Wüster[1] — [1]Department of Physics, Indian Institute of Science Education and Research, Bhopal, Madhya Pradesh 462 066, India — [2]Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany — [3]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany — [4]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany

Recent experiments with Bose-Einstein condensates have entered a regime in which thousands of ground-state condensate atoms fill the Rydberg-electron orbit. After the excitation of a single atom into a highly excited Rydberg state, scattering off the Rydberg electron sets ground-state atoms into motion, such that one can study the quantum-many-body dynamics of atoms moving within the Rydberg atom. Here we study this many-body dynamics using Gross-Pitaevskii and truncated Wigner theory. Our simulations focus in particular on the scenario of multiple sequential Rydberg excitations on the same Rubidium condensate which has become the standard tool to observe quantum impurity dynamics in Rydberg experiments. We investigate to what extent such experiments can be sensitive to details in the electron-atom interaction potential, such as the rapid radial modulation of the Rydberg molecular potential, or p-wave shape resonance. Finally, we explore the local dynamics of condensate heating.

Q 32.6 Wed 11:45 A-H2

Quantum Rabi dynamics of trapped atoms far in the deep strong coupling regime — •Geram Hunanyan[1], Johannes Koch[1], Enrique Rico[2,3], Enrique Solano[2,3], and Martin Weitz[1] — [1]Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, 53115 Bonn, Germany — [2]Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain — [3]IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain

The coupling of a two-level system with a field mode, whose fully quantized field version is known as the quantum Rabi model (QRM), is among the central topics of quantum physics and recent quantum information technologies. When the coupling strength reaches the field mode frequency, the full QRM Hamiltionian comes into play, where excitations can be created out of the vacuum.

We demonstrate a novel approach for the realization of a periodic variant of the quantum Rabi model using two coupled vibrational modes of cold atoms in optical potentials, which has allowed us to reach a Rabi coupling strength of 6.5 times the bosonic field mode frequency, i.e., far in the so called deep strong coupling regime. For the first time, the coupling term dominates over all other energy scales. Field mode creation and annihilation upon e.g., de-excitation of the two-level system here approach equal magnitudes, and we observe the atomic dynamics in this novel experimental regime, revealing a subcycle timescale raise in field mode excitations, in good agreement with theoretical predictions.

Q 32.7 Wed 12:00 A-H2

orbital many-body dynamics of bosons in the second bloch band of an optical lattice — •jose vargas[1], marlon nuske[1,2,3], raphael eichberger[1,2], carl hipper[1], ludwig mathey[1,2,3], and andreas hemmerich[1,2,3] — [1]Institut für Laserphysik, Universität Hamburg, 22761 Hamburg, Germany — [2]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [3]The Hamburg Center for Ultrafast Imaging, Luruper Chaussee 149, Hamburg 22761, Germany

We explore Josephson-like dynamics of a Bose-Einstein condensate of rubidium atoms in the second Bloch band of an optical square lattice providing a double well structure with two inequivalent, degenerate energy minima. This oscillation is a direct signature of the orbital changing collisions predicted to arise in this system in addition to the conventional on-site collisions. The observed oscillation frequency scales with the relative strength of these collisional interactions, which can be readily tuned via a distortion of the unit cell. The observations are compared to a quantum model of two single-particle modes which reproduces the observed oscillatory dynamics and show the correct dependence of the oscillation frequency on the ratio between the strengths of the on-site and orbital changing collision processes.

Q 33: Quantum Gases

Time: Wednesday 14:00–15:30 Location: Q-H10

Q 33.1 Wed 14:00 Q-H10

First and Second Sound in a compressible 3D Bose fluid — •Timon A. Hilker[1,2], Lena H. Dogra[1], Christoph Eigen[1], Jake A. P. Glidden[1], Robert P. Smith[3], and Zoran Hadzibabic[1] — [1]University of Cambridge — [2]Max Planck Institute of Quantum Optics — [3]University of Oxford

One of the hallmarks of superfluidity is the existence of two distinct sound modes with the same wavelength. In the incompressible-liquid regime, this phenomenon has been extensively studied with superfluid Helium.

In this talk, I will present our observation and characterization of first and second sound in a compressible 3D ultracold Bose gas. Using a magnetic field gradient, we excite center-of-mass oscillations of a homogeneous K-39 Bose gas in a box trap revealing two distinct resonances. We find quantitative agreement with the hydrodynamic description of Landau's two-fluid model, both for the sound speeds and for the mode structure in terms of in-phase/out-of-phase oscillations dominated by the thermal/BEC atoms for the first/second sound. In addition, we study the full crossover from the hydrodynamic to the collisionless regime above T_c and find a decreasing speed of sound with increasing damping.

Q 33.2 Wed 14:15 Q-H10

Quantum gas microscopy of ultracold cesium atoms — •Alexander Impertro[1,2,3], Julian Wienand[1,2,3], Sophie Häfele[1,2,3], Till Klostermann[1,2,3], Hendrik von Raven[1,2,3], Scott Hubele[1,2,3], Cesar Cabrera[1,2,3], Immanuel Bloch[1,2,3], and Monika Aidelsburger[1,2] — [1]Ludwig-Maximilians-Universität, Schellingstraße 4, 80799 München, Germany — [2]Munich Center for Quantum Science and Technology, Schellingstraße 4, 80799 München, Germany — [3]MPI für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Ultracold cesium atoms provide a promising experimental platform for quantum simulation of topological many-body phases in the presence of interactions. This is due to a convenient control of the scattering length via a low-lying Feshbach resonance and the possibility to engineer state-dependent lattices. Additionally, high-resolution imaging techniques allow the probing of novel experimental observables at the single-atom and single-site level. In this new quantum gas microscope, we prepare a 2D sample of ultracold cesium atoms in optical lattices and probe them using fluorescence imaging. As a first step towards studying topological quantum phases, we demonstrate the preparation of a bosonic Mott-insulating state. Additionally, we present how we employ machine learning techniques to reconstruct the site-resolved lattice occupation despite a lattice spacing that is more than a factor of two smaller than the imaging resolution.

Q 33.3 Wed 14:30 Q-H10

Interference of composite particles — •Mama Kabir Njoya Mforifoum, Gabriel Dufour, and Andreas Buchleitner — Institut of Physics, Albert-Ludwigs university of Freiburg

The dynamics of systems of identical particles are characterized by many-body interference. However, the interfering particles (bosons or fermions) can be composite objects, raising the question of the conditions under which bound states of several particles behave as ideal elementary bosons or fermions. Here, we consider the dynamics on a 1D lattice of two composite bosons, each a bound state of two elementary fermions or bosons, and observe their Hong-Ou-Mandel interference on a potential barrier. We compare numerically exact simulations of the composite particles' dynamics with an effective model for tightly bound pairs. The latter allows us to identify parameter regimes where the composite objects exhibit strong bosonic interference.

Q 33.4 Wed 14:45 Q-H10

Towards Bose polarons in an ultracold Fermi-Bose mixture of ^{6}Li and ^{133}Cs — •Tobias Krom[1], Binh Tran[1], Eleonora Lippi[1], Michael Rautenberg[1], Manuel Gerken[1], Robert Freund[1], Bing Zhu[1,2], Tilman Enss[3], Manfred Salmhofer[3], Lauriane Chomaz[1], and Matthias Weidemüller[1] — [1]Physikalisches Institut, Ruprecht Karl University of Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — [2]Shanghai Branch, University of Science and Technology of China, Shanghai 201315, China — [3]Institut for Theoretical Physics, Ruprecht Karl University of Heidelberg, Philosophenweg 19, 69120 Heidelberg, Germany

Experiments with a mixture of ultracold gases allow to probe the behavior of impurities in an environment. In our experiment we are working with the highest possible mass ratio between the impurity and the environment which can be achieved with stable alkali atoms. We are currently aiming for the creation a Bose polaron quasiparticle which describes a single Li impurity inside a Cs BEC. This scenario can be mapped to the Fröhlich polaron model in condensed matter physics.

We describe the trap arrangement and the cooling scheme which will allow us to reach a degenerate Fermi gas and a BEC within one setup. Finally, we will overlap the two ultracold gases while keeping them within their own dipole trap. Furthermore, we give an overview of the necessary characterization steps of our system and the approach towards the experimental observation of the Bose polaron.

Q 33.5 Wed 15:00 Q-H10

From heteronuclear Efimov effect to Fermi polarons - (quasi-) bound states and induced scattering properties — •Michael Rautenberg[1], Binh Tran[1], Tilman Enss[2], Manuel Gerken[1], Eleonora Lippi[1], Bing Zhu[1,3], Juris Ulmanis[1], Moritz Drescher[2], Manfred Salmhofer[2], and Matthias Weidemüller[1] — [1]Physikalisches Institut, Ruprecht Karl University of Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — [2]Institut for Theoretical Physics, Ruprecht Karl University of Heidelberg, Philosophenweg 19, 69120 Heidelberg, Germany — [3]Shanghai Branch, University of Science and Technology of China, Shanghai 201315, China

We report on the results of our theoretical investigation of two heavy bosons immersed in a Fermi sea of light fermions. Using the Born-Oppenheimer approximation - allowing an effective few-particle description of this quantum many-body problem - both the bound state spectrum as well as fermion-induced scattering properties of the bosons are investigated. The bound state spectrum is discussed as a function of inter- and intraspecies interactions as well as the fermion density, also including the zero density limit where the system recovers the three-body Efimov spectrum. Numerical calculations of potentials and spectra are performed for the mass ratio of a ^{6}Li-^{133}Cs mixture.

Additionally, we find resonances in the induced boson-boson scattering length at the positions where the in-medium Efimov bound states cross the continuum threshold. For sufficiently large impurity-bath mass ratio, quasibound states can be observed.

Q 33.6 Wed 15:15 Q-H10

Thouless Pumps and Bulk-Boundary Correspondence in Higher-Order Symmetry-Protected Topological Phases — •Julian Wienand[1,2], Friederike Horn[1], Monika Aidelsburger[1], Julian Bibo[3], and Fabian Grusdt[1] — [1]Department of Physics, Ludwig-Maximilians-Universität München, Theresienstr. 37, D-80333 Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany — [3]Department of Physics, T42, Technical University of Munich, D-85748 Garching, Germany

The bulk-boundary correspondence relates quantized edge states to bulk topological invariants in topological phases of matter. In symmetry-protected topological systems (SPTs), this fundamental concept is revealed by quantized topological Thouless pumps. Higher-order topological phases of matter (HOSPTs) also feature a bulk-boundary correspondence, but its connection to quantized charge transport remains elusive. In this talk we will show that quantized Thouless pumps connecting C_4-symmetric HOSPTs can be described by a tuple of four Chern numbers that measure quantized bulk charge transport in a direction-dependent fashion. This tuple of Chern numbers allows to predict the sign and value of the fractional corner charges. We show that the topologically non-trivial phase can be characterized by both quadrupole and dipole configurations, shedding new light on current debates about the multi-pole nature of the HOSPT bulk. Our approach paves the way for an in-depth description of future dynamical experiments.

Q 34: Precision Measurements and Metrology V (joint session Q/A)

Time: Wednesday 14:00–15:30 Location: Q-H11

Q 34.1 Wed 14:00 Q-H11

A two-way free-space link for optical frequency comparisons — •Jingxian Ji[1,2], Alexander Kuhl[1], Atif Shehzad[1], and Sebastian Koke[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]DLR-Institute for Satellite Geodesy and Inertial Sensing, Hannover, Germany

Optical clock networks connected by phase-coherent links have enormous potential in basic and applied sciences such as geodesy, astronomy and global navigation satellite systems. Free-space links extend fiber-based connection capabilities and offer to connect a larger community of users. In future, free-space links may even link earthbound stations, satellites or the international space station.

Here we investigate a two-way free-space frequency comparison link using a continuous wave laser signal. Through this two-way approach, the influence of the path length fluctuations is supressed by processing the beat signals at the two end points. This system enables us to characterize the non-reciprocity of free-space connections, i.e., the fundamental uncertainty limit. Different from earlier publications, we elimate the interferometric noise contributions completely. By this we achieve fractional frequency comparison uncertainties below 10^{-21} for the averaging time of only 1000 s showing a significant improvement in resolution. This result opens the way to the high-resolution frequency comparison with simple electronics over free-space links.

Q 34.2 Wed 14:15 Q-H11

Highly stable transportable UV laser system for an optical clock — •Benjamin Kraus[1,2], Stephan Hannig[1,2], Sofia Herbers[1,2], Fabian Dawel[1], Johannes Kramer[1], Constantin Nauk[1,2], Christian Lisdat[1], and Piet O. Schmidt[1,2,3] — [1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [2]DLR-Institute for Satellite Geodesy and Inertial Sensing, 30167 Hannover, Germany — [3]Leibniz Universität Hannover, Institut für Quantenoptik, 30167 Hannover, Germany

Optical atomic clocks provide the most precise frequency standards. They enable high accuracy tests of fundamental physics, relativistic geodesy, and a possible future redefinition of the SI second. For side-by-side clock comparisons, accurate transportable optical clocks are necessary. We present a rack-integrated highly stable clock laser system at 267.4 nm for a transportable Al^{+} clock. The system consists of a fibre laser at 1069,6 nm locked to a cavity designed to reach fractional frequency instabilities as low as 10^{-16}. Two sequential single-pass second harmonic generation stages are hermetically sealed inside an aluminium box to form a robust, compact, and stable fibre-coupled frequency quadrupling module. The setup is interferometrically phase-stabilized, enabling second long probe times.

Q 34.3 Wed 14:30 Q-H11

Rubidium vapor-cell frequency reference based on 5S to 5D two-photon transition for space applications — •Julien Kluge[1,2], Klaus Döringshoff[1,2], Daniel Emanuel Kohl[1], Aaron Strangfeld[1,2], and Markus Krutzik[1,2] — [1]Institut für Physik, Humboldt-Universität zu Berlin — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik

Optical frequency standards based on two-photon spectroscopy using rubidium vapor are a promising candidate for realization of simple and compact optical clocks for space applications.

In this presentation, we show the development of an optical clock working at the rubidium 5S to 5D two-photon transition at 778 nm. For short timescales, a fractional frequency in-stability in the order of 10^{-13} is achieved in a setup with a small size, weight and power (SWaP) budget. Details of the corresponding vapor cell assembly, the supporting simulations and its parameters are shown as well. Recent progress towards miniaturization and automated operation of the physics package enables the future development of a compact and reliable setup to meet the stringent requirements of a prospective space mission.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant numbers 50RK1971, 50WM2164.

Q 34.4 Wed 14:45 Q-H11

Towards a strontium optical frequency reference based on Ramsey-Bordé interferometry — •Ingmari C Tietje[1], Oliver Fartmann[1], Martin Jutisz[1], Conrad L Zimmermann[2], Vladimir Schkolnik[1,2], and Markus Krutzik[1,2] — [1]Humboldt-Universität zu Berlin, Institut für Physik — [2]Ferdinand-Braun-Institut GmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin

We present the status of our optical frequency reference based on Ramsey-Bordé interferometry using the $^1S_0 \rightarrow {}^3P_1$ intercombination line in strontium. Next to the current state of the atom interferometer based on a thermal atomic beam, we will present details of our compact and high-flux atomic oven as well as the cavity-stabilised laser system at 689 nm.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR50WM1852 and by the German Federal Ministry of Education and Research within the program quantum technologies - from basic research to market under grant number 13N15725.

Q 34.5 Wed 15:00 Q-H11

Dynamical decoupling for a robust Lorentz Symmetry test with ^{172}Yb$^+$ ions — •Chih-Han Yeh[1], Kai C. Grensemann[1], Laura S. Dreissen[1], Henning A. Fürst[1,2], Dimitri Kalincev[1], André P. Kulosa[1], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

We report on our progress of a novel test of local Lorentz invariance (LLI) in the electron-photon sector using the meta-stable electronic F-state of trapped ^{172}Yb$^+$ ions [1]. The Zeeman structure of the F-state contains highly relativistic, orthogonally oriented electron orbitals which provide access for testing LLI violation. A potential violation would lead to an anomalous fluctuation of the energy splitting between the substates. We measure this fluctuation via detection of the population imbalance after a dynamical decoupling (DD) [2] sequence. This sequence uses rf pulses to suppress magnetic field noise for enabling long coherence times.

Starting with a single ion, we have demonstrated coherent excitation to the F-state via an electric octupole transition [3]. A coherence time of several seconds has been achieved with the DD sequence in the F-state. With these preparations, we have recently demonstrated a 24 h-run of the LLI test sequence and are now evaluating the systematics.

[1] V.A. Dzuba et al., *Nature Physics* **12**, 465-468 (2016). [2] R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018). [3] H. A. Fürst et al., *Phys. Rev. Lett.* **125**, 163001 (2020)

Q 34.6 Wed 15:15 Q-H11

A dual-species multi-ion clock — •Hartmut Nimrod Hausser[1], Tabea Nordmann[1], Jan Kiethe[1], Jonas Keller[1], Nishant Bhatt[1], Moritz von Boehn[1], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Leibniz Universität Hannover, Hannover, Germany

The best optical ion clocks achieve systematic uncertainties around 1×10^{-18} enabling new applications such as relativistic geodesy with cm-level height resolution [1] and advancing the search for physics beyond the standard model. The major drawback of single-ion clocks is the low signal-to-noise ratio due to quantum projection noise which requires averaging times of several weeks to achieve a matching systematic uncertainty. Increasing the number of ions for example by a factor N ideally leads to N-times shorter averaging time for a given frequency resolution. Due to its intrinsically low sensitivities, ^{115}In$^+$ is an ideal candidate for a multi-ion clock with low systematic shifts [2]. We characterize clock operation with an ^{115}In$^+$ ion sympathetically cooled by an ^{172}Yb$^+$ ion in a segmented linear Paul trap and discuss its systematic uncertainty budget at the 10^{-17}-level. We present our solution for scaling up the number of clock and cooling ions including the control of their order within the crystal and show multi-ion spectroscopy results that are optimized for contrast. The observed excitation agrees with our simple model, which accounts for the Debye-Waller effect due to the crystal dynamics after sympathetic cooling.

[1] T.E. Mehlstäubler et al., *Rep. Prog. Phys.* **81**, 6 (2018)
[2] N. Herschbach et al., *Appl. Phys. B* **107**, 891-906 (2012)

Q 35: Quantum Information (Quantum Communication) II

Time: Wednesday 14:00–16:00 Location: Q-H12

Q 35.1 Wed 14:00 Q-H12

Quantum communication networks with solid-state nodes and multi-photon entangled states — •Durga Dasari[1], Roland Nagy[2], Florian Kaiser[1], and Durga B Dasari[1] — [1]3. Physics Institute, University of Stuttgart, 70569 Stuttgart, Germany — [2]Dept. Elektrotechnik-Elektronik-Informationstechnik, FAU Erlangen-Nürnberg, 91058 Erlangen

Quantum Internet is an entangled communication network in which the quantum nodes are connected by entangled connections established by single photons. Optically active solid-state spin registers have demonstrated their unique potential in quantum computing, communication, and sensing. They can be used to realize scalable quantum networks based on establishing entanglement amongst multiple systems via photonic interference. We will present here schemes to realize memory-enhanced quantum networks based on spin-defects in 4H-SiC [1] and diamond [2].

[1] R. Nagy et al., Appl. Phys. Lett. 118, 144003 (2021). [2] D. Dasari et al., Phys. Rev. B 92, 081301 (2015).

Q 35.2 Wed 14:15 Q-H12

A portable decoy-state QKD sender — •Michael Auer[1,2,3], Peter Freiwang[1,2], Adomas Baliuka[1,2], Lukas Knips[1,2,4], and Harald Weinfurter[1,2,4] — [1]Ludwig-Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology, Munich, Germany — [3]Universität der Bundeswehr München, Neubiberg, Germany — [4]Max-Planck-Institut für Quantenoptik, Garching, Germany

Quantum Key Distribution (QKD) enables secure key exchange, based on fundamental laws of quantum mechanics. Widespread commercial use of this technology requires robust and scalable QKD modules with low cost, size, weight and maintenance.

Here we present a small-size, low-power, FPGA-controlled QKD sender electronics used to drive an array of four vertical-cavity surface-emitting lasers (VCSELs) at 100MHz. The sender is capable of implementing a decoy-state BB84 protocol with four separate driving lanes to create short electrical signals, which allow to individually adjust the pulse-shape and timing for the respective laser diode. With the goal to keep the optics small and mostly passive, the different optical intensities needed for the decoy protocol are created electronically.

Our module enables classical communication and synchronization by modulating a beacon laser, which can be also used for beam tracking. The sender is powered and operated only via a single USB-C host, and features a low power consumption of around 10 watts in total. This, together with its compact size and weight makes it suitable for a broad spectrum of future applications.

Q 35.3 Wed 14:30 Q-H12

Concepts and development of a receiver for satellite quantum key distribution — •Conrad Rössler[1,2], Kevin Günthner[1,2], Bastian Hacker[1,2], Gerd Leuchs[1,2], and Christoph Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany — [2]Friedrich Alexander University Erlangen-Nuremberg, Staudstr. 7/B2, 91058 Erlangen, Germany

Since its first proposal in 1984 with the BB84 protocol, quantum key distribution (QKD) has evolved to a fairly mature and most promising quantum technology. QKD allows two parties to share a key in an information-secure way, which overcomes the potential security threat quantum computers pose to public key cryptography. We present a high-rate fiber integrated quantum receiver for phase-encoded satellite-based QKD as well as the corresponding discrete variable QKD protocol. We highlight concepts for single-photon-detection-based phase locking and real time synchronization of sender and receiver as well as compensation for the Doppler shift and optimized quantum signal processing.

Q 35.4 Wed 14:45 Q-H12

Open-Source LDPC Error Correction for QKD — •Adomas Baliuka[1,2], Elsa Dupraz[3], Rengaraj Govindaraj[1,2], Michael Auer[1,2,4], Peter Freiwang[1,2], Lukas Knips[1,2,5], and Harald Weinfurter[1,2,5] — [1]Ludwig-Maximilian-University (LMU), Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]IMT Atlantique, Lab-STICC, UMR CNRS 6285, F-29238, France — [4]Universität der Bundeswehr München, Neubiberg, Germany — [5]Max Planck Institute of Quantum Optics (MPQ), Garching, Germany

Error correction is an essential step in the classical post-processing of all quantum key distribution (QKD) protocols. We present error correction methods optimized for discrete variable (DV) QKD. Our methods are based on irregular quasi-cyclic (QC) low density parity check (LDPC) codes and state-of-the-art rate adaption techniques, thereby increasing the efficiency for key generation. The codes are freely available as an ongoing open-source project (doi.org/10.5281/zenodo.5589543 and github.com/XQP-Munich/LDPC4QKD).

Q 35.5 Wed 15:00 Q-H12

Quantum network with interacting network qubits — •Emanuele Distante, Severin Daiss, Stefan Langenfeld, Stephan Welte, Philip Thomas, Lukas Hartung, Olivier Morin, and Emanuele Distante — Max Planck Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Quantum networks allow the realization of distributed architectures where local network modules, containing addressable memory qubits and linked together via photonic channels, operate as distributed quantum machine. Such architecture represents a promising route to scale up the number of cross-talk free qubits in a quantum computer. Its realization, however, requires strong, controllable interactions among stationary qubits located in different network modules. Here, we report on our progress on the realization of an elementary network link where the interaction among qubits located in separated modules is mediated by traveling photonic qubits. Each module is based on a single ^{87}Rb atom trapped at the center of an optical cavity. We will show that single photons sequentially reflected off the modules mediate strong interaction between the network qubits allowing the realization of fundamental logic-gate between the remotely located qubits, the faithful transfer of information via a simple/novel teleportation scheme, as well as realization of joint nondestructive measurement on distant qubits.

[1] S. Daiss *et al.*, Science **371**, 614-617 (2021)
[2] S. Langenfeld *et al.*, Phys. Rev. Lett. **126**, 130502 (2021)
[3] S. Welte *et al.*, Nat. Phot. **15**, 504-509 (2021)

Q 35.6 Wed 15:15 Q-H12

Readout-noise analysis and optimization of a warm vapor EIT memory on the Cs D1 line — •Luisa Esguerra[1,2], Leon Messner[1,3], Elizabeth Robertson[1,2], Norman Vincenz Ewald[1], Mustafa Gündoğan[1,3], and Janik Wolters[1,2] — [1]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Optische Sensorsysteme, Rutherfordstr. 2, 12489 Berlin, Germany. — [2]TU Berlin, Institut für Optik und Atomare Physik, Hardenbergstr. 36, 10623 Berlin, Germany. — [3]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, Berlin 12489, Germany.

Noise-free quantum memories are a missing building block in the implementation of quantum repeaters, which will be crucial for long distance quantum communication [1]. We have realized a technologically simple, in principle satellite-suited quantum memory in Cesium vapour, based on electromagnetically induced transparency (EIT) on the ground states of the Cs D1 line, similar to [2]. We focus on the simultaneous optimization of end-to-end efficiency and signal-to-noise level in the memory, and have achieved light storage at the single-photon level with end-to-end efficiencies up to 12%. Simultaneously we achieve a minimal noise level corresponding to $\bar{\mu}_1 = 0.029$ signal photons. Furthermore, we have determined the limiting noise source at this level to be four-wave mixing in the Λ-system and present solutions to minimize this read-out noise.

[1] M. Gündoğan et al., npj Quantum Information 7, 128 (2021)
[2] J. Wolters, et al., PRL 119, 060502 (2017)

Q 35.7 Wed 15:30 Q-H12

Integrated photonics for quantum communications on a CubeSat — •Jonas Pudelko[1,2], Ömer Bayraktar[1,2], Imran Khan[1,2], Winfried Boxleitner[3], Stefan Petscharnig[3], Christoph Pacher[3], Gerd Leuchs[1,2], and Christoph Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Institute of Optics, Information and Photonics, Friedrich-Alexander University Erlangen-Nürnberg, Germany — [3]AIT Austrian Institute of Technology GmbH, Center for Digital Safety & Security, Vienna, Austria

The limited range of quantum key distribution (QKD) in fiber based systems led to several projects aiming for the development of a satellite based QKD infrastructure. Photonic integrated circuits (PICs) are a convenient way to implement all necessary optical functions for QKD, while meeting the stringent demands on size, weight and power in satellite missions.

In this work, we present our payload intended for the demonstration of integrated quantum communication technology in space. It is based on two Indium-Phosphide PICs implementing a source for modulated weak coherent states as well as a quantum random number generator (QRNG) based on homodyne measurements of the quantum mechanical vacuum state. The whole system is implemented on a 10 cm x 10 cm PCB including electronics, making it compatible to the CubeSat standard.

These developments will be tested as a part of the CubeSat mission QUBE, which is scheduled for launch in 2022.

Q 35.8 Wed 15:45 Q-H12

Free-space continuous-variable quantum key distribution using discrete modulation — •Kevin Jaksch[1,2], Thomas Dirmeier[1,2], Yannick Weiser[1,2], Stefan Richter[1,2], Ömer Bayraktar[1,2], Bastian Hacker[1,2], Conrad Rössler[1,2], Imran Khan[1,2], Andrej Krzic[3], Teresa Kopf[3], René Berlich[3], Matthias Goy[3], Daniel Rieländer[3], Fabian Steinlechner[3], Florian Kanitschar[4], Stefan Petscharning[4], Thomas Grafenauer[4], Ömer Bernhard[4], Christoph Pacher[4], Twesh Upadhyaya[5], Jie Lin[5], Norbert Lütkenhaus[5], Gerd Leuchs[1,2], and Christoph Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Friedrich Alexander University Erlangen-Nürnberg, Germany — [3]Fraunhofer Institute for Applied Optics and Precision Engineering, Jena, Germany — [4]AIT Austrian Institute of Technology, Center for Digital Safety&Security, Vienna, Austria — [5]Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Canada

In future metropolitan quantum key distribution (QKD) networks, point-to-point free-space links will allow to secure the communication beyond the existing but inflexible fiber backbone. For this purpose, we investigate a continuous-variable QKD system using a discrete modulation pattern in the polarization degree of freedom. We present our results obtained in an experiment over an urban 300m free-space link between the Federal Ministry of Education and Research (BMBF) and the Federal Office for Information Security (BSI) in Bonn.

Q 36: Optomechanics II

Time: Wednesday 14:00–15:15 Location: Q-H13

Q 36.1 Wed 14:00 Q-H13

Stationary entanglement of feedback-cooled nanoparticles — •Henning Rudolph, Klaus Hornberger, and Benjamin Stickler — Faculty of Physics, University of Duisburg-Essen, Germany

The motion of levitated nanoparticles has recently been cooled into the quantum groundstate by electric feedback [1]. In this talk we demonstrate how two interacting nanoparticles, co-levitated in adjacent tweezer traps, exhibit stationary entanglement if the individual particles can be detected and feedback cooled. We find that the stationary two-particle state can be entangled if the detection efficiency of the feedback loop exceeds the ratio of the mechanical normal mode frequencies. As an important experimental constraint, we show that the degree of entanglement decreases with increasing bandwidth of the signal-to-feedback filter.

[1] L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. G. Hofer, S. Hong, N. Kiesel, A. Kugi, M. Aspelmeyer, Real-time optimal quantum control of mechanical motion at room temperature. Nature 595, 373-377 (2021).

Q 36.2 Wed 14:15 Q-H13

Testing quantum mechanics with heavy objects – using magnetically-levitated superconducting microparticles — •Gerard Higgins[1,2], Joachim Hofer[3], Philip Schmidt[1], Stefan Minniberger[3], Jannek Hansen[3], Michael Trupke[1,3], Markus Aspelmeyer[1,3], Martí Gutierrez Latorre[2], Achintya Paradkar[2], Avan Mirkhan[2], and Witlef Wieczorek[2] — [1]IQOQI, Vienna, Austria — [2]Chalmers University of Technology, Gothenburg, Sweden — [3]Vienna Centre for Quantum Science and Technology, Austria

It is unclear how our classical world emerges from the quantum world. It is also unclear how to incorporate effects of gravity into quantum mechanics. To get experimental insights into these problems, we need to prepare larger masses in quantum states.

Magnetically-levitated superconducting microparticles make promising systems for doing this. We work with a lead microsphere of $\sim 10^{18}$ amu ($\sim 1\,\mu$g) which we isolate from its surroundings using magnetic levitation. We read out the sphere's COM motion using a SQUID and cool the motion by applying additional magnetic fields. We will extend our control by coupling the sphere's motion to superconducting resonators and qubits.

Q 36.3 Wed 14:30 Q-H13

Direct loading of levitated nanoparticles into optical traps via hollow core photonic crystal fibers — •Stefan Lindner — University of Vienna, Vienna, Austria

Levitated nanoparticles have been established as a promising platform for testing quantum physics on a macroscopic scale, but as of today environmental decoherence still poses a substantial roadblock hindering the access to extended quantum experiments with these objects. Especially the coherence destroying interaction with background gas molecules has to be overcome by reducing the pressure these experiments are conducted in. The attainable pressures for most levitation experiments are directly related to the type of particle loading scheme in place. Here we present a novel method for loading nanoparticles via hollow core photonic crystal fibers, that will allow direct loading of these nanoparticles into pressures in the ultra high vacuum regime.

In this method two counter-propagating laser beams of equal wavelength are guided through the hollow core fiber to create an optical standing wave. This fiber connects the main vacuum chamber to a secondary "loading" vacuum chamber. Particles are dispersed in the loading chamber and by detuning one of the two lasers with respect to the other, these particles can be transported through the fiber. Once the fiber is aligned with respect to the target trap, the particles can be directly deposited into it. This handover of particles has been demonstrated down to pressures of 10^{-2} mbar and is currently extended to enable direct loading into ultra high vacuum environments.

Q 36.4 Wed 14:45 Q-H13

Light mediated coupling of levitated nanoparticles — •Jakob Rieser[1], Mario Ciampini[1], Henning Rudolph[2], Klaus Hornberger[2], Benjamin Stickler[2], Nikolai Kiesel[1], Markus Aspelmeyer[1], and Uros Delic[1] — [1]University of Vienna, Vienna, Austria — [2]University of Duisburg-Essen, Duisburg/Essen, Germany

Optical binding, the self organization of multiple particles in optical traps, has been studied using dielectric microparticles as well as liquid suspended metallic nanoparticles, usually trapped in a single optical potential. These particles are either comparable in size to the wavelength or plasmonic and cannot be approximated as dipoles.

In this talk, I will introduce an experiment studying light mediated interactions in the dipole regime. By using two independent optical traps to levitate two Rayleigh nanoparticles, we can study true dipole-dipole coupling effects. These arise due to interference between coherently scattered light and the trapping beams. By tuning the relative phase, amplitude, and position of the trapping light fields we can explore the interaction for a wide range of parameters, showing that we achieve strong coupling between two nanoscale dielectric objects.

Finally, we show that we can turn off the dipole-dipole interaction, which allows us to study different coupling mechanisms, such as Coulomb coupling.

Q 36.5 Wed 15:00 Q-H13

Quantum control of a nanoparticle optically levitated in cryogenic free space — •Felix Tebbenjohanns[1,2], Maria Luisa Mattana[1], Massimiliano Rossi[1], Martin Frimmer[1], and Lukas Novotny[1] — [1]Photonics Laboratory, ETH Zürich, 8093 Zürich, Switzerland — [2]Currently with the Department of Physics, Humboldt-Universität zu Berlin, 10099 Berlin

Nanospheres levitated in optical tweezers are a versatile platform and have become an indispensable tool across many disciplines ranging from biology to physics. The key ingredient, radiation pressure, couples light to mechanical motion of macroscopic objects. In an ultra-high vacuum, the system can be sufficiently decoupled from its environment, such that this optomechanical interaction becomes dominant over all other sources of heat, a prerequisite to ground-state cool the system. In my talk, I will explain how we employed a measurement-based feedback mechanism to cool the mechanical motion of a levitated nanosphere to 0.65 quanta of motion, opening the door for levitated quantum optomechanics.

[1] L. Magrini, P. Rosenzweig, C. Bach. et al. Nature 595, 373 (2021).

[2] F. Tebbenjohanns, M.L. Mattana, M. Rossi, et al. Nature 595, 378 (2021)

Q 37: Quantum Optics (Miscellaneous) V

Time: Wednesday 14:00–16:00 Location: Q-H14

Invited Talk Q 37.1 Wed 14:00 Q-H14

Nanophotonic structure-mediated free-electron acceleration and manipulation in the classical and quantum regimes — •Roy Shiloh — Chair of Laser Physics, Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen, Germany

Dielectric laser accelerators (DLA) are, fundamentally, photons interacting with free electrons, with a nanostructure mediating energy and momentum conservation. The potential of accelerating electrons to high energies using this method recently propelled DLA skywards; fabricated using standard (silicon) clean-room technology, their size advantage over conventional RF accelerator schemes promise tabletop compact sources of high-energy electrons for tunable radiation generation and medical treatments. To reach this goal, we have already demonstrated electron beam transport on a nanophotonic chip, using the alternating phase focusing technique [1,2]. However, using the same setup we can also demonstrate quantum photon-electron interaction such as photon-induced electron-microscopy (PINEM). Observable as a spectral comb in the free electron wavepacket's energy spectrum, where the peaks are photon-energy separated, we measured this in a scanning electron microscope for the first time [3].

[1] Shiloh, Illmer, Chlouba, Yousefi, N. Schönenberger, Niedermayer, Mittelbach, and Hommelhoff, Nature 592, 498 (2021); [2] Shiloh, Chlouba, and Hommelhoff, J. Vac. Sci. Technol. B (2022); [3] Shiloh, Chlouba, and Hommelhoff, arxiv.org/abs/2110.00764 (2021)

Q 37.2 Wed 14:30 Q-H14

Fabrication of quantum light emitting diodes based on qiant shell quantum dots (GSQLED) — •Ekaterina Salikhova, Hendrik Schlicke, Jan-Steffen Niehaus, and Horst Weller — Fraunhofer CAN, Grindelallee 117, 20146 Hamburg, Germany

Colloidal semiconductor nanoparticles, so-called quantum dots (QDs), have several unique properties such as a narrow emission bandwidth and a high photoluminescence quantum yield. While QDs are used for photoluminescence-based color-conversion in TVs, there are still no commercial devices employing QLED (quantum light emitting diode) technology, where the QDs are driven by direct electronic charge injection. Quasi-type II quantum dots with a 'giant' shells (GSQDs) show a good stability and near-unity photoluminescence quantum yields. When using these particles as emitter layer in QLEDs, high electroluminescence intensities and an improved device stability are expected. However, QLEDs based on such particles are rarely described in the literature. The hindered charge carrier injection when using GSQDs in QLEDs, especially green-emitting particles, is still a current challenge.

In this talk, the production of 1x1 cm^2 GSQLEDs based on red (CdSe/CdS, 11 nm diameter) and green ($CdSe/Cd_{0.5}Zn_{0.5}S$, 14 nm diameter) emitting GSQDs with a stack sequence ITO/PEDOT:PSS/HTL/QDs/ZnO NP/Al is presented. The polymers PVC or TFB were used as hole transport layers (HTL). Through the use of the PVC, as well as a ligand exchange of the QDs' native ligands with aminoethanol during an optimized layer production as part of the developed layer-by-layer process, the QLED properties were significantly improved.

Q 37.3 Wed 14:45 Q-H14

Two-photon absorption spectroscopy in nonlinear interferometers — •Shahram Panahiyan[1,2], Carlos Sanchez Munoz[3], Maria V. Chekhova[4], and Frank Schlawin[1,2] — [1]Max Planck Institute for the Structure and Dynamics of Matter, Center for Free Electron Laser Science, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany — [3]Departamento de Fisica Teorica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autonoma de Madrid, Madrid, Spain — [4]Max-Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany

We study two-photon absorption in a nonlinear SU(1,1)-interferometer [1], where a sample is placed between two optical parametric amplifiers which are used to squeeze and (re-)un-squeeze an input state of light. The advantages of nonlinear spectroscopy with two-photon absorption and squeezed light have to compete with photon losses that can happen due to imperfect detectors or scattering originating from interaction with the sample. To address this challenge, we study the influence of photons losses. We quantify their influence by investigating the sensitivity of measurement of the expectation value of operators [2]. Furthermore, we calculate quantum and classical Fisher information and use Cramer-Rao bounds to assess the achievable sensitivity.

[1] M. V. Chekhova and Z. Y. Ou, Adv. Opt. Photon. 8, 104 (2016).
[2] C. S. Munoz, G. Frascella, and F. Schlawin, Phys. Rev. Research 3, 033250 (2021).

Q 37.4 Wed 15:00 Q-H14

Higher-order photon statistics as a new tool to reveal hidden excited states in a plasmonic cavity — •Philipp Stegmann[1], Satyendra Nath Gupta[2], Gilad Haran[2], and Jianshu Cao[1] — [1]Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA — [2]Department of Chemical and Biological Physics, Weizmann Institute of Science, Rehovot 761001, Israel

Among the best known quantities obtainable from photon correlation measurements are the $g^{(m)}$ correlation functions. Here, we introduce a new procedure to evaluate these correlation functions based on higher-order factorial cumulants $C_{\mathrm{F},m}$ which integrate over the time dependence of the correlation functions, i.e., summarize the available information at different time spans [1]. In a systematic manner, the information content of higher-order correlation functions as well as the distribution of photon waiting times is taken into account. Our procedure greatly enhances the sensitivity for probing correlations and, moreover, is robust against a limited counting efficiency and time resolution in experiment. It can be applied even in case $g^{(m)}$ is not accessible at short time spans. We use the new evaluation scheme to analyze the photon emission of a plasmonic cavity coupled to a quantum dot. We derive criteria which must hold if the system can be described by a generic Jaynes-Cummings model. A violation of the criteria is explained by the presence of an additional excited quantum dot state.
[1] P. Stegmann, S. N. Gupta, G. Haran, and J. Cao, arXiv:2112.02201 (2021).

Q 37.5 Wed 15:15 Q-H14

First detection time statistics of many partially distinguishable particles — •Niklas Neubrand[1], Christoph Dittel[1,2], and Andreas Buchleitner[1,2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104 Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104 Freiburg, Germany

We show how partial distinguishability between many identical bosons or fermions impacts the first detection time statistics after the particles' coherent evolution on a finite lattice. To this end, we generalize the formalism of stroboscopic projective measurements from the single-particle to the many-particle domain, and present numerical results for two non-interacting particles evolving on a one-dimensional lattice. We observe clear signatures of the particles' indistinguishability in the total detection probability and the first detection time. For particular evolution times between consecutive measurements, we find a discontinuous behavior of these quantities, which can be understood through degeneracies of the corresponding many-particle unitary evolution operator.

Q 37.6 Wed 15:30 Q-H14

Atomic spin-controlled non-reciprocal Raman amplification of fibre-guided light — •Christian Liedl, Sebastian Pucher, Shuwei Jin, Arno Rauschenbeutel, and Philipp Schneeweiss — Department of Physics, Humboldt-Universität zu Berlin, 10099 Berlin, Germany

In a non-reciprocal optical amplifier, gain depends on whether the light propagates forwards or backwards through the device. Typically, one requires either the magneto-optical effect, a temporal modulation, or an optical nonlinearity to break reciprocity. By contrast, here, we demonstrate non-reciprocal amplification of fibre-guided light using Raman gain provided by spin-polarized atoms that are coupled to the nanofibre waist of a tapered fibre section. The non-reciprocal response originates from the propagation direction-dependent local polarization of the nanofibre-guided mode in conjunction with polarization-dependent atom-light coupling. We show that this novel mechanism can also be implemented without an external magnetic field and that it allows us to fully control the direction of amplification via the atomic spin state. Our results may simplify the construction of complex optical networks. Moreover, using other suitable quantum emitters, our scheme could be implemented in photonic integrated circuits and in circuit quantum electrodynamics.

Q 37.7 Wed 15:45 Q-H14

First detection times of tunneling events — •Robin L. Grether, Christoph Dittel, Andreas Buchleitner, and Felix Thiel — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Deutschland

We provide an in-depth analysis of the stroboscopically detected first arrival time of a quantum walker, with the dynamics generated by a Hamiltonian with a spectrum which may contain both, an absolutely continuous part and discrete eigenstates. Specifically, we address the first arrival time upon tunneling across an energy barrier, for a tight-binding quantum walker on a one-dimensional lattice.

Q 38: Photonics II

Time: Wednesday 14:00–15:15 Location: Q-H15

Q 38.1 Wed 14:00 Q-H15

Cryogenic electro-optic modulation in titanium in-diffused lithium niobate waveguides — •Frederik Thiele[1], Felix vom Bruch[2], Julian Brockmeier[1], Maximilian Protte[1], Thomas Hummel[1], Raimund Ricken[2], Victor Quiring[2], Sebastian Lengeling[2], Harald Herrmann[2], Christof Eigner[2], Christine Silberhorn[2], and Tim J. Bartley[1] — [1]Mesoscopic Quantum Optics, Department of Physics, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany — [2]Integrated Quantum Optics, Department of Physics, Paderborn University, Warburger Str. 100, 33098 Paderborn, Germany

Lithium niobate is an important platform for integrated quantum photonics given its high second-order nonlinearity and electro-optic properties. The integration of superconducting single photon detectors offers new prospects for efficiency and scalability. In recent years frequency conversion, integrated SNSPDs and electro-optic modulation has been shown in lithium niobate at cryogenic temperatures. To combine single photon detection together with modulators, the electrooptic modulation in lithium niobate must be characterized. We show the characterization of electro-optic modulators in titanium in diffused lithium niobate waveguides at cryogenic temperatures. To do so, we realized a phase modulator, directional coupler and polarization converter below 8.5K. The decrease of the operation temperature shows an increase of the required operation voltage for all three modulators. Additionally, we give an outlook on the optimization for the cryogenic operation.

Q 38.2 Wed 14:15 Q-H15

Inverse Design of Nanophotonic Devices based on Reinforcement Learning — •Marco Butz[1], Alexander Leifhelm[1], Marlon Becker[2], Benjamin Risse[2], and Carsten Schuck[1] — [1]Institute of Physics, University of Münster, Germany — [2]Institute of Computer Science, University of Münster, Germany

Photonic integrated circuits are being employed for increasingly complex quantum optics experiments on compact and interferometrically stable chips. The integration of an ever-increasing number of circuit components poses challenging requirements on the footprint and performance of individual nanophotonic devices thus raising the need for sophisticated design algorithms. While various approaches, for instance based on direct search algorithms or analytically calculated gradients, have been demonstrated, they all suffer from drawbacks such as reliance on convex optimization methods in non-convex solution spaces or exponential runtime scaling for a linear increase in user-specified degrees of freedoms. Here we show how reinforcement learning can be applied to the nanophotonic pixel-discrete inverse design problem. Our method is capable of producing highly efficient devices with small footprints and arbitrary functionality. A distributed software architecture allows us to make efficient use of state-of-the-art high performance parallel computing resources. Multiple interfaces to the dataflow of the algorithm enable us to bias the resulting structures for realizing arbitrary design constraints. To demonstrate the broad applicability of our method, we show a wide range of devices optimized in 3D for different material platforms.

Q 38.3 Wed 14:30 Q-H15

Optimization of photonic multilayer structures to increase upconversion efficiency — •Fabian Spallek[1,2], Thomas Wellens[1,3], Stefan Buhmann[2], and Andreas Buchleitner[1] — [1]Institute of Physics, Albert-Ludwigs-University Freiburg, Germany — [2]Institute of Physics, University of Kassel, Germany — [3]Fraunhofer IAF, Freiburg, Germany

The efficiency of solar silicon solar cells can be substantially improved by widening the spectral operating window by means of upconversion materials [1]. These convert two low-energy photons into one photon with higher energy. Embedding the upconverter material in photonic dielectric nanostructures allows to influence the interplay of absorption and emission rates, energy transfer processes, local irradiance and local density of (photonic) states which in turn determines the overall efficiency.

We utilize methods from macroscopic quantum electrodynamics to calculate the influence of multilayer nanostructures on spontaneous emission and absorption rates in the upconverter. This allows us to propose specific designs optimized for upconversion efficiency [2]. Considering robustness, we take into account manufacturing errors and compare our indicators for the achievable upconversion luminescence and quantum yield of our optimized design to existing experimentally implemented [1] Bragg structures.

[1] C.L.M.Hofmann et al., Nat. Commun. 12, 14895 (2021)
[2] F.Spallek et al., J.Phys.B: At. Mol. Opt. Phys. 50, 214005 (2017)

Q 38.4 Wed 14:45 Q-H15

Probing intracavity fields of high Q-microresonators with free electrons — Jan-Wilke Henke[1,2], Arslan Sajid Raja[3], Armin Feist[1,2], Guanhao Huang[3], Germaine Arend[1,2], Yujia Yang[3], •F. Jasmin Kappert[1,2], Rui Ning Wang[3], Hugo Lourenco-Martins[1,2], Jiahe Pan[3], Junqiu Liu[3], Ofer Kfir[1,2,4], Tobias J. Kippenberg[3], and Claus Ropers[1,2] — [1]Georg-August-Universität, Göttingen, Germany — [2]Max Planck Institute of Multidisciplinary Sciences, Göttingen, Germany — [3]Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland — [4]School of Electrical Engineering, Tel-Aviv University, Tel-Aviv, Israel

Ultrafast electron microscopes are a powerful platform for investigating confined optical modes in photon-induced near-field electron microscopy (PINEM). Mapping nanophotonic devices promises a unique access to evanescent optical fields and nonlinear phenomena.

In this work, we use free electrons to characterize the intracavity field of a high-Q Si3N4 microresonators, both spatially and spectrally [1]. Moreover, when altering the intracavity state, changes in the electron energy spectra signal the onset of four-wave mixing and the population of multiple optical modes in the resonator.

Future studies will explore the impact of multimode intracavity fields on the electron-light scattering, and might ultimately enable a nanoscale characterization of non-linear states like dissipative Kerr solitons by means of electron microscopy.

[1] J.-W. Henke, A. S. Raja et al., Nature, 600, 653-658, (2021)

Q 38.5 Wed 15:00 Q-H15

Correlative fluorescence and Soft X-ray-microscopy in the water window region in an integrated laboratory-based setup — •Sophia Kaleta[1], Julius Reinhard[1,2], Felix Wiesner[1], Johann Jakob Abel[1], Martin Wünsche[1,2], Jan Nathanael[1,2], Katharina Reglinski[3], Christian Franke[3], Alexander Iliou[4], Falk Hillmann[4], Christian Eggeling[3,5], Silvio Fuchs[1,2], and Gerhard Paulus[1,2] — [1]IOQ, FSU Jena, Germany — [2]Helmholtz Institute Jena, Germany — [3]IAOB, FSU Jena, Germany — [4]Leibniz-HKI, Jena, Germany — [5]Leibniz-IPHT, Jena, Germany

We present a correlative fluorescence and SXR-microscope that combines both methods in an integrated setup, which allows subsequent imaging without removing the sample. While a fluorescence microscope offers functional contrast it is not sufficient for a holistic structural characterization of the sample. This gap can be closed by the correlation with other microscopy methods, for example SXR microscopy in the water window region (2.3 to 4.4nm), which allows a high natural structural contrast in biological samples. The correlation of fluorescence and SXR microscopy has already been realized at synchrotron beam sources, but not in an integrated laboratory setup as presented here. We use a laser-produced gas plasma source, based on a gas-puff target which has also been used for other X-ray and XUV imaging methods [1]. We are able to reach 100nm half pitch resolution which has been measured using a Siemens star. Additionally, we demonstrate correlative imaging of fluorescent nanobeads and cyanobacteria.

[1] Skruszewicz, S., et al. Applied Physics B 127.4 (2021)

Q 39: Precision spectroscopy of atoms and ions II (joint session A/Q)

Time: Wednesday 14:00–15:15 Location: A-H2

Q 39.1 Wed 14:00 A-H2

Ionization potential, atomic and nuclear structure of $^{244-248}$Cm by laser spectroscopy — •Nina Kneip[1], Felix Weber[1], Magdalena A. Kaja[1], Christoph E. Düllmann[1,2,3], Christian M. Marquardt[4], Christoph Mokry[1,2], Petra J. Panak[4], Sebastian Raeder[2,3], Jörg Runke[1,3], Dominik Studer[1], Petra Thörle-Pospiech[1], Norbert Trautmann[1], and Klaus Wendt[1] — [1]Johannes Gutenberg University, 55099 Mainz — [2]Helmholtz Institute, 55099, Mainz — [3]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt — [4]Karlsruhe Institute of Technology, 76131 Karlsruhe

Curium (Z=96) is located in the middle of the actinide series and has a half-filled atomic f shell with a ground state configuration $5f^7 6d7s^2$ $^9\mathrm{D}^o_2$. One ton of spent nuclear fuel, contains up to 20 g of ^{248}Cm, generated by multiple neutron capture of ^{238}U. This environmental aspect in combination with its long half-life of 328 Ma motivates fundamental laser spectroscopic studies on the actinide. Resonance ionization spectroscopy was applied to study the atomic and nuclear structure of the isotopes, $^{244-248}$Cm was spectroscopically investigated. Three different ground state transitions were used as first excitation steps. Scanning the laser around the expected value of the ionization potential (IP), numerous Rydberg levels and auto-ionizing levels were located. The IP was re-determined using field ionization and Rydberg convergence techniques for comparison. The hyperfine structure of ^{245}Cm and ^{247}Cm and the isotopic shift in the isotope chain $^{244-248}$Cm were measured for the first time by laser spectroscopy.

Q 39.2 Wed 14:15 A-H2

A new type of spectroscopy: Direct observation of hyperfine transitions with energy differences of 10 neV and below — •Chrysovalantis Kannis — Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany — III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany

Spectroscopy is a tool commonly used for the study of the energy levels of a sample. In most applications the sample is trapped, however this is not always feasible. An alternative type of spectroscopy includes a static external field and a moving sample. In particular, we use two opposed solenoidal coils which provide a static magnetic field with field direction reversal along the polarization axis. This produces a sinusoidal longitudinal (along the quantization axis) magnetic field component with a zero crossing between the coils. In addition to the longitudinal component, a radial component is also induced which is proportional to the gradient of the first and the distance from the center of the quantization axis.

For an atomic beam of metastable hydrogen with a kinetic energy of about 1 keV and a magnetic field configuration with a wavelength $\lambda \sim 10$ cm, the induced transitions correspond to an RF frequency $f = v/\lambda$ in the MHz range. Equivalently, the energy difference between various levels is of the order of 10^{-8} eV and below. These can be found between hyperfine substates of hydrogen atoms at low magnetic fields in the Breit-Rabi diagram. Here we present first measurements, their interpretation, and possible applications.

Q 39.3 Wed 14:30 A-H2

Laser spectroscopy of muonic ions and other simple atoms — •Randolf Pohl — Johannes Gutenberg Universität Mainz

Laser spectroscopy of simple atoms is sensitive to properties of the atomic nucleus, such as its charge and magnetization distribution. This allows determining the nuclear parameters from atomic spectroscopy, but also limits the attainable precision for the determination of fundamental constants or the test of QED and the Standard Model. In light muonic atoms and ions, one negative muon replaces all atomic electrons, resulting in a calculable hydrogen-like system. Due to the muon's large mass (200 times the electron mass), the muon orbits the nucleus on a 200 times smaller Bohr radius, increasing the sensitivity of muonic atoms to nuclear properties by 200^3 = 10 million. Our laser spectroscopy of muonic hydrogen through helium has resulted in a 10fold increase in the precision of the charge radius of the proton, deuteron, and the stable helium nuclei. Next we're measuring the hyperfine splitting in muonic hydrogen to obtain information about the magnetization of the proton. In Mainz, we're setting up an experiment to determine the triton charge radius by laser spectroscopy of atomic tritium.

Q 39.4 Wed 14:45 A-H2

Resonance ionization mass spectroscopy on Americium — •Matou Stemmler[1], Felix Weber[1], Christoph Düllmann[2,3,4], Dominik Studer[1], Anjali Ajayakumar[5], and Klaus Wendt[1] — [1]Institut of Physics, Johannes Gutenberg-Universität Mainz, Germany — [2]Department of Chemistry - TRIGA site, Johannes Gutenberg-Universität, Germany — [3]Helmholtz Institut Mainz, Germany — [4]GSI Helmholtzzentrum für Schwerionenforschung GmbH Darmstadt, Germany — [5]GANIL, France

Americium (Am, Z=95) is a transuranic member of the actinide series which can be produced artificially by neutron bombardment in nuclear reactors or explosions. All its isotopes are radioactive and the two most long-lived isotopes are ^{241}Am and ^{243}Am with half-lifes of $t_{1/2}$=432.2 y and $t_{1/2}$=7370 y respectively. Here we report on high resolution laser spectroscopy on Am. About $3 \cdot 10^{13}$ atoms of both isotopes ^{241}Am and ^{243}Am were prepared on zirconium foil and loaded into a resistively heated tantalum oven. A wide range tuneable, frequency doubled, continuous wave Titan:Sapphire laser was used for spectroscopy by injection locking of a high power pulsed Ti:Sa ring laser setup. Hyperfine structures of the two isotopes were investigated in two different ground state transitions, which served as first excitation steps for resonant ionisation via suitable autoionizing states. In addition, the isotope shift was determined in one of these transitions. Data analysis regarding the atomic structure of Am as well as hyperfine parameters extracted will be discussed.

Q 39.5 Wed 15:00 A-H2

Laser spectroscopy of neptunium - excitation schemes, atomic structure and the ionization potential — •Magdalena Kaja, Dominik Studer, Felix Weber, Felix Berg, Nina Kneip, Tobias Reich, and Klaus Wendt — Johannes Gutenberg University, 55099 Mainz

Neptunium is a radioactive actinide and the first transuranic element. In particular, ^{237}Np is generated quantitatively within the nuclear fuel cycle with amounts on average ~10 kg in each conventional pressurized water reactor each year. Due to its long half-live of $2.1 \cdot 10^6$ years and high radiotoxicity, it represents a major hazard in the final disposal of nuclear waste. Under environmental conditions, Np can be present in oxidation states +III to +VI and can form soluble species. In this context trace analysis of environmental samples is of high relevance. The development of efficient and selective laser ionization schemes plays an important role for Np spectroscopy and trace analysis.

The spectrum of Np has been studied at the Mainz Atomic Beam Unit, using widely tunable frequency-doubled Ti:Sapphire lasers. The ionization scheme development, spectra above and below the ionization potential (IP), as well as the electric field ionization technique, which allows the determination of the IP, are presented in this contribution. Narrow-band spectroscopy is planned to determine hyperfine structures and isotope shift. So far, only ^{237}Np has been studied by laser spectroscopy and only in broad-band mode. Therefore, high-resolution spectroscopy is planned on ^{237}Np and possibly on the short-lived isotope ^{239}Np.

Q 40: Optomechanics and Photonics

Time: Wednesday 16:30–18:30 Location: P

Q 40.1 Wed 16:30 P

Exploring dynamics of coupled optically levitated nanoparticles — Manuel Reisenbauer[1], •Livia Egyed[1], Anton Zasedatelev[1,2], Iurie Coroli[1,2], Benjamin A. Stickler[3], Henning Rudolph[3], Markus Aspelmeyer[1,2], and Uros Delic[1,2] — [1]University of Vienna, A-1090 Vienna, Austria — [2]IQOQI, Austrian Academy of Sciences, A-1090 Vienna, Austria — [3]University of Duisburg-Essen, 47048 Duisburg, Germany

Arrays of coupled mechanical oscillators have been proposed for studies of collective optomechanical effects such as topological phonon transport or multipartite entanglement. However, up to date any experimental advances have typically been cavity-mediated, thus limiting the number of objects and their interaction tunability, as well as prohibiting individual detection of the oscillators.

Here, we present a novel platform in optomechanics: trap arrays for levitated nanoparticles. In our setup we can use an optically driven, programmable dipole-dipole interaction in order to realize nonreciprocal strong coupling between mechanical degrees of freedom. The directly coupled particles together with the independent readout could in the future allow us to generate steady-state entanglement in absence of a cavity, which would create the possibility to probe decoherence, something that has so far been unattainable in other optomechanical systems. Furthermore, the setup could lead to enhanced (quantum) sensing, investigations into the limits of master equations in the ultrastrong coupling limit or exploring the Casimir-Polder force between nanoscale objects.

Q 40.2 Wed 16:30 P

Dry & clean loading of nanoparticles in vacuum — •Ayub Khodaee[1,2], Kahan Dare[1], Aisling Johnson[1], Uros Delic[1], and Markus Aspelmeyer[1,2] — [1]University of Vienna, Boltzmanngasse 5, 1090 Wien, Vienna, Austria — [2]IQOQI - Vienna, Boltzmanngasse 3, 1090 Wien, Vienna, Austria

Expanding the optomechanical experiments with nanoparticles to ultrahigh vacuum is required in order to isolate the nanoparticle from the environment sufficiently well to realize macroscopic quantum states, e.g. a superposition. One of the most commonly used loading mechanisms is spraying water/alcohol diluted particles into the chamber using a nebulizer. The drawback of this method is contaminating the whole chamber with liquid, making high and ultrahigh vacuum out of reach. On the other hand, laser-induced acoustic desorption (LIAD) has been successful in loading dry nanoparticles into a trapping potential; however, the method requires expensive components to achieve dry loading. Recently, loading of microparticles using piezoelectric shaking has been demonstrated, thus providing a simple method for launching dry particles. However, launching nanoparticles has remained a challenge due to the strong binding forces between the deposited particles and the launching pad. Here, we will present successful launching of nanoparticles with piezoelectric shaking. We report loading a silica nanoparticle with diameter as small as 143 nm directly into an optical tweezer at high pressure. Finally, we discuss the limits of the launching method and propose a way to load the particles directly into an optical trap in high vacuum.

Q 40.3 Wed 16:30 P

Force measurements with nanoparticles in microgravity — •Vincent Hock, Govindarajan Prakash, Marian Woltmann, Sven Herrmann, Claus Lämmerzahl, and Christian Vogt — Universität Bremen, ZARM (Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation

Optically trapped levitated nanoparticles are well suited to measure tiny and/or small range forces. Due to efficient cooling methods, they can be prepared in the motional ground state [1] allowing for precise spatial control. In addition, their position can be continuously determined with very high precision.

By observing the free evolution of a test particle in a force field one can investigate the underlying potential [2]. In a laboratory environment most measurements are dominated by gravity. Operating such a sensor in microgravity, like in the 146 m tall drop tower in Bremen, greatly increases its force sensitivity.

[1] Magrini, L. et al. Real-time optimal quantum control of mechanical motion at room temperature. Nature 595, 373-377 (2021).
[2] Hebestreit, E. et al. Sensing Static Forces with Free-Falling Nanoparticles. Phys. Rev. Lett. 121, 063602 (2018)

Q 40.4 Wed 16:30 P

Pump asymmetry compensation in a quantum hybrid system — •Christian Felix Klein[1], Jakob Butlewski[1], Klaus Sengstock[1], Roland Wiesendanger[2], Alexander Schwarz[2], and Christoph Becker[1] — [1]Center for Optical Quantum Technologies, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]Institute for Applied Physics, University of Hamburg, Jungiusstr. 11, 20355 Hamburg, Germany

Hybrid Quantum Systems combine advantages of different quantum systems and are promising candidates for future quantum information and technology applications. In our experiment, we create a hybrid system through light-mediated, long-distance coupling of motional degrees of freedom of cold atoms in an optical lattice to the fundamental mode of a cryogenically cooled micromechanical trampoline oscillator inside a Fiber Fabry Pérot Cavity (FFPC).

Owing to inevitable losses between the two systems this coupling is intrinsically asymmetric which delays the backaction of the atoms on the mechanical resonator. For large atomic densities and lattice light detuned to the red side of the atomic resonance, this delay turns negative into positive feedback and drives the system resonantly into limit cycle oscillations. This effect limits the number of atoms that can contribute to the coupling strength $C_{\mathrm{hybrid}} \propto N_{\mathrm{atoms}}$ and diminishes i.e. feedback cooling performance.

Here we suggest a new approach to compensate this asymmetry with an additional auxiliary lattice beam and present detailed characterization measurements.

Q 40.5 Wed 16:30 P

Multi-wavelength single mode integrated optical waveguides for trapped-ion quantum computing — •Pascal Gehrmann[1,2], Anastasiia Sorokina[1,2], Steffen Sauer[1,2], Johannes Dickmann[1,2], and Stefanie Kroker[1,2,3] — [1]TU Braunschweig, Institute for Semiconductor Technology, Hans-Sommer-Str. 66, 38106 Braunschweig, Germany — [2]LENA Laboratory for Emerging Nanometrology, Langer Kamp 6a/b, 38106 Braunschweig — [3]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Trapped-ion quantum computers are based on ions as quantum systems to realize the qubits. In these systems, certain trapped ions are controlled and manipulated by laser light of multiple wavelengths ranging from the near-ultraviolet to the near-infrared spectral range. Integrated photonic elements like waveguides and couplers are required for scalable compact chip-based trapped-ion quantum computers. State-of-the-art research solutions utilize multiple waveguides and couplers to address individual wavelengths. Thus, each ion must be controlled by multiple waveguides and couplers. This sets a limit to the realization of compact systems in the long-term view. To minimize the size of a single ion trap chip, photonic devices for multi-wavelength operation are necessary. In this contribution, we show and discuss optical simulations of the broadband performance for single mode integrated optical buried channel waveguides. Furthermore, we present approaches for broadband waveguide designs to achieve the desired goal of multi-wavelength single mode operation.

Q 40.6 Wed 16:30 P

Towards net energy gain in photonic chip-based particle accelerators — •Stefanie Kraus, Roy Shiloh, Johannes Illmer, Tomas Chlouba, Peyman Yousefi, Norbert Schönenberger, and Peter Hommelhoff — Physics Department, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstraße 1, 91058 Erlangen

Particle accelerators are not only widely used in research and industry, but also in clinical practice. Nevertheless, the enormous costs and dimensions of the meter-long accelerators limit their application even for tabletop accelerators in laboratories. Taking advantage of photonic nanostructures and ultrashort laser pulses, a new scheme for high-gradient particle accelerators has been developed. Until now, the transverse forces acting on the electrons have limited the beam transport through longer structures due to significant particle loss and dephasing. The alternating phase focusing (APF) scheme here eliminates this loss by alternating focusing and defocusing the electrons in the transverse and longitudinal directions, thus confining them in a narrow channel. We have experimentally demonstrated this low-loss electron transport over a 77.7 micrometer long silicon-based nanostructure in agreement with particle tracking simulations [1,2]. In this contribution we discuss the current state of the experiment towards building the particle accelerator on a chip.

Q 40.7 Wed 16:30 P

Coupling of a nanofiber to an intracavity optical lattice — •Bernd Welker, Thorsten Österle und Sebastian slama — Center for Quantum Science and Physikalisches Institut, Universität Tübingen

Recently, nanofiber-induced losses inside optical cavities have been analyzed [1]. The subwavelength dimension of the nanofiber leads to a considerably small loss rate, described by Mie scattering at a dielectric cylinder. This makes these nanofibers potentially useful as substrates for achieving strong coupling of nanoparticles with optical cavity modes. Here, we show how the loss rate and scattering of light from the cavity mode into the guided mode of the fiber depends on the fiber position along the intracavity optical lattice. We observe a strong dependence on the fiber diameter and the polarization of light.

[1] Bernd Welker, Thorsten Österle, Sebastian Slama, Thomas Hoinkes, and Arno Rauschenbeutel. Nanofiber-Induced Losses Inside an Optical Cavity, Phys. Rev. Appl. 16, 064021 (2021)

Q 40.8 Wed 16:30 P

Adding Doublons to a Floquet-Topological Insulator — •Helena Drüeke and Dieter Bauer — University of Rostock, Germany

We characterize a Floquet-topological insulator on a finite square lattice with a linear defect in the form of an additional on-site potential along the diagonal. In addition to the usual bulk and edge states, this system also exhibits doublon states on its primary and secondary diagonals. The doublons' energies increase with the diagonal potential, which leads to a rich band structure, including crossings and avoided crossings with other states.

In real-time propagation, an edge state traveling along the boundary of the system will split when hitting the linear defect and continue propagating along the edge and the diagonal simultaneously. The strength of the diagonal potential determines the ratio between both parts. This behavior could allow for the non-destructive measurement of topological edge states. We find and explain a temporal delay between the two contributions traveling around and through the defect.

Q 40.9 Wed 16:30 P

Non-destructive 3D imaging of encapsulated monoatomic layers using XUV coherence tomography — •Florian Funke[1], Felix Wiesner[1], Johann Jakob Abel[1], Slawomir Skruszewicz[2], Julius Reinhard[3], Jan Nathanael[4], Martin Wünsche[3], Christian Rödel[5], Silvio Fuchs[1,3], and Gerhard G. Paulus[1,3] — [1]IOQ, FSU Jena, Germany — [2]DESY, Hamburg, Germany — [3]Helmholtz Institut Jena, Germany — [4]IOF, Jena, Germany — [5]TU Darmstadt, Germany

For many applications of 2D materials an encapsulation in bulk materials is required [1]. In order to further investigate them, it is crucial to have reliable methods for structural and functional characterization. While a variety of such methods exists only for uncovered 2D materials, there is a need for imaging techniques of encapsulated 2D materials as well as their surrounding matter.

We use non-destructive extreme-ultraviolet coherence tomography (XCT) [2,3] in order to generate 3D images of encapsulated monolayers of graphene and MoS2. XCT measures the broadband XUV reflectivity, which contains the depth profile information imprinted via spectral modulations. From these modulations the depth structure is reconstructed with a specialized phase retrieval algorithm for each illumination point. A 3D image is generated by lateral scanning of the sample.

[1] Z. Li, Nat. Com. 11, 1151 (2020)
[2] F. Wiesner, Optica 8, 230-238 (2021)
[3] S. Fuchs, Optica 4, 903-906 (2017)

Q 40.10 Wed 16:30 P

Modeling of non-linear and active materials in interaction with plasmonic nano structures — •Viktor Bender — Institute for Physics, Humboldt University of Berlin, Berlin, Germany

A framework to investigate the interaction of 2D materials with electromagnetic radiation has been developed in the joint group between the Humboldt University of Berlin and the Max Born Institute on Theoretical Optics & Photonics on the example of graphene flakes. Here, using a tight binding approach to model the electronic structure, the material is additionally treated as a conductive current sheet to calculate the electromagnetic feedback. Introducing a minimal coupling between the time-dependant Schrödinger equation and Maxwell's equations allows then for a numerical treatment of the respective fields in time-domain. A crucial role to perform numerical simulations is here played by the group's implementation of the Discontinuous Galerkin Time-Domain (DGTD) finite element method. In my work I extend the mentioned framework for graphene to MoS2, using the DGTD software tool to study respective optical properties and effects, collaborating with and providing predictions for the experiment. Adjustments to respective tight-binding approaches for MoS2 have already been reported and an extension of the model for the treatment of excitons seems also feasible.

Q 40.11 Wed 16:30 P

Waveguide-Intergrated Superconducting Nanowire Avalanche Single-Photon Detectors — •Connor A. Graham-Scott[1,2], Erik M. Baldauf[1,2], Matthias Häussler[1,2], Mikhail Yu. Mikhailov[3], and Carsten Schuck[1,2] — [1]University of Münster, Physics Institute, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany — [2]CeNTech - Center for NanoTechnology, Heisenbergstr. 11, 48149 Münster, Germany — [3]B. Verkin Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine, 61103 Kharkiv, Ukraine

Superconducting nanowire single-photon detectors (SNSPDs) are of great interest for applications in quantum sciences and technologies. SNSPDs fabricated from amorphous superconducting thin films adapt to a wide range of substrate-materials and show high sensitivities over broad spectral range. A drawback of these however is a low signal-to-noise ratio of the electrical output resulting from a lower critical current when operated close to the superconductor*s critical temperature in user-friendly cost-efficient cryogenic systems.

This challenge can be overcome by parallelizing SNSPDs in an avalanche system to create a superconducting nanowire avalanche single photon detector (SNAP).

Here we show how SNAPs can be integrated with nanophotonic circuitry to allow for on-chip single-photon counting with ultra-high signal-to-noise ratio. We furthermore present simulation results on how the SNAP architecture can benefit both internal and absorption efficiencies of waveguide-integrated SNSPDs.

Q 40.12 Wed 16:30 P

Efficient and broadband in-plane interfacing to nanophotonic circuitry — •Hendrik Hüging[1], Daniel Wendland[1], Wladick Hartman[2], Helge Gehring[1], and Wolfram Pernice[1] — [1]Institute of Physics, University of Münster, Germany — [2]Pixel Photonics GmbH

Efficient coupling over a wide wavelength regime between nanophotonic circuits and fiber optic components is crucial for optical communication, computing and sensing. It requires overcoming the size mismatch between the mode of the fiber core and that of the planar waveguide. This is currently archieved by edge coupling with inverse taper or by out-of-plane coupling via 3D laser written structures.

Here we present our work on 3D nanostructures for in-plane interfacing to reach high efficiency and broadband coupling. Finite difference time domain simulations are performed to find a suitable geometry for a coupling structure consisting of a linear taper and a focusing lens. Our experimental realization shows a coupling efficiency of -1.5dB/coupler at a wavelength of 1550nm. We plan to further optimize the geometry and test the adaptability of this approach for different wavelength regimes and fiber mode-field diameters. The structures are manufactured via Direct Laser Writing of IP-n162 at tapered Si3N4 photonic waveguides on a SiO2 on Si substrate.

Q 40.13 Wed 16:30 P

Estimating the point spread function of a THz imaging system based on real image data — •Florian Lemke[1,2], Konstantin Wenzel[1], Clemens Seibold[1], Martin Schell[1,2], Peter Eisert[1], Björn Globisch[1,2], and Lars Liebermeister[1] — [1]Fraunhofer Heinrich Hertz Institute, Einsteinufer 37, 10587 Berlin, Germany — [2]Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstraße 36, 10623 Berlin, Germany

Time-Domain-Spectroscopy (TDS) based on pulsed Terahertz (THz) radiation has steadily improved in recent years, leading to diverse applications in science and industry. Since THz radiation is reflected by conductors and transmitted by dielectric materials, THz TDS is well suited for non-destructive inspection of complex devices through raster scan imaging. In practice, however, the image quality of THz scans is not only limited by wavelength (0.03 mm to 3 mm) but also by the THz optical setup. In conventional image restoration, a sharpened image can be reconstructed by deconvolution of the recorded image with the optical system's characteristic point spread function (PSF). For THz imaging, this has only been done with a theory-based modeled PSF that does not account for aberrations caused by the setup itself. In our work, we estimate the PSF of a THz TDS imaging system using real image data through deconvolution of THz scans of specifically designed samples with their corresponding sharp models. This opens the possibility for image restoration with the obtained PSF and provides a method to evaluate the imaging quality of THz optical setups and components.

Q 41: Nano-Optics

Time: Wednesday 16:30–18:30 Location: P

Q 41.1 Wed 16:30 P

Nanoscale Cavity Antennae for Photoemission Enhancement of Color Centers in Silicon Carbide — •Jonah Heiler[1], Jonathan Körber[1], Philipp Fuchs[2], Erik Hesselmeier[1], Rainer Stöhr[1], Christoph Becher[2], Jörg Wrachtrup[1], and Florian Kaiser[1] — [1]3rd Institute of Physics, University of Stuttgart and Institute for Quantum Science and Technology IQST, 70569 Stuttgart, Germany — [2]Universität des Saarlandes, Fachrichtung Physik, Campus E2.6, 66123 Saarbrücken, Germany

Color centers in solids form a promising quantum information processing platform. Their quantum state can be initialized with lasers and read out optically through emitted photons. The high refractive index of common host crystals like diamond or silicon carbide causes total internal reflection, thus limiting the photon emission rate into free space. An emission enhancement, together with a reduction of the saturation excitation laser power, was recently achieved by coating a diamond membrane with silver on both sides, acting as mirrors to form a planar Fabry-Pérot cavity [1]. Our goal is the fabrication of a similar cavity-based antenna for silicon vacancy color centers in silicon carbide. Optimization of the structure for the V2 center promises a theoretical photon collection enhancement of factor 70 compared to the bulk crystal. Here, we show the latest results of our work, including the fabrication of sub-micrometer membranes with chemical mechanical polishing and subsequent reactive ion etching and the spin-optical properties of silicon vacancy centers in thin silicon carbide membranes.

[1] Philipp Fuchs et al., APL Photonics 6, 086102 (2021)

Q 41.2 Wed 16:30 P

Fabrication of photonic crystal cavities towards a coherent spin-photon interface with color centers in SiC — •Jonathan Körber[1], Marcel Krumrein[1], Rainer Stöhr[1], Jonah Heiler[1], Vadim Vorobyov[1], Raphael Nold[1], Lukas Niechziol[1], Lin Jin[2], Patrick Berwian[3], Wolfram Pernice[2], Jörg Wrachtrup[1], and Florian Kaiser[1] — [1]3rd Institute of Physics, IQST and Research Centre SCoPE, University of Stuttgart, Germany — [2]Institute of Physics, AG Pernice, University of Münster, Germany — [3]Fraunhofer Institute for Integrated Systems and Device Technology IISB, Erlangen, Germany

Color centers in SiC promise applications in the fields of distributed quantum computing and quantum sensing. However, as a consequence of the high refractive index, SiC-based color centers in the bulk show small photon count rates due to total internal reflection. Moreover, Debye-Waller factors of 8 (9)% [1] for the V1 (V2) center in SiC further lower the rate of resonantly emitted photons. To overcome these limitations we fabricate photonic crystal cavities in SiC, based on the approach from [2] in diamond, aiming at a Purcell enhancement of 10-100 and near-deterministic fiber coupling. Here, we report on the most recent updates of our work based on rectangular cross-section photonic structures that are patterned by electron-beam lithography and transferred into the SiC by reactive-ion etching. Furthermore, we show perspectives for color center integration.

[1]: Udvarhelyi, P. et al., Phys. Rev. Applied 13:054017 (2020)
[2]: Quan, Q. et al., Appl. Phys. Lett. 96:203102 (2010)

Q 41.3 Wed 16:30 P

Fabrication of Photonic Crystal Cavities with Triangular Cross-Section in Silicon Carbide — •Marcel Krumrein[1], Rainer Stöhr[1], Jonathan Körber[1], Vadim Vorobyov[1], Raphael Nold[1], Lukas Niechziol[1], Lin Jin[2], Patrick Berwian[3], Wolfram Pernice[2], Florian Kaiser[1], and Jörg Wrachtrup[1] — [1]3rd Institute of Physics, IQST, and Research Centre SCoPE, University of Stuttgart, Germany — [2]Institute of Physics, AG Pernice, University of Münster, Germany — [3]Fraunhofer Institute for Integrated Systems and Device Technology IISB, Erlangen, Germany

Defect centers in Silicon Carbide (SiC) are promising candidates for quantum information applications as they possess very good optical and spin properties. As published recently, triangular-shaped waveguides can guide the defect centers' emission very efficiently and are quite resilient to fabrication imperfections [1]. The implantation of the V2 center into waveguides with triangular cross-section while preserving their spin-optical properties as nearly lifetime-limited emission was recently shown [2]. On this basis, the integration of these defect centers into cavities to enhance the photon emission is desirable. This is important for efficient single-shot read-out and other quantum information protocols. In this contribution, we present the necessary steps of fabricating photonic crystal cavities in 4H-SiC including e-beam lithography and reactive ion etching. Our focus lies on the simultaneous realization of an efficient interface for waveguide-fiber coupling.

[1] Sridhar Majety et al., J. Phys. Photonics 3 034008 (2021).
[2] Charles Babin et al., arXiv:2109.04737 [quant-ph] (2021).

Q 41.4 Wed 16:30 P

An organic molecule strongly coupled to a microcavity: Single-photon nonlinearity — •André Pscherer[1], Manuel Meierhofer[1], Daqing Wang[1], Hrishikesh Kelkar[1], Diego Martín-Cano[1], Tobias Utikal[1], Stephan Götzinger[2,1,3], and Vahid Sandghdar[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander University Erlangen-Nürnberg (FAU), Erlangen, Germany — [3]Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander University Erlangen-Nürnberg, Erlangen, Germany

The response of a single quantum emitter to a single photon is qualitatively different from its response to classical light. In a free-space scheme, optical nonlinearities are intrinsically weak. Here, we show that by reaching the strong coupling regime of cavity quantum electrodynamics, four-wave mixing and optical switching become possible at the level of single photons and single molecules. Furthermore, we demonstrate vacuum Rabi oscillations and super bunching [1].

[1] A. Pscherer, *et al.*, Phys. Rev. Lett. **127**, 133603 (2021)

Q 41.5 Wed 16:30 P

Influence of sample preparation on the optical properties of NV centers in nanodiamonds — •Jana Bauer[1,2], Justus Christinck[1,2], Franziska Hirt[1,2], Helmuth Hofer[1], and Stefan Kück[1,2] — [1]Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany — [2]Laboratory for Emerging Nanometrology (LENA), Braunschweig, Germany

Nitrogen vacancy (NV-) centers are promising candidates as single-photon emitters in quantum metrology, though a reproducible preparation of samples based on nanodiamonds containing NV centers is still a major challenge. Especially the single-photon purity is fundamentally influenced by the sample preparation. We present a preparation routine based on cover glasses cleaned in oxygen plasma and the ensuing application of the nanodiamond particles via spin coating. Atomic force microscope as well as confocal microscope measurements were performed to examine the samples. The correlation of data sets allowed the identification of clusters as well as the classification of the diamond particles regarding their position and their optical properties. A metrological characterization in terms of the single-photon purity, spectral distribution, and the recording of the count rate as a function of the excitation power was performed. A detailed evaluation will be shown at the conference.

Q 41.6 Wed 16:30 P

Preparation methods for growing a stabilizing organic matrix for molecule-based single-photon emitters — •Franziska Hirt[1,2], Justus Christinck[1,2], Mike Stummvoll[1,3], Andreas Reutter[1,3], Uta Schlickum[1,3], and Stefan Kück[1,2] — [1]Laboratory for Emerging Nanometrology, Braunschweig, Deutschland — [2]Physikalisch-Technische Bundesanstalt, Braunschweig, Deutschland — [3]Technische Universität Braunschweig, Braunschweig, Deutschland

Polycyclic aromatic hydrocarbons, such as dibenzoterrylene (DBT), offer promising properties as emitters in a single-photon source. One prerequisite is their embedding in a crystalline matrix and a cryogenic environment. When fulfilled, high photostability and quantum yield, as well as a short excited state lifetime with a lifetime-limited spectral emission mainly in the zero-phonon-line are observed.

We report on two strategies concerning the fabrication of a stable, crystalline matrix surrounding a single DBT molecule.

One approach is based on a reprecipitation method that ideally leads to the production of anthracene nanocrystals with a size of less than 450 nm, containing single DBT.

The second approach deals with the deposition of C60-fullerenes using organic molecular beam epitaxy, which can serve as a capsule for one dibenzoterrylene molecule and, on the other hand, act as a protective layer, when the molecules are placed between two C60 layers.

A detailed overview about the procedures will be given at the conference.

Q 41.7 Wed 16:30 P

Laser Annealing of Quantum Emitters in Hexagonal Boron Nitride — •Tjorben Matthes[1], Antonia Klein[2], Uwe Zeitner[1,2], Falk Eilenberger[1,2], and Tobias Vogl[1] — [1]Institute of Applied Physics, Friedrich-Schiller-University Jena, Albert-Einstein-Straße 15, 07745 Jena, Germany — [2]Fraunhofer-Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany

Quantum emitters based on fluorescent defects in wide-bandgap materials such as the 2D material hexagonal boron nitride (hBN) are promising candidates for usage in quantum information applications. There are several fabrication mechanisms of these emitters, however, in most of these methods the emitter formation is probabilistic at random locations. The crystals are typically irradiated extensively with defects forming over the entire area and subsequently annealed as a whole. The position and number of the thereby created emitters are not reliably controllable.

In this presentation we localize the emitter formation using a high power laser. With an ultrashort pulse it is possible to induce damage to the crystal lattice. Using slightly less intense recurring pulses we subsequently anneal the sample in a small area within the laser spot size. Simulations have shown that the typical annealing temperatures of 850°C are reached within 0.5 ms for our laser configuration. With confocal excitation through a second laser, we can monitor the fluorescence count-rate and get a feedback when an emitter has been formed and activated, thereby making this fabrication method deterministic.

Q 41.8 Wed 16:30 P

Towards a cryogenic quasi-deterministic single-photon source — •Siwei Luo[1], Luis Morales[1], Michael Becker[1], Jan Renger[1], Tobias Utikal[1], Vahid Sandoghdar[1,2], and Stephan Götzinger[2,1] — [1]Max Planck Institute for the Science of Light, 91058 Erlangen, Germany — [2]Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany

Highly efficient single-photon sources are key elements for many applications in emerging quantum technologies. Our strategy to realize a quasi-deterministic single-photon source relies on the combination of a metallo-dielectric antenna and single molecules at cryogenic temperature. Theoretical calculations predict a near-unity photon collection efficiency, larger than 99% for an arbitrarily oriented emitter. However, this concept so far has only been verified at room temperature [1]. Our new antenna design, compatible with a cryogenic environment, comprises molecules in a crystalline matrix which are sandwiched between a solid immersion lens and a reflective metal layer. We will showcase our latest results on single molecules embedded in these new antenna structures.

[1] X.-L. Chu et al., Nature Photonics 11, 58 (2017).

Q 41.9 Wed 16:30 P

Coupling of quantum emitters in 2D materials to laser-written waveguides — •Josefine Krause[1], Simone Piacentini[2], Roberto Osellame[2], Falk Eilenberger[1], Giacomo Corrielli[2], and Tobias Vogl[1] — [1]Institute of Applied Physics, Friedrich-Schiller-University Jena, Germany — [2]Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche (IFN-CNR) and Dipartimento di Fisica, Politecnico di Milano, Italy

Optical quantum technologies have the potential to revolutionize future information processing and sensing. For practical applications, it is essential to combine the required components to manipulate light as well as the photon source itself within compact optical chips. A possible route is combining room temperature solid-state emitters with ultrafast laser-written waveguides. Quantum emitters hosted by atomically thin 2D materials can be easily attached to the optical circuits. Moreover, the photon extraction is near-ideal, as the emitters are not surrounded by any high refractive index material.

In this work, we transfer 2D material-based emitters to the entry facet of a laser-written waveguide. We use the fluorescence of the free exciton in monolayer WS_2 as a benchmark to demonstrate the coupling between 2D emitters and the waveguide. The excellent optical properties of the free exciton are preseved after the transfer. The waveguide features an on-chip directional coupler that allows us to measure the photon statistics. We are currently extending our platform to single photon emitters in hexagonal boron nitride and actively-tunable Mach-Zehnder interferometers for quantum state manipulation.

Q 41.10 Wed 16:30 P

Improving the optical coherence of tin vacancy centres in diamond by long term low temperature and low pressure annealing — •Dennis Herrmann[1], Johannes Görlitz[1], Philipp Fuchs[1], Michael Kieschnik[2], Jan Meijer[2], and Christoph Becher[1] — [1]Fachrichtung 7.2, Universität des Saarlandes — [2]Applied Quantum Systems, Felix-Bloch Institute for Solid-State Physics, Universität Leipzig

The negatively charged tin-vacancy (SnV) centre is a promising candidate for applications in QIP combining single photon emission rates exceeding the well-known silicon-vacancy (SiV) centre by a factor of 10 while still offering large Debye-Waller factors, high single photon purity (g2(0)=0.05) and narrow Fourier limited linewidths down to 20 MHz. Furthermore the large ground state splitting of 850 GHz together with an optical stabilization of the defect charge state allows for spin dephasing times on the order of $T_2^* \sim 5\mu s$. Since strain being induced during implantation of heavy tin ions dramatically influences the SnV properties a consequent annealing step is crucial to heal the diamond lattice. Up to now a high temperature and high pressure (HPHT, 2100°C at 7.7 GPa) annealing has shown a strong reduction of implantation-induced strain. As HPHT annealing is an elaborate process we here present an alternative way of reducing strain by a long term annealing procedure at lower temperatures and low pressures (LPLT, 1200 °C and vacuum) leading to improved spectral properties such as a narrow inhomogeneous distribution of line positions and reduced linewidths/ground state splittings indicating low strain.

Q 41.11 Wed 16:30 P

Plasmon assisted ultrafast photodynamic of silicon-vacancy color centers in nanodiamond — •Tanya Agrawal[1], Assegid M. Flatae[1], Haritha Kambalathmana[1], and Mario Agio[1,2] — [1]Laboratory of Nano-Optics and Cμ, University of Siegen, Siegen, Germany — [2]National Institute of Optics (INO), National Research Council (CNR), 50019 Sesto Fiorentino, Italy

Nanoscale ultrafast single-photon sources based on color centers in diamond are desirable in quantum technologies and fundamental quantum optics. Particularly, silicon-vacancy (SiV) color centers in diamond have shown promising results as its emission is concentrated in a narrow zero-phonon line and has an excited state lifetime in the order of 1 ns. Currently, we are developing optical- and microscopy techniques for a controlled nearfield coupling of plasmonic nanostructures (gold nanorods/ nanocones) to SiV color centers in nanodiamond for ultrafast photon emission. [1] S. Lagomarsino, et al., Diam. Relat. Mater. 84, 196 (2018). [2] H. Kambalathmana, et al., Proc.SPIE 11091, 1109108 (2019). [3] A. M. Flatae, et al., J. Phys. Chem. Lett. 10, 2874 (2019).

Q 41.12 Wed 16:30 P

High-yield placement of colloidal quantum dot single-photon sources on nanophotonic chips — •Tobias Spiekermann, Alexander Eich, Helge Gehring, Lisa Sommer, Julian Bankwitz, Wolfram Pernice, and Carsten Schuck — Institute of Physics, University of Münster, Germany

Integrated photonics benefits many quantum technology applications because it allows for replicating crucial circuit components with high yield and high reproducibility. While the integration of single-photon sources with nanophotonic devices has recently been achieved [1], extending the approach to larger numbers of independently controllable emitters has remained challenging. Here we introduce an iterative procedure for site-selective placement of individual colloidal quantum dots (CQD) that provides means for embedding single-photon sources with high yield into photonic integrated circuits at wafer-scale. We lithographically pattern arrays of apertures in polymer thin films, apply CQDs in solution to the sample and remove excess emitters in a lift-off process. We assess emitter placement at aperture positions via confocal microscopy and repeat the process with a modified lithography mask that only contains aperture locations which had remained vacant. This iterative procedure quickly converges towards high-yield and we confirm single-photon emission from predefined sites by recording second-order autocorrelation functions. We further passivate CQD-sites employing atomic layer deposition of alumina (Al_2O_3), which benefits the emitters photostability.

[1] Alexander Eich et al., arXiv:2104.11830, (2021)

Q 41.13 Wed 16:30 P

Creation of luminescent defects in SiC by focused ion beam processing — •Osamah Sufyan[1], Neha Aggarwal[2], Kevin Thommes[1], Victor Deinhart[1], Sofia Pazzagli[3], Arno Rauschenbeutel[3], João Marcelo Lopez[2], and Katja Höflich[1] — [1]Ferdinand-Braun-Institut gGmbH, Berlin, Germany — [2]Paul-Drude-Institut für Festkörperelektronik, Berlin, Germany — [3]Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany

Defects in silicon carbide (SiC) can serve as colour centers which enable single-photon emission and coherent spin state control. Given its large transparency window and technical maturity, SiC is thus a promising platform for photonic quantum technologies. Focused ion beam processing is a powerful direct writing tool that can be employed as scalable method to create defects in materials. It was recently shown that a He focused ion beam can be used to create defects in epitaxial graphene on SiC. These defects acted as nucleation sites in the epitaxial growth of hexagonal boron nitride (hBN).

Based on these encouraging results, we plan to investigate the defect formation in the underlying SiC substrate due to the focused ion beam processing by varying the beam parameters. We will characterize the defects in view of their use as quantum emitters in a custom-built confocal epifluorescence microscope. Samples consisting of epitaxial graphene on SiC are favourable in this context as the graphene quenches near-surface emitters in SiC that have broad a spectral distribution and may hide the colour centers in the bulk.

Q 41.14 Wed 16:30 P

High-Accuracy Localization of Defect Centers in Diamond for Deterministic Fabrication of Quantum Photonic Structures — Julian M. Bopp[1,2], Maarten van der Hoeven[1], •Maximilian Kähler[1], Tommaso Pregnolato[1,2], and Tim Schröder[1,2] — [1]Department of Physics, Humboldt-Universität zu Berlin, Berlin, Germany — [2]Ferdinand-Braun-Institut, Berlin, Germany

For the past decades, color centers in diamond have evolved into possible key ingredients for quantum photonic applications such as quantum light sources or quantum memories [1] because of their promising optical characteristics. Quantum light sources as a building-block for photonic integrated circuits can be realized by embedding a single diamond color center into a diamond cavity [2]. The reliable fabrication of such photonic stuctures requires the localization of single color centers in bulk diamond with an accuracy of down to tens of nanometers [3].

We present our progress in improving the localization accuracy towards the required level. This will enable the high-yield deterministic fabrication of diamond-based quantum emitters.

[1] S. Mouradian et al., Phys. Rev. X 5, 031009 (2015)
[2] S. Mouradian et al., Appl. Phys. Lett. 111, 021103 (2017)
[3] T. Pregnolato et al., APL Photon. 5, 086101 (2020)

Q 41.15 Wed 16:30 P

Direct writing of chiral and nonlinear plasmonic devices — •Aleksei Tsarapkin[1], Thorsten Feichtner[2], and Katja Hoeflich[1] — [1]Ferdinand-Braun-Institut gGmbH, 12489 Berlin, Germany — [2]Politecnico di Milano, 20133 Milano, Italy

The miniaturization of electrical and optical components allowed many technological and economic advancements over the last decades. Devices that permit control over the polarization of light are crucial in telecommunication and quantum optics but are usually realized as bulky optical systems and thus require further miniaturization. Here we aim at designing a uniquely compact converter and detector based on plasmonics. The structure consists of a vertically oriented gold double helix coupled to a planar two-wire transmission line. The helix acts as a sensitive antenna for circularly polarized light, while the plasmonic transmission line exhibits two different modes depending on the incident polarization state and guides them on-chip. FEM and FDTD analysis show that antisymmetric modes can be excited in both double helix and two-wire waveguide. Furthermore, one can adjust the geometry of these structures to optimize coupling strength and finely tune their optical response to the desired wavelength range. Finally, we developed fabrication protocols: while the helices can be directly written with an electron-induced deposition, the plasmonic waveguides can be cut from single-crystalline gold flakes utilizing focused gallium-ion beam milling. We achieved high structuring resolution with both methods, allowing for efficient coupling to transform linear to circular polarization while retaining a device size of just a few microns.

Q 41.16 Wed 16:30 P

Broadband home-built confocal microscope for the characterization of quantum emitters — •Kevin Thommes[1,2], Katja Höflich[1,2], Arno Rauschenbeutel[2], and Sofia Pazzagli[2] — [1]Ferdinand-Braun-Institut gGmbH - Leibniz-Institut für Höchstfrequenztechnik — [2]Humboldt-Universität zu Berlin - Institut für Physik

In the field of future quantum technologies, single-photon emitters are of fundamental importance. However, it is still unclear which of the many possible solid-state-based quantum emitters, such as molecules or defects in crystals, will be most suitable for specific future applications. Therefore, we have established a multi-color setup for confocal epi-fluorescence microscopy, which allows different wavelengths in excitation and detection and thus gives access to different solid-state systems. Combined with a configurable beam path in excitation, we can acquire white light and photoluminescence images as well as spectra with an electron multiplier CCD camera and spectrometer over a wide spectral range. Controlling the excitation polarization and the choice of detection polarization gives us additional information about the absorption and emission characteristics and, if necessary, the orientation of the dipolar emitter. To accurately determine the position of the emitters on the sample with respect to a current configuration, we can perform confocal scans. Finally, photon emission statistics can be measured determining the second-order autocorrelation function in a Hanbury-Brown-Twiss setup. We will show example measurements for defect centers in hexagonal boron nitride, which are characterized by high brightness and robustness of quantum emission.

Q 41.17 Wed 16:30 P

Flat-top beam shaping and it's use in modern microscopy — •Leona Licht[1], Philipp Kellner[1], Giovanni DeAngelis[1], Christian Eggeling[1,2], and Herbert Gross[3] — [1]Institut für angwandte Optik und Biophysik, Friedrich-Schiller-Universität, Philosophenweg 7, 07743 Jena — [2]Leibnitz-Institut für photonische Technologien, Albert-Einstein-Straße 9, 07745 Jena — [3]Institut für angwandte Physik, Friedrich-Schiller-Universität, Albert-EInstein-Straße 15, 07745 Jena

Light microscopy, although known for more then 300 years by now, is still one of the most versatile tools for observation of living biological samples and their analysis. Nowadays illumination in most microscopes is done by laser-radiation and it's inherent gaussian profile. On this poster we present recent developments in microscope illumination using flat-top shaped laser-beams paving the way towards highly uniform illumination used in single-molecule tracking or as a prerequisite in advanced analysis methods. The beam shaping can be achieved by microstructured phaseplates or by special optical components. We will elaborate on the usability of these all-optics approaches to beam-shaping in widefield and confocal microscope configurations.

Q 42: Laser and Laser Applications

Time: Wednesday 16:30–18:30 Location: P

Q 42.1 Wed 16:30 P

All-glass cell for Rydberg physics in hollow-core photonic crystal fibres — •Daniel Rainer Häupl[1,2], Daniel Weller[3], Robert Löw[3], and Nicolas Yann Joly[2,1] — [1]University of Erlangen-Nürnberg, Staudtstraße 7/B2, 91058 Erlangen, Germany — [2]Max Planck Institute for the Science of Light, Staudtstraße 2, 91058 Erlangen, Germany — [3]5th Physical Institute, University of Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

We present a new type of all-glass vapour cell integrating a hollow-core photonic crystal fibre, which then can be filled with alkali metal vapour. The temperature of the cell itself and its reservoir can be independently adjusted. The small size of this cell permits both a high temperature accuracy and rapid adjustment of the temperature and respectively the atomic density. Additionally, the entire fibre is optically accessible from the side since the cell is all-glass made. In this way, analysis of the properties of the optical system does not only rely on transmission through the fibre but local fluorescence spectroscopy along the whole length of the fibre is possible. This allows us for the very first time to study the real-time diffusion of atoms in and out of the fibre by changing the atomic density of Rubidium atoms inside the vapour cell. Such measurements confirm that the fibre can be rapidly filled with Rubidium atoms. The atomic density reaches an equilibrium only after a few days, compared to months. We believe that such a cell makes an attractive tool for atomic spectroscopy, Rydberg physics and non-linear optics, as well as being much smaller than previous setups.

Q 42.2 Wed 16:30 P

Microcavity based photothermal spectroscopy — •Matthias Mader[1,2] and Theodor W. Hänsch[1,2] — [1]Ludwig-Maximilians-Universität München, Fakultät für Physik, Geschwister-Scholl-Platz 1, 80539 München — [2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Sensitive optical spectroscopy of tiny amounts of gases allows to study dynamic processes as well as processes where only small gas volumes are involved e.g. in biology or medicine. Furthermore, a small detection volumes enables miniaturization of the measurement devices making it possible to easily perform to experiments also outside the lab, e.g. for climate research.

Here, cavity-sensed photo thermal-spectroscopy is used to perform background free absorption spectroscopy. For macroscopic volumes, this technique has been shown to be extremely sensitive [1]. Combining it with microscopic fiber-based high-finesse Fabry-Pérot cavities [2] allows to miniaturize the detection volume while sustaining high sensitivity.

We present first experiments towards miniaturization of photo thermal absorption spectroscopy using a microscopic cavity as detector with a detection volume of $900\,\mu\mathrm{m}^3$ and we show first measurements on oxygen achieving a sensitivity below 5% for the volume concentration.

[1] Waclawek et al, Opt. Express 29, 7794-7808 (2021)

[2] Hunger et al, New J. Phys. 12 065038 (2010)

Q 42.3 Wed 16:30 P

A compact ultrafast electron source and its application for cell irradiation experiments — •Bastian Löhrl, Leon Brückner, and Peter Hommelhoff — Chair for Laser Physics, Friedrich-Alexander-University Erlangen-Nuremberg (FAU), Staudtstr. 1, 91058 Erlangen

Dielectric Laser Acceleration (DLA) could open new avenues in clinical radiotherapy due to its potential to create a compact accelerator on a chip [1]. DLAs place strong requirements on the emittance and brightness of the electron beam. Motivated by this, we are investigating the performance of a compact electron source [2] containing nano tips. The emitters are placed in ultra-high vacuum and are laser triggered by near-infrared laser pulses. The source can create ultrashort electron pulses with a high bunch charge. We are aiming towards using this source for biological experiments such as cell irradiation. The current state of the experiment will be discussed.

[1] England, R. Joel, et al. "Dielectric laser accelerators." Reviews of Modern Physics 86.4 (2014): 1337.

[2] Hirano, Tomohiko, et al. "A compact electron source for the dielectric laser accelerator." Applied Physics Letters 116.16 (2020): 161106.

Q 42.4 Wed 16:30 P

Paleoclimate Reconstruction with the ArTTA Quantum Technology — •David Wachs[1,2], Julian Robertz[1], Yannis Arck[2], Florian Meienburg[1,2], Florian Freundt[2], Werner Aeschbach[2,3], and Markus Oberthaler[1] — [1]Kirchhoff Institute for Physics, Heidelberg, Germany — [2]Institute of Environmental Physics, Heidelberg, Germany — [3]Heidelberg Center for the Environment, Heidelberg, Germany

The ArTTA method for measuring ^{39}Ar concentrations represents an applied quantum technology to perform age dating of environmental samples. The isotope with its half life of 269 years uniquely enables dating in the age range between 150 and 1000 years. However, the very low isotopic abundance of about 10^{-16} sets high demands on the measurement method. Applied to different environmental archives the age itself can provide information about environmental changes and processes. However, combining the dating method with information obtained from other tracers can help to shed light on past conditions in certain environments.

In the past years several sampling and measurement campaigns involving ^{39}Ar and aiming at paleoclimate reconstruction have been realized. Firstly, samples obtained from groundwater were analyzed towards their age distribution and additionally their recharge temperatures. Secondly, alpine glacier ice was sampled and measured with the goal of reconstructing the impact of climate fluctuations at higher altitudes. Altogether such studies provide the opportunity to better understand climate fluctuations of the last millennium.

Q 42.5 Wed 16:30 P

Novel Approches in Distributed Raman Temperature Sensing — •Esther Renner[1,2], Lisa-Sophie Haerteis[1,2], and Bernhard Schmauss[1,2] — [1]Institute of Microwaves and Photonics, Friedrich-Alexander University Erlangen-Nürnberg — [2]Max Planck School of Photonics

Fiber optical sensors for temperature or strain sensing offer unique advantages compared to common electrical sensors, e.g. immunity to electromagnetic fields, (durability in rough environments and) chemical inertness and coverage of both, long sensing distances and multiple sensing points. Well known fiber sensors for temperature sensing are Fiber Bragg Gratings (FBG), used to determine temperatures at distinctive points of interest along the fiber. To obtain a distributed temperature measurement along the whole fiber, FBG interrogation can be combined with the detection of the temperature dependent spontaneous Raman backscattering [1].

Besides interrogation based on optical time domain reflectometry, spatial resolution can be obtained by incoherent optical frequency domain reflectometry (IOFDR). Here, we present two cost-efficient novel approaches for the integration of distributed Raman temperature sensing in a simple IOFDR system for FBG interrogation [2] using first, a broadband light source and second, a L-band pump laser diode.

[1] Koeppel, M. et al., J. Sens. Sens. Syst., 7, 91-100, 2018.

[2] Haerteis, L. et al., in OSA Optical Sensors and Sensing Congress 2021, paper SM5A.7.

Q 42.6 Wed 16:30 P

Thermische Effekte in der Einzephotonendetektion — •Julian Dietz — Helmut-Schmidt-Universität, Universität der Bundeswehr Hamburg, Holstenhofweg 85, 22043 Hamburg

Die ALPS Kollaboration präsentiert: Für das ALPS II Experiment am DESY, Hamburg, wird ein Einzelphotonendetektor benutzt, um die Existenz von in Licht umgewandelte Axion-ähnliche Teilchen zu beweisen. Als Signal wird lediglich ungefähr 1 Photon pro Tag bei einer Wellenlänge von 1064 nm (= 1,165 eV) erwartet, was hohe Anforderungen an die Dunkelrauschrate des Detektors stellt. Die Dunkelrauschrate ist durch Schwarzkörperstrahlung dominiert, und liegt laut Simulationen 3 Größenordnungen über der Signalstärke.

Schmalbandige optische Filter können bei einer Temperatur von 40 K diese Strahlung reduzieren und wurden innerhalb der in diesem Vortrag vorgestellten Versuchsreihe charakterisiert. Ein experimenteller Aufbau wurde entwickelt, der aufzeigt, dass sich die Zentralwellenlänge

von Filtern um +0,0125 nm/K +- 6,25 % unter Temperaturerhöhung verschiebt. Die zu erwartende Zentralwellenlänge bei einer Umgebungstemperatur von 40 K wurde abgeschätzt und beträgt 1066,63 nm +- 6,25 %, wobei die Transmissionseffizienz hier 68,93 % +- 0,25 % (relative Messabweichung) beträgt. Parallel wurde ein Effizienzverlust von 25 % einer Filterbank gemessen, während diese um 260 K abgekühlt wurde. Zusammengesetzt ergibt sich bei 40 K eine Effizienz von 51,71 % +- 0,25 % (relative Messabweichung) bei 1064 nm. Im Anschluss werden Verbesserungsvorschläge diskutiert, um die Messunsicherheiten zu reduzieren und die Effizienz zu verbessern.

Q 42.7 Wed 16:30 P

Influence of Temperature and Salinity on the Spectral Characteristics of Brillouin Scattering in Water — •Daniel Koestel and Thomas Walther — TU Darmstadt, Institut für Angewandte Physik, 64289 Darmstadt

In our group we are developing a LIDAR system for remote measurement of temperature and salinity in the ocean upper-mixed layer ($\sim 100\,\mathrm{m}$ depth). We successfully demonstrated the functionality of this setup with a temperature resolution of up to $0.07\,^{\circ}\mathrm{C}$ and a depth resolution of up to 1 m [1]. Both spectral Brillouin shift and Brillouin linewidth (FWHM) depend on temperature and salinity. The spectral shift dependency of said parameters has already been studied extensively in the past [2,3]. This contribution aims to bring light to the less researched linewidth dependency on temperature and salinity [4]. For this purpose, we generated spontaneous Brillouin scattering at 530 nm in water in a laboratory environment at different temperatures and salinity. The scattering signal is then analyzed by a scanning FPI (Fabry-Pérot interferometer). We will present our latest results and discuss further steps in the development. [1] Th. Walther et al., Opt. Eng. 53(5) (2014). [2] Th. Walther et al., Appl. Phys. B 97(4), (2009). [3] E. S. Fry et al., Appl. Opt. (1997). [4] E. S. Fry et al., J. Modern Opt. (2002).

Q 42.8 Wed 16:30 P

Novel tunable cw and pulsed UV laser systems for laser cooling of bunched relativistic ion beams — •Jens Gumm[1], Benedikt Langfeld[1], Daniel Kiefer[1], Sebastian Klammes[2], and Thomas Walther[1] — [1]TU Darmstadt — [2]GSI Darmstadt

Experiments with highly charged ions at relativistic energies are of great interest for many atomic and nuclear physics experiments at accelerator facilities. To decrease the longitudinal momentum spread and emittance, laser cooling has proven to be a powerful tool.
In this work, we present two UV-laser systems operating at 257.25 nm for ion beam cooling at ESR in Darmstadt. The first laser is a Fourier limited, pulsed master-oscillator-power-amplifier system with individually adjustable pulse duration from 50 ps to 735 ps and repetition rates between 1 MHz to 10 MHz for broadband laser cooling in order to reduce ion beam heating due to intrabeam scattering. The second laser is a cw system that can be scanned mode-hop free, via two SHG stages, over 20 GHz (50 Hz scan rate). It will be used to minimize the final ion beam momentum spread and, therefore, the ion bunch length. For the cw system, we aim to achieve a power of 1 Watt in the UV-regime.

Q 42.9 Wed 16:30 P

Coupling in optical Microcavity Arrays — •Tom Rodemund, Lukas Seemann, and Martina Hentschel — TU Chemnitz, Chemnitz, Germany

Optical microcavities have proven their potential as microlasers. Their circular shape promotes the formation of whispering-gallery modes (WGM), which possess the high Q factor necessary for efficient lasing operation. However, the directionality of the far field of single cavities can still be improved by utilizing an array of several cavities. This gives rise to new phenomena due to the coupling between the constituents of the array. This contribution investigates possible avenues in which the coupling taking place can be characterized.

When two microdisc cavities approach one another, eigenfrequency splitting takes place. Considering discs with radius R and a distance between them D, the splitting is significant for $D/R < 0.3$. At that point, the distance is low enough for the WGMs to meaningfully pass from one resonator to the other by optical tunneling, which indicates strong coupling between the resonators. The influence of this on the modes is apparent in the Husimi functions of the cavities, which are a phase space representation of the system. The coupling is also reflected in the time a signal starting in one resonator needs to get back to its origin. These tools are applied to arrays consisting of verious amounts of oscillators, where the exact array size can have a pronounced influence on the system dynamics.

Q 42.10 Wed 16:30 P

Experimental Analysis of Raman interactions underlying intracavity coupling of femtosecond soliton molecules — •Timo Wirth and Georg Herink — Experimental Physics VIII - Ultrafast Dynamics, University of Bayreuth, Germany

The phononic contribution of the nonlinear refractive index n_2 governs bound states of femtosecond pulses or "soliton molecules" inside Ti:sapphire laser oscillators, as recently resolved via real-time spectroscopy [1]. In this contribution, we present an experimental analysis of the relative contribution of electronic and nuclear nonlinearities based on different extra-cavity detection schemes for time-resolved Raman spectroscopy. In particular, we compare results from impulsive stimulated Raman scattering (ISRS) obtained via optical Kerr effect (OKE), spectrally resolved two-beam coupling (SRTBC) and Kerr-lens spectroscopy. The latter detection scheme is closely related to intra-cavity soliton binding and yields quantitative insights into the fundamental soliton interaction.

[1] A. Völkel, et al., "Intracavity Raman Scattering couples Soliton Molecules via Terahertz Phonons" (in review, 2021)

Q 42.11 Wed 16:30 P

Tracing sub-cycle electron dynamics in two-colour nearfields of nanometric metal tips — •Philip Dienstbier[1], Lennart Seiffert[2], Timo Paschen[3], Thomas Fennel[2], and Peter Hommelhoff[1] — [1]Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen — [2]Institut für Physik, Universität Rostock, Rostock — [3]Fraunhofer-Institut für Keramische Technologien und Systeme IKTS, Forchheim

Metal nanostructures exposed to intense laser fields enable the realization of strongly localized and well-controlled sub-cycle electron dynamics. These targets are readily used as high-brightness electron sources and initial building blocks for petahertz electronics. Despite broad initial success in these applications, the mapping of electron emission and propagation with attosecond precision has so far been restricted to gas phase atomic and molecular systems. Here, we show that phase-resolved photoemission in two color-laser fields can disentangle the propagation from ionization dynamics at the surface of nanometer sharp tungsten needle tips. In the experiment, the relative phase dependent plateau and cut off features in the electron spectra yields a characteristic energy dependent modulation depth and optimal phase. Matching the results with the solution of the time-dependent Schrödinger equation and with results from the simple-man's model allow us to identify the electron wavepacket dynamics, determine precise values for the optical nearfield strengths, and enable us to infer a duration of 710±30 attoseconds for the electron emission from a solid.

Q 42.12 Wed 16:30 P

Enhanced high-harmonic generation from silicon metasurfaces — •Pavel Peterka[1], Martin Kozák[1], Zbyňek Šobáň[2], František Trojánek[1], and Petr Malý[1] — [1]Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 12116 Prague 2, Czech Republic — [2]Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 162 00 Prague 6, Czech Republic

We report on the enhancement of high harmonic generation (HHG) yield in a metasurface consisting of amorphous silicon disks in periodic array on insulator substrate. The structure was designed by the finite-difference time-domain method, which allows us to optimize the geometry of the metasurface to reach the highest enhancement of HHG due to local field enhancement effect. The HHG was driven by 20 fs pulses at central wavelength 2 μm in reflective geometry. High harmonics are diffracted by the periodic structure and zero order signal is collected. The measured enhancement factors of the fifth and seventh harmonics with photon energies 3.1 eV and 4.3 eV, respectively, are larger than 20x compared to unpatterned amorphous silicon with the same width, even though the area from which the harmonics are generated is 4-times smaller in the case of metasurface. Our theoretical and experimental results demonstrate the possibility of creating engineered structures to study ultrafast strong field phenomena at the nanoscale.

Q 43: Quantum Technologies

Time: Wednesday 16:30–18:30 Location: P

Q 43.1 Wed 16:30 P

Quantum Imaging of Living Tissues with Magnetic Nanoparticles — •Andre Pointner and Roland Nagy — LEB, FAU Erlangen-Nuremberg, Erlangen, Germany

The fight against cancer is one of the greatest challenges for clinicians, oncologists and researchers in this century. The main goal of cancer therapy is to prevent the tumor cell dissemination. Unfortunately, detecting the movement of individual cancer cells *in vivo* and in real time over an extended period of time has not been achieved so far. A promising solution to the aforementioned problem is the research field of quantum sensing. Quantum sensors such as the NV-Center in diamond are very well established and ready to be applied in the field of biology. We intend to use the outstanding properties of the NV center in diamond as a quantum magnetic field sensor to characterize the invasion potential of cancer cells and to describe how their interaction with immune cells triggers or inhibits proliferation. Therefore, we will selectively attach superparamagnetic iron oxide nanoparticles (SPIONs) to live cancer cells in tissues (200 μm thickness) contained in a life-sustaining incubator. The vector magnetic field generated by the SPIONs is measured by evaluating the spin hamiltonians along the four crystallographic [111] directions through NV centers. We will use optically detected continuous magnetic resonance (CW-ODMR) to measure the magnetic field with a wide-field microscope. A sequence of these measurements will result in magnetic vector images. The overlap of these images will accurately determine the migration of individual cancer cells in the tissue samples.

Q 43.2 Wed 16:30 P

Robust and miniaturized Zerodur based optical and vacuum systems for quantum technology applications — •Sören Boles[1], Jean Pierre Marburger[1], Moritz Mihm[3], André Wenzlawski[1], Ortwin Hellmig[2], Klaus Sengstock[2], and Patrick Windpassinger[1] — [1]Institut für Physik, JGU, Mainz — [2]Institut für Laserphysik, UHH, Hamburg — [3]Centre for Quantum Technologies, National University of Singapore

In the ongoing quantum revolution of science, many current studies aim to bring quantum systems to market maturity, such as quantum computers and quantum sensors. Ongoing efforts attempt to increase the accessibility of such systems, while minimizing size, mass and power requirements. We previously demonstrated the succesful use of stable optical and laser systems based on Zerodur glass ceramic in space borne atom interferometry experiments, e.g. FOKUS, KALEXUS, MAIUS and BECCAL.

Current developments target the usage of Zerodur glass ceramic as a material of choice for highly compact vacuum systems.

On this poster, we present techniques of Zerodur to metal flanges, enabling the manufacturing of accessible, yet mechanically and thermally stable vacuum systems. Furthermore, we report on the ongoing effort of the construction of a passively pumped Zerodur vacuum chamber for quantum sensoric applications, using optical activation of passive pumps and atom dispensers to demonstrate a MOT. With this technology, we aim to lay the foundation for a miniaturized, fully integrated and highly stable Zerodur based quantum system.

Q 43.3 Wed 16:30 P

Machine learning optimal control pulses in an optical quantum memory — •Elizabeth Robertson[1,2], Luisa Esguerra[1], Guillermo Gallego[2,3], and Janik Wolters[1,2,3] — [1]Deutsches Zentrum für Luft- und Raumfahrt, Institute for Optical Sensor Systems, Rutherfordstraße 2, 12489 Berlin, Germany — [2]Technische Universität Berlin, Str. des 17. Junis 135, 10623 Berlin, Germany — [3]Einstein Center Digital Future Robert-Koch-Forum, Wilhelmstraße 67, 10117 Berlin, Germany

Optical quantum memories are key components for quantum communication systems, and improving their storage and retrieval efficiency is key for the adoption of the technology [1]. We present a method for machine learning the shape of the optical control pulses used in a hot cesium vapor EIT memory, to maximize the efficiency [2]. Using a genetic algorithm [4], with genes encoded as weighted coefficients of Legendre polynomials, we generate a variety of waveforms, which are given as input into the memory experiment simulation [3]. The retrieval efficiency evaluated, which serves as the fitness function, and subsequent populations are chosen by tournament selection. In the memory simulation, the optimal efficiency could be improved to be 0.51, starting with 0.12 for a unoptimized gaussian control pulse. We will give an outline of the experimental implementation of the method.

[1] Gündoğan, M., et al., npj Quantum Inf 7, 128 (2021).
[2] Wolters, J., et al., Phys. Rev. Lett. 119, (2017)
[3] Rakher, M., et al., Phys. Rev. A 88, (2013)
[4] Katoch, S.,et al., Multimed Tools Appl 80, (2021).

Q 43.4 Wed 16:30 P

Investigation of a SiV$^-$-ensemble towards a diamond magnetic sensor — •Anna Fuchs and Christoph Becher — Universität des Saarlandes, Saarbrücken 66123, Germany

Quantum sensing promises new opportunities in applied physics and life sciences due to high sensitivity, precision, and high spatial resolution. A possible implementation of a quantum sensor that became well known in recent years is based on NV centers in diamond. Whereas NV center based quantum sensors are based on microwave manipulation of their spin states, the negatively charged group IV-vacancy centers in diamond offer the option of an all-optical, microwave-free coherent control of their spin states. This allows for applications where the use of microwave fields is detrimental or technically challenging.

We here investigate an ensemble of negatively charged silicon-vacancy (SiV$^-$) centers for its suitability for quantum sensing. To this end we use an experimental implementation based on coherent population trapping where two spin states are coupled to an excited state via two laser fields. To detect small magnetic changes we fix the laser frequency to the steepest slope of the dark-state resonance and detect the Zeeman shift by a change in the absorption signal. We report first experimental results on characterizing our samples for achievable sensitivities.

Q 43.5 Wed 16:30 P

Fabrication of micro 4H-SiC lenses for quantum and photonic applications — •Marina Scharin-Mehlmann[1], Julietta Foerthner[1], Mathias Rommel[1], Christian Gobert[1], Susanne Beuer[1], Patrick Berwian[1], and Roland Nagy[2] — [1]Fraunhofer Institute for Integrated Systems and Device Technology IISB, Schottkystrasse 10, 91058 Erlangen, Germany — [2]Chair of Electron Devices, Friedrich-Alexander-University Erlangen-Nuremberg, Cauerstrasse 6, 91058 Erlangen, Germany

Silicon carbide (4H-SiC) is a very promising material platform for quantum applications and nanophotonics, such as quantum sensing, computation or communication. However, the main drawback of 4H-SiC is its high refractive index, which reduces the collected defect photoluminescence. In our previous work, we showed that lens structures optimized by numerical simulation can have a strong impact on the collection efficiency. Now, in order to increase the total photon collection efficiency, we demonstrate two possible approaches of producing micro lens structures in 4H-SiC. Firstly, we successfully manufacture lens structures by focus ion beam milling. Secondly, we use a scalable method of fabricating 4H-SiC lenses by photolithography and a reflow process in order to create hemispherical droplets, followed by an etching process. We fabricate the optimized simulated lens shape variations for investigating and maximizing collection efficiency.

Q 43.6 Wed 16:30 P

Fabrication of nanostructured van der Waals heterostructures — •Khairi Elyas[1], Hannah C. Nerl[2], Johanna Richter[3], Kirill Bolotin[3], and Katja Höflich[1] — [1]Ferdinand Braun Institut gGmbH, Berlin, Germany — [2]Humboldt Universität zu Berlin, Berlin, Germany — [3]Freie Universität Berlin, Berlin, Germany

Two-dimensional (2D) materials can exhibit a significantly enhanced light-matter interaction making them interesting for highly-confined and low-loss light transport. When combining different 2D materials the corresponding polaritonic modes may hybridize providing the strong localization of plasmonic excitations in combination with the long propagation distances of phonon modes.

Here we report on the fabrication of heterostructures of the (semi)metallic graphene and the wide-bandgap material hexagonal boron (hBN) nitride. The dry-release transfer of graphene and hBN makes use of polydimethylsiloxane(PDMS) and poly(propylene) carbonate (PPC) films. Due to the strong adhesion between PPC and 2D materials at room temperature, we show that single-layer to few-layer graphene as well as few-layer hBN can be produced on a spin coated PPC film/SiO2/Si substrates by mechanical exfoliation. Using He ion beam patterning we further modify the geometry of the heterostructures on the nanoscale with the specific aim to tune hybrid polaritonic modes. The optical properties of the fabricated heterostructures are then mapped using monochromated low-loss scanning transmission electron microscopy (STEM) electron energy-loss spectroscopy (EELS).

Q 43.7 Wed 16:30 P

Argon Trap Trace Analysis: Working principle of the applied Quantum Technology and its dating application in Oman's groundwater — •Florian Meienburg[1,2], Julian Robertz[1], Yannis Arck[2], David Wachs[1,2], Martin Stute[4], AN Paukert Vankeuren[5], Juerg M. Matter[6,4], Markus Oberthaler[1], and Werner Aeschbach[2,3] — [1]Kirchhoff Institute for Physics, Heidelberg, Germany — [2]Institute of Environmental Physics, Heidelberg, Germany — [3]Heidelberg Center for the Environment, Heidelberg, Germany — [4]Columbia University, Palisades, USA — [5]California State University Sacramento, Sacramento, USA — [6]University of Southampton, Southampton, UK

Radioisotopes are a widely used and important tool for dating environmental systems. The half-life of 269 years, a constant input function and its chemical inertness render ^{39}Ar a valuable tracer for dating between 50 and 1000 years. This time scale corresponds to processes like ocean circulation, deeper groundwater flow or the flow of alpine glaciers. However, a very small abundance in the range of 10^{-16} requires an ultra-sensitive and highly selective detection method which is achieved by the Quantum Technology Argon Trap Trace Analysis (ArTTA). The slightly different resonance frequencies of the isotopes together with multiple resonant scattering processes allows to detect single ^{39}Ar atoms in a magneto-optical trap (MOT).

In addition to the important features of this spectroscopy technique, the poster will present a groundwater study in the Sultanate of Oman in the context of carbon sequestration as an application of ArTTA.

Q 43.8 Wed 16:30 P

Towards on-chip pump filtering of quantum light sources — •Julian Brockmeier[1], Nina Lange[1], Thomas Hummel[1], Maximilian Protte[1], Viktor Quiring[2], Raimund Ricken[2], Harald Herrmann[2], Christof Eigner[2], Christine Silberhorn[2], and Tim Bartley[1] — [1]Mesoskopische Quantenoptik, Department Physik, Universität Paderborn, Warburger Straße 100, 33098 Paderborn, Germany — [2]Integrierte Quantenoptik, Department Physik, Universität Paderborn, Warburger Straße 100, 33098 Paderborn, Germany

Our goal is the realization of on-chip experiments including spontaneous down-conversion sources (SPDC) and detection by superconducting integrated detectors at cryogenic temperatures. The integration of the source on-chip is realized by using periodically poled lithium niobate waveguides. However, in order to be able to differentiate the created photon pairs from the pump light it is crucial to suppress the latter by at least 100 dB. This must be realized while maintaining low losses for the quantum light. We present approaches towards on-chip pump filtering by utilizing various effects such as wavelength selective routing and reflective coatings. Another key factor is the dispersion of pump and signal due to the different group velocities in the crystal, which can take advantage of with our high-speed response of superconducting integrated detectors.

Q 43.9 Wed 16:30 P

Towards a quantum memory for single photons from semiconductor quantum dots — •Benjamin Maass[1,2,3], Florian Günther[1,2], Luisa Esguerra[1,2], David Becker[1,2], Norman Ewald[1], and Janik Wolters[1,2] — [1]Deutsches Zentrum für Luft- und Raumfahrt, Berlin — [2]Institut für Optik und atomare Physik, Technische Universität Berlin — [3]Optische Systeme, Institut für Physik, Humboldt Universität Berlin

We present our approach to use room temperature cesium vapour as storage medium for single photons from semiconductor quantum dots at the D1 line employing a ladder-type configuration of electromagnetically induced transparency (FLAME[1],ORCA[2]). As first steps towards storage of photons in the collective spin state of the atoms we investigate the initialisation of all atoms in the maximally polarised state $m_f = 4$ of the $F = 4$ hyperfine level of the $6^2S_{1/2}$ groundstate. Two-colour optical pumping with circularly polarised light enables efficient preparation of this individual Zeeman sublevel.

We present our experimental setup and discuss its prospects for storing attenuated laser pulses and even true single photons. We give an outlook on interfacing the memory with a strain tunable semiconductor quantum dot.

[1] R. Finkelstein et.al., Fast, noise-free memory for photon synchronization at room temperature. Sci. Adv. 4,(2018). [2] K. T. Kaczmarek et.al., High-speed noise-free optical quantum memory, Phys. Rev. A 97, 042316 (2018).

Q 44: Precision spectroscopy of atoms and ions (joint session A/Q)

Time: Wednesday 16:30–18:30 Location: P

Q 44.1 Wed 16:30 P

Precise solution of the two-center Dirac equation using a finite-element-technique — •Ossama Kullie[1], Stephan Schiller[2], and Vladimir I. Koborov[3] — [1]Theoretical Physics, Institute of Physics, University of Kassel — [2]Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany — [3]Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna 141980, Russia

In the field of spectroscopy of the molecular hydrogen ions H_2^+, HD^+ etc., precise experimental transition frequencies are compared with ab initio predictions [3]. The solution of the two-center Dirac problem, one electron in the field of two fixed nuclei at distance R, is therefore of interest. Here, $R \simeq 2\,\mathrm{Bohr}$. The numerical solution of the problem utilizes the finite-element method (FEM) [1,2]. Our technique allows determining the relativistic contribution to various rovibrational transition frequencies with spectroscopic accuracy. Our results are compared with perturbation theory based on the nonrelativistic one-body variational solution. The deviations found are smaller than the theory uncertainty stemming from uncalculated quantum-electrodynamic effects, and are therefore not resolvable experimentally. [1] O. Kullie et al, Chemical Physics Letters 383 (2004) 215-221. [2] O. Kullie, S. Schiller and V. I. Koborov, in preparation. [3] S. Alighanbari et al, Nature 581, 152 -158 (2020).

Q 44.2 Wed 16:30 P

Towards high precision quantum logic spectroscopy of single molecular ions — •Maximilian Jasin Zawierucha[1], Till Rehmert[1], Fabian Wolf[1], and Piet O. Schmidt[1,2] — [1]Physikalisch- Technische Bundesanstalt, Braunschweig, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany

High precision spectroscopy of trapped molecular ions constitutes a promising tool for the study of fundamental physics. Possible applications include the search for a variation of fundamental constants and measurement of the electric dipole moment of the electron. Compared to atoms, molecules offer a rich level structure, permanent dipole moment and large internal electric fields which make them exceptionally well suited for those applications. However, the additional rotational and vibrational degrees of freedom result in a dense level structure and absence of closed cycling transitions. Therefore, standard techniques for cooling, optical pumping and state detection cannot be applied. This challenge can be overcome by quantum logic spectroscopy. In addition to the molecular ion, a well-controllable atomic ion is co-trapped, coupling strongly to the molecule via the Coulomb interaction. The shared motional state can be used as a bus to transfer information about the internal state of the molecular ion to the atomic ion, where it can be read out using fluorescence detection. Here, we present the status of our experiment, aiming at high precision quantum logic spectroscopy of molecular oxygen ions.

Q 44.3 Wed 16:30 P

Precision x-ray spectroscopy of transitions in He-like ura-

nium at the CRYRING@ESR electron cooler — •Felix Martin Kröger[1,2,3], Steffen Allgeier[4], Andreas Fleischmann[4], Marvin Friedrich[4], Alexandre Gumberidze[3], Marc Oliver Herdrich[1,2,3], Daniel Hengstler[4], Patricia Kuntz[4], Michael Lestinsky[3], Bastian Löher[3], Esther Babette Menz[1,2,3], Philip Pfäfflein[1,2,3], Uwe Spillmann[3], Günter Weber[1,3], Christian Enss[4], and Thomas Stöhlker[1,2,3] — [1]HI Jena, Fröbelstieg 3, Jena, Germany — [2]IOQ, FSU Jena, Max-Wien-Platz 1, Jena, Germany — [3]GSI, Planckstraße 1, Darmstadt, Germany — [4]KIP, RKU Heidelberg, Im Neuenheimer Feld 227, Heidelberg, Germany

We present the first application of metallic magnetic calorimeter detectors for high resolution x-ray spectroscopy at the electron cooler of CRYRING@ESR, the low energy storage ring of GSI-Darmstadt. Within the experiment, x-ray emission associated with radiative recombination cooler electrons and stored U^{91+} ions was studied. For this purpose, two maXs detectors were positioned under observation angles of 0° and 180° with respect to the ion beam axis. This report will focus on preliminary results of the data analysis, namely the first observation of the splitting of the $K_{\alpha 2}$ line into its fine-structure for a high-Z He-like system.

This research has been conducted in the framework of the SPARC collaboration, experiment E138 of FAIR Phase-0 supported by GSI. We acknowledge substantial support by ErUM-FSP APPA (BMBF n° 05P19SJFAA).

Q 44.4 Wed 16:30 P

Towards the setup of a calcium beam clock — •Lara Becker and Simon Stellmer — Physikalisches Institut der Universität Bonn, Nussallee 12, Bonn, Germany

Since the invention of atomic clocks the precision of time-keeping has been significantly enhanced and the clock stabilities reach even higher levels for systems based on optical transitions.

We would like to build a robust and compact optical clock which relies on a Ramsey-Bordé interferometer of a thermal beam of calcium and is envisaged attaining instabilities in the order of 10^{-16}. The goal is to implement the beam clock as an experiment to the students' laboratory course to allow physics master students access to this field of recent research.

We refer to the work at NIST [1] for the main setup and we report on the current status of our project.

[1] Judith Olson et al. "Ramsey-Bordé Matter-Wave Interferometry for Laser Frequency Stabilization at 10^{-16} Frequency Instability and Below". In: Physical Review Letters 123, 073202 (2019)

Q 44.5 Wed 16:30 P

Towards 1S-2S Spectroscopy in Atomic Tritium — •Hendrik Schürg, Merten Heppener, Jan Haack, Gregor Schwendler, and Randolf Pohl — Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik & Exzellenzcluster PRISMA$^+$, Mainz, Germany

The study of the hydrogen-deuterium isotope shift for the 1S-2S transition successfully demonstrated access to a high-precision result for the root-mean-square charge radius of the deuteron [1, 2]. We are currently setting up an experiment to perform a complementing measurement of the hydrogen-tritium 1S-2S isotope shift on magnetically trapped cold tritium atoms – allowing for a 400-fold improvement of uncertainty for the triton charge radius [3]. For an intermediate result, we plan to perform 1S-2S spectroscopy on hot tritium atoms inside a discharge. The excitation can be monitored using the optogalvanic signal induced by a change of conductivity in the hot gas. The available high-precision result for the 1S-2S transition frequency in atomic hydrogen [4] will be used to determine systematic effects in our apparatus. We will present details about our laser system and preliminary measurements with atomic hydrogen.

[1] C. G. Parthey et al. Phys. Rev. Lett. 104, 233001 (2010)
[2] U. D. Jentschura et al. Phys. Rev. A 83, 042505 (2011)
[3] S. Schmidt et al. J. Phys.: Conf. Ser. 1138, 012010 (2018)
[4] C. G. Parthey et al. Phys. Rev. Lett. 107, 203001 (2011)

Q 44.6 Wed 16:30 P

Towards Magnetic Trapping of Atomic Hydrogen — •Merten Heppener, Gregor Schwendler, Jan Haack, Hendrik Schürg, and Randolf Pohl — Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik & Exzellenzcluster PRISMA$^+$, Mainz, Germany

We are currently setting up an experiment to determine the root mean square triton charge radius via two-photon 1S-2S laser spectroscopy at 243 nm on magnetically trapped tritium atoms [1]. For preparation of trapping, an atomic hydrogen source including a microwave dissociation was set up, followed by a cryogenic nozzle and a magnetic quadrupole guide for velocity selection. In the future, it is planned to load the slow hydrogen atoms into a magnetic minimum trap using a cold lithium buffer gas, for which we will present the planned trap configuration. Parallel, a spectroscopy laser system at 243 nm is being developed. The available laser power for exciting the 1S-2S two-photon transition is increased in a stabilized enhancement cavity. The population of the hydrogen 2S state can be monitored by detecting quenched Lyman-α photons using micro-channel plate-based system. In the next stage, we will test our laser system on an atomic hydrogen sample.

[1] S. Schmidt et al. J. Phys. Conf. Ser. 1138, 012010 (2018)

Q 44.7 Wed 16:30 P

Enhancing Atom-photon Interaction with Integrated Nano-photonic Resonators — •Xiaoyu Cheng[1], Benyamin Shnirman[1,4], Artur Skljarow[1], Hadiseh Alaeian[2], Wei Fu[3], Sunny Yang[3], Hong Tang[3], Markus Greul[4], Mathias Kaschel[4], Tilman Pfau[1], and Robert Loew[1] — [1]5. Physikalisches Institut and Center for Integrated Quantum Science and Technology (IQST), Universität Stuttgart, Germany — [2]School of Electrical and Computer Engineering, Purdue University, Indiana, USA — [3]Department of Electrical Engineering, Yale University, Connecticut, USA — [4]Institut für Mikroelektronik Stuttgart (IMS-Chips), Stuttgart, Germany

We study hybrid devices consisting of thermal atomic vapours and Nano-photonic waveguides for manipulating the interaction of atoms with single photons. This allows applications of collective and cooperative effects in the field of quantum technologies. One goal here is to reach the strong coupling regime for a single atom interacting with the mode of photonic crystal cavity (PhC). Our first resonator design is a suspended photonic crystal cavity, which allows us to tightly confine the mode into the interaction region. We have fabricated these devices with a novel high selectivity under-etching technique. A second line of research is to make use of the Rydberg blockade effects to generate single photons. We work with high Q (Q>400000) resonators coupled with bus waveguides. This allows high intensities to excite the weak dipole transitions to Rydberg states. In addition, we plan to taper the waveguides to enhance the range of the evanescent field such that we will be less vulnerable to transit time effects and surface interactions.

Q 44.8 Wed 16:30 P

Rydberg systems under a reaction microscope — •Max Althön, Markus Exner, Philipp Geppert, and Herwig Ott — TU Kaiserslautern

With our MOTRIMS-type reaction microscope we observed collisions between Rydberg atoms and ground state atoms. In these inelastic collisions, the Rydberg electron can change to a lower-lying state. The resulting energy is imparted onto the Rydberg core and the ground state atom as kinetic energy. We measured the final state distribution after these state-changing collisions and observed a wide range of possible final Rydberg states. State-changing collisions are a major decay channel of Rydberg atoms in a dense environment and are of importance for Rydberg molecules. Rydberg molecules are bound by the scattering interaction between the Rydberg electron and a ground state atom. In this context, we aim to directly photoassociate Trilobite molecules, which can be addressed efficiently due to 3-photon excitation. We also show how another type of Rydberg molecule can be used to create a Heavy-Rydberg system, which consists of an ion and anion bound in a high vibrational state.

Our sample consists of ^{87}Rb atoms in a crossed optical dipole trap. Using a 3-photon excitation scheme, atoms are excited to atomic or molecular Rydberg states and photoionized by a short laser pulse from a CO_2 laser after a variable evolution time. Following small homogeneous electric fields, the produced ions are subsequently detected by a time and position sensitive micro channel plate detector. This allows momentum resolved measurements of few-body Rydberg dynamics.

Q 44.9 Wed 16:30 P

Most Precise *g*-Factor Comparison at Alphatrap — •Tim Sailer[1], Vincent Debierre[1], Zoltán Harman[1], Fabian Heisse[1], Charlotte König[1], Jonathan Morgner[1], Bingsheng Tu[4], Andrey Volotka[2,3], Christoph H. Keitel[1], Klaus Blaum[1], and

Sven Sturm[1] — [1]Max-Planck-Institut für Kernphysik, Heidelberg — [2]Helmholtz-Institut Jena, Jena — [3]Department of Physics and Engineering, ITMO University, St. Petersburg, Russia — [4]Institute of Modern Physics, Fudan University, Shanghai, China

The Alphatrap experiment is a cryogenic Penning-trap setup, designed to measure the g factor of the bound electron of heavy highly-charged ions (HCI) to provide tests of fundamental physics in strong fields. Recently, a novel measurement technique based on the coupling of ions as an ion crystal has been developed and applied to measure the most precise g-factor difference to date. By coupling two neon ions, $^{20}Ne^{9+}$ and $^{22}Ne^{9+}$, in a magnetron crystal, a coherent measurement of the Larmor frequency difference of the respective bound electrons becomes possible. The strong suppression of magnetic field fluctuations due to the close proximity of the ions results in a common behaviour of the electron spin states. This allows a determination of the isotopic shift of the g factor to an unprecedented precision of 5.6×10^{-13} relative to the absolute g factors, and, in combination with theory, resolves and confirms the QED contribution to the nuclear recoil for the first time. Alternatively, the result can be applied to improve upon the precision of the charge radius difference of the isotopes or to apply constraints on a potential fifth force in the Higgs portal mechanism.

Q 44.10 Wed 16:30 P

A cold atomic lithium beam via a 2D MOT — •Hendrik-Lukas Schumacher, Marcel Willig, Gregor Schwendler, and Randolf Pohl — Johannes Gutenberg-Universität Mainz Institut für Physik, QUANTUM und Exzellenzcluster PRISMA+

We plan to build a source for a very high flux of cold atomic Li for spectroscopy [1], and for using trapped cold Li as a buffer gas to enable trapping of atomic hydrogen, deuterium and tritium. Laser spectroscopy of atomic ^{6,7}Li has been used to determine the (squared) rms charge radius difference of the stable Li nuclei [2]. One important systematic effect in this experiment, as well as in most other precision spectroscopy measurements, is the distortion and apparent shift of resonance line by quantum interference of close-lying states [3]. Li with its unresolved hyperfine structure is an excellent testbed for precision studies of quantum interference [4].

In another line of research, we plan to trap large amounts of cold Li and use it as a cold buffer gas to enable trapping and laser spectroscopy of atomic hydrogen from a cryogenic beam [2].

[1] T.G. Tiecke, S.D. Gensemer, A. Ludewig, J.T.M. Walraven, Phys. Rev. A 80, 013409 (2009), arXiv
[2] S. Schmidt et al., J. Phys. Conf. Ser. accepted (2018), arXiv
[3] M. Horbatsch, E.A. Hessels, Phys.Rev. A 84, 032508 (2011)
[4] R. C. Brown et al., Phys.Rev. A 87, 032504 (2013)

Q 44.11 Wed 16:30 P

Probing physics beyond the standard model using ultracold mercury — •Thorsten Groh, Quentin Lavigne, Felix Affeld, and Simon Stellmer — Physikalisches Institut, Universität Bonn, 53115 Bonn, Germany

Searches for physics beyond the standard model (SM) range from high-energy collision experiments to low-energy table-top experiments. Cosmological phenomena suggest the existence of yet undiscovered particles, described as dark matter.

Recently, it was proposed to employ high precision spectroscopy of atomic isotope shifts [Delaunay, PRD 96, 093001 (2017); Berengut, PRL 120, 091801 (2018)] to search for a new force carrier that directly couples quarks and leptons. Signatures of such new particles would emerge as nonlinearities in King plots of scaled isotope shifts on different electronic transitions.

Mercury is one of the heaviest laser-coolable elements and possesses five naturally occurring bosonic isotopes, all of which have been laser-cooled in a magneto-optical trap. We report on optimizing these trap parameters and we present our latest results of precision isotope spectroscopy in ultracold mercury on various optical transitions. Our King plot analysis of the nonlinearities indicates deviations from SM predictions.

Q 44.12 Wed 16:30 P

Two-loop self-energy corrections to the bound-electron g-factor: M-term — •Bastian Sikora[1], Vladimir A. Yerokhin[2], Christoph H. Keitel[1], and Zoltán Harman[1] — [1]Max-Planck-Institut für Kernphysik, Heidelberg, Germany — [2]Center for Advanced Studies, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia

The theoretical uncertainty of the bound-electron g-factor in heavy hydrogenlike ions is dominated by uncalculated two-loop Feynman diagrams. Due to the presence of ultraviolet divergences, diagrams with two self-energy loops need to be split into the loop-after-loop (LAL) contribution and the so-called F-, M- and P-terms which require different numerical techniques. In our previous work, we have obtained full results for LAL and the F-term [1].

In this work, we present our results for the M-term contribution. This corresponds to the ultraviolet finite part of nested and overlapping loop diagrams in which the Coulomb interaction in intermediate states is taken into account exactly.

Our results are highly relevant for ongoing and future experiments with high-Z ions as well as for an independent determination of the fine-structure constant α from the bound-electron g-factor [2].

[1] B. Sikora, V. A. Yerokhin, N. S. Oreshkina, et al., Phys. Rev. Research 2, 012002(R) (2020).
[2] S. Sturm, I. Arapoglou, A. Egl, et al., EPJ ST 227, 1425 (2019)

Q 44.13 Wed 16:30 P

Status of the Alphatrap *g*-factor experiment — •Fabian Heisse[1], Charlotte König[1], Jonathan Morgner[1], Tim Sailer[1], Bingsheng Tu[1,2], Sven Sturm[1], and Klaus Blaum[1] — [1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg — [2]Fudan University, China

Quantum electrodynamics (QED) is considered to be the most successful quantum field theory in the Standard Model. Its most precise test is conducted via the comparison of QED calculations with the measurement of the free electron g-factor. However, this test is restricted to low electrical field strengths. Consequently, it is of utmost importance to perform similar tests at high field strengths.

The Alphatrap experiment is a dedicated cryogenic Penning-trap setup to measure the g-factor of bound electrons in highly charged ions up to hydrogen-like uranium [1]. There, an electric field strength on the order of 10^{16} V/cm acts on the electron, allowing to test bound state QED with highest precision.

Our latest measurements of the g-factor for different charge states of a single tin ion are presented. Furthermore, an outlook on upcoming studies and prospects will be given.

[1] S. Sturm *et al.*, Eur. Phys. J. Spec. Top. **227**, 14251491 (2019)

Q 44.14 Wed 16:30 P

Pound method of stabilizing the trap frequencies of an ion trap — •Martin Fischer[1], Atish Roy[1], Sebastian Luff[1,2], Markus Sondermann[1,2], and Gerd Leuchs[1,2,3,4] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Friedrich-Alexander University Erlangen- Nürnberg (FAU), Department of Physics, Erlangen, Germany — [3]Department of Physics, University of Ottawa, Canada — [4]Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia

We report on the stabilization of the secular motion frequencies of an ion trapped in the potential of a Paul-trap by analyzing the phase of the reflected trapping filed. This is done by mixing the field reflected from the LC-circuit[1] made up by the helical resonator and the trap with the RF-drive frequency. By adjusting the relative phase of the two signals it is possible to determine how far the driving field is detuned from the resonance of the LC-circuit. Feeding this signal back to the RF-drive one can lock it to the resonance of the trap. In this way the power coupled into the trap system remains almost constant while the small relative variations of the drive field hardly change the magnitude of the trap frequencies. The stability of the method is measured by directly monitoring the trap frequencies visible in the detected fluorescence light when it is filtered by imaging it onto a knife edge.

[1] R. V. Pound, Review of Scientific Instruments **17**, 490-505 (1946)

Q 44.15 Wed 16:30 P

maXs100: A 64-pixel Metallic Magnetic Calorimeter Array for the Spectroscopy of Highly-Charged Heavy Ions — •S. Allgeier[1], A. Abeln[1], M. Friedrich[1], A. Gumberidze[2,3,4], M.-O. Herdrich[2,3,4], D. Hengstler[1], F. M. Kröger[2,3,4], P. Kuntz[1], A. Fleischmann[1], M. Lestinsky[2], E. B. Menz[2,3,4], Ph. Pfäfflein[2,3,4], U. Spillmann[2], B. Zhu[4], G. Weber[2,3,4], Th. Stöhlker[2,3,4], and Ch. Enss[1] — [1]KIP, Heidelberg University — [2]GSI, Darmstadt — [3]IOQ, Jena University — [4]HI Jena

Metallic magnetic calorimeters (MMCs) are energy-dispersive X-ray detectors which provide an excellent energy resolution over a large dynamic range combined with a very good linearity. They are operated at mK temperatures and convert the energy of each incident photon into a temperature rise which is monitored by a paramagnetic sensor.

We present the MMC array maXs-100, which was used to investigate electron transitions in U^{90+} at CRYRING@FAIR. The detector features 8x8 pixels with a detection area of 1 cm^2 and a stopping power of 40 % for 100 keV X-rays. We discuss details of the two detector systems used during the beam time, including the cryogenic setup and magnetic shielding. An absolute energy calibration with eV-precision at 100 keV as well as an energy resolution of 40 eV (FWHM) at 60 keV were demonstrated, allowing for high-precision X-ray spectroscopy.

This research has been conducted in the framework of the SPARC collaboration, experiment E138 of FAIR Phase-0 supported by GSI. We acknowledge substantial support by ErUM-FSP APPA (BMBF no 05P19VHFA1).

Q 44.16 Wed 16:30 P

Laser photodetachment threshold spectroscopy at FLSR: the experiment preparation — •Vadim Gadelshin[1], Oliver Forstner[2,3,4], Lothar Schmidt[5], Kurt Stiebing[5], Dominik Studer[1], and Klaus Wendt[1] — [1]Institut für Physik, Johannes Gutenberg-Universität Mainz — [2]Friedrich Schiller-Universität Jena — [3]Helmholtz-Institut Jena — [4]GSI Helmholtzzentrum Darmstadt — [5]Institut für Kernphysik, Goethe-Universität Frankfurt

The Frankfurt Low-energy Storage Ring (FLSR) is a room-temperature electrostatic storage ring, which can reduce the internal energy of stored ions almost to the ambient temperature, being suitable for laser photodetachment threshold (LPT) spectroscopy to determine the electron affinity of negatively charged ions. The latter play a key role in accelerator mass spectrometry (AMS): lasers can selectively neutralize undesired isobars, providing a purified beam of an isotope of interest. To extend the range of available for AMS nuclides, it is necessary to identify neutralization schemes for unwanted ions.

With this intention, a compact laser lab was constructed with an optical path, guiding laser beams into FLSR. The laser setup is based on a tunable Ti:Sapphire laser and a pulsed Nd:YAG laser, serving as a pump laser for Ti:Sapphire crystal and as a high-energy laser beam at 532 nm. The RF plasma ion source with a Rb charge exchange cell was installed to produce beams of negatively charged ions.

The results of the experiment preparation and of first tests will be presented. The proof-of-principle of the setup is carried out for O- and OH- ions. An overview of planned LPT studies will be given.

Q 44.17 Wed 16:30 P

A variable out-coupling optical parametric oscillator for the laser system of the ground hyperfine splitting in muonic hydrogen experiment. — •Ahmed Ouf on behalf of the CREMA collaboration[1], Siddarth Rajamohanan[1], Lukas Goerner[1], and Randolf Pohl[2] — [1]Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik — [2]Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik & Exzellenzcluster PRISMA +, Mainz, Germany

We are working on a measurement of the ground-state hyperfine splitting in the exotic muonic hydrogen atom, i.e. a proton orbited by a negative muon. From this measurement, we will be able to determine the parameters of the magnetization distribution inside the proton. The experiment requires a unique pulsed laser system delivering 5mJ pulses at a wavelength of 6.8 μm. The laser has to be triggered on detected muons which enter the apparatus at stochastic times with an average rate of about $\frac{1000}{s}$. Because of the short $2\mu s$ lifetime of the muon, the laser has to produce pulses within about $1\mu s$ after a random trigger. We use a novel Yb:YAG thin-disk laser with a line width less than 10 MHz at 1030nm, whose light output will be shifted in frequency by several OPO/OPA stages in 2 parallel branches at 3.15 μm and $2.1\mu m$, before a DFG yields the intense pulses at 6.8 μm. To enable easy optimization of the OPOs conversion we have developed an OPO cavity with variable finesse, based on polarization optics. We will present this cavity, an optimized specific PDH locking scheme, and first experimental results.

Q 44.18 Wed 16:30 P

The muonic hydrogen ground state hyperfine splitting experiment — •Ahmed Ouf on behalf of the CREMA collaboration[1], Siddarth Rajamohanan[1], Lukas Goerner[1], and Randolf Pohl[2] — [1]Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik, Mainz, Germany — [2]Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik & Exzellenzcluster PRISMA +, Mainz, Germany

The ground state hyperfine splitting (1S-HFS) in ordinary hydrogen (the famous 21 cm line) has been measured with 12 digits accuracy almost 50 years ago [1], but its comparison with QED calculations is limited to 6 digits by the uncertainty of the Zemach radius determined from elastic electron-proton scattering. The Zemach radius encodes the magnetic properties of the proton and it is the main nuclear structure that contributes to the hyperfine splitting (HFS) in hydrogen together with the proton polarizability. The ongoing experiment of the CREMA Collaboration at PSI aims at the first measurement of the 1S-HFS in muonic hydrogen (μp). The measurement aims at determining the proton structure effects referred to as the two-photon exchange with an accuracy of 1×10^{-4}, which is a hundredfold improved determination of (Zemach radius and the proton polarizability). Eventually, then this will improve the QED test using the 21 cm line by a factor of 100. We will present the current status of the experimental effort including the unique detection system and the novel laser development.

Q 44.19 Wed 16:30 P

Study of Highly Charged Ions for the Tests of Bound-State QED — •Manasa Chambath[1], Khwaish Anjum[1,2], Patrick Baus[3], Gerhard Birkl[3], Kanika Kanika[1,4], Jeffrey Klimes[1,4,5], Wolfgang Quint[1], and Manuel Vogel[1] — [1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany — [2]Delhi Technological University, Delhi, India — [3]Institute for Applied Physics, TU Darmstadt, Germany — [4]Heidelberg Graduate School for Fundamental Physics, Heidelberg, Germany — [5]Max Planck Institute for Nuclear Physics, Heidelberg, Germany

The high-precision measurement of the Zeeman splitting of fine- and hyper-fine structure levels can be performed using spectroscopy techniques. The Penning trap ARTEMIS at the HITRAP facility at GSI utilises the method of laser-microwave double-resonance spectroscopy to measure the magnetic moment and to test bound-state QED calculations by g-factor measurements of heavy, highly charged ions like Ar13+ and Bi82+. Non-destructive electronic detection is used to analyse and resistively cool the stored ions. Different ion species in the trap are resolved according to their charge-to-mass ratio by fixing the detection frequency and ramping over a range of trapping potentials. By selectively exciting the axial motion, Ar13+ ions are isolated from the ion cloud for the g-factor measurements. Studies are also done to determine the phase transition of dense ion clouds due to the discontinuous behaviour of spectral features during cooling.

Q 44.20 Wed 16:30 P

Detector for Atomic Hydrogen — •Benedikt Tscharn, Hendrik-Lukas Schumacher, Gregor Schwendler, Jan Haack, and Randolf Pohl — Johannes Gutenberg-Universität Mainz, Institut für Physik, QUANTUM & Excellenzcluster PRISMA+, Mainz, Germany

Laser spectroscopy is the most precise way to experimentally determine the RMS charge radius of light nuclei.[1] Performing it on muonic hydrogen has raised the proton radius puzzle, a 5.6σ difference to previous electron scattering experiments.[2] Measuring the isotope shift of the 1S-2S transition in atomic tritium will yield the radius of triton, the mirror nucleus to the helion, by two orders of magnitude improved precision.[1] Together with muonic hydrogen, deuterium and helium, this will allow for precise tests of nuclear theory.

The T-REX experiment aims to perform laser spectroscopy on cooled and trapped atomic tritium. The atomic tritium flux to the MOT where the measurement takes place has to be monitored with a non-destructive detector for optimisation. Since tritium is radioactive, hydrogen is used during build-up.

We have developed such a detector measuring the resistance change of a $5\mu m$ diameter tungsten wire due to recombination energy. It is sensitive to a hydrogen flux of 10^{17} atoms per second and can distinguish molecular and atomic hydrogen beams.

[1] S. Schmidt et al., J. Phys. Conf. Ser. (2018), arXiv 1808.07240
[2] R. Pohl et al., Nature 466.723, 213-216 (2010)

Q 44.21 Wed 16:30 P

Recoil correction to the energy level of heavy muonic atoms — •Romain Chazotte[1,2] and Natalia Oreshkina[2] — [1]Universität Heidelberg — [2]Max-Plank-Institut

In this work, the relativistic recoil correction to the energies of heavy muonic atoms has been considered, based on the formalism suggested by Borie and Rinker.

Muonic atoms are atoms, which have a bound muon instead of an electron. The lifetime of a muon is long enough so it can be considered stable on the atomic scale. Additionally, an atom with a single bound muon can be considered as a hydrogenlike system. As muons are about 200 times heavier than electrons, they orbit around the nucleus 200 times closer. This leads to a larger contribution of all kinds of nuclear effects to the energy.

We calculated the recoil effect for the shell, sphere and Fermi nuclear models. The model and nuclear parameters dependence has been studied. The results have been compared with previous studies. They also can be used for the high-precision theoretical predictions of the spectra of heavy muonic atoms, and in the further comparison with experimental data, aiming at the extraction of the nuclear properties and parameters. In the future, a more rigorous quantum electrodynamics formalism can be applied for enhancing the accuracy of the relativistic recoil effect.

Q 45: Ultracold Atoms and Molecules I (joint session Q/A)

Time: Thursday 10:30–12:30 Location: Q-H10

Q 45.1 Thu 10:30 Q-H10

Optical bench system for the BECCAL ISS quantum gas experiment — •Jean Pierre Marburger[1], Faruk Alexander Sellami[1], Esther del Pino Rosendo[1], André Wenzlawski[1], Ortwin Hellmig[2], Klaus Sengstock[2], Patrick Windpassinger[1], and THE BECCAL TEAM[1,3,4,5,6,7,8,9,10,11] — [1]Institut für Physik, JGU, Mainz — [2]ILP, UHH, Hamburg — [3]HUB — [4]FBH — [5]LUH — [6]ZARM — [7]Universität Ulm — [8]DLR-SC — [9]DLR-SI — [10]DLR-QT — [11]OHB

The DLR-NASA BECCAL multi-user experimental facility is intended for the study of quantum gases in the microgravity environment of the ISS. In this talk, we present a stable optical bench system that enables frequency stabilization, as well as efficient light distribution and manipulation for this facility. In contrast to a lab-based setup, this system needs to withstand the mechanical loads during launch, and be mechanically stable under varying temperature conditions on the ISS over a timeframe of many years. To this end, we use and expand upon an optical toolkit based on the glass-ceramic Zerodur, which has a negligible coefficient of thermal expansion. This toolkit has already been successfully deployed in the scope of the sounding rocket missions KALEXUS, FOKUS, MAIUS-1, and will be used for the upcoming MAIUS-2/3 missions.

Our work is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50 WP 1433, 50 WP 1703 and 50 WP 2103.

Q 45.2 Thu 10:45 Q-H10

Rapid generation of all-optical ^{39}K Bose-Einstein condensates — •Alexander Herbst, Henning Albers, Vera Vollenkemper, Knut Stolzenberg, Sebastian Bode, and Dennis Schlippert — Institute of Quantum Optics, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany

Ultracold potassium is a promising candidate for fundamental research and quantum sensing applications as it offers multiple broad Feshbach resonances at small magnetic fields. These can be used to control the atomic scattering length and therefore allow, e.g., for the suppression of phase diffusion or the generation of solitons. To apply this technique the magnetic field must be kept as an external degree of freedom thus necessitating optical trapping. However, compared to their magnetic counterparts, optical traps suffer from slower evaporative cooling. This poses a major challenge if the experiment requires a high repetition rate. We investigate the production of all-optical ^{39}K BECs under different scattering lengths in a time-averaged crossed optical dipole trap. By tuning the scattering length in a range between 75 a_0 and 350 a_0 we demonstrate a trade off between evaporation speed and final atom number and decrease our evaporation time by a factor of five while approximately doubling the atomic flux. To this end, we are able to produce fully condensed ensembles with 5×10^4 atoms within 850 ms evaporation time at a scattering length of 234 a_0 and 1.5×10^5 atoms within 4 s at 160 a_0, respectively. We analyze the flux scaling with respect to collision rates and describe routes towards high-flux sources of ultra-cold potassium for inertial sensing.

Q 45.3 Thu 11:00 Q-H10

Optical dipole trap in microgravity - the PRIMUS-project — •Marian Woltmann[1], Christian Vogt[1], Sven Hermann[1], and The PRIMUS-Team[1,2] — [1]University of Bremen, Center of Applied Space Technology and Microgravity (ZARM) — [2]Institut für Quantenoptik, LU Hannover

The application of matter wave interferometry in a microgravity (μg) environment offers the potential of largely increased interferometer times and thereby highly increased sensitivities in precision measurements, e.g. of the universality of free fall. While most μg-based cold atom experiments use magnetic trapping on an atom chip, we develop an optical dipole trap as an alternative source for matter wave interferometry in weightlessness. Solely using optical potentials offers unique advantages like improved trap symmetry, trapping of all magnetic sublevels and the accessibility of Feshbach resonances. Equipping a 50W trapping laser at a wavelength of 1064nm we implement a cold atom experiment for use in the drop tower at ZARM in Bremen, offering 4.7s of microgravity time. We demonstrated Bose-Einstein condensation of Rubidium in a compact setup on ground while now focusing on a fast, efficient preparation in microgravity using painted optical potentials. Within this talk we will report on the current status and latest results of the experiment. The PRIMUS-Project is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) under grant number DLR 50 WM 2042.

Q 45.4 Thu 11:15 Q-H10

Compact and Robust Laser System for Cold Atom Experiments in BECCAL on the ISS — •Tim Kroh[1], Victoria A. Henderson[1], Jean Pierre Marburger[2], Faruk Alexander Sellami[2], Esther del Pino Rosendo[2], André Wenzlawski[2], Matthias Dammasch[3], Ahmad Bawamia[3], Andreas Wicht[3], Patrick Windpassinger[2], Achim Peters[1,3], and THE BECCAL TEAM[1,2,3,4,5,6,7,8,9,10,11] — [1]HUB, Berlin — [2]JGU, Mainz — [3]FBH, Berlin — [4]DLR-SC — [5]DLR-SI — [6]DLR-QT — [7]IQ & IMS, LUH — [8]ILP, UHH — [9]ZARM, Bremen — [10]IQO, UULM — [11]OHB

BECCAL (Bose-Einstein Condensate–Cold Atom Laboratory) is a cold atom experiment designed for operation on the ISS. This DLR and NASA collaboration builds upon the heritage of sounding rocket and drop tower experiments as well as NASA's CAL. Fundamental physics with Rb and K BECs and ultra-cold atoms will be explored in this multi-user facility in microgravity, providing prolonged timescales and ultra-low energy scales compared to those achievable on earth. Matching the complexity of the required light fields to the stringent size, weight, and power limitations presents a unique challenge for the laser system design, which is met by a reliable and robust combination of micro-integrated diode lasers (from FBH) and miniaturized free-space optics on Zerodur boards (from JGU), interconnected with fiber optics. The design of the BECCAL laser system will be presented, alongside the requirements, concepts, and heritage which formed it. This work is supported by DLR with funds provided by the BMWi under grant numbers 50 WP 1433, 1702, 1703, 1704, 2102, 2103, and 2104.

Q 45.5 Thu 11:30 Q-H10

Few-Body Physics in Spherical Shell Traps — C. Moritz Carmesin[1] and •Maxim A. Efremov[2,1] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ$^{\mathrm{ST}}$), Universität Ulm, 89069 Ulm, Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), 89081 Ulm, Germany

With the recent progress in cold atom physics in microgravity [1–5] it is feasible to trap atoms in spherical shell-shaped traps. We start our analysis from exploring both bound and scattering states of two identical particles in spherical shell traps. Due to the non-separability of the center-of-mass and relative motions, we have solved the 6-dimensional Schrödinger equation numerically. Moreover, we have derived analyti-

cal models for the effective interaction between the particles for small and large shell radii, where the latter features quasi-two-dimensional dynamics in curved space.

[1] D. C. Aveline et al., Nature 582,193 (2020).
[2] K. Frye et al., EPJ Quantum Technol. 8, 1 (2021).
[3] N. Lundblad et al., npj Microgravity 5, 30 (2019).
[4] R. A. Carollo et al., arXiv:2108.05880
[5] A. Wolf et al., arXiv:2110.15247

Q 45.6 Thu 11:45 Q-H10

A lattice model for traid anyons — •Sebastian Nagies[1], Botao Wang[1], Nathan Harshman[2], and André Eckardt[1] — [1]Institute of Theoretical Physics, Technical University Berlin, Berlin — [2]Department of Physics, American University, Washington DC, USA

Hard-core two-body interactions in two dimensions leave the configuration space of particles not simply connected. This gives rise to anyons exhibiting fractional exchange statistics governed by the braid group. Recently it was pointed out that hardcore three-body interactions in one dimension leave similar defects in configuration space. This allows for novel exchange statistics described by the traid group, for which the Yang-Baxter relation no longer holds. Here we propose a lattice model realizing a specific abelian representation of this traid group. Our model uses bosons with number-dependent hopping phases to generate alternating bosonic and fermionic exchange phases. By combining numeric simulations with analytic derivation in the continuum limit, we find interesting ground state density distributions and energies that differ greatly from bosons, fermions and braid anyons. We define new traid anyon operators satisfying non-local commutation relations, and predict distinctive traid anyon quasi-momentum distributions. We discuss their possible relation with Haldane's exclusion statistics.

Q 45.7 Thu 12:00 Q-H10

Reservoir-engineered shortcuts to adiabaticity via quantum non-demolition measurements — •Raphael Menu[1], Josias Langbehn[2], Christiane Koch[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany — [2]Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany

The preparation of a quantum state via a slow tuning of the parameters of the system lies at the heart of the concept of adiabatic quantum computing. Yet, the realization of such types of computation requires a wide time-window over which dissipation effects may occur, ultimately leading to errors. Here, we propose a protocol that achieves fast adiabatic Landau-Zener dynamics by coupling a spin to an external system. The coupling realizes a quantum non-demolition (QND)Hamiltonian, where the external system acts as a meter. When the meter's decay rate is the largest frequency scale of the dynamics, the QND coupling induces an effective dephasing of the spin in the adiabatic basis and the spin dynamics is described by a quantum adiabatic master equation. We show, however, that adiabaticity can be maximized in the non-adiabatic limit when the coupling with the meter tends to suppress diabatic transitions via effective cooling processes. We investigate the protocol efficiency in terms of non-Markovianity measures for the spin-meter dynamics and qualitatively discuss the spectral gap of the incoherent dynamics. We finally show that the protocol is robust against imperfection in the implementation of the QND Hamiltonian.

Q 45.8 Thu 12:15 Q-H10

Engineering of Feshbach Resonances by a Floquet Drive — •Christoph Dauer, Axel Pelster, and Sebastian Eggert — Physics Department and Research Center OPTIMAS, TU Kaiserslautern, 67663 Kaiserslautern, Germany

Feshbach resonances are a common tool in order to control the scattering length in ultracold quantum gases [1]. In this talk we discuss how time-periodic driving enables to induce novel resonances that are fully controllable by the parameters of the drive [2,3]. A theory allowing a deeper understanding of these driving induced resonances within the Floquet picture is given. Our method is capable of describing resonance positions and widths for general inter-particle potentials. We demonstrate our results on an experimentally relevant example.

[1] C. Chin et al., Rev. Mod. Phys. 82, 1225 (2010)
[2] D.H. Smith, Phys. Rev. Lett. 115, 193002 (2015)
[3] A.G. Sykes et al., Phys. Rev. A 95, 062705 (2017)

Q 46: Nano-Optics I

Time: Thursday 10:30–12:30 Location: Q-H11

Invited Talk Q 46.1 Thu 10:30 Q-H11

Nanoscale heat radiation in non-reciprocal and topological many-body systems — •Svend-Age Biehs — Institut für Physik, Carl von Ossietzky Universität Oldenburg, Germany

I will start with a short introduction to the experimental and theoretical advances achieved in the rapidly evolving field of nanoscale heat radiation with a focus on the theoretical development of the many-body theory within the framework of fluctuational electrodynamics. Of particular interest are non-reciprocal systems giving rise to effects like the Hall effect for heat radiation and heat flux rectification by means of non-reciprocal surface waves. On the other hand, topological many-body systems offer the possibility to use edge modes for heat transport. I will discuss this heat flux channel in a topological Su-Schrieffer-Heeger chain and a honeycomb lattice of plasmonic nanoparticles.

Q 46.2 Thu 11:00 Q-H11

Shallow implantation of color centers in silicon carbide with high-coherence spin-optical properties — •Timo Steidl[1], Tobias Linkewitz[1], Raphael Wörnle[1], Charles Babin[1], Rainer Stöhr[1], Di Liu[1], Erik Hesselmeier[1], Marcel Krumrein[1], Naoya Morioka[1], Vadim Vorobyov[1], Andrej Denisenko[1], Mario Hentschel[1], Christian Gobert[2], Patrick Berwian[2], Georgy Astakhov[3], Wolfgang Knolle[4], Sridhar Majety[5], Pranta Saha[5], Marina Radulaski[5], Nguyen Tien Son[6], Jawad Ul-Hassan[6], Florian Kaiser[1], and Jörg Wrachtrup[1] — [1]Universität Stuttgart, GER — [2]Fraunhofer IISB, Erlangen, GER — [3]HZDR, Dresden, GER — [4]IOM, Leipzig, GER — [5]University of California, Davis, USA — [6]Linköping University, SWE

The accurate positioning of optically active color centers in the center of efficient photonic interfaces is a requirement for next-generation solid-state quantum information devices. Here, we report the creation of shallow V_{Si} centers in SiC with high spatial resolution using low ion energy implantation of protons, He ions and Si ions. We observe remarkably robust spin-optical properties attributed to the minimized collateral crystal damage. In particular, we show nearly lifetime limited absorption lines and the highest reported Hahn echo time of the system. We will also show our initial results on defect generation based on He focussed ion beam implantation, which is a promising solution for nanophotonic devices. Our results highlight the tremendous potential of the SiC platform, and provide a crucial step towards the integration of V_{Si} into nanophotonic resonators.

Q 46.3 Thu 11:15 Q-H11

High-resolution vibronic spectroscopy of a single molecule embedded in a crystal — •Johannes Zirkelbach[1,2], Masoud Mirzaei[1,2], Burak Gurlek[1,2], Irena Deperasińska[3], Boleslaw Kozankiewicz[3], Alexey Shkarin[1], Tobias Utikal[1], Stephan Götzinger[1,2,4], and Vahid Sandoghdar[1,2] — [1]Max Planck Institute for the Science of Light, 91058 Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany — [3]Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland — [4]Graduate School in Advanced Optical Technologies (SAOT), Friedrich Alexander University Erlangen-Nuremberg, 91052 Erlangen, Germany

Vibrational states of single organic dye molecules in solid-state hosts are known to relax within 10 ps although they could last by up to seconds in some molecules in vacuum. The resolution of conventional grating spectrometers puts a lower bound on the observed linewidths of vibrational transitions, i.e., an upper limit on measured lifetimes. Here, we present high-resolution vibronic spectra of single dibenzoterrylene molecules in para-dichlorobenzene crystals at T < 100 mK. The spectra were recorded in electronic ground and excited states using stimulated emission depletion (STED) and fluorescence excitation spectroscopy, respectively. We identified several narrow lines associated with vibrational lifetimes up to 80 ps. Using DFT calculations, we explain the intensity distribution of the vibronic lines of the dopant molecules in the solid-state environment.

Q 46.4 Thu 11:30 Q-H11

Manipulating ground-state properties of hBN quantum emitters — •Chanaprom Cholsuk[1], Sujin Suwanna[2], Falk Eilenberger[1], and Tobias Vogl[1] — [1]Institute of Applied Physics, Friedrich-Schiller-University, Albert-Einstein-Straße 15, 07745 Jena — [2]Optical and Quantum Physics Laboratory, Department of Physics, Faculty of Science, Mahidol University, Bangkok, 10400, Thailand

Quantum key distribution exploits quantum properties such as unclonable single photon states for unconditionally secure communication. As a result, nanoscale single photon emitters (SPEs) have become highly sought-after. The color-centers or fluorescent defects in hexagonal boron nitride (hBN) emit single photons at room temperature with high brightness and short excited state lifetime. The specific types of defects, however, remain unclear and require some manipulation to enhance the quantum efficiency while preserving photon purity.

In this presentation, we provide a rigorous density functional theory (DFT) calculation-based overview of the formation mechanism of SPEs in hBN. A large class of defects has been investigated and identified in the electronic structure. Consequently, we can now classify the emission wavelengths of such defects and attribute defect types to specific sources. Moreover, the DFT calculations allow us to explore tuning mechanisms as well as to tailor the photophysical properties of the emitters. We can therefore develop feasible approaches to enhance the quantum efficiency and use external strain to both manipulate the defect states as well as to reduce the defect formation energy to enhance the probability for a defect to form.

Q 46.5 Thu 11:45 Q-H11

Preparation of germanium-vacancy centers in diamond for metrological applications — •Justus Christinck[1,2], Franziska Hirt[1,2], Helmuth Hofer[1], Zhe Liu[2,3], Markus Etzkorn[2,3], Toni Dunatov[4], Milko Jakšić[4], Jacopo Forneris[5,6,7], and Stefan Kück[1,2] — [1]Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany — [2]Laboratory for Emerging Nanometrology (LENA), Braunschweig, Germany — [3]Technische Universität Braunschweig, Braunschweig, Germany — [4]Ruder Bošković Institute, Zagreb, Croatia — [5]University of Torino, Torino, Italy — [6]Istituto Nazionale di Fisica Nucleare (INFN), Torino, Italy — [7]Istituto Nazionale di Ricerca Metrologica (INRiM), Torino, Italy

Germanium-vacancy (GeV-) centers in diamond are promising candidates for metrological applications of single-photon sources, e.g., the calibration of single-photon avalanche diode (SPAD) detectors. We present the successful generation of GeV-centers in bulk diamond and their metrological characterization in a confocal microscope setup. Acid bath treatment has been evaluated to significantly reduce the background luminescence from the sample surface, which lead to a higher single-photon purity of the sample's emission. The Focused Ion Beam (FIB) technique was used to mill solid immersion lenses (SILs) into the diamond surface. Compared to untreated GeV-centers, an increase in photon flux was detected from the GeV centers that were below a SIL, and a careful analysis of the single photon purity was performed. Further details will be presented at the conference.

Q 46.6 Thu 12:00 Q-H11

Design of Novel Waveguide-coupled Diamond Nanostructures for Efficient Photonic Integration — •Julian M. Bopp[1,2], Matthias Plock[3], Maarten van der Hoeven[1], Tommaso Pregnolato[1,2], Sven Burger[3,4], and Tim Schröder[1,2] — [1]Department of Physics, Humboldt-Universität zu Berlin, Berlin, Germany — [2]Ferdinand-Braun-Institut, Berlin, Germany — [3]Zuse Institute Berlin (ZIB), Berlin, Germany — [4]JCMwave GmbH, Berlin, Germany

Defect centers in diamond are promising candidates for being used as quantum memories [1] and quantum emitters. Nowadays, it is still challenging to provide high coupling efficiencies between light emitted from a single defect center located in a diamond cavity and a travelling light mode of a connected waveguide [2]. Such high coupling efficiencies are required to apply the defect centers as single-photon sources in photonic integrated circuits (PICs) [3].

Here, we present our progress towards increasing the interaction strength between single tin-vacancy centers in diamond (SnV) and light fields by embedding the SnV in new types of waveguide-integrated resonators with high quality factors and small mode volumes. We investigate different design parameters of the waveguide-coupled resonator to ensure efficient adiabatic coupling and propose a way for deterministic high-yield fabrication of the developed nanostructures.

[1] S. Mouradian et al., Phys. Rev. X 5, 031009 (2015)
[2] S. Mouradian et al., Appl. Phys. Lett. 111, 021103 (2017)
[3] N. H. Wan et al., Nature 583, pp. 226-231 (2020)

Q 46.7 Thu 12:15 Q-H11

Coherent splitting of a vibronic line in a single molecule — Johannes Zirkelbach[1,2], •Masoud Mirzaei[1,2], Burak Gurlek[1,2], Alexey Shkarin[1,2], Tobias Utikal[1,2], Stephan Götzinger[1,2,3], and Vahid Sandoghdar[1,2] — [1]Max Planck Institute for the Science of Light, 91058 Erlangen, Germany — [2]Friedrich-Alexander University Erlangen Nürnberg, 91058 Erlangen, Germany — [3]Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander University Erlangen Nürnberg, 91052 Erlangen, Germany

Single organic dye molecules in the solid state offer a promising platform for quantum technology because of their strong zero-phonon transitions. Coherent access to vibronic states of these molecules has so far not been considered in this context due to their fast relaxation rates. We now report on experimentally observed coherent splitting of a vibronic level obtained by tuning a strong laser beam to the transition between two vibronic states. The experiments were performed with a single dibenzoterrylene molecule in a para-dichlorobenzene crystals at * < 100 mK. In this scheme, the resulting non-Lorentzian resonance profiles can be described only by accounting for the coherent evolution of the density matrix elements.

Q 47: Quantum Information (Quantum Communication and Quantum Repeater)

Time: Thursday 10:30–12:15 Location: Q-H12

Q 47.1 Thu 10:30 Q-H12

Commercializing QKD with continuous variables — •Ulrich Eismann, Emanuel Eichhammer, Emmeran Sollner, Martin Hauer, Oliver Maurhart, and Imran Khan — KEEQuant GmbH, Gebhardtstr. 28, 90762 Fürth, Germany

QKD was proposed in the 1980s as a means of distributing cryptographic keys with information-theoretic security based on quantum physics. However it is still awaiting widespread adoption, because early protocols were based on single-photon detectors, that are not easily scalable into commercial use cases because of their elevated size and cost.

In the advent of the quantum computer threat, we aim to make QKD a commodity by relying on standard telecom components, integrated photonics and electronics. This makes QKD invisible for the end user, and hence commercially viable.

We present KEEQuant's first QKD system, highlighting some of its technical challenges. We will elaborate on our QKD scaling approach using integrated photonics. Finally, we give an overview of how cryptographic keys are handled in a telecom network with our key management system (KMS).

Q 47.2 Thu 10:45 Q-H12

Security analysis of encryption based on a quantum-provisioned root of trust — •Donika Imeri[1,2] and Ralf Riedinger[1,2] — [1]Institut für Laserphysik und Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg, Germany

Over the years, quantum key distribution paved the way for physically secured communication by generating a cryptographic key via a quantum channel. Due to the loss of quantum information in this channel, the distance between two directly communicating parties is constrained. Trusted-node and quantum repeater networks could overcome this challenge, requiring expensive infrastructure. Here, we present a protocol for quantum-secured key distribution based on an information-theoretically secure root of trust provisioned over a short quantum channel. Methods like over-the-air rekeying provide the system with security similar to conventional quantum key distribution even after disconnection from the quantum channel. As no physical quantum channel is needed in the communication phase, arbitrary distances can be realized and the use of mobile end-devices is possible. For further research, this protocol can be extended to network architectures, combining flexibility and scalability with secure communication.

Q 47.3 Thu 11:00 Q-H12

Universal crosstalk decay of OAM photons in random media — •David Bachmann[1], Asher Klug[2], Mathieu Isoard[1], Vyacheslav Shatokhin[1], Giacomo Sorelli[3], Andreas Buchleitner[1], and Andrew Forbes[2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität, Freiburg i. Br., Germany — [2]School of Physics, University of the Witwatersrand, Private Bag 3, Johannesburg 2050, South Africa — [3]Laboratoire Kastler Brossel, Sorbonne Université, ENS-Université PSL, Collège de France, CNRS; 4 place Jussieu, F-75252 Paris, France

High-dimensional free-space quantum communication is an active, application-oriented, research area. Most implementations of high-dimensional spatial encoding rely on photonic orbital angular momentum (OAM), but the phase fronts of the corresponding spatial modes are distorted in random media such as turbulence. Recently, it has been predicted [1] that Kolmogorov turbulence may induce crosstalk between Laguerre-Gaussian (LG) modes of opposite OAM. We confirm this behavior numerically as well as experimentally by propagating LG modes in emulated turbulence and artificial random media. Furthermore, we show that the crosstalk decay may be rescaled to a universal function of a single parameter – the ratio between the transverse correlation length of the random medium and the OAM beam's phase correlation length.

[1] Giacomo Sorelli et al., New J. Phys. 21 023003 (2019)

Q 47.4 Thu 11:15 Q-H12

Towards a nitrogen-vacancy center based quantum repeater — •Javid Javadzade[1,2], Vadim Vorobyov[1,2], Rainer Stöhr[1], Wolfgang Fischer[1], Florian Kaiser[1,2], and Jörg Wrachtrup[1,2,3] — [1]3rd Institute of Physics, University of Stuttgart, Stuttgart, Germany — [2]Institute for Quantum Science and Technology IQST, Germany — [3]Max-Planck Institute for Solid State Research, Stuttgart, Germany

The architecture of quantum repeaters is designed to solve the problem of signal fading in quantum communication lines (quantum internet) [1,2]. Single NV centers have shown their ability to be a working platform for the transmission of quantum signals [3]. Our strategy is to use NV center electron spin-photon time-bin entanglement in combination with nearby 13C spin (memory qubit) to establish communication links between repeater node and communication parties. We will present results of spin-bath characterization, where 4 suitable, weakly coupled 13C qubits were found with coupling strength in a range of 10-100 kHz. Moreover, Spin photon correlations - pre-entanglement measurement - with a fidelity of 0.8 will be shown. Additionally, the interferometer stabilization problem as long as further setup improvements will be discussed.

[1] D. Luong et al. Appl. Phys. B 122, 96 (2016). [2] C.H. Bennett & G. Brassard. Sci. 560, 7 (2014). [3] M. Pompili et al. Sci. 372, 259 (2021).

Q 47.5 Thu 11:30 Q-H12

Spectral multiplexing of individual Erbium dopants with stable transition frequency — •Alexander Ulanowski[1], Benjamin Merkel[1], and Andreas Reiserer[1,2] — [1]MPI of Quantum Optics, Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Ludwig-Maximilians-Universität München, München, Germany

In a future quantum internet, coherent emitters will exchange quantum states over global distances, preferably using optical fibers. Erbium dopants exhibit an optical transition at telecommunication wavelength that would enable a low-loss transmission over long distances. To achieve an efficient spin-photon interface for single dopants, we embed a thin crystalline membrane into a tunable Fabry-Perot resonator with a finesse of $9.0(7)\cdot 10^4$ which leads up to a 70-fold Purcell enhancement. Our approach avoids the proximity of the emitters to interfaces and thus allows us to preserve the coherence up to the lifetime limit [1]. At the tail of the inhomogeneous broadening we spectrally resolve and control around 100 individual dopants with low spectral diffusion below 0.2 MHz [2]. Furthermore, at high magnetic fields some dopants reveal slow diffusion dynamics, allowing us to apply a feed-forward correction on the emission frequency and reducing the linewidth down to 0.1 MHz. Our findings enable frequency-multiplexed spin-qubit readout, control and entanglement, opening unique perspectives for the implementation of repeater nodes in a quantum network.

[1] B. Merkel et al., Phys.Rev.X 10, 041025 (2020).
[2] A. Ulanowski, B. Merkel, A. Reiserer, ArXiv:2110.09409 (2021).

Q 47.6 Thu 11:45 Q-H12

Retrieval of single photons from solid-state quantum transducers — •Tom Schmit[1], Luigi Giannelli[1,2,3], Anders Søndberg Sørensen[4], and Giovanna Morigi[1] — [1]Theoretical Physics, Department of Physics, Saarland University, 66123 Saarbrücken, Germany — [2]Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Via S. Sofia 64, 95123 Catania, Italy — [3]INFN, Sezione Catania, 95123 Catania, Italy — [4]Center for Hybrid Quantum Networks, Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen Ø, Denmark

Quantum networks using photonic channels require control of the interactions between the photons, carrying the information, and the elements comprising the nodes. In this work we analyze theoretically the spectral properties of an optical photon emitted by a solid-state quantum memory, which acts as a converter of a photon absorbed in another frequency range. We determine explicitly the expression connecting the stored and retrieved excitation taking into account possible mode and phase mismatch of the experimental setup. The expression we obtain describes the output field as a function of the input field for a transducer working over a wide range of frequencies, from optical-to-optical frequencies to microwave-to-optical frequencies. We apply this result to analyze the photon spectrum and the retrieval probability as a function of the optical depth for microwave-to-optical transduction.

Q 47.7 Thu 12:00 Q-H12

Indistinguishable single photons from negatively charged tin-vacancy centres in diamond — •R. Morsch[1], J. Görlitz[1], B. Kambs[1], D. Herrmann[1], P. Fuchs[1], P.-O. Colard[2], M. Markham[2], and C. Becher[1] — [1]Universität des Saarlandes, Saarbrücken 66123, Germany — [2]Element Six Global Innovation Centre, OX11 0QR, UK

For various applications in the field of quantum information processing (QIP) long-lived, stationary qubits are required that can be controlled coherently and read out optically. Quantum computing with linear optics (LOQC) moreover inherently relies on bright light-matter interfaces that provide single indistinguishable photons.

Colour centres in diamond have emerged as a promising candidate among solid state qubits. Recent experiments have shown that among those the negatively charged tin-vacancy centre (SnV−) exhibits both individually addressable spins with long coherence times and bright emission of single, close-to-transform limited photons.

By means of Hong-Ou-Mandel interferometry we here investigate the indistinguishability of single photons emitted by a single SnV-centre. We find high Hong-Ou-Mandel visibilities, being a direct measure for high indistinguishability of the single photons. We compare the experimental results with the predictions of a theoretical model and extract the magnitude of spectral diffusion potentially affecting single photon indistinguishability in the present system. Furthermore, we estimate the timescale of spectral diffusion by repeating the experiment with various delays between emission of the interfering photons.

Q 48: Quantum Effects II

Time: Thursday 10:30–12:30 Location: Q-H13

Q 48.1 Thu 10:30 Q-H13

Atomic Dynamics in Strongly Coupled Multimode Cavities under Continuous Measurement — Valentin Link[1], •Kai Müller[1], Rosaria G. Lena[2], Kimmo Luoma[3], François Damanet[4], Walter T. Strunz[1], and Andrew J. Daley[2] — [1]Institut für Theoretische Physik, TU Dresden, Dresden, Germany — [2]Department of Physics and SUPA, University of Strathclyde, Glasgow, United Kingdom — [3]Department of Physics and Astronomy, University of Turku, Turun Yliopisto, Finland — [4]Department of Physics and CESAM, University of Liège, Liège, Belgium

Atoms in multimode cavity QED systems provide an exciting platform to study many-body phenomena in regimes where the atoms are strongly coupled amongst themselves and with the cavity. An important challenge in this, and other related non-Markovian open quantum systems is to understand what information we gain about the atoms from continuous measurement of the output light, as most of the existing theoretical frameworks are restricted to either few cavity modes or weak atom-cavity coupling. In this work, we address this problem, describing the reduced atomic state via a hierarchy of equations of motion, which provide an exact conditioned reduced description under monitoring. We utilise this formalism to study how different monitoring for modes of a multimode cavity affects our knowledge about an atomic state, and to improve spin squeezing via measurement and feedback in a strong coupling regime. Our work opens opportunities to understand continuous monitoring of non-Markovian open quantum systems, both on a practical and fundamental level.

Q 48.2 Thu 10:45 Q-H13

***Ab initio* cavity QED - modifying chemistry with strong light-matter interaction** — •Christian Schäfer[1,2], Enrico Ronca[3], Johannes Flick[4,5], Prineha Narang[5], and Angel Rubio[2,4] — [1]Department of Microtechnology and Nanoscience, MC2, Chalmers University of Technology, 412 96 Göteborg, Sweden — [2]Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany — [3]Istituto per i Processi Chimico Fisici del CNR (IPCF-CNR), Via G. Moruzzi, 1, 56124, Pisa, Italy — [4]Center for Computational Quantum Physics (CCQ), The Flatiron Institute, 162 Fifth Avenue, New York NY 10010, USA — [5]John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

The alchemical dream of altering a given material on demand into something desirable is at the very heart of chemistry. Optical-Cavity environments provide a novel handle to non-intrusively control materials and chemistry. The self-consistent interaction between complex electromagnetic environments and realistic materials gave birth to a new discipline, sometimes referred to as '*ab initio* QED', on the interface of condensed matter, chemistry and quantum optics.

I will provide a brief introduction into this newly emerged field and illustrate its application that gives rise to the control of chemical reactions [1] and intermolecular interactions.

[1] Schäfer, C., Flick, J., Ronca, E., Narang, P., and Rubio, A., arXiv:2104.12429 (2021).

Q 48.3 Thu 11:00 Q-H13

Nitrogen vacancy centers in diamond membranes coupled to an optical microcavity — •Maximilian Pallmann[1], Kerim Köster[1], Jonathan Körber[3], Julia Heupel[2], Rainer Stöhr[3], Timon Eichhorn[1], Larissa Kohler[1], Cyril Popov[2], and David Hunger[1] — [1]Karlsruher Institut für Technologie — [2]Universität Kassel — [3]Universität Stuttgart

Color centers in diamond centers are very promising candidates for applications in quantum communication and metrology. The nitrogen vacancy center (NV) stands out due to its exceptional spin coherence properties. On the other hand, it suffers from rather bad optical properties due to significant phonon coupling, and only 3% of the emitted light belongs to the Zero phonon line (ZPL). This can be overcome by coupling the emitters to optical cavities, making use of the Purcell effect.

In our experiment, we integrate a diamond membrane to an open access fiber-based Fabry-Perot microcavity [1] to attain emission enhancement into a single well-collectable mode as well as spectral filtering. We investigate the influence of the diamond membrane on the optical properties of the cavity.

Furthermore, we present Purcell-enhanced ensemble-fluorescence of shallow-implanted NV centers and observe cavity-induced collective effects that lead to a bunching behavior in the emission.

[1] Heupel,Pallmann,Körber.Micromachines 2020, 11, 1080;

Q 48.4 Thu 11:15 Q-H13

Nonequilibrium quantum state preparation with Floquet systems in engineered baths — •Francesco Petiziol and André Eckardt — Technische Universität Berlin, Institut für Theoretische Physik, Hardenbergstr. 36, 10623 Berlin, Germany

I will discuss how interesting nonequilibrium quantum states can be prepared and stabilized by combining time-periodic driving with engineered quantum baths, as they are realizable in circuit QED systems. Considering arrays of periodically driven artificial atoms individually coupled to leaky cavities, I will first show that, while the periodic driving allows to engineer desired effective system properties, the cavities can be exploited to cool the systems to their effective ground states. I will illustrate how this mechanism can be used for the robust preparation of states with non-trivial properties. Concretely, I will discuss the preparation of Aharonov-Bohm cages, in which quantum interference constrains the dynamics in small subsystems, and chiral ground state currents.

Q 48.5 Thu 11:30 Q-H13

Inverse design approach to x-ray cavity quantum optics with Mössbauer nuclei — Oliver Diekmann, Dominik Lentrodt, and •Jörg Evers — Max Planck Institute for Nuclear Physics, Heidelberg

Nanometer-sized thin-film cavities containing ensembles of Mössbauer nuclei have been demonstrated to be a rich platform for x-ray quantum optics. At low excitation, these systems can be described by effective few-level schemes, thereby providing tunable artificial quantum systems at hard x-ray energies. With the recent advent of an ab-initio theory [1,2], a numerically efficient description of these systems is now possible. On this basis, we introduce the inverse design and develop a comprehensive optimization which allows one to determine optimum cavity systems realizing few-level schemes with desired properties [3]. Using this approach, we characterize the accessible parameter spaces of artificial two- and three-level systems and determine optimum cavity designs for several applications. Further, we discover a number of qualitative insights into x-ray photonic environments for nuclei that will likely impact the design of future x-ray cavities and thereby improve their performance.

[1] D. Lentrodt and J. Evers, Phys. Rev. X **10**, 011008 (2020).
[1] D. Lentrodt *et al.*, Phys. Rev. Research **2**, 023396 (2020).
[2] O. Diekmann *et al.*, arXiv:2108.01960 [quant-ph].

Q 48.6 Thu 11:45 Q-H13

Dynamics of strongly coupled Yb atoms in a high-finesse cavity — •Dmitriy Sholokhov, Saran Shaju, and Jürgen Eschner — University of Saarland, Saarbrücken, Germany

We investigate the possibility of MOT trapping of ^{174}Yb atoms using the 182 kHz narrow $^1S_0$ - $^3P_1$ (556 nm) transition, in order to generate lasing on the $^1S_0$ - $^3P_0$ clock transition (578 nm) using the virtual-state lasing mechanism described in [1]. While trapping with 556 nm light, the atomic cloud is considerably colder and denser as compared to the case of MOT trapping on the 28 MHz wide $^1S_0$ - $^1P_1$ line at 399 nm, which was used in [1]. We observe strong interaction between cavity and atoms in the scattering of frequency-shifted trap light into the cavity. The interaction, including the time-dependent atom number inside the cavity mode, leads to complex dynamics of the quantum system, which we characterize and analyze in this contribution.

[1] H. Gothe, D. Sholokhov, A. Breunig, M. Steinel, J. Eschner, Phys. Rev. A 99, 013415 (2019)

Q 48.7 Thu 12:00 Q-H13

Quantum State Preparation in a Micromaser — Andreas Jan Christoph Woitzik[1,2], Edoardo Carnio[1,2], and •Andreas Buchleitner[1,2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104, Freiburg im Breisgau, Germany} — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104, Freiburg im Breisgau, Germany

Quantum algorithms process information encoded into quantum states via an appropriate unitary transformation. Their purpose is to deliver a sought-after target state that represents the solution of a predefined computational problem. From a physical perspective, this process can be interpreted as a quantum state control problem where a given target state is to be prepared through an optimally tailored unitary transformation. In this talk we adopt the one-atom (or micro-) maser as a model to study the transfer of quantum information in state space. We consider a string of atoms that interact sequentially with a cavity mode, to understand the relation between the cavity's convergence towards a given target state and the entanglement content of the injected atomic string.

Q 48.8 Thu 12:15 Q-H13

Coupling a single trapped atom to a whispering-gallery-mode microresonator — •Xinxin Hu[2], Elisa Will[1], Luke Masters[2], Arno Rauschenbeutel[2], Michael Scheucher[1], and Jürgen Volz[2] — [1]Vienna Center for Quantum Science and Technology, Technische Universität Wien, 1020 Vienna, Austria — [2]Department of Physics, Humboldt Universität zu Berlin, 10099 Berlin, Germany

We demonstrate trapping of a single ^{85}Rb atom at a distance of 200 nm from the surface of a whispering-gallery-mode bottle microresonator. The atom is trapped in an optical potential, which is created by retroreflecting a red-detuned focused laser beam from the resonator surface. We counteract the trap-induced light shift of the atomic transition frequency by superposing a second laser beam with suitably chosen power and detuning. This allows us to observe a vacuum Rabi-splitting in the excitation spectrum of the coupled atom-resonator system. This first demonstration of stable and controlled interaction of a single atom with a whispering-gallery-mode in the strong coupling regime opens up the route towards the implementation of quantum protocols and applications that harvest the chiral atom-light coupling present in this class of resonators.

Q 49: Ultra-cold atoms, ions and BEC III (joint session A/Q)

Time: Thursday 10:30–12:15 Location: A-H2

Invited Talk Q 49.1 Thu 10:30 A-H2

Chemistry of an impurity in a Bose-Einstein condensate — •Arthur Christianen[1,2], Ignacio Cirac[1,2], and Richard Schmidt[1,2] — [1]Max-Planck-Institut für Quantenoptik, Garching, Germany — [2]Munich Center for Quantum Science and Techonology, Munich, Germany

In ultracold atomic gases, a unique interplay arises between phenomena known from condensed matter, few-body physics and chemistry. Similar to an electron in a solid, a quantum impurity in an atomic Bose-Einstein condensate is dressed by excitations from the medium, forming a polaron quasiparticle with modified properties. At the same time, the atomic impurity can undergo the chemical reaction of three-body recombination with atoms from the BEC, which can be resonantly enhanced due to universal three-body Efimov bound states crossing the continuum. As an intriguing example of chemistry in a quantum medium, we show that such Efimov resonances are shifted to smaller interaction strenghts due to participation of the polaron cloud in the bound state formation. Simultaneously, the shifted Efimov resonance marks the onset of a polaronic instability towards the decay into larger Efimov clusters and fast recombination.

References: [1] A. Christianen, J.I. Cirac, R. Schmidt, "Chemistry of a light impurity in a Bose-Einstein condensate", arXiv:2108.03174 [2] A. Christianen, J.I. Cirac, R. Schmidt, "From Efimov Physics to the Bose Polaron using Gaussian States", arXiv:2108.03175

Q 49.2 Thu 11:00 A-H2

Formation of spontaneous density-wave patterns in DC driven lattices – an experimental study — •Henrik P. Zahn, Vijay P. Singh, Marcel N. Kosch, Luca Asteria, Lukas Freystatzky, Klaus Sengstock, Ludwig Mathey, and Christof Weitenberg — Universität Hamburg, Hamburg, Deutschland

Driving a many-body system out of equilibrium induces phenomena such as the emergence and decay of transient states, which can manifest itself as pattern and domain formation. The understanding of these phenomena expands the scope of established thermodynamics into the out-of-equilibrium domain. Here, we observe the out-of-equilibrium dynamics of a Bose-Einstein condensate in an optical lattice subjected to a strong DC field, realized by strongly tilting the lattice. We observe the emergence of pronounced density wave patterns – which spontaneously break the underlying lattice symmetry – using a novel single-shot imaging technique with two-dimensional single-site resolution in three-dimensional systems, which also resolves the domain structure. Further, we investigate formation and decay time scales of the pattern formation as well as the role of tunnelling transverse to the tilt for the type of emerging pattern.

Q 49.3 Thu 11:15 A-H2

Formation of spontaneous density-wave patterns in DC driven lattices - a theoretical study — •Lukas Freystatzky[1,2], Vijay Singh[1,3], Henrik Zahn[4], Marcel Kosch[4], Luca Asteria[4], Klaus Sengstock[1,2,4], Christof Weitenberg[2,4], and Ludwig Mathey[1,2,4] — [1]Zentrum für optische Quantentechnologien, Universität Hamburg, Hamburg, Germany — [2]The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Hamburg, Germany — [3]Institut für Theoretische Physik, Leibniz Universität Hannover, Hanover, Germany — [4]Institut für Laserphysik, Universität Hamburg, Hamburg, Germany

We study the phenomenon of spontaneous density-wave patterns, which emerges in a Bose-Einstein condensate in an optical lattice subjected to a strong DC field, realized by strongly tilting the lattice. We use dynamical classical field simulations and analytical approaches to analyse the out-of-equilibrium dynamics of the system, which shows the emergence of pronounced density-wave patterns that spontaneously break the underlying lattice symmetry. This observation and the corresponding formation and decay time scales of the pattern formation are consistent with the measurements. We identify the dominant processes using Magnus expansion and describe the emergence of the density wave pattern in a perturbative approach.

Q 49.4 Thu 11:30 A-H2

Exploring orbital extensions of the Fermi-Hubbard model with ultracold ytterbium atoms — •Giulio Pasqualetti[1,2,3], Oscar Bettermann[1,2,3], Nelson Darkwah Oppong[1,2,3], Immanuel Bloch[1,2,3], and Simon Fölling[1,2,3] — [1]Ludwig-Maximilians-Universität, Munich, Germany — [2]Max-Planck-Institut für Quantenoptik, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany

The Fermi-Hubbard model (FHM) represents a paradigmatic milestone in condensed-matter physics. In the last decades, neutral atoms in optical lattices have become a powerful platform for investigating its properties in a clean and well-controlled environment. However, experiments have so far mostly explored the single-orbital limit of the FHM.

Here, we explore orbital extensions of the FHM with ultracold ytterbium atoms. The electronic ground state of neutral ytterbium possesses a SU(N) symmetry, which allows the study of the FHM with larger spin multiplicity. Moreover, a metastable electronic state known as the clock state can serve as a completely independent orbital degree of freedom, enabling the study of the mass-imbalanced FHM utilizing state-dependent potentials. In our experiment, we probe these orbital extensions of the FHM in different dimensionalities, investigating their spectroscopic properties, their thermodynamics, and dynamic response.

Q 49.5 Thu 11:45 A-H2

Quantum thermodynamics: Heat leaks and fluctuation dissipation — •Oleksiy Onishchenko[1], Daniël Pijn[1], Janine Hilder[1], Ulrich Poschinger[1], Raam Uzdin[2], and Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Universität Mainz, Mainz, Germany — [2]Fritz Haber Center for Molecular Dynamics, The Hebrew University, Jerusalem, Israel

Quantum thermodynamics focuses on extending the notions of heat and work to microscopic systems, where the concepts of non-commutativity and measurement back-action play a role [1]. In this work, we show a novel way to test the unitary functioning of a quantum processor by detecting heat leaks [2]. We also observe the first experimental signatures of operator non-commutativity on work fluctuations, as suggested theoretically [3]. Our experimental system consists of one or multiple Ca+ ion qubits held in a microstructured Paul trap. We initialize qubits in a statistical mixture of |0> and |1>, thus emulating thermal states. For the heat leak test, we reveal the amount of non-unitary evolution of the system qubits by measuring only in the computational basis and without accessing the environment. For the quantum work measurement, we set the operation and measurement bases to be non-commuting, and then evaluate the resulting work distribution.

[1] Sai Vinjanampathy and Janet Anders, Contemporary Physics 57, 545-579 (2016).
[2] D. Pijn et. al., arXiv:2110.03277v1 (2021).
[3] M. Scandi et. al., Physical Review Research 2, 023377 (2020)

Q 49.6 Thu 12:00 A-H2

Methods for atom interferometry with dual-species BEC in space — •Jonas Böhm[1], Maike D. Lachmann[1], Baptist Piest[1], Ernst M. Rasel[1], and the MAIUS team[1,2,3,4,5,6] — [1]Institut für Quantenoptik, LU Hannover — [2]ZARM, U Bremen — [3]DLR RY Bremen — [4]Institut für Physik, HU Berlin — [5]Institut für Quantenoptik, JGU Mainz — [6]FBH, Berlin

Atom interferometry is a promising tool for precise measurements, e.g. for quantum tests of the weak equivalence principle. As the sensitivity scales with the squared time atoms spend in the interferometer, this recommends low expansion velocities of the atomic ensembles. Hence, conducting these experiments in microgravity with Bose-Einstein-Condensates (BEC) is of great interest. The sounding rocket mission MAIUS-1 demonstrated the first creation of a BEC and matter wave interferences in space [1,2]. With the follow-up missions MAIUS-2 and -3, we extend the apparatus by another species to perform atom interferometry with ^{87}Rb and ^{41}K, paving the way for implementing and testing the methods of dual-species interferometers on board of space stations or satellites. In this contribution, the manipulation of BECs using Raman double-diffraction processes to form (asymmetric) Mach-Zehnder-type interferometers, e.g. for inertial sensing, are presented for a compact, robust, and autonomously operating setup that generates ^{87}Rb and ^{41}K BECs with a high repetition rate.

[1] D. Becker, et al., Nature 562, 391-395 (2018). [2] M.D. Lachmann, H. Ahlers, et al., Ultracold atom interferometry in space. Nat Commun 12, 1317 (2021).

Q 50: Precision spectroscopy of atoms and ions III (joint session A/Q)

Time: Thursday 10:30–12:15 Location: A-H3

Invited Talk Q 50.1 Thu 10:30 A-H3

Spectroscopy of a Highly Charged Ion Clock with Sub-Hz Uncertainty — •Lukas J. Spiess[1], Steven A. King[1], Peter Micke[1,2], Alexander Wilzewski[1], Tobias Leopold[1], Erik Benkler[1], Nils Huntemann[1], Richard Lange[1], Andrey Surzhykov[1], Robert Müller[1], Lisa Schmöger[2], Maria Schwarz[2], José R. Crespo López-Urrutia[2], and Piet O. Schmidt[1,3] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Max-Planck-Institut für Kernphysik, Heidelberg, Germany — [3]Institut für Quantenoptik, Leibniz Universität Hannover, Germany

Modern optical clocks are the most accurate metrological devices ever built. So far, such systems were only based on neutral and singly charged atoms. Potential further candidates are highly charged ions (HCI) which are intrinsically less sensitive to several types of external perturbations [1]. In previous work, we have demonstrated quantum logic spectroscopy of a HCI [2], enabling the first ever clock-like spectroscopy of these species.

We will present the first sub-Hz accuracy measurement of an optical transition in a HCI. The transition frequency of the 441 nm line in Ar^{13+} is compared to the electric octupole transition frequency in $^{171}Yb^{+}$. Measurements were performed for the two isotopes ^{40}Ar and ^{36}Ar which yields the isotope shift at sub-Hz accuracy and provides input for theoretical studies.

[1] M. G. Kozlov et al., Rev. Mod. Phys. **90** (2018)
[2] P. Micke et al., Nature **578** (2020)

Q 50.2 Thu 11:00 A-H3

Tailored Optical Clock Transition in $^{40}Ca^{+}$ — •Lennart Pelzer[1], Kai Dietze[1], Johannes Kramer[1], Fabian Dawel[1], Ludwig Krinner[1], Nicolas Spethman[1], Victor Martinez[2], Nati Aharon[3], Alex Retzker[3], Klemens Hammerer[2], and Piet Schmidt[1,2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Institut für Theoretische Physik, Appelstraße 2, 30167 Hannover 30167 Hannover, Germany — [3]Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

Optical clocks based on single trapped ions are often impeded by long averaging times due to the quantum projection noise limit. Longer probe time would improve the statistical uncertainty, but currently, phase coherence of clock laser systems is limiting probe times for most clock candidates. We propose pre-stabilization of the laser to a larger $^{40}Ca^{+}$ ion crystal, offering a higher signal-to-noise ratio. We engineer an artificial optical clock transition with a two stage continuous dynamical decoupling scheme, by applying near-resonant rf dressing fields. The scheme suppresses inhomogeneous tensor shifts as well as the linear Zeeman shift, making it suitable for multi-ion operation. This tailored transition has drastically reduced magnetic-field sensitivity. Even without any active or passive magnet-field stabilization, it can be probed close to the second-long natural lifetime limit of the $D_{5/2}$ level. This ensures low statistical uncertainty. In addition, we show a significant suppression of the quadrupole shift on a linear five-ion crystal by applying magic angle detuning on the rf-drives.

Q 50.3 Thu 11:15 A-H3

Towards continuous superradiance driven by a thermal beam of Sr atoms for an active optical clock — •Francesca Famà, Camila Beli Silva, Sheng Zhou, Stefan Alaric Schäffer, Shayne Bennetts, and Florian Schreck — Institute of Physics, University of Amsterdam

Continuous superradiant lasers have been proposed as next generation optical atomic clocks for precision measurement, metrology, quantum sensing and the exploration of new physics [1]. A superradiant laser consists of phase-synchronized atoms showing an enhanced single atom emission rate, allowing direct lasing on narrow clock transitions [2]. Despite pulsed superradiance having been demonstrated [3-4], steady-state operation remains an open challenge. Here we describe our machine aimed at validating a proposal [5] for a rugged superradiant laser operating on the 1S0-3P1 transition of 88Sr using a thermal collimated continuous atomic beam. The elegance of this approach is that a single cooling stage and a low finesse cavity appear sufficient to fulfill the requirements for continuous superradiance. Expected performances are up to 1 μW output power with a reduced output linewidth of 2π x 8 Hz and a sensitivity to frequency drift due to cavity-mirrors fluctuations suppressed by two orders of magnitude. Such a device promises a compact, robust and simple optical frequency reference, ideal for a wide range of industrial and scientific applications. [1] Chen, Chi.Sci.Bull. 54, 3,(2009). [2] Dicke, Phys.Rev. 93, 99 (1954). [3] Norcia et al., Sci.Adv. 2, e1601231(2016). [4] Schaffer et al., Phys.Rev.A 101, 013819(2020). [5] Liu et al., Phys.Rev.Lett. 125, 253602(2020).

Q 50.4 Thu 11:30 A-H3

Investigation of frequency shifts induced by thermal radiation for an $^{88}Sr^{+}$ optical clock — •Martin Steinel[1], Hu Shao[1], Thomas Lindvall[2], Melina Filzinger[1], Richard Lange[1], Burghard Lipphardt[1], Tanja Mehlstäubler[1,3], Ekkehard Peik[1], and Nils Huntemann[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]VTT Technical Research Centre of Finland, National Metrology Institute VTT MIKES, P.O. Box 1000, 02044 VTT, Finland — [3]Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

To realize transition frequencies in optical clocks with high accuracy, a careful investigation of all frequency shifts is required. For most systems operated at room temperature, the AC Stark shift induced by thermal radiation is important. It shows a T^4-dependence, and is proportional to the differential polarizability of the states. For an ion in a radiofrequency (rf) trap, it is challenging to determine the effective temperature T of blackbody radiation, if the trap assembly is heated by rf-losses. Temperature sensors and infrared cameras can be employed to determine T from FEM simulations. Because of the low thermal conductivity of our trap assembly, we expect large uncertainties from such investigations. Thus, we determine the frequency shift from thermal radiation by measuring the clock transition frequency of a single $^{88}Sr^{+}$ ion at three different trap drive powers using our $^{171}Yb^{+}$ clock as the reference. Using the known polarizability of $^{88}Sr^{+}$, we find a temperature uncertainty of only 4 K and determine the ratio of the unperturbed transition frequencies with 6×10^{-17} fractional uncertainty.

Q 50.5 Thu 11:45 A-H3

Two-color grating magneto-optical trap for narrow-line laser cooling — •Saskia Anna Bondza[1,2], Christian Lisdat[1], Stefanie Kroker[3,4,1], and Tobias Leopold[2] — [1]1Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]2DLR-Institute for Satellite Geodesy and Inertial Sensing c/o Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [3]Technische Universität Braunschweig, Institut für Halbleitertechnik, Hans-Sommer-Str. 66, 38106 Braunschweig — [4]LENA Laboratory for Emerging Nanometrology, Langer Kamp 6, 38106 Braunschweig, Germany

We present for the first time design and operation of a two-color grating magneto-optical trap (gMOT) optimized for cooling and trapping of ^{88}Sr atoms on the first and second cooling transition. We trap 10^6 ^{88}Sr atoms on the $^1S_0 \rightarrow {}^1P_1$ transition at 461 nm with a linewidth of 30.2 MHz that are initially cooled to few mK and subsequently transferred to the second cooling stage on the narrow line $^1S_0 \rightarrow {}^3P_1$ transition at 689 nm with a linewidth of 7.48 kHz where they are further cooled to a temperature of 5 μK. We reach a transfer efficiency of 25%. We outline general design considerations for two-colour cooling with a gMOT transferable to other atom species. These results present an important step in further miniaturization of quantum sensors based on cold alkaline-earth atoms.

Q 50.6 Thu 12:00 A-H3

ARTEMIS - HITRAP: Status of the beamline — •Khwaish Kumar Anjum[1,2], Patrick Baus[3], Gerhard Birkl[3], Manasa Chambath[1,4], Kanika Kanika[1,5], Jeffrey Klimes[1,5,6], Wolfgang Quint[1,5], and Manuel Vogel[1] — [1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany — [2]Dept. of Applied Physics, Delhi Technological University, New Delhi, India — [3]Institut für Angewandte Physik, TU Darmstadt, Darmstadt, Germany — [4]Amrita Vishwa Vidyapeetham, Kollam, India — [5]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany — [6]International Max Planck Research School for Quantum Dynamics in Physics, Chemistry and Biology, Heidelberg, Germany

In ARTEMIS (AsymmetRic Trap for measurement of Electron Magnetic moment in IonS), at HITRAP, we aim to perform the g-factor measurements of medium to heavy highly charged ions. It serves as a test of QED in strong fields and we do this using laser-microwave double-resonance spectroscopy. Currently, we are in the process of attaching the cold valve to ARTEMIS which will mark the completion of the beamline. This connects the experiment to the HITRAP facility and the EBIT, an offline ion source, and is on schedule for the planned beamtime of May 2022. Alongside this, in-situ production and analysis of Ar13+ ions are being successfully carried out (up to a few weeks). As of 2021, we have completed the individual assembly of the parts of the beamline connecting ARTEMIS to the HITRAP facility and have received ions in the final Faraday cup of the vertical beamline.

Q 51: General Assembly of the Quantum Optics and Photonics Division

Time: Thursday 13:00–14:00 Location: Q-MV

General Assembly

Q 52: Ultracold Atoms and Molecules II (joint session Q/A)

Time: Thursday 14:00–15:30 Location: Q-H10

Invited Talk Q 52.1 Thu 14:00 Q-H10

Self-bound Dipolar Droplets and Supersolids in Molecular Bose-Einstein Condensates — •Tim Langen — 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Germany

I will discuss the prospects of exploring quantum many-body physics with ultracold molecular gases.

On the theory side, I will present a numerical study of molecular Bose-Einstein condensates with strong dipole-dipole interactions. We observe the formation of self-bound droplets, and explore phase diagrams that feature a variety of exotic supersolid states. In all of these cases, the large and tunable molecular dipole moments enable the study of unexplored regimes and phenomena, including liquid-like density saturation and universal stability scaling laws for droplets, as well as pattern formation and the limits of droplet supersolidity.

On the experimental side, I will discuss progress in molecular laser cooling towards the ultracold regime. I will further present a realistic approach to realize both the collisional stability of ultracold molecular gases and the independent tunability of their contact and dipolar interaction strengths using a combination of microwave and DC electric fields.

Taken together, these results provide both a blueprint and a benchmark for near-future experiments with bulk molecular Bose-Einstein condensates.

Q 52.2 Thu 14:30 Q-H10

Single-beam laser cooling using a nano-structured atom chip — •Hendrik Heine[1], Joseph Muchovo[1], Aaditya Mishra[1], Waldemar Herr[1,2], Christian Schubert[1,2], and Ernst M. Rasel[1] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR), Institut für Satellitengeodäsie und Intertialsensorik, c/o Leibniz Universität Hannover, DLR-SI, Callinstr. 36, D-30167 Hannover, Germany

Matterwave interferometry with Bose Einstein Condensates (BEC) promises exciting prospects in inertial sensing and research on fundamental physics both on ground and in space. BECs can be efficiently created using atom chips and compact setups have already been shown. However, for transportable or space applications further reduction in complexity is desired in order to lower size, weight, and power demands.

I will present a nano-structured atom chip with results on magneto-optical trapping and sub-Doppler cooling using only a single beam of light. This reduces the overall complexity and promises greater long-term stability. We demonstrate state-of-the-art performance and magnetic trapping with the atom chip.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under grant number DLR 50WM1947 (KACTUS-II) and by the German Science Foundation (DFG) under Germany's Excellence Strategy (EXC 2123) "QuantumFrontiers".

Q 52.3 Thu 14:45 Q-H10

Real-Time detection and feedback cooling of the secular motion of an ion — •Hans Dang[1,2], Martin Fischer[1], Atish Roy[1], Lakhi Sharma[1], Markus Sondermann[1,2], and Gerd Leuchs[1,2,3,4] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Friedrich-Alexander University Erlangen-Nürnberg (FAU), Department of Physics, Erlangen, Germany — [3]Department of Physics, University of Ottawa, Canada — [4]Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia

We report on the direct observation of the secular motion of a single ion by imaging it onto a knife-edge using a deep parabolic mirror. The unique misalignment functionals of the phase front of the light collected by the mirror together with its high collection efficiency[1] allow us to detect the motion in a time shorter than the coherence time of the harmonic motion of the ion. Using a known oscillation amplitude to calibrate the detection the temperature of the ion can be extracted from the rms voltage of the measured signal. By applying the phase-shifted and amplified signal to one of the compensation electrodes of the ion trap it is possible to dampen the amplitude of the harmonic oscillation and hence cool the ion. Prospects of expanding the detection to all three motional modes simultaneously will be discussed.

[1] R. Maiwald *et al.*, Physical Review A **86**, 043431 (2012)

Q 52.4 Thu 15:00 Q-H10

Surface charge removal in a microstructured electrostatic trap for cold polyatomic molecules — •Jindaratsamee Phrompao, Michael Ziemba, Florian Jung, Martin Zeppenfeld, Isabel Rabey, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Cold polar molecules are an excellent platform to explore fascinating research areas in both physics and chemistry, such as cold collisions, cold chemistry, and tests of fundamental physics. Motivated by these applications, techniques in the field are advancing rapidly with the overall goal of producing dense and cold molecular samples. To achieve these, electric trapping provides long trapping times and deep confinement of the molecules. In our electrostatic trap [1], we combine two parallel microstructured capacitor plates and a surrounding ring electrode to provide a tunable homogeneous electric control field and transverse confinement, respectively. By combining the various electrodes, polar molecules are confined within a boxlike potential. However, the trap depth is limited by high-voltage breakdown and surface charge accumulation, which possibly also induces early breakdown.

In this talk, we will present induced removal of charges by applying UV light and heating to test samples. We find that heating these to more than $200°C$ can remove the charge almost completely, but the characteristics are not reproducible. In contrast, charge removal by shining in UV light is more reliable and capable of providing rapid and complete charge removal.

[1] B.G.U. Englert et al., Phys. Rev. Lett. 107, 263003 (2011)

Q 52.5 Thu 15:15 Q-H10

Creating an ensemble of cooled and trapped formaldehyde molecules in their ortho ground state — •Maximilian Löw, Martin Ibrügger, Martin Zeppenfeld, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

Direct cooling methods to produce polar molecules in the ultracold regime have improved significantly in recent years. Optoelectrical Sisyphus cooling is one of the most promising techniques in this field providing a large number of electrically trapped molecules at submillikelvin temperatures [1]. However, this method is not applicable to molecules in their absolute ground state.

Cooled ground state molecules can still be obtained by first applying Sisyphus cooling to formaldehyde (H_2CO) molecules in the rotational states $|J{=}3,K_a{=}3,K_c{=}0>$ and $|4,3,1>$. Afterwards, they are transferred to their ortho ground state $|1,1,0>$ by optical pumping via a vibrational transition. In a proof-of-principle experiment we thereby obtained trapped ground state molecules with a temperature of 65 mK and trapping times of several seconds. Colder temperatures should be easily achievable in the future.

As molecules in this state are stable against inelastic two-body collisions this fulfills an important requirement for evaporative or sympathetic cooling of formaldehyde in e.g. a microwave trap which takes us one step further on the envisioned road towards quantum degeneracy.

[1] A. Prehn *et al.*, *Phys. Rev. Lett.* **116**, 063005 (2016).

Q 53: Nano-Optics II

Time: Thursday 14:00–16:15 Location: Q-H11

Q 53.1 Thu 14:00 Q-H11

Spectral stability of nitrogen-vacancy defect centers in diamond nanostructures — •Laura Orphal-Kobin[1], Kilian Unterguggenberger[1], Tommaso Pregnolato[1,2], Natalia Kemf[2], Mathias Mattala[2], Ralph-Stephan Unger[2], Ina Ostermay[2], Gregor Pieplow[1], and Tim Schröder[1,2] — [1]Department of Physics, Humboldt-Universität zu Berlin, Berlin, Germany — [2]Ferdinand-Braun-Institute, Berlin, Germany

Coherent photons are an important resource for many quantum applications, for example, in long-distant quantum networks stationary qubits can be entangled by photon-mediated protocols. In solid-state systems, noise in the environment of a quantum emitter, such as fluctuations of the local charge density, lead to a change of the optical transition frequency over time and therefore to inhomogeneous broadening, which is referred to as spectral diffusion. Overcoming spectral diffusion is still a major challenge for solid-state quantum emitters and limits the generation of indistinguishable single photons.

In our work, we investigate the spectral properties of NV defect centers in diamond nanostructures by performing photoluminescence excitation measurements. We analyze the impact of different excitation parameters on the optical linewidth and spectral dynamics of the NV zero-phonon-line. Moreover, excitation power and energy-dependent measurements combined with nanoscopic Monte Carlo simulations provide fundamental insights, relating the spectral properties of the NV to its charge environment. Based on our results, we propose a protocol for entanglement generation using NVs in nanostructures.

Q 53.2 Thu 14:15 Q-H11

Improving the purity of single photon emission from SnV^- centers in diamond — •Philipp Fuchs[1], Johannes Görlitz[1], Michael Kieschnick[2], Jan Meijer[2], and Christoph Becher[1] — [1]Universität des Saarlandes, Fachrichtung Physik, Campus E2.6, 66123 Saarbrücken, Germany — [2]Universität Leipzig, Angewandte Quantensysteme, Linnéstraße 5, 04103 Leipzig, Germany

Color centers in diamond have been demonstrated to be versatile systems that can be used as quantum sensors, long-living qubits, and single photon sources. However, their performance is often limited by imperfections from fabrication. For the negatively-charged tin vacancy center (SnV^-) in diamond, we found the ion implantation in combination with the subsequent annealing to induce severe surface and subsurface damage, leading to strongly fluctuating background fluorescence. This uncorrelated fluorescence reproducibly limits the achievable single photon purity of SnV^- centers created via ion implantation.

We demonstrate that a simple thermal oxidation process enables us to significantly reduce this damage and by this the background fluorescence, yielding a strongly enhanced single photon purity. We propose that the fluctuating background fluorescence originates from unoccupied surface states that become depleted after the thermal oxidation induces a proper surface termination. Finally, we distill all information from these and earlier experiments to a simple rate equation model, that helps gaining new insights into the charge stability and quantum efficiency of SnV^- centers in diamond.

Q 53.3 Thu 14:30 Q-H11

Experimental and theoretical investigation on spin-optical dynamics of silicon vacancy centers in silicon carbide — •Di Liu[1,2], Naoya Morioka[3], Öney Soykal[4], Nguyen Tien Son[5], Jawad Ul-Hassan[5], Florian Kaiser[1,2], and Jörg Wrachtrup[1,2] — [1]3rd Institute of Physics, University of Stuttgart, Stuttgart, Germany — [2]Institute for Quantum Science and Technology (IQST), Germany — [3]Institute for Chemical Research, Kyoto University, Japan — [4]Booz Allen Hamilton, McLean, VA, USA — [5]Department of Physics, Chemistry, and Biology, Linköping University, Sweden

Silicon vacancy centers (V_{Si}) in silicon carbide are promising spin-based quantum emitters for quantum information applications owing to their excellent spin-optical properties. Yet, the internal spin-optical dynamics of V_{Si} centers remains poorly understood, mainly due to the intrinsic limitations of $g^{(2)}$ measurements. In this work, we present a high-accuracy study of the electronic fine structure of V_{Si} including all interaction mechanisms. Our results are based on a new set of resonant and above-resonant excitation schemes in the high-power regime offering excellent data quality. Our results are confirmed by theory based on quantum mater equations. We also estimate the system's quantum efficiency with measured rates. In summary, our work provides an in-depth understanding of silicon vacancy centers' spin-optical dynamics and assists optimum designing of nanophotonic enhancement structures which play an important role in scalable quantum applications.

Q 53.4 Thu 14:45 Q-H11

Colloidal quantum dots as integrated single photon sources — •Alexander Eich, Tobias Spiekermann, Helge Gehring, Lisa Sommer, Julian Bankwitz, Wolfram Pernice, and Carsten Schuck — Institute of physics, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany

The integration of nano-scale quantum emitters with photonic integrated circuits holds great promise for realizing a scalable quantum technology platform. However, interfacing large numbers of independently controllable single emitter systems efficiently with nanophotonic structures for quantum technologies is a major challenge.

In our work, we employ colloidal quantum dots as single photon emitter system that can be processed in solution at wafer-scale. We embed such quantum dots into tantalum pentoxide (Ta2O5) nanophotonic waveguides by utilizing lithographically patterned apertures in polymer thin-films that achieve high overlay accuracy with nanophotonic devices. We further employ broad-band polymer coupling structures produced in 3D direct laser writing 1 as fiber-chip interconnects and demonstrate anti-bunching behavior for the photoluminescence collected from waveguide-integrated quantum dots 2. Our work paves the way towards large-scale integration of quantum light sources into photonic integrated circuits. [1] Gehring, Helge, et al., Optics letters 44.20 (2019): 5089-5092. [2] Eich, Alexander, et al, arXiv preprint arXiv:2104.11830 (2021).

Q 53.5 Thu 15:00 Q-H11

Coherent control of group-4 vacancies in diamond for the purpose of cluster state creation — •Gregor Pieplow, Joseph H. D. Munns, Mariano I. Monsalve, and Tim Schröder — Department of Physics, Humboldt-Universität zu Berlin, Germany

One of the biggest challenges in measurement-based photonic quantum computation is the creation of 2d-cluster states, a type of highly entangled resource state. Cluster states enable quantum computation through purely local operations and measurements on the individual qubits that make up the state. Crucially, measurement-based quantum computation does not require additional entangling operations, because entanglement is already present in the resource state. The difficulty in entangling individual photons is thus separated from the details of the computation and can be studied in isolation. In this contribution we address the generation of a linear cluster state with group-4 vacancies such as the Silicon Vacancy (SiV) and Tin Vacancy (SnV) in diamond. An emission-based scheme for the generation of a linear cluster state on a group-4 vacancy platform requires local control operations and Purcell enhancement. This work explores local gate operations with a Raman scheme and addresses additional challenges that arise when Purcell enhancement is introduced.

Q 53.6 Thu 15:15 Q-H11

Electrical excitation of color centers in phosphorus-doped diamond Schottky diodes — •Florian Sledz[1], Igor A. Khramtsov[2], Assegid M. Flatae[1], Stefano Lagomarsino[1], Navid Soltani[1], Shannon S. Nicley[3], Ken Haenen[3], Jin Qun[4], Xin Jiang[4], Paul Kienitz[5], Peter Haring Bolivar[5], Dmitry Yu. Fedyanin[2], and Mario Agio[1] — [1]Laboratory of Nano-Optics, University of Siegen, Siegen Germany — [2]Laboratory of Nanooptics and Plasmonics, Moscow Institute of Physics and Technology, Dolgoprudny Russian Federation — [3]Institute for Materials Research (IMO) & IMOMEC, Hasselt University & IMEC vzw, Diepenbeek, Belgium — [4]Institute of Materials Engineering, University of Siegen, Siegen Germany — [5]Institute of Graphene-based Nanotechnology, University of Siegen, Siegen Germany

A robust single-photon source operating upon electrical injection at ambient condition is desirable for quantum technologies. Silicon-vacancy color centers in diamond are promising candidates as their emission is concentrated in a narrow zero-phonon line with a short excited-state lifetime of ≈ 1 ns. Under optical excitation we observed single silicon-vacancy color centers in n-type diamond [1]. In contrast to common approaches based on p-n or p-i-n structures, we developed an approach for the electrical excitation based on color centers in a Schottky barrier diode. This paves the way for the predicted bright luminescence of electrically driven color centers in diamond [2]. Ref.: [1]. Flatae et al Diam. Relat. Mater. 105, 107797 (2020). [2]. Fedyanin and Agio, New J. Phys. 18, 073012 (2016).

Q 53.7 Thu 15:30 Q-H11

Direct Measurement of Emission Probabilities in Single Photon Emitters — •Pablo Tieben[1,2] and Andreas W. Schell[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Gottfried Wilhelm Leibniz Universität, Hannover, Germany

Single photon sources are an essential part in the development of a number of quantum technologies. Understanding the intrinsic properties of new sources of single photons is paramount for their successful application. One of the key properties, among others, is their saturation behavior in terms of the ratio of the number of excitation photons to the number of emitted photons. Especially for photoactive defect centers in semiconductors, the existence of intermediate dark states has been shown, which leads to a shelving effect at high excitation powers. To circumvent this limitation of the photon yield, a repumping from these long lived states can be implemented via two-color excitation, where the second wavelength is matched to the transition energy between the intermediate and the excited state. We report on a measurement technique to directly determine the excitation probability as a function of the pulse intensity by using a tunable, strongly fluctuating, pulsed source of laser light and performing time correlated measurements between the pulse intensity and the photon count events in a synchronized time basis. Furthermore, we apply this scheme to two-color excitation measurements of single photon emitters in hexagonal boron nitride (hBN) to simultaneously retrieve saturation functions over the two dimensional parameter space of wavelength dependent excitation power.

Q 53.8 Thu 15:45 Q-H11

Purcell effect and strong extinction observed on a single molecule coupled to a chip-based micro-resonator — •Dominik Rattenbacher[1,2], Alexey Shkarin[1], Jan Renger[1], Tobias Utikal[2], Stephan Götzinger[2,1], and Vahid Sandoghdar[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Friedrich Alexander University, Erlangen, Germany

Coupling organic molecules to integrated optical circuits is a promising route to creating compact and controlled ensembles of interacting quantum emitters. We present our recent advances in realizing such an experimental platform based on sub-wavelength waveguides (nanoguides) and micro-resonators on a chip. We demonstrate the coupling of single molecules to linear nanoguides [1,2] and the control of the resonance frequencies via integrated microelectrodes [2,3]. Since the coupling efficiency between the molecule and the nanoguide is inherently limited by geometric and material constraints, we employed different host matrices and discuss various resonator designs to enhance the coupling. We demonstrate a resonator finesse up to 250 ($Q = 16000$), leading to significant Purcell enhancement and extinction dips of 60 % [3]. Furthermore, we show the controlled manipulation and tuning of molecular resonances, leading to the simultaneous coupling of two individual molecules to well-defined resonator modes [3].

[1] D. Rattenbacher et al., New J. Phys. 21, 062002 (2019)
[2] A. Shkarin et al., Phys. Rev. Lett. 126, 133602 (2021)
[3] D. Rattenbacher, A. Shkarin et al., in progress

Q 53.9 Thu 16:00 Q-H11

Photoelectrical imaging of the dark state of SiV in diamond — •Ilia Chuprina[1], Milos Nesladek[2], Adam Gali[3], Petr Siyushev[1], and Fedor Jelezko[1] — [1]Institute for Quantum Optics, Ulm University, D-89081 Germany — [2]Institute for Materials Research (IMO), Hasselt University, Wetenschapspark 1, 3590 Diepenbeek, Belgium — [3]Wigner Research Centre for Physics, P.O. Box 49, H-1525, Budapest, Hungary

Group-IV defects in diamond are promising candidates for quantum information processing. Among them, silicon-vacancy (SiV) is the most studied one, and yet, many questions remain, particularly about optimization of the creation yield, stabilization in different charge states, etc. Recently, a developed photoelectrical imaging technique might be a powerful tool to unravel some of that questions. In this work, we present our recent results on the charge dynamics of SiV centers in diamond using optical and photoelectrical detection technics. Exploiting photoelectrical measurements, we visualize optically inactive defects, which can be turned on and off upon applying a different bias voltage to the electrodes. Using a combination of photoluminescence spectroscopy and photoelectrical imaging, we attribute these dark defects to another SiV charge state and discuss possible models of charge state dynamics. This behavior can be fairly extended to the whole family of the group-IV defects in diamond. Our findings might be useful for the development of the active charge state control of the group-IV defects.

Q 54: Quantum Information (Quantum Repeater)

Time: Thursday 14:00–15:45 Location: Q-H12

Q 54.1 Thu 14:00 Q-H12

Atom-Atom Entanglement over 33 km Telecom Fiber — •Pooja Malik[1,2], Tim van Leent[1,2], Matthias Bock[3], Florian Fertig[1,2], Robert Garthoff[1,2], Sebastian Eppelt[1,2], Yiru Zhou[1,2], Tobias Bauer[3], Wei Zhang[1,2], Christoph Becher[3], and Harald Weinfurter[1,2,4] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Fachrichtung Physik, Universität des Saarlandes, Saarbrücken, Germany — [4]Max-Planck Institut für Quantenoptik, Garching, Germany

Scalable quantum networks will allow for secure quantum communication and distributed quantum computing. Heralded entanglement between distant quantum memories is one of the building blocks for such networks. To this end, we present our results of heralded entanglement between two independent quantum memories generated over fiber links with a length of up to 33 km. The two quantum memories consist of a single Rubidium (^{87}Rb) atom each and are located 400 m apart [1]. In order to entangle the two (^{87}Rb) atoms, we start with entangling the spin state of an atom with the polarization state of a photon in each node. The emitted photons (780 nm) are then converted to the low loss telecom S band (1517 nm) to overcome high attenuation loss in optical fiber over longer distances [2]. Finally, these photons are guided to a middle station where a Bell-state measurement swaps the entanglement to the atoms.

[1] T.van Leent et al., arXiv:2111.15526 (2021)
[2] T.van Leent et al., Phys. Rev. Lett. 124, 010510 (2020)

Q 54.2 Thu 14:15 Q-H12

Coupling Erbium Dopants to Nanophotonic Silicon Structures — •Andreas Gritsch, Lorenz Weiss, Stephan Rinner, Johannes Früh, Florian Burger, and Andreas Reiserer — Quantum Networks Group, Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany – Munich Center for Quantum Science and Technology (MCQST), Ludwig-Maximilians-Universität München, Fakultät für Physik, Schellingstraße 4, D-80799 München, Germany

Erbium dopants are promising candidates for the implementation of large-scale quantum networks since they can combine second-long ground state coherence [1] with coherent optical transitions at telecommunication wavelength [2].

Recent results show that erbium ions implanted into silicon nanostructures are integrated at well-defined lattice sites with narrow inhomogeneous (~1 GHz) and homogeneous (<20 kHz) linewidths and long lifetimes of the optical excited states (~0.25 ms) [3]

We proceed towards the control of individual erbium dopants by fabricating photonic crystal cavities which may reduce the lifetime by more than three orders of magnitude. This will allow us to resolve and control individual dopants, making our system a promising candidate for the implementation of distributed quantum information processing over large distances.

[1] M. Rancic, et. al., Nat. Physics, 14, 50-54 (2018), [2] B. Merkel, et. al., Phys. Rev. X 10, 041025 (2020), [3] A. Gritsch, et. al., Arxiv, 2108.05120 (2021).

Q 54.3 Thu 14:30 Q-H12

A one-node quantum repeater — Stefan Langenfeld, Philip Thomas, •Olivier Morin, and Gerhard Rempe — Max-Planck-Institute für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

For long distance quantum communication, losses in optical fibers constitute a real hurdle. Indeed, because the transmission efficiency scales exponentially with distance, any qubit exchange is basically impossible beyond typically 500km. The quantum repeater solves this problem via an improved rate-versus-distance scaling by dividing a long link into multiple short ones.

Using a cavity QED platform, ^{87}Rb atoms in a high-finesse optical cavity, we have developed all the necessary features required to implement a quantum repeater: long coherence time qubit memories [1], accurate control of the photon shape [2], low-cross-talk random access memories [3]. With these capabilities in hand, we have implemented an elementary quantum repeater. At the central node, two atoms send photons (entangled with the atomic states) repeatedly until it is received by each end of the link. Eventually, a Bell measurement is realized on the two atoms which entangles the two ends of the link. With this experimental realization, we observed an improvement by a factor 2 in the rate-versus-distance scaling, the central feature of a quantum repeater [4].

[1] M. Körber *et al.*, Nat. Photonics **12**, 18 (2018).
[2] O. Morin *et al.*, Phys. Rev. Lett. **123**, 133602 (2019).
[3] S. Langenfeld *et al.*, npj Quantum Inf **6**, 86 (2020).
[4] S. Langenfeld *et al.*, Phys. Rev. Lett. **126**, 230506 (2021).

Q 54.4 Thu 14:45 Q-H12

Larmor precession-free atom-photon entanglement using Raman scattering from a single ^{40}Ca$^+$ ion — •Matthias Kreis, Jelena Ritter, Stephan Kucera, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

Atom-photon entanglement is an essential resource for a sender-based quantum repeater scheme. One implementation is a flying qubit, encoded in the polarization of an emitted photon, which is entangled with a stationary qubit, encoded in the internal state of a single ion. If Zeeman leves are used for the ionic qubit, the phase of the generated atom-photon state depends on the emission time of the photon, due to the magnetic energy splitting [1,2].

In order to make the phase time-independent, one can use an ion trapped inside a cavity [3]. In this scheme, a bi-chromatic laser with the same frequency difference as the involved Zeeman-shifted transitions in the ion is used.

Here, we report on a alternative scheme using a single ^{40}Ca$^+$-ion together with an external cavity that acts as a quantum eraser. The cavity filter removes unwanted spectral components, which results in detection-time independent atom-photon entanglement. We present the generation of phase-stable atom-photon entanglement at 393 nm and at 854 nm wavelength with fidelity 0.95.

[1] C. Kurz et al., Phys. Rev. A **93**, 062348 (2016).
[2] M. Bock et al., Nat. Commun. **9**, 1998 (2018).
[3] A. Stute et al., Nature **485**, 482-485 (2012).

Q 54.5 Thu 15:00 Q-H12

Coherent manipulation of RF-dressed qubit states in a single ^{40}Ca$^+$ ion — •Pascal Baumgart, Hubert Lam, Stephan Kucera, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, D-66123 Saarbrücken

Fluctuating environmental magnetic fields are detrimental for quantum coherence of Zeeman levels of single trapped ions, which may be utilised as stationary quantum bits in quantum communication protocols. By properly dressing the Zeeman levels, one may create magnetic field-independent qubits (clock transitions) [1]. We study the dressed manifolds of the $S_{1/2}$ and $D_{5/2}$ levels in a single ^{40}Ca$^+$ ion by Ramsey spectroscopy, combining RF and laser excitation (similar to [2]), with the perspective of storing quantum information in magnetic field-insensitive qubits with long coherence time.

[1] N. Aharon et al., New J. Phys. **21**, 083040 (2019)
[2] K. N. Dietze, MSc Thesis, TU Braunschweig, (2019)

Q 54.6 Thu 15:15 Q-H12

Quantum teleportation based on a full 4-state atom-photon Bell measurement — •Jan Arenskötter, Omar Elshehy, Christian Haen, Floriane Brunel, Stephan Kucera, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, D-66123 Saarbrücken

The projection on Bell states is a key procedure for quantum-state teleportation and for entanglement swapping schemes as required for a quantum repeater [1,2]. We present a scheme that distinguishes between all four hybrid atom-photon Bell-states. It is based on heralded absorption [3] of the photonic qubit by a ^{40}Ca$^+$ ion whereby the nonabsorbed photons pass the ion in a second passage by a time delayed back-reflection. The scheme is demonstrated via atom-to-photon quantum teleportation of a qubit encoded in the $D_{5/2}$ Zeeman sub-levels of the ion onto the polarization qubit of a single 854 nm photon. We use a cavity-enhanced spontaneous parametric down-conversion source in interferometric configuration as resource of polarization entanglement which is tailored to match the $D_{5/2}$ - $P_{3/2}$ transition at 854 nm. Quantum process tomography between the atomic input states and the photonic output states validates the successful projection onto the Bell-states.

[1] M. Zukowski et al., Phys. Rev. Lett. **71**, 4287 (1993)
[2] H.-J. Briegel et al., Phys. Rev. Lett. **81**, 5932 (1998)
[3] C. Kurz et al., Nat. Commun. **5**, 5527 (2014)

Q 54.7 Thu 15:30 Q-H12

Simultaneous single-photon extraction from two $^{40}Ca^{+}$ ions in a single trap — •Max Bergerhoff, Omar Elshehy, Stephan Kucera, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

Atom-photon interfaces [1,2] are a basic requirement for any ion-based quantum network [3]. We are pursuing the implementation of a 'quantum repeater cell' according to [4] on the basis of photon emission and absorption; some steps of the required functionality have been realized, such as high-fidelity entanglement between a single ion and a telecom photon [2].

Here, we report an experiment for creating atom-photon entanglement with two $^{40}Ca^{+}$ ions in the same trap, separately coupled to single-mode fibers. We present the optical setup to separate the 854 nm photons from the two ions and characterize it with arrival time measurements of the photons.

The width of the wave packets of the separately collected photons gives us lower bounds for the quantum repeater functionality. We further discuss the $g^{(2)}$-function obtained by correlating arrival times of the two wave packets. We detect 0.56 photon pairs per second.

[1] C. Kurz et al., Nat. Commun. 5, 5527 (2014)
[2] M. Bock et al., Nat. Commun. 9, 1998 (2018)
[3] H. Kimble, Nature 453, 1023-1030 (2008)
[4] D. Luong et al., Appl. Phys. B 122, 96 (2016)

Q 55: Quantum Effects III

Time: Thursday 14:00–15:30 Location: Q-H13

Q 55.1 Thu 14:00 Q-H13

Observation of long-lived metastable structures in a quantum gas with long-range interactions — •Simon Hertlein[1], Alexander Baumgärtner[1], Carlos Máximo[1], Tom Schmit[2], Giovanna Morigi[2], Davide Dreon[1], and Tobias Donner[1] — [1]Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich, 8093 Zurich, Switzerland — [2]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany

We study relaxation of a quantum gas after quenches across a phase transition and in the presence of competing long-range interactions. The interactions are mediated by two cavity modes, which induce competing spatial ordering. The quenches are implemented by changing the detuning between an external laser frequency and the cavity resonances. Using the real-time access to the order parameters provided by the leaking cavity fields, we observe metastability for a large range of parameters. The atoms remain frozen in the initial pattern with lifetimes that exceed any natural time scale of the system before relaxing to the stable configuration. From an ab- initio treatment we derive a Vlasov equation. We show that its fixed points are the metastable configurations, which can be understood as quasi-stationary states due to the long-range interactions. By this mean we theoretically reproduce the character- istic time scale of relaxation and their dependence on the physical parameters. We attribute the observed metastability to the competing global range interactions.

Q 55.2 Thu 14:15 Q-H13

Characterisation of lasing from cold trapped Yb atoms — •Saran Shaju, Dmitriy Sholokhov, and Jürgen Eschner — — Universität des Saarlandes, Germany

We observe optical gain and laser emission from a medium of a few thousand Ytterbium-174 atoms which are magneto-optically trapped (MOT), using their $^1S_0 \rightarrow {}^1P_1$ transition at 399 nm, inside a 5-cm long high-finesse cavity. The cavity output is observed as continous wave lasing on the $^1S_0 \rightarrow {}^3P_1$ intercombination line at 556 nm when the atoms are laser-pumped on the same transition. The physics behind the observation is understood as a multi-photon lasing mechanism involving the MOT transition [1]. By heterodyne analysis, we analyse the frequency characteristics of the system versus pump and cavity detuning. By cooling the atoms near the Doppler limit of the intercombination transition, we observe an increase in atomic density and a corresponding reduction of the laser threshold.

[1] H. Gothe, D. Sholokhov, A. Breunig, M. Steinel, and J. Eschner. Phys. Rev. A, 99, 013415, 2019.

Q 55.3 Thu 14:30 Q-H13

Emergent atom pump in a non-hermitian system — •Alexander Baumgärtner, Davide Dreon, Simon Hertlein, Xiangliang Li, Tilman Esslinger, and Tobias Donner — Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich, 8093 Zürich, Switzerland

The time evolution of a quantum system can be strongly affected by dissipation. Although this mainly implies that the system relaxes to a steady state, in some cases it can make new phases appear and trigger emergent dynamics. In our experiment, we study a Bose-Einstein Condensate dispersively coupled to a high finesse resonator. The cavity is pumped via the atoms, such that the sum of the coupling beam(s) and the intracavity standing wave gives an optical lattice potential. When the dissipation and the coherent timescales are comparable, we find a regime of persistent oscillations where the cavity field does not reach a steady state. In this regime the atoms experience an optical lattice that periodically deforms itself, even without providing an external time dependent drive. Eventually, the dynamic lattice triggers a pumping mechanism. We show complementary measurements of the light field dynamics and of the particle transport, proving the connection between the emergent non-stationarity and the atomic pump.

Q 55.4 Thu 14:45 Q-H13

Anisotropy of multiple quantum fluorescence signals — •Friedemann Landmesser[1], Ulrich Bangert[1], Lukas Bruder[1], Edoardo Carnio[1,2], Mario Niebuhr[1], Vyacheslav Shatokhin[1,2], Andreas Buchleitner[1,2], and Frank Stienkemeier[1] — [1]Institute of Physics, University of Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, University of Freiburg, Germany

We investigate collective effects in thermal atomic alkali vapors by multiple-quantum coherence experiments, where multiphoton processes can be separated from one-photon transitions and can be assigned to specific particle numbers [1, 2]. The technique is sensitive enough to reveal weak interparticle interactions, despite the thermal motion and the spatial separation of the atoms in the micrometer-range [3]. We experimentally investigate the dependence of such signals on the laser polarization, which was previously predicted theoretically for a similar physical system [4].

[1] L. Bruder et al., Phys. Rev. A 92, 053412 (2015).
[2] S. Yu et al., Opt. Lett. 44, 2795 (2019).
[3] L. Bruder et al., Phys. Chem. Chem. Phys. 21, 2276 (2019).
[4] B. Ames et al., J. Chem. Phys. 155, 44306 (2021).

Q 55.5 Thu 15:00 Q-H13

Characterization of a localization transition in a power-law interacting spin model without disordered potentials — •Adrian Braemer[1] and Martin Gärttner[1,2,3] — [1]Physikalisches Institut, Heidelberg, Deutschland — [2]Kirchhoff-Institut für Physik, Heidelberg, Deutschland — [3]Institut für Theoretische Physik, Heidelberg, Deutschland

The impact of disorder on quantum many-body systems has been studied extensively over the past decade. Disorder commonly takes the form of random potentials which leads to localized eigenstates at sufficiently high disorder strength. Here we study the localization transition in a Heisenberg XXZ spin chain, where the disorder is exclusively due to random spin-spin couplings, arising from power-law interactions between randomly positioned sites. We use established spectral and eigenstate properties and entanglement entropy to show that there is indeed a transition from an ergodic to a localized regime. We identify strongly interacting pairs as emergent local conserved quantities in the system, leading to an intuitive physical picture consistent with our numerical results.

Q 55.6 Thu 15:15 Q-H13

Does a disordered Heisenberg spin system thermalize? — •Titus Franz[1], Adrien Signoles[2], Adrian Braemer[3], Renato Ferracini Alves[1], Sebastian Geier[1], Annika Tebben[1], André Salzinger[1], Nithiwadee Thaicharoen[1,4], Clément Hainaut[1,5], Gerhard Zürn[1], Martin Gärttner[1], and Matthias Weidemüller[1] — [1]Physikalisches Institut, Heidelberg University, Germany — [2]Pasqal, France — [3]Kirchhoff-Institut für Physik, Heidelberg University, Germany — [4]Research Center for Quantum Technology, Chiang Mai University, Thailand — [5]Université de Lille, CNRS, UMR 8523 - PhLAM, France

The far-from-equilibrium dynamics of generic disordered systems is expected to show thermalization, but this process is yet not well understood and shows a rich phenomenology ranging from anomalously slow relaxation to the breakdown of thermalization. While this problem is notoriously difficult to study numerically, we can experimentally probe the relaxation dynamics in an isolated spin system realized by a frozen gas of Rydberg atoms. The long-time magnetization as a function of a transverse external field shows striking features including non-analytic behavior at zero field. These can be understood from mean-field, perturbative, and spectral arguments. The emergence of these distinctive features seems to disagree with Eigenstate Thermalization Hypothesis (ETH), which indicates that either a better theoretical understanding of thermalization is required or ETH breaks for the here studied quench in a disordered spin system.

Q 56: Ultra-cold plasmas and Rydberg systems (joint session A/Q)

Time: Thursday 14:00–15:45 Location: A-H1

Q 56.1 Thu 14:00 A-H1

Ion-Rydberg interactions observed by a high-resolution ion microscope — •Moritz Berngruber, Nicolas Zuber, Viraatt Anasuri, Yiquan Zou, Florian Meinert, Robert Löw, and Tilman Pfau — 5. Physikalisches Institut, Universität Stuttgart, Center for Integrated Quantum Science and Technology (IQST)

In this talk, we present the latest experimental results on spatially resolved ion-Rydberg-atom interaction studied with our high-resolution ion microscope. The apparatus provides a highly tunable magnification, ranging from 200 to over 1500, a spatial resolution better than 200 nm and a depth of field of more than 70 μm. These properties and the excellent electric field compensation enable the observation of ion-Rydberg-interaction in cold bulk quantum gases. The direct spatial imaging method allows for in-situ images of a new type of long-range Rydberg-atom-ion molecule in rubidium, which arises from a binding mechanism that is based on the interaction between the ionic charge and a flipping induced dipole of a Rydberg atom [1].
In addition, the ion microscope also allows for spectroscopic studies of the vibrational level structure. Moreover, the good temporal resolution of the detector enables the observation of dynamic phenomena during the interaction process which compared to traditional molecules are slowed down by many orders of magnitude.
[1] Zuber, N., et al. "Spatial imaging of a novel type of molecular ions." arXiv preprint arXiv:2111.02680 (2021).

Q 56.2 Thu 14:15 A-H1

Chiral Rydberg States of Laser Cooled Atoms — •Stefan Aull[1], Steffen Giesen[2], Markus Debatin[1], Peter Zahariev[1,3], Robert Berger[2], and Kilian Singer[1] — [1]Institut für Physik, Universität Kassel, Heinrich-Plett-Str. 40, 34132 Kassel — [2]Fb. 15 - Chemie, Hans-Meerwein-Straße 4, 35032 Marburg — [3]Institute of Solid State Physics, Bulgarian Academy of Sciences, 72, Tzarigradsko Chaussee, 1784 Sofia, Bulgaria

We propose a protocol for the preparation of chiral Rydberg states. It has been shown theoretically that using a suitable superposition of hydrogen wavefunctions, it is possible to construct an electron density and probability current distribution that has chiral nature. Following a well established procedure for circular Rydberg state generation and subsequent manipulation with taylored radio frequency pulses under the influence of a magnetic field, the necessary superposition with correspondingly set phases can be prepared. Enantio-selective excitation using photo-ionization circular dichroism is under theoretical and experimental development.

Q 56.3 Thu 14:30 A-H1

Coherent delocalization in a frozen Rydberg gas — •Matthew Eiles, Ghassan Abumwis, Christopher Wächtler, and Alexander Eisfeld — Max Planck Institut für Physik komplexer Systeme, Nöthnitzer Str. 38 01187 Dresden

The long-range dipole-dipole interaction can create delocalized states due to the exchange of excitation between Rydberg atoms. We show that even in a random gas many of the single-exciton eigenstates are surprisingly delocalized, composed of roughly one quarter of the participating atoms. We identify two different types of eigenstates, one which stems from strongly-interacting clusters and one which extends over large delocalized networks, and show how to excite and distinguish them via appropriately tuned microwave pulses. The extent of delocalization can be enhanced by degeneracies in the atomic states which be controllably lifted using the Zeeman splitting provided by a magnetic field.

Q 56.4 Thu 14:45 A-H1

From Highly Charged to Neutral Microplasma — •Mario Grossmann, Julian Fiedler, Jette Heyer, Markus Drescher, Klaus Sengstock, Philipp Wessels-Staarmann, and Juliette Simonet — The Hamburg Centre for Ultrafast Imaging (CUI), Luruper Chaussee 149, 22761 Hamburg

By combining an ultracold quantum gas of ^{87}Rb with strong-field ionization in femtosecond laser pulses, we investigate the dynamics of highly charged to neutral microplasmas.
Our experimental setup enables us to detect ions and electrons separately and resolve their kinetic energies.
We locally ionize an ultracold target with densities of up to $10^{20}\mathrm{m}^{-3}$ within a micrometer sized focus. This allows creating initially strongly coupled plasmas with ion temperatures below 40 mK and a few hundred to thousand charged particles.
The excess energy of the electrons can be tuned via the wavelength of the ionizing laser pulse resulting in initial electron temperatures from 5800 K to 65 K. This directly impacts the neutrality of the plasma:
High excess energies yield a highly charged plasma with rapid electron cooling whereas low excess energies trigger a neutral plasma with greatly increased lifetimes. Below the ionization threshold we observe ultrafast excitation of Rydberg states.
The small number of particles permits us to compare our results to molecular dynamics simulations that grant access to the non-equilibrium plasma dynamics on picosecond timescales.

Q 56.5 Thu 15:00 A-H1

Non-equilibrium Spin Dynamics using the Discrete Truncated Wigner Approximation — •Neethu Abraham[1,2] and Sebastian Wüster[1] — [1]Department of Physics, Indian Institute of Science Education and Research, Bhopal, Madhya Pradesh 462 066, India — [2]Department of Physics, Indian Institute of Science Education and Research, Tirupati, Andhra Pradesh 517 507, India

Approximate simulation methods play a crucial role in the efficient numerical computation of quantum dynamics in many body spin systems, since the exponentially increasing dimension of their Hilbert space cannot be treated exactly. We have investigated the realm of applicability of a very recently developed phase space method, based on the Monte Carlo sampling of the discrete Wigner function: the discrete truncated Wigner approximation (DTWA). Using the DTWA, we show that an aggregate of Rydberg atoms immersed in a background of detector atoms can serve as a quantum simulating platform for various many body physics problems. Decoherence in the excitation transport induced by the interactions with the background atoms can be controlled by altering the distance between the aggregate and detector atoms. This may allow for an experimental platform to examine energy transport subject to an environment.

We were also able to look at quench dynamics in condensed matter spin systems using essentially the same techniques due to the mathematical similarities between the Hamiltonians of these two systems. We explore the possible supremacy of DTWA over other methods, such as tDMRG, for the study of Domain Wall melting in a 2D spin lattice.

Q 56.6 Thu 15:15 A-H1

Quantum simulations with circular Rydberg atoms — •Christian Hölzl, Aaron Götzelmann, Alexander Buhl, Achim Scholz, Moritz Wirth, and Florian Meinert — 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Stuttgart, Germany

Highly excited low-l Rydberg atoms in configurable mircotrap arrays have recently proven highly versatile for studying quantum many-body spin systems with single particle control. I will report on the advances of a new project pursuing to harness high-l circular Rydberg atoms for quantum simulation. When stabilized against black body radiation (BBR) in a suitable cavity structure, circular Rydberg states promise orders of magnitude longer lifetimes compared to their low-l counterparts and thus provide an appealing potential to strongly boost coherence times in Rydberg-based interacting atom arrays. To maintain excellent high-NA optical access we exploit a novel approach using an indium tin oxide (ITO) capacitor, capable of surpressing the parasitic microwave BBR even in a non-cryogenic environment while beeing transparent to visible light.

Q 56.7 Thu 15:30 A-H1

Phonon dressing of a facilitated one-dimensional Rydberg lattice gas — •Matteo Magoni, Paolo P. Mazza, and Igor Lesanovsky — Institut für Theoretische Physik, Eberhard Karls Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

We study the dynamics of a one-dimensional Rydberg lattice gas under facilitation conditions which implement a so-called kinetically constrained spin system. Here an atom can only be excited to a Rydberg state when one of its neighbours is already excited. Once two or more atoms are simultaneously excited mechanical forces emerge, which couple the internal electronic dynamics of this many-body system to the external vibrational degrees of freedom in the lattice. This electron-phonon coupling results in a so-called phonon dressing of many-body states which in turn impacts on the facilitation dynamics.

In our theoretical study we focus on a scenario in which all energy scales are sufficiently separated such that a perturbative treatment of the coupling between electronic and vibrational states is possible. This allows to analytically derive an effective Hamiltonian for the evolution of clusters of consecutive Rydberg excitations in the presence of phonon dressing [1]. We analyse the spectrum of this Hamiltonian and show, by employing Fano resonance theory, that the interaction between Rydberg excitations and lattice vibrations leads to the emergence of slowly decaying bound states that inhibit fast relaxation of certain initial states. We supplement our analysis by providing detailed experimental considerations on the validity of the approximations used.

[1] M. Magoni et al., arXiv: 2104.11160 (2021)

Q 57: Quantum Gases II

Time: Thursday 16:30–18:30 Location: P

Q 57.1 Thu 16:30 P

An algebraic geometric study of the solution space of the 1D Gross-Pitaevskii equation — •David Reinhardt[1], Matthias Meister[1], Dean Lee[2], and Wolfgang P. Schleich[1] — [1]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany — [2]Michigan State University, Facility for Rare Isotope Beams and Department of Physics and Astronomy, East Lansing, Michigan, USA

The stationary solutions of the Schrödinger equation considering box or periodic boundaries show a clear correspondence to solutions found for the non-linear Gross-Pitaevskii equation commonly used to model Bose-Einstein condensates. However, in the non-linear case there exists an additional class of solutions for periodic boundaries first identified by L.D. Carr et al. [1]. These nodeless complex symmetry breaking solutions have no corresponding counterpart in the linear case. To examine how these solutions behave in the limit of vanishing non-linearity we consider an algebraic geometric picture. Therefore, we treat both equations in the hydrodynamic framework, resulting in a first-order differential equation for the density determined by a quadratic polynomial in the linear case and by a cubic polynomial in the non-linear case, respectively. Our approach allows for a clear geometric interpretation of the solution space in terms of the nature and location of the roots of these polynomials.

[1] L.D. Carr, C.W. Clark, W.P. Reinhardt, Phys. Rev. A 62, 063610 & 063611 (2000)

Q 57.2 Thu 16:30 P

Emerging long-range magnetic phenomena in a quantum gas coupled to a cavity — •Nicola Reiter, Rodrigo Rosa-Medina, Fabian Finger, Francesco Ferri, Tobias Donner, and Tilman Esslinger — Institute for Quantum Electronics, ETH Zürich, 8093 Zürich, Switzerland

Dissipative and coherent processes are at the core of the evolution of many-body systems. Their interplay can lead to new phases of matter and complex non-equilibrium dynamics. However, probing these phenomena microscopically in a setting of controllable coherent and dissipative couplings proves challenging.

We realize such a system using a ^{87}Rb spinor Bose-Einstein condensate (BEC) strongly coupled to a single optical mode of a lossy cavity. Two transverse laser fields incident on the BEC allow for cavity-assisted Raman transitions between different motional states of two neighboring spin levels. Adjusting the drive imbalance controls coherent dynamics and dissipation, with the appearance of a dissipation-stabilized phase and bistability. By characterizing the properties of the underlying polariton modes, we give a microscopic interpretation of our observations.

Moreover, we realize dynamical superradiant currents in a spin-textured lattice in momentum space. Real-time, frequency-resolved measurements of the leaking cavity field allow us to locally resolve individual tunneling events and cascaded dynamics. Together, our results open new avenues for investigating spin-orbit coupling in dissipative settings and dynamical gauge fields in driven-dissipative settings.

Q 57.3 Thu 16:30 P

Observation of unconventional many-body scarring in a quantum simulator — •Guo-Xian Su[1], Hui Sun[1], Ana Hudomal[2], Jean-Yves Desaules[2], Zhao-Yu Zhou[1], Bing Yang[3], Jad Halimeh[4], Zhen-Sheng Yuan[1], Zlatko Papić[2], and Guoxian Su[1] — [1]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — [2]Im Neuenheimer Feld 226 — [3]Department of Physics, Southern University of Science and Technology, Shenzhen, China — [4]INO-CNR BEC Center and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy

Quantum many-body scarring has recently opened a window into novel mechanisms for delaying the onset of thermalization, however its experimental realization remains limited to the $\mathbb{Z}_2$ state in a Rydberg atom system. Here we realize unconventional many-body scarring in a Bose–Hubbard quantum simulator and extend scarring to the unit-filling state. Our measurements of entanglement entropy illustrate that scarring traps the many-body system in a low-entropy subspace. Further, we develop a quantum interference protocol to probe out-of-time correlations, and demonstrate the system's return to the vicinity of the initial state by measuring single-site fidelity. Our work makes the resource of scarring accessible to a broad class of ultracold-atom experiments, and it allows to explore its relation to constrained dynamics in lattice gauge theories, Hilbert space fragmentation, and disorder-free localization.

Q 57.4 Thu 16:30 P

Investigation of Josephson vortices in coaxial ring-shaped Bose-Einstein condensates — •Dominik Pfeiffer[1], Ludwig Lind[1], Daniel Derr[1], Gerhard Birkl[1], Nataliia Bazhan[2], Yelyzaveta Nikolaieva[2], Anton Svetlichnyi[2], and Alexander Yakimenko[2] — [1]Institut für Angewandte Physik, TU Darmstadt,

Schlossgartenstraße 7, 64289 Darmstadt, Germany — [2]Department of Physics, Taras Shevchenko National University of Kyiv, Kyiv 01601, Ukraine

Josephson vortices (JV) attract considerable interest due to their perspectives for application in ultra-sensitive rotation sensors and quantum information processing systems. Remarkably, Josephson vortices, being extensively investigated for decades, have not yet been demonstrated experimentally in atomic BECs. The first direct observation of rotational JVs in bosonic junctions now appears as a realistic goal. We investigate the generation of JVs between two coaxial toroidal BECs coupled in a coplanar and in a vertically stacked system. In both systems we generate counter-rotating flows and demonstrate the formation of the JVs. Our results open up a way to the first direct experimental observation of rotational JVs in atomic BECs. We present experimental schemes for the creation of two coupled coaxial rings in a coplanar system based on optical dipole potentials and ultra cold-atoms. Utilizing a digital micromirror device, arbitrary topological charges can be accessed and imprinted onto the coaxial rings. We investigate the feasibility of these techniques to create the desired states, atom distributions, and dynamic behavior.

Q 57.5 Thu 16:30 P

Hole pairing in Fermi-Hubbard ladders systems observed with a quantum gas microscope — •Thomas Chalopin[1], Sarah Hirthe[1], Dominuk Bourgund[1], Petar Bojović[1], Annabelle Bohrdt[3], Fabian Grusdt[2], Eugene Demler[4], Immanuel Bloch[1,2], and Timon Hilker[1] — [1]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany — [2]Ludwig-Maximilians-Universität, 80799 München, Germany — [3]Harvard University, Cambridge, MA 02138, USA — [4]ETH Zurich, 8093 Zurich, Switzerland

The Fermi-Hubbard model is an iconic model of solid state physics that is believed to capture the intricate physics of strongly correlated phases of matter such as High-Tc superconductivity. Such a state of matter supposedly achieved upon doping a cold antiferromagnetic Mott insulator. Pairing of dopants (holes), in particular, is considered to be a key mechanism for the occurrence of unconventional superconductivity.

Here, I will present our experimental observation of hole pairing due to magnetic order in a Fermi-Hubbard-type system in our Lithium quantum-gas microscope. We engineer mixed-dimensional*Fermi-Hubbard ladders in which an offset suppresses the tunneling along the rungs, while it enhances spin exchange and singlet formation, thus drastically increasing the binding energy. We observe that holes preferably sit on the same rung in order to maintain magnetic ordering, i.e. singlets on the other rungs of the ladder. We furthermore find indications for repulsion between pairs when there is more than one pair in the system.

Q 57.6 Thu 16:30 P

Exploration of spin imbalanced few fermion systems in position and momentum space — •Sandra Brandstetter, Carl Heintze, Keerthan Subramanian, Marvin Holten, Philipp Preiss, and Selim Jochim — Physics Institute, University of Heidelberg, Germany

Recent advances in the preparation of ultracold few-fermion systems combined with a spin resolved TOF imaging technique with single particle resolution, have led us to the first observation of Cooper pairs of interacting atoms [1]. However, the exploration of correlations in real space has so far remained elusive, owing to the small system size, which we can't resolve with our optical imaging setup.

In this poster we present the addition of a matter wave microscopy scheme [2], enabling us to access the spatial distribution of our atoms. While it is too small to resolve with our imaging setup, we can magnify it using a combination of two T/4 evolutions in traps with different trapping frequencies.

Additionally, we have recently achieved the preparation of imbalanced systems with different number of particles in the two spin states. Combining this with our access to both the momentum and real space correlations, we aim to explore open questions on the nature of the phase diagram and pairing in spin imbalanced systems [3,4].

[1] M. Holten, et al. arXiv:2109.11511 (2021).
[2] L. Asteria et al. Nature 599, 571*575 (2021).
[3] R. Schmidt and T. Enss. Phys. Rev. A 83 (2011)
[4] Felipe Attanasio et al. 2021. arXiv: 2112.07309 (2021)

Q 57.7 Thu 16:30 P

Towards fast, deterministic preparation of few-fermion states — •Maximilian Kaiser, Tobias Hammel, Micha Bunjes, Armin Schwierk, Matthias Weidemüller, Philipp Preiss, and Selim Jochim — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg (Germany)

Measurements of higher-order correlations in quantum systems, e.g. for the tomography of complex quantum states, requires large data sets. This demand stands in contrast to typical cycle times of 10 seconds or more in traditional experiments with ultracold quantum gases.

We report on the ongoing development of an apparatus for fast, experimental quantum simulations using ultracold Lithium-6 with envisioned cycle times of less than 1 second. Within each run, few-fermion states are being prepared in a sequence based upon [1]. The resulting high data output will especially be key for iteration-intensive research in the future.

[1] Deterministic Preparation of a Tunable Few-Fermion System - F.Serwane et Al., Science Vol. 332 (2011)

Q 57.8 Thu 16:30 P

Realizing a superlattice for studying topological systems with interacting fermions — •Nick Klemmer, Janek Fleper, Jens Samland, Andrea Bergschneider, and Michael Köhl — Physikalisches Institut, University of Bonn, Bonn, Germany

Quantum simulation of the Hubbard model using ultracold atoms in optical lattices has been essential for studying strongly correlated matter. Optical superlattices, mostly realized by a superposition of two trapping wavelengths, have enabled the emulation of more complex systems. For instance, on our experiment we used an out-of-plane superlattice to study magnetic correlations in a coupled-bilayer Hubbard model [1].

In our experiment, we prepare atoms in a few-layer stack of two-dimensional lattices. Currently, we are setting up an in-plane superlattice that provides us with a chain of double wells with tunable coupling strengths. For characterizing and stabilizing the superlattice phase, we have implemented a bichromatic Michelson interferometer. This will allow us to deterministically prepare atoms in the superlattice with any desired energy tilt of the double wells. Combined with the control over the scattering length we will investigate interacting topological systems and study transport properties in time-dependent superlattices.

[1] Gall, Wurz, et al., Nature 589, 40-43 (2021)

Q 57.9 Thu 16:30 P

Realization of the symmetry-protected Haldane phase in Fermi-Hubbard ladders — •Petar Bojović[1], Pimonpan Sompet[1,2], Sarah Hirthe[1], Dominik Bourgund[1], Thomas Chalopin[1], Joannis Koepsell[1], Guillaume Salomon[1,3], Julian Bibo[4], Ruben Verresen[5], Frank Pollmann[4], Christian Gross[1,6], Immanuel Bloch[1,7], and Timon Hilker[1] — [1]Max-Planck-Institut für Quantenoptik, Garching — [2]Research Center for Quantum Technology, Chiang Mai University, Chiang Mai, — [3]Institut für Laserphysik, Universität Hamburg, Hamburg — [4]Department of Physics, Technical University of Munich, Garching — [5]Department of Physics, Harvard University, Cambridge — [6]Physikalisches Institut, Universität Tübingen, Tübingen — [7]Fakultät für Physik, Ludwig-Maximilians-Universität, München

The Haldane antiferromagnetic spin-1 chain constitutes a paradigmatic model of a quantum system which holds a symmetry-protected topological phase. Here, we experimentally realize the Haldane phase using Fermi-Hubbard ladders in an ultracold quantum gas microscope. Site-resolved potential shaping allows us to create tailored spin-1/2 geometries which permit the exploration of such a topological chain and its comparison to a trivial configuration. We use spin- and density-resolved measurements to probe edge and bulk properties of the system, revealing a non-local string order parameter and localized spin-1/2 edge states We furthermore investigate the robustness of the topological phase upon the onset of density fluctuations by tuning the Hubbard interaction.

Q 57.10 Thu 16:30 P

Modulation Transfer Spectroscopy in Atomic Lithium-6 — •Leo Walz, Tobias Hammel, Maximilian Kaiser, Selim Jochim, and Matthias Weidenmüller — Physikalisches Institut, Heidelberg, Germany

Good experimental control and imaging of ultracold quantum gasses is in many parts achieved through precisely tuned laser pulses, often with a frequency specifically detuned to an atomic transition or directly on resonance. This requires active frequency stabilization of the laser system.

This poster shows the implementation of a modulation transfer spectroscopy setup to exploit the strong dispersive property of atomic transitions on modulated laserlight within the Doppler-free saturation regime. Modulation transfer through degenerate four-wave mixing leads to a zero baseline error signal with a steep signal slope at the zero crossing, that is centered on the atomic transition. Further optimization guided by theory from [1] leads to a fast and high fidelity error signal well suitable for external laser locking. With this setup, frequency deviations on a scale of 1/10th to the natural linewidth are resolvable. In this regime, the leading contribution to frequency noise comes from pressure fluctuations through acoustic noise in the lab.

[1] Tilman Preuschoff, Malte Schlosser, and Gerhard Birkl Opt. Express 26, 24010-24019 (2018)

Q 58: Matter Wave Optics

Time: Thursday 16:30–18:30 Location: P

Q 58.1 Thu 16:30 P

Coulomb-induced loss of spatial coherence of femtosecond laser-triggered electrons from needle tips — •Jonas Heimerl, Stefan Meier, and Peter Hommelhoff — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

In the past, tungsten needle tips have been a playground to study a plethora of effects around non-linear electron photoemission. The emitted electrons from such tips are strongly localized to nanometer length and femtosecond time scales when using few-cycle laser pulses. Because of the spatial localization, the electrons possess a high spatial coherence, which can be probed by matter wave interference experiments [1]. In this contribution, we show how Coulomb interactions in the multi-electron regime reduce the spatial coherence, well supported by numerical simulations. In a further step, we use these results to make estimations towards the correlation between two electron wavepackets.

[1] S. Meier *et al.*, Appl. Phys. Lett. **113**, 143101 (2018).

Q 58.2 Thu 16:30 P

Using interferometers to measure molecular properties — •Philipp Rieser, Armin Shayeghi, and Markus Arndt — University of Vienna, Faculty of Physics, Vienna Center for Quantum Science and Technology (VCQ), , Boltzmanngasse 5, A-1090 Vienna, Austria

The wave nature of molecules is a perfect example of the peculiarities of quantum physics. Molecular quantum optics deals with phenomena related to this wave nature, particularly the interaction of molecules with light.

The working principle of molecule interferometers, namely generating nanoscale fringes in the density distribution of molecular beams, makes them sensitive to external perturbations at nanometre scale. This high sensitivity to beam shifts and dephasing effects can be used to extract a variety of intrinsic molecular electronic properties[1].

Molecular matter-wave experiments have the potential of opening a wide field of research at the interface between quantum optics and chemical physics. Complex many-body systems have a vast variety of electric, magnetic and optical properties that make controlled perturbations an interesting and possibly useful tool for future applications[2].

References

[1] S. Eibenberger et al., Phys. Rev. Lett. 112, 250402 (2014).

[2] J. Rodewald, et al., Appl. Phys. B 123,3 (2017).

Q 58.3 Thu 16:30 P

Towards diffracting atoms through graphene — •Jakob Bühler and Christian Brand — German Aerospace Center (DLR), Institute of Quantum Technologies

Modifying graphene by introducing foreign atoms and defects is a commonly used approach to augment its properties [1]. While often beams of fast atoms are used, the interaction process is only partly understood. To resolve this issue, we plan to diffract atomic hydrogen with a velocity of up to 120 000 m/s through the 246 pm lattice of graphene [2]. Thereby, we aim to directly probe the atom-graphene interaction during transmission, using the diffraction pattern as the read out. Using fast atoms will also provide new opportunities for fundamental tests of physics, such as quantum friction [3]. [1] Wang and Shi, Phys. Chem. Chem. Phys. **17**, 28484 (2015) [2] Brand et al. New J. Phys. **21**, 033004 (2019) [3] Silveirinha, New J. Phys. **16** 063011 (2014)

Q 58.4 Thu 16:30 P

Femtosecond laser-triggered electron emission from cooled needle tips — •Manuel Knauft, Norbert Schönenberger, Stefan Meier, Jonas Heimerl, and Peter Hommelhoff — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

Dielectric laser acceleration offers a miniaturized framework of creating high-energy beams of charged particles, enabling applications where large-scale accelerators are unfeasible. The nanometric dimensions of these require electron sources with utmost beam quality. Similarly, in the context of microscopy and fundamental research coherent electron sources are of high specific interest. It is well known that reducing the operating temperature of the tip emitter positively influences coherence. In this contribution, we present initial experimental results from cooled needle emitters triggered with femtosecond laser pulses.

Q 58.5 Thu 16:30 P

Creating auto-ponderomotive potentials with planar, chip-based electrodes for electron beam manipulation — •Franz Schmidt-Kaler, Michael Seidling, and Peter Hommelhoff — Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

Advances in complex free electron beam manipulation are shown to be possible based on planar electrodes and electrostatic fields. In the frame of the moving electrons these static fields transform into an alternating auto-ponderomotive potential. This confining pseudopotential resembles the one of a radiofrequency-driven Paul trap. Well-designed electrode layouts enable electron beam splitting and curved guiding, which we demonstrated. The applied electron energies range from a few eV to 1.7 keV (splitting) and 9.5 keV (guiding) permitting integration into standard scanning electron microscopes to allow entirely new electron control.

Q 58.6 Thu 16:30 P

The logarithmic phase singularity in the inverted harmonic oscillator — •Freyja Ullinger[1,2], Matthias Zimmermann[2], and Wolfgang P. Schleich[1,2] — [1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ^{ST}), Universität Ulm, 89081 Ulm, Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), 89081 Ulm, Germany

Relevant phenomena in quantum field theory, such as Hawking radiation and acceleration radiation [1,2], are based on a logarithmic phase singularity and the presence of an event horizon in spacetime.

In this poster, we show that related effects emerge in the simple quantum system of a one-dimensional inverted harmonic oscillator. In fact, the Wigner function corresponding to an energy eigenfunction of this system [3,4] clearly displays a horizon in phase space. Although usually hidden, even a logarithmic phase singularity in combination with an amplitude singularity emerges with the help of a suitable coordinate transformation.

Our insights into this simple quantum system lay the foundation for future applications in the field of matter wave optics.

[1] S. W. Hawking, Nature **248**, 30 (1974)

[2] M. O. Scully, S. Fulling, D. M. Lee, D. N. Page, W. P. Schleich, and A. A. Svidzinsky, Proc. Natl. Acad. Sci. U.S.A. **115**, 8131 (2018)

[3] N. L. Balazs and A. Voros, Ann. Phys. (N. Y.) **199**, 123 (1990)

[4] D. M. Heim, W. P. Schleich, P. M. Alsing, J. P. Dahl, and S. Varro, Phys. Lett. A **377**, 1822 (2013)

Q 58.7 Thu 16:30 P

QUANTUS 2 - Towards dual species atom interferometry in microgravity — •Laura Pätzold[1], Merle Cornelius[1], Julia Pahl[2], Peter Stromberger[3], Waldemar Herr[4,5], Sven Herrmann[1], Markus Krutzik[2,6], Patrick Windpassinger[3], Christian Schubert[5], Ernst M. Rasel[4], and The QUANTUS

Team[1,2,3,4,6,7,8] — [1]U Bremen — [2]HU Berlin — [3]JGU Mainz — [4]LU Hannover — [5]DLR-SI — [6]FBH Berlin — [7]U Ulm — [8]TU Darmstadt

Matter wave interferometry allows for quantum sensors with a wide range of applications, e.g. in geodesy or tests of fundamental physics. As a testbed for future space missions, the QUANTUS-2 experiment enables rapid BEC production of Rb-87 atoms with 10^5 atoms and performs atom interferometry in free fall at the ZARM drop tower in Bremen. In combination with a magnetic lens, we are able to reduce the total internal kinetic energy to 38 pK in three dimensions [1]. Here, we present the latest results on our single species interferometry experiments and an outlook on the integration of a potassium laser system, which will open up the possibility to study and manipulate quantum gas mixtures, as well as to perform dual species atom interferometry in microgravity. This project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant numbers DLR 50WM1952-1957.

[1] C. Deppner et al., Phys. Rev. Lett. **127**, 100401 (2021)

Q 58.8 Thu 16:30 P

Second-order correlations of scattering electrons — •Florian Fleischmann[1], Mona Bukenberger[2], Raul Corrêa[3], Simon Mährlein[1], Anton Classen[4], Marc-Oliver Pleinert[1], and Joachim von Zanthier[1] — [1]Department Physik, Universität Erlangen-Nürnberg — [2]Department of Environmental Systems Science, ETH Zürich — [3]Departamento de Física, Federal University of Minas Gerais, Brazil — [4]Institute for Quantum Science and Engineering, Texas A&M University, USA

We investigate the spatial second-order correlation function of two scattering electrons in the far field. We first estimate semi-classically how the Pauli exclusion principle and the Coulomb repulsion affect the expected correlation pattern. We then treat the problem fully quantum-mechanically. To that aim, in analogy to the solution of the hydrogen atom, the system is separated into center-of-mass and relative coordinates. In the relative system, we solve the Coulomb scattering problem while the center of mass system can be described in a plane wave ansatz. After incorporating the time evolution, the function is evaluated in the far field. The formal solutions of the problem are shown and the current state of the numerical investigation is discussed.

Q 58.9 Thu 16:30 P

Ray Tracing for Matter Wave Optics — •Maurice Bardel and Reinhold Walser — Institute of Applied Physics, Technical University Darmstadt, Germany

Ray tracing is an effective method for the semi-classical simulation of the dynamics of thermal clouds [1]. It is based on the idea of studying the dynamics of quantum gases in phase space. For this purpose, the cold thermal clouds ($T > T_{BEC}$) are described in the Wigner representation. By applying the truncated Wigner approximation (semi-classical limit), the time evolution expressed by the quantum Liouville-von-Neumann equation corresponds to the classical transport equation. This allows us to consider the solutions of the associated Hamilton's equations to obtain the evolution of the Wigner distribution function.

We simulate the optical guiding of a thermal cloud inside a laser beam (optical dipole potential) and delta kick collimation with magnetic lense [2, 3]. This is helpful for testing and optimising matter wave optics, as needed for matter wave interferometers [1].

References:

[1] Mathias Schneider, *Semi-classical description of matter wave interferometers and hybrid quantum systems*, Doktorarbeit, Technische Universität Darmstadt (2014)

[2] Hubert Ammann and Nelson Christensen, *Delta Kick Cooling: A New Method for Cooling Atoms*, Phys. Rev. Lett. 78, 2088 (1997)

[3] H. Müntinga et al., *Interferometry with Bose-Einstein Condensates in Microgravity*, Phys. Rev. Lett. 110, 093602 (2013)

Q 58.10 Thu 16:30 P

Time-averaged potentials for optical matter-wave lensing — •Simon Kanthak[1,2], Gilad Kaplan[1], Martina Gebbe[3], Ekim Hanimeli[3], Matthias Gersemann[4], Mikhail Cheredinov[4], Sven Abend[4], Ernst M. Rasel[4], Markus Krutzik[1,2], and the QUANTUS team[1,2,3,4] — [1]Institut für Physik, HU Berlin — [2]Ferdinand-Braun-Institut, Berlin — [3]ZARM, Universität Bremen — [4]Institut für Quantenoptik, LU Hannover

Residual expansion and size of Bose-Einstein condensates, determined by the features of the release trap and repulsive atom-atom interactions, become the limiting factors for signal extraction in atom interferometry on long timescales. Attempts to overcome these limitations include precisely shaping the expansion of the atomic ensembles after the release via matter-wave lensing.

Optical potentials allow for the flexible creation of matter-wave lenses of different shapes and refractive powers [1]. Here, we report on the realization of and results with our dipole trap setup, which features an acousto-optical deflector to tailor potentials in multiple dimensions. With this setup, versatile optical lens systems can be engineered in pulsed schemes for ground-based sensors, which open the opportunity to compensate the center-of-mass motion of the atoms or to counteract anharmonicities of the release traps.

This work is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under Grant No. 50WM1952 (QUANTUS-V-Fallturm).

[1] S. Kanthak et al., 2021, *New J. Phys.* 23, 093002

Q 59: Precision Measurements and Metrology II (joint session Q/A)

Time: Thursday 16:30–18:30 Location: P

Q 59.1 Thu 16:30 P

Experimental and theoretical investigations for an all optical coherent quantum noise cancellation scheme — •Bernd Schulte[1,2], Jonas Junker[1,2], Mariia Matiushechkina[1,2,3], Roman Kossak[1,2], Nived Johny[1,2], and Michèle Heurs[1,2,3] — [1]Max Planck Institute for Gravitational Physics and Institute for Gravitational Physics, Hannover, Germany — [2]Quantum Frontiers — [3]PhoenixD

Optomechanical detectors can and have been used successfully for the ultra-precise measurement of weak forces. The sensitivity of such detectors is limited by the standard quantum limit (SQL) which is defined by the shot noise of the probe beam and the quantum radiation pressure back action noise. To surpass the SQL Tsang and Caves suggested a scheme [1] with an anti-noise (ancilla cavity) path which is coupled to the measurement device (meter cavity) to destructively interfere the radiation pressure back action noise. In this scheme the anti-noise path contains a two-mode squeezer and a beam splitter interaction. To achieve perfect coherent quantum noise cancellation (CQNC), exact matching of the respective coupling strengths is required. Additionally, the linewidths of the ancilla cavity and mechanical oscillator needs to be matched and the ancilla cavity needs to be sideband-resolved. Our group has conducted a detailed analysis of the proposed method under experimentally feasible conditions and has shown that even for non-perfect matching one can surpass the SQL [2].

[1] M. Tsang and C. Caves, Phys. Rev. Lett. 105, 123601, (2010)

[2] M. H. Wimmer et al, Phys. Rev. A 89, 053836 (2014)

Q 59.2 Thu 16:30 P

Towards magneto-optical trapping of Zinc — •Marc Vöhringer Carrera, David Röser, and Simon Stellmer — Physikalisches Institut, University of Bonn, Germany

In the pursuit of increasingly precise time and frequency standards, optical lattice clocks belong to the prime candidates. Among the various approaches and elements currently under investigation, it remains unclear which element will eventually turn out to be the most suitable for the numerous applications.

We investigate the element Zinc as a potential candidate for an optical lattice clock. This study is motivated by various favorable properties of Zinc, including a very low sensitivity to black-body radiation shifts [1]. Its core advantage however is the possible derivation of its clock transition frequency as the fifth harmonic of 1547.5 nm [2], lying in the telecom C-band, thus allowing convenient frequency transfer via optical fibers.

To construct an optical lattice clock based on Zinc, many challenges lie ahead. One of them is the construction of a 214 nm laser system for the first cooling stage, as well as the implementation of a two-stage

MOT. We report on progress from the lab regarding these challenges.

[1] Dzuba et al., J. Phys. B 52, 215005 (2019)
[2] Büki et al., Appl. Opt. 60, 9915-9918 (2021)

Q 59.3 Thu 16:30 P

Current status of the Al^+ ion clock at PTB — •Fabian Dawel[1,2], Johannes Kramer[1,2], Marek B. Hild[1,2], Steven A. King[1,2], Ludwig Krinner[1,2], Lennart Pelzer[1,2], Stephan Hannig[1,2], Kai Dietze[1,2], Nicolas Spethmann[1], and Piet O. Schmidt[1,2] — [1]QUEST Institute for Experimental Quantum Metrology, Physikalisch Technische Bundesanstalt, 38116 Braunschweig — [2]Leibniz Universität Hannover, 30167 Hannover

Since 1967 time is defined via a hyperfine transition in caesium-133. Optical clocks offer advantages over microwave clocks in terms of statistical and systematic uncertainties. A particularly promising candidate is the $^1S_0 \rightarrow ^3P_0$ transition of $^{27}Al^+$. The advantageous atomic properties resulting in small uncertainties in magnetic, electric and black-body shifts. Here we report on the design and operation of the $^{27}Al^+$ clock at PTB. In our clock implementation, Al^+ is co-trapped with $^{40}Ca^+$ in a linear Paul trap. The working principle of quantum logic spectroscopy and a lifetime-limited excitation rabi cycle on the Al^+ logic transition is demonstrated. We will present an evaluation of systematic frequency shifts using the more sensitive Ca^+ as a proxy. All investigated shifts have an uncertainty below 10^{-18}. We will show measurements of the ac-Zeeman shift of our trap and unveil first measurements on the Al^+ clock transition with a power-broadened linewidth of 48 Hz.

Q 59.4 Thu 16:30 P

Towards testing Local Lorentz Invariance in a Coulomb crystal of $^{172}Yb^+$ ions — •Kai C. Grensemann[1], Chih-Han Yeh[1], Laura S. Dreissen[1], Henning A. Fürst[1,2], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Institut für Quantenoptik, Leibniz Universität Hannover,Welfengarten 1, 30167 Hannover, Germany

We report on our recent progress towards testing Local Lorentz Invariance on a Coulomb crystal of $^{172}Yb^+$ ions. The F-state of $^{172}Yb^+$ is highly sensitive to low-energy Lorentz violation (LV) and the ion offers excellent experimental controllability [1]. While the Earth rotates, the quantization axis of our setup probes different directions in space. Thus, a potential LV would manifest itself in a modulation of the energy splitting between Zeeman sublevels throughout the sidereal day. However, the octupole transition to the F-state strongly suffers from a large AC-Stark shift of a few 100 Hz and a first order Zeeman sensitivity [2]. Therefore, to achieve efficient excitation of all ions, spatial homogeneity of the laser beam's intensity and the magnetic field is needed. We address these challenges with simulations and experimentally, using ions as precise quantum sensors. In addition, we will discuss robust dynamical decoupling schemes [3] that make the measurement insensitive to slow magnetic field and intensity fluctuations.

[1] V.A. Dzuba et al., *Nature Physics* **12**, 465-468 (2016). [2] H. A. Fürst et al., *Phys. Rev. Lett.* **125**, 163001 (2020). [3] R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018).

Q 59.5 Thu 16:30 P

Uncertainty Characterization of an In^+ Single Ion Clock — •Moritz von Boehn[1], Hartmut Nimrod Hausser[1], Tabea Nordmann[1], Jan Kiethe[1], Nishant Bhatt[1], Jonas Keller[1], Oleg Prudnikov[3], Valera I. Yudin[3], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Leibniz Universität Hannover, Hannover, Germany — [3]Institute of Laser Physics SB RAS, Novosibirsk, Russia

Nowadays optical ion clocks achieve fractional frequency uncertainties on the order of 10^{-18} and below. Due to its low systematic shift sensitivities, $^{115}In^+$ is a promising candidate to go beyond this uncertainty level. Moreover, it has favorable properties for scaling to multiple clock ions, such as a transition for direct state detection [1]. We present the first clock operation in our setup using an $^{115}In^+$ ion sympathetically cooled by an $^{172}Yb^+$ ion in a linear Paul trap and its uncertainty characterization at the 10^{-17} level.

The In^+ ion's residual thermal motion causes a time dilation frequency shift. A way to further decrease the resulting frequency uncertainty is via a reduced final temperature of the cooling process. We report on our progress towards direct laser cooling of indium. Indium offers a narrow intercombination line $^1S_0 \leftrightarrow ^3P_1$ ($\gamma = 360$ kHz), enabling temperatures close to the motional ground state. Cooling on this transition could sufficiently decrease the time dilation related frequency uncertainty, to allow for overall systematic uncertainties at the 10^{-19} level [2]. [1] N. Herschbach et al., *Appl. Phys. B* **107**, 891-906 (2012). [2] J. Keller et al., *PRA* **99**, 013405 (2019).

Q 59.6 Thu 16:30 P

Characterization of a Laser System for a Rubidium Two-Photon Frequency Reference — •Daniel Emanuel Kohl[1,2], Julien Kluge[1,2], Klaus Döringshoff[1,2], and Markus Krutzik[1,2] — [1]Institut f. Physik - Humboldt-Universität zu Berlin — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik

Global navigation satellite systems and deep space navigation require precise clocks with stringent requirements on size, weight and power budgets. Besides advanced RF clocks, optical clocks are envisioned for application in next generation GNSS. Laser spectroscopy of atomic vapor in conjunction with optical frequency combs may provide such compact, high precision frequency standards with fractional instabilities comparable to optical state-of-the-art GNSS systems.

Rubidium offers narrow linewidth two-photon transition at 778 nm from 5S to 5D, which can be detected via monochromatic fluorescence at 420 nm. In this poster, we present a two-photon Rubidium frequency reference featuring an extended cavity diode laser applied to a heated and magnetically shielded vapor cell. With this setup we achieved a fractional frequency instability of $7 \cdot 10^{-13}$. Recent spectroscopy results will be presented as well as considerations for the most suitable transition within the Manifold. We further report on details of the lasers system including power stabilization and suppression of residual amplitude modulation.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50RK1971.

Q 59.7 Thu 16:30 P

Frequency stability of a cryogenic silicon resonator with crystalline mirror coatings — •Jialiang Yu[1], Thomas Legero[1], Fritz Riehle[1], Daniele Nicolodi[1], Sophia Herbers[1], Chun Yu Ma[1], Dhruv Kedar[2], Eric Oelker[3], Jun Ye[2], and Uwe Sterr[1] — [1]Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany — [2]JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado, USA — [3]University of Glasgow, UK

The state-of-the-art performance of ultra-stable lasers is limited by various noise contributions like Brownian thermal noise of the optical coatings. In our 21 cm long optical resonator at 124 K, made from single-crystal silicon with low noise $Al_{0.92}Ga_{0.08}As/GaAs$ crystalline mirror coatings, we have investigated a new type of noise associated with the birefringence of these coatings.

To elucidate its nature we have expanded our set-up to lock two independent laser frequencies to two polarization eigenmodes of the resonator, separated by 200 kHz. The observed anti-correlated fluctuations allowed us to cancel the birefringence noise by taking their mean, resulting in an instability below $3.5 \cdot 10^{-17}$. We investigated spatial noise correlations by observing the fluctuations of the difference frequency between TEM_{00} and TEM_{01} modes, and find that local noise like Brownian thermal noise of the coating is below 10^{-17}, consistent with previous estimates. However, there is significant excess noise; most likely from the coating's semiconducting properties.

Q 59.8 Thu 16:30 P

PTB's transportable Al^+ ion clock - concept and current status — •Constantin Nauk[1], Benjamin Kraus[1,2], Stephan Hannig[1,2], and Piet O. Schmidt[1,2,3] — [1]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [2]DLR-Institute for Satellite Geodesy and Inertial Sensing, 30167 Hannover, Germany — [3]Leibniz Universität Hannover, Institut für Quantenoptik, 30167 Hannover, Germany

Optical atomic clocks provide significantly lower fractional systematic and statistical frequency uncertainties compared to state-of-the-art microwave atomic clocks. A particularly promising candidate for high-accuracy applications is $^{27}Al^+$ as its $^1S_0 \rightarrow ^3P_0$ transition is relatively insensitive towards external electromagnetic fields, especially to black body radiation. However, direct laser cooling of $^{27}Al^+$ is more than challenging. Instead, the clock ion can be cooled sympathetically by a co-trapped and well-controllable $^{40}Ca^+$ ion, which additionally allows state detection of the Al^+ ion via quantum logic spectroscopy.
Besides its design, we present the current status of our transportable

ion quantum logic optical clock towards fractional frequency uncertainties on the order of 10^{-18} and review compact and robust breadboarding for UV laser systems.

Q 59.9 Thu 16:30 P

Decreasing ion optical clock instability by multi-ion operation — •Hartmut Nimrod Hausser[1], Tabea Nordmann[1], Jan Kiethe[1], Jonas Keller[1], Nishant Bhatt[1], Moritz von Boehn[1], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Leibniz Universität Hannover, Hannover, Germany

The statistical uncertainty of single-ion clocks is fundamentally limited by quantum projection noise which can be reduced by scaling up the number of ions [1]. We are working on a demonstration of a multi-ion clock using $^{115}In^{+}$ clock ions, sympathetically cooled by $^{172}Yb^{+}$ in a linear segmented Paul trap. This trap is optimized for multi-ion operation and offers e. g. low axial micromotion for spatially extended linear Coulomb crystals and low heating rates [2]. We discuss sympathetic cooling of mixed-species crystals and its dependence on the cooling ion positions. To ensure reproducible conditions in the presence of decrystallizing background gas collisions, we experimentally implement crystal ordering sequences and characterize their reliability. Chains up to 10 In^{+} ions can be ordered with reliabilities >90%. We show multi-ion spectroscopy results with a fixed crystal configuration, obtained by conditionally triggering such sequences when required.

[1] N. Herschbach et al., *Appl. Phys. B* **107**, 891-906 (2012)
[2] J. Keller et al., *Phys. Rev. A* **99**, 013405 (2019)

Q 59.10 Thu 16:30 P

Towards a miniaturized, all diode laser based strontium lattice clock demonstrator — •Christoph Pyrlik[1,5], Vladimir Schkolnik[1,5], Ronald Holzwarth[2], Robert Jördens[3], Enrico Vogt[4], Andreas Wicht[5], Markus Krutzik[1,5], and the SOLIS1G team[1,2,3,4,5] — [1]Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin — [2]Menlo Systems GmbH, Bunsenstr. 5, 82152 Martinsried — [3]QUARTIQ GmbH, Rudower Chaussee 29, 12489 Berlin — [4]Qubig GmbH, Balanstr. 57, 81541 München — [5]Ferdinand Braun Institut gGmbH, Gustav-Kirchhoffstraße 4, 12489 Berlin

SOLIS1G is a joint project targeting to develop critical technologies for future space-born optical lattice clocks and verify these by operating a miniaturized, all diode laser based strontium lattice clock demonstrator.

We will report on the current design of the SOLIS1G clock and give an overview on the technological concepts to be developed towards reducing the size, weight and power budget such as micro-integrated laser and distribution modules, compact optical modulators, miniaturized physics package and robust frequency combs.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR50WM2151 and DLR50RP2190B.

Q 59.11 Thu 16:30 P

Active optical clocks: Towards continuous superradiance on the clock transition of strontium — •Sheng Zhou, Francesca Famà, Camila Beli Silva, Stefan Alaric Schäffer, Shayne Bennetts, and Florian Schreck — Institute of Physics, University of Amsterdam

Active optical clocks based on superradiance have been proposed to directly obtain light with the stability of an atomic transition [1]. This approach decouples clock performance from limitations in ultrastable resonators, and could dramatically reduce limitations due to cavity pulling and required averaging times.

Superradiant pulses have been experimentally demonstrated on the 1S0-3P0 'mHz' transition of 87Sr [2]. However, continuous operation is needed to achieve state-of-the-art performance.

We will describe a continuous superradiant laser using the mHz clock transition of strontium. Our approach is based on loading a cold atomic beam [3] of 3P0 excited atoms into a moving magic lattice propagating along the mode of a bow-tie cavity. In this way, large numbers of atoms can be loaded along the cavity mode while maintaining low atomic densities and long lifetimes [5]. Using the fluxes from [3] and [4], an estimation of emitted powers of 0.3 pW for 87Sr and 9 pW for 88Sr should be possible with our setup.

[1] Meiser et al., PRL 102, 163601 (2009). [2] Norcia et al., Phys. Rev. X, 8, 021036 (2018). [3] Chen et al., Phys. Rev. Applied 12, 044014, (2019). [4] Escudero et al., Phys. Rev. Research 3, 033159 (2021). [5] Cline et al., E08.09, DAMOP (2021).

Q 59.12 Thu 16:30 P

Correlation spectroscopy on a $^{40}Ca^{+}$ two ion system for optical atomic clocks — •Kai Dietze[1,2], Ludwig Krinner[1,2], Lennart Pelzer[1,2], Fabian Dawel[1,2], Johannes Kramer[1,2], Nicolas Spethmann[1,2], and Piet O. Schmidt[1,2] — [1]QUEST Institute for Experimental Quantum Metrology, Physikalisch Technische Bundesanstalt, 38116 Braunschweig — [2]Leibniz Universität Hannover, 30167 Hannover

Time and Frequency are the most accurately determined physical quantities. Though for optical clocks based on trapped ions like $^{40}Ca^{+}$ the reachable statistical uncertainty is limited by the interrogation time due to decoherence processes and a low signal-to-noise ratio (SNR). Both can be significantly enhanced by employing correlated interrogation techniques within a decoherence-free subspace (DFS) of multiple ions. We utilize Bell-states of opposing magnetic quantum numbers to create a two-particle state whose phase evolution is independent of the ambient magnetic field. Using a pair of fully entangled ions the SNR of this measurement technique can even surpass the standard-quantum-limit (SQL). In our experiments, the correlation of both ions within a Ramsey-interferometer is used to disseminate the differential phase evolution against our clock laser. We present measurements showing the preparation of entangled and correlated two-ion states, demonstrating the increased interrogation time as well as first results showing the potential of the correlation spectroscopy used in an optical atomic clock.

Q 59.13 Thu 16:30 P

Proceedings on Ultrastable Cryogenic Cavities and Ring-Cavities used as Spectral Pre-Filters — •Erich Günter Leo Pape, Marc Kitzmann, and Achim Peters — Humboldt Universität zu Berlin, AG QOM, Newtonstr. 15, 12489 Berlin, Germany

Cryogenic Cavities: We present our new cryogenic sapphire cavities in order to reach relative frequency stability of $10^{-16}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ towards a modern Michelson Morley experiment testing for possible Lorentz violations.

Filter Cavity: We present our new triangular ring cavity used as a spectral prefilter in double pass. We stabilize the cavity to a laser with a piezo ring actuator while using the tilt lock method.

Q 59.14 Thu 16:30 P

2D phase sensitivity beyond the shot-noise limit in an SU(1,1) interferometer. — •Ismail Barakat[1], Klaus Mantel[2], Mahmoud Kalash[1], Norbert Lindlein[1], and Maria Chekhova[2] — [1]University of Erlangen-Nuremberg,Institut für Optik, Information und Photonik, Staudtstraße 7/B2 91058 Erlangen,Germany — [2]1Max-Planck Institute for the Science of Light, Staudtstr. 2, Erlangen D-91058, Germany

2D phase measurements are necessary for characterizing rough and smooth surfaces. In classical interferometry, these measurements are always bounded by the shot-noise limit (SNL). To overcome the SNL, we use a wide-field SU(1,1) interferometer where spatially multimode bright squeezed vacuum is sensing the phase. This non-linear interferometer promises to enhance the overall phase sensitivity in quantum and optical metrology and in imaging. The 2D phase is extracted using the N-steps phase shifting interferometry algorithm. We compare the obtained 2D phase values with the SNL and use the repeatability as a measure of precision for the extracted phase maps. We also test the 2D phase sensitivity by sensing the strain applied to an optical surface.

Q 59.15 Thu 16:30 P

Measuring small coefficients of thermal expansion with Fabry-Perot resonators — •Nina Meyer, Maryam Ghazi Zahedi, Tobias Ohlendorf, Uwe Sterr, and Thomas Legero — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Materials with small coefficients of thermal expansions (CTEs) are needed for industrial and scientific applications as in extreme-ultraviolet lithography, in telescopes or ultra-stable resonators [1]. Such materials, like Zerodur and Corning ULE glass, show a very small CTE of about $10^{-8}\,\mathrm{K}^{-1}$, with zero crossing near room temperature. CTE measurements based on two-beam Michelson interferometers for measuring length have reached $10^{-9}\,\mathrm{K}^{-1}$ uncertainties [2].
In this poster, we present a multiple-beam approach based on a Fabry-

Perot resonator, consisting of a test-material spacer and two optically contacted reflecting endcaps in a temperature-controlled vacuum chamber. We discuss a refined uncertainty budget taking the temperature homogeneity of the spacer and the impact of the CTE mismatch between the end caps and the spacer into account [3]. This allows us to determine the CTE with uncertainties in the range of $10^{-9}\,\mathrm{K}^{-1}$.

[1] F. Riehle, Meas. Sci. Technol. **9**, 1042–1048 (1998).
[2] R. Schödel, Meas. Sci. Technol. **19**, 084003 (2008).
[3] T. Legero et al., J. Opt. Soc. Am. B **27**, 914-919 (2010).

Q 59.16 Thu 16:30 P

Towards a continuous wave superradiant Calcium Laser — •David Nak and Andreas Hemmerich — Institut für Laserphysik, Universität Hamburg, Hamburg, Deutschland

Superradiant Lasers are suitable as narrow light sources with ultralow bandwidth, as their emission frequency is only weakly dependent on an eigenfrequency of the laser cavity. They can be used as a read-out tool for precise optical atomic clocks. Currently, our experiment loads cold Calcium-40 atoms from a magneto optical trap into a one-dimensional optical lattice prepared inside a cavity. By incoherent population of the metastable triplet state, pulsed superradiant emission on the intercombination line was realized [1].

At present, the setup is being extended by an incoherent repumping mechanism, which will allow continuous wave operation.

[1] T. Laske, H. Winter, and A. Hemmerich, Pulse Delay Time Statistics in a Superradiant Laser with Calcium Atoms, Phys. Rev. Lett. 123, 103601 (2019).

Q 60: Quantum Information II

Time: Thursday 16:30–18:30 Location: P

Q 60.1 Thu 16:30 P

Adiabatic coupling via tapered optical fibers — •Tim Turan[1] and Tim Schröder[1,2] — [1]Institut für Physik, Humboldt-Universität zu Berlin, Berlin — [2]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Berlin

In a network where quantum information is shared via single photons, the coupling efficiency is crucial. One option to couple a quantum node, such as a vacancy center in diamond, to an optical fiber, is utilizing a tapered waveguide to tapered optical fiber interface. [1]

If the geometry is chosen right, the fundamental mode can be transferred adiabatically from the waveguide to the fiber with minimal losses. We use an established theory of this transfer [2] together with statistical methods to find optimal waveguide and fiber taper geometries for near-unity transmission. Furthermore, we provide methods to reliably fabricate these optimal fiber tapers.

[1] M. J. Burek et. al., Fiber-Coupled Diamond Quantum Nanophotonic Interface, Phys. Rev. Applied 8, 024026 (2017).
[2] J. D. Love et al., Tapered Single-Mode Fibers and Devices. Part 1: Adiabaticity Criteria, IEE Proc. J Optoelectron. UK 138, 343 (1991).

Q 60.2 Thu 16:30 P

Photon pair generation using spontaneous four-wave mixing (SFWM) in microring resonators on a photonic silicon chip — •Florian Vogel, Erik Fitzke, Jakob Kaltwasser, and Thomas Walther — TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt

We employ spontaneous four-wave mixing (SFWM) in ring resonators on a photonic chip with silicon nitride waveguides to generate a photon pair spectrum with a spectral shape determined by the mode of the resonator. The frequencies of the resulting photon pairs differ by a multiple of the free spectral range and can be separated from one another by wavelength division multiplexing. Various filters are also used to remove unwanted frequency components that make it difficult to identify the photon pairs from the spectrum. A Pound-Drever-Hall (PDH)-Locking is set up for the compensation of thermal changes in the length of the resonator.

Q 60.3 Thu 16:30 P

A scalable four user quantum key hub for phase-time coding quantum key distribution — •Maximilian Tippmann, Erik Fitzke, Lucas Bialowons, Oleg Nikiforov, and Thomas Walther — TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt

Quantum key distribution (QKD) systems have been widely tested with various protocols. However, there is a very limited number of experiments on QKD networks allowing the connection of more than two users within a single system. Here, we report on a QKD system with an untrusted node for simultaneous pairwise key exchange for four users based on phase-time coding. In terms of network scalability, the untrusted node consisting of an entangled photon pair source enables simultaneous operation of dozens of user pairs. Additionally, we demonstrate the interconnectibility of our system allowing plug-and-play reconfiguration of the linked parties. Our source is highly flexible to allow various operation modes in terms of repetition rates as well as integration of new coding modules.

Q 60.4 Thu 16:30 P

Time-dependent single photon detector tomography — •Maximilian Mengler, Erik Fitzke, Robin Krebs, Thorsten Haase, Gernot Alber, and Thomas Walther — TU Darmstadt, Institute for Applied Physics, 64289 Darmstadt

Many modern applications in quantum physics depend on the usage of single photon detectors. Especially for quantum key distribution a detailed understanding of the detector's reaction to certain input states is important. We present an experimental setup to perform time dependent detector tomography, to obtain time-dependent POVMs as a general way of describing the detector's behavior. We used coherent states of known mean photon numbers as a set of known input states to implement the tomography. Finally, we present results regarding timing jitter and detector efficiency for multiple single photon avalanche detectors.

Q 60.5 Thu 16:30 P

Simulation of fiber-based quantum key distribution (QKD) with highly entangled states including multi-photon pair effects — •Philipp Kleinpass, Erik Fitzke, and Thomas Walther — TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt

The security of QKD protocols relies on the fact that a potential eavesdropper reveals its presence by introducing additional errors to the final key. Thus, to ensure a secure key exchange, other errors, namely due to device imperfections within the setup, need to be quantified and minimized, while maintaining a sufficiently high bit rate. Here, a model is presented that may be used to simulate the expected key rates for entanglement-based phase-time coding, considering many important error sources like multi-photon pair creations, chromatic dispersion and interferometer imperfections by employing a phase-space approach. Depending on the entanglement of the states used for the protocol, two methods are discussed, distinguishing between highly entangled states featuring a large number of Schmidt modes and states that may be represented explicitly by their Schmidt decomposition.

Q 60.6 Thu 16:30 P

Quantum Key Distribution based on time-bin entanglement in a scalable star-shaped network — •Till Dolejsky, Erik Fitzke, Maximilian Tippmann, Lucas Bialowons, Oleg Nikiforov, and Thomas Walther — TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt

We demonstrate quantum key distribution in a star-shaped multi user network with time-bin entangled photon pairs employing four users simultaneously. The setup is tested at a facility of Deutsche Telekom AG and photons are sent over a commercial optical fiber route. We achieve stable key distribution over distances of more than 75 km and durations of up to several hours. This QKD system is robust and allows to extend the network to dozens of users by standard multiplexing techniques, such as wavelength division multiplexing and time division multiplexing.

Q 60.7 Thu 16:30 P

Double nondestructive detection of an optical photon — •Lukas Hartung, Emanuele Distante, Severin Daiss, Stefan Langenfeld, Philip Thomas, Olivier Morin, Stephan Welte, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

In this talk, we will present an experiment demonstrating the double nondestructive detection of an optical photon [3]. The photon propagates in a 60 m long glass fiber, to which two nondestructive detectors are attached. Each detector consists of a single rubidium atom strongly coupled to an optical resonator. To detect a photon, each of the atoms is prepared in superposition state. When reflecting a photon off the cavity, a π-phase shift is imprinted on the superposition state. The photon is successively reflected from the two resonators and the subsequent readout of the phase of the superposition state of each atom heralds the presence of the photon. Correlations between the detector clicks are observed, and it is demonstrated that the detection efficiency of the two concatenated detectors surpasses the detection efficiencies of each individual detector. Furthermore, the experiment shows that the signal-to-noise ratio of the double detection is enhanced by about two orders of magnitude compared to the signal-to-noise ratios of the individual detectors.

[1] E. Distante et al., Phys. Rev. Lett. 126, 253603 (2021)

Q 60.8 Thu 16:30 P

Quantum teleportation with only a single photon as a resource — •Lukas Hartung, Stefan Langenfeld, Stephan Welte, Severin Daiss, Philip Thomas, Olivier Morin, Emanuele Distante, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching

We report on the teleportation of a single qubit between two distant rubidium atoms each trapped at the center of a cavity in the strong-coupling regime connected by a 60m long glass fiber.

The teleportation of a quantum state allows for the deterministic transmission of qubits over lossy channels. In the common implementation of teleportation experiments, the sender and the receiver have to share a pair of entangled qubits to then transmit the source qubit to the receiver. The novel approach of our teleportation protocol is that a preshared entangled qubit pair is not required. The only necessary resource is a single photon which is first reflected off the receiver's cavity and afterwards off the cavity of the sender and subsequently detected. The detection of the photon combined with feedback on the receiver's atom heralds the succesful teleportation. This protocol allows for, in principle, unconditional teleportation. We teleport six mutually unbiased qubit states with an average fidelity $F = (88.3 \pm 1.3)\%$ at a rate of 6Hz over 60m [1].

[1] Langenfeld et al., Phys. Rev. Lett. 126, 130502 (2021)

Q 60.9 Thu 16:30 P

A nondestructive Bell-state measurement on two distant atomic qubits — •Matthias Seubert, Stephan Welte, Philip Thomas, Lukas Hartung, Severin Daiss, Stefan Langenfeld, Oliver Morin, Emanuele Distante, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

To exploit the full capability of quantum networks, it is necessary to develop schemes to generate, store and detect entanglement. Most of the detection techniques presented so far, are impaired by being local, destructive or not complete.

Here, we describe a complete and nondestructive entanglement detection scheme on two spatially separated network nodes. Each node is realized by a single ^{87}Rb atom stored in a strong coupling optical resonator connected by a 60 m optical fiber link. At first, an ancillary photon is consecutively reflected on each resonator, performing atom-photon gates at each reflection [1]. Repeating this sequence with a second ancillary photon, any initial two atom state is projected onto one of the four Bell-states [2]. The generated state is identified by polarization measurements of both photons. As this scheme does not destroy the quantum states, it can be utilized in future applications to preserve entanglement from dephasing by repetitive measurements using the quantum Zeno effect.

[1] Andreas Reiserer *et al.*, Nature **508**, 237 (2014)
[2] Stephan Welte *et al.*, Nature Photonics **15**, 504-509 (2021)

Q 60.10 Thu 16:30 P

Towards a WGMR based source optimized for photon-ion coupling in a deep parabolic mirror — •Sheng-Hsuan Huang[1,2], Thomas Dirmeier[1,2], Hadi Sedaghat-Pisheh[1,2], Martin Fischer[1,2], Markus Sondermann[1,2], Gerd Leuchs[1,2], and Christoph Marquardt[1,2] — [1]Max-Planck-Institute for the Science of Light, Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

Optical Whispering Gallery Mode Resonators (WGMR) have been proven to be compact and efficient sources of quantum states, e.g. squeezed states [1] or narrow-band heralded single photons. It has been shown, that they can be tuned to the resonance alkali metal vapours [2]. In addition to this versatility, it is also possible to operate WGMRs in a genuinely single-mode regime [3]. Together, it is these characteristics that make WGMRs a suitable system to efficiently couple to narrow-band atomic systems.

In our presentation, we discuss the concept and progress of the realization of a compact WGMR source that is specifically tailored to couple to the $D_{3/2} \Rightarrow D[3/2]_{1/2}$ transition at 935 nm of $^{174}Yb^+$ ions.

[1]A. Otterpohl, et.al., Optica 6, 1375-1380 (2019)
[2]G. Schunk, et.al., Journal of Modern Optics 63 (2016)
[3]M. Förtsch, et al., Physical Review A 91(2) 023812 (2015)

Q 60.11 Thu 16:30 P

A compact and versatile DM-CV QKD system for the QuNET initiative — •Stefan Richter[1,2], Ömer Bayraktar[1,2], Kevin Jaksch[1,2], Bastian Hacker[1,2], Imran Khan[1,2,5], Emanuel Eichhammer[1,5], Emmeran Sollner[1,5], Twesh Upadhyaya[3], Jie Lin[3], Norbert Lütkenhaus[3], Florian Kanitschar[4], Stefan Petscharnig[4], Thomas Grafenauer[4], Ömer Bernhard[4], Christoph Pacher[4], Gerd Leuchs[1], and Christoph Marquardt[1] — [1]QIV Research Group, MPI for the Science of Light, Erlangen, Germany — [2]Friedrich Alexander University Erlangen-Nuremberg, Erlangen, Germany — [3]Institute for Quantum Computing, Dept. of Physics and Astronomy, University of Waterloo, Canada — [4]Security & Communication Technologies Unit, Austrian Institute of Technology, Vienna, Austria — [5]now with KEEQuant GmbH, Fürth, Germany

Continuous-variable quantum key distribution (CV-QKD) is poised to become a key technology for securing critical communication infrastructure against the emerging threats of quantum computers. We present our implementation of a compact and versatile fiber-coupled discrete modulation CV-QKD system for metropolitan networks. We also show preliminary key rate estimates and channel characterization results obtained during a public technology demonstration in August 2021. Some aspects and challenges of the implementation are discussed, including error correction requirements.

Q 60.12 Thu 16:30 P

QKD and key management at KEEQuant — •Ulrich Eismann, Emanuel Eichhammer, Emmeran Sollner, Martin Hauer, Oliver Maurhart, and Imran Khan — KEEQuant GmbH, Gebhardtstr. 28, 90762 Fürth, Germany

In the advent of the quantum computer threat, we aim to make QKD a commodity by relying on standard telecom components, integrated photonics and electronics. This makes QKD invisible for the end user, and hence commercially viable.

We present our first QKD product and its the fitting into existing telecommunication networks. One layer above the physical layer of such networks, keys need to be handled using key management systems (KMS) and we will discuss the interplay between QKD, KMS and the application layer.

Q 60.13 Thu 16:30 P

Towards a quantum memory on a silicon chip — •Stephan Rinner[1], Lorenz Weiss[1], Andreas Gritsch[1], Johannes Früh[1], Florian Burger[1], and Andreas Reiserer[1,2] — [1]Max-Planck-Institut für Quantenoptik, Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Ludwig-Maximilians-Universität, München, Germany

For the implementation of large-scale quantum networks Erbium dopants are promising candidates since they can combine second-long ground state coherence with coherent optical transitions at telecommunication wavelength. Among the potential host crystals for erbium, silicon stands out because it allows for the scalable fabrication of nanophotonic devices based on established processes of the semiconductor industry. In contrast to observations made in previous studies, we have shown that erbium ions implanted into silicon nanostructures can be integrated at well-defined lattice sites with narrow inhomogeneous ($\sim$1 GHz) and homogeneous ($<$0.1 GHz) linewidths. By optimizing the implantation conditions and by using high-purity silicon-on-insulator samples, we have recently decreased the homogeneous linewidth down to 20 kHz at 2 K. These improvements are a crucial step towards the implementation of coherent storage of light in a scalable physical platform. We will present recent results in spectroscopy and give an outlook on realizing a silicon based on-chip quantum memory operated at telecom wavelength.

Q 60.14 Thu 16:30 P

Quantum Frequency Conversion of SnV-Resonant Photons to the Telecom C-Band — •David Lindler, Tobias Bauer, and Christoph Becher — Universität des Saarlandes, FR Physik, Campus E2.6, 66123 Saarbrücken

Quantum nodes such as Tin-Vacancy-Centers (SnV) in diamond store and distribute quantum information in quantum communication networks. Transferring the spin state of the SnV-Center onto single photons enables the exchange of information between these nodes over long distances through optical fiber links. The problem of high loss in fibers for SnV-resonant photons is solved by quantum frequency down-conversion of the photons into the low-loss telecom bands.

We here present a 2-step scheme for quantum frequency conversion of SnV-resonant photons to the telecom C-band based on difference frequency generation in PPLN waveguides. Due to pumping in the long wavelength regime, the two step process 619 nm − 2061 nm = 885 nm, 885 nm − 2061 nm = 1550 nm drastically reduces noise at the target wavelength compared to the single step process 619 nm − 1030.5 nm = 1550 nm. We will present the characterization of key components as well as first results on wavelength stabilization of the the Cr^{2+}:ZnS/Se pump laser, which is needed to avoid conversion-induced frequency fluctuations of the single photons.

Q 60.15 Thu 16:30 P

Two-Stage Quantum Frequency Down-Conversion of Single Photons from Silicon-Vacancy Centers in Diamond — •Marlon Schäfer, Benjamin Kambs, Dennis Herrmann, Tobias Bauer, and Christoph Becher — Universität des Saarlandes, FR Physik, Campus E2 6, 66123 Saarbrücken

The silicon-vacancy (SiV) center in diamond is a promising system as qubit for quantum communication networks due to its long spin coherence time, fourier-limited linewidth and all-optical coherent spin control. Since SiV centers show optical transitions in the visible red spectral range, quantum frequency conversion (QFC) to low-loss telecommunication wavelengths is vital for fiber-linked networks [1]. However, direct conversion schemes suffer from strong conversion-induced noise caused by Raman scattering and SPDC of the pump beam [2].
Here, we present efficient and low-noise QFC of single photons emitted by SiV centers into the telecom C-band using a two-stage conversion scheme. Through difference frequency generation in PPLN waveguides SiV photons at 737 nm are first converted to 999 nm followed by a conversion to 1549 nm. As a key advantage, the large spectral distance to the pump wavelength at 2813 nm bypasses SPDC noise and minimizes Raman noise. Thereby, we achieve a low unconditional conversion noise of less than 1 photon/s/GHz, an overall external conversion efficiency of 29 % and preservation of the single photon statistics.

[1] Bock, M. et al., Nat Commun 9, 1998 (2018).
[2] Zaske, S. et al., Opt. Express 19, 12825-12836 (2011).

Q 60.16 Thu 16:30 P

Polarization-preserving quantum frequency conversion for entanglement distribution in trapped-atom based quantum networks — •Tobias Bauer[1], Jan Arenskötter[1], Matthias Bock[1,2], Stephan Kucera[1], Benjamin Kambs[1], Jürgen Eschner[1], and Christoph Becher[1] — [1]Universität des Saarlandes, FR Physik, Campus E2.6, 66123 Saarbrücken, Germany — [2]Universität Innsbruck, Institut für Experimentalphysik, Technikerstrasse 25/4, A-6020 Innsbruck, Austria

In quantum communication networks information is stored in internal states of quantum nodes, which can be realized e.g. in trapped ions like $^{40}Ca^{+}$. By transferring the states onto flying quantum bits, i.e. photons, it is possible to exchange information between these nodes over long distances via optical fiber links. In order to minimize attenuation in fibers, which is particularly high for typical transition frequencies of trapped ions, quantum frequency down-conversion of the transmitted photons to low-loss telecom bands is utilized.

We present a high-efficiency, rack-integrated quantum frequency converter for polarization-preserving conversion of $^{40}Ca^{+}$-resonant photons to the telecom C-band. It relies on the difference frequency generation process 854 nm - 1904 nm = 1550 nm in a PPLN waveguide, which is arranged in a Sagnac configuration to achieve polarization preservation. We will further present the application of the converter in entanglement distribution experiments, e.g. the distribution of entangled SPDC-photon pairs and quantum state teleportation over large fiber distances.

Q 60.17 Thu 16:30 P

Efficient spin-photon interface for NV centers in diamond — •Kerim Köster[1], Maximilian Pallmann[1], Matthias Klausmann[1], Jonathan Körber[2], Jeremias Resch[1], Jonas Grammel[1], Julia Heupel[3], Cyril Popov[3], Rainer Stöhr[2], and David Hunger[1] — [1]Physikalisches Institut, Karlsruher Institut für Technologie — [2]3. Physikalisches Institut, Universität Stuttgart — [3]Institut für Nanostrukturtechnologie und Analytik, Universität Kassel

Building a long distance quantum network is one of the big challenges in the field of quantum communication, which requires the development of a quantum repeater. A crucial component of this device is an efficient, coherent spin photon interface. Coupling color centers in diamond to a microcavity is a promising approach therefore.

In our experiment, we integrate a diamond membrane into an open access fiber-based Fabry-Perot microcavity to attain emission enhancement in a single well-collectable mode. We present our fully tunable, cryogenic cavity platform operating in a closed-cycle cryostat, and we achieve a sub-picometer mechanical stability during quiet periods.

We observe cavity-enhanced fluorescence spectra of an ensemble of shallow-implanted nitrogen vacancy centers in diamond, showing Purcell-enhancement of the zero-phonon line (ZPL). Furthermore, the emission yields temporal bunching of ZPL photons, which indicates a collective behavior in the emission process that can be attributed to superradiance.

Q 60.18 Thu 16:30 P

Towards long Coherence Times for a Single-Atom Quantum Memory — •Florian Fertig[1,2], Tim van Leent[1,2], Yiru Zhou[1,2], Pooja Malik[1,2], Anastasia Reinl[1,2], Robert Garthoff[1,2], Wei Zhang[1,2], and Harald Weinfurter[1,2,3] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Max-Planck-Institut für Quantenoptik, Garching, Germany

For large scale quantum networks, long coherence times are crucial to distribute high quality entanglement over long distances. Our experiment consists of two nodes employing optically trapped single-atoms as quantum memories including quantum frequency conversion to the low loss telecom S band. The two atoms are entangled using an entanglement swapping protocol. For fiber links with a length of multiple kilometers, the quality is limited by the coherence time of the atomic states [1].

Here, we report on the implementation of a new trap geometry mitigating any decoherence effects ($T_2 \approx 330\ \mu$s) stemming from the optical dipole trap (ODT). These effects emerge from longitudinal components of the electric field that arise due to the tightly focused ($w_0 < 2\ \mu$m) ODT beam. For this, we overlap the single ODT beam with another counterpropagating one to set up a standing-wave geometry. As the effective magnetic field of the second beam has an opposite sign, perfect overlap will cancel the effective magnetic field and increase the coherence time to the millisecond scale.

[1] T. van Leent et al., arXiv:2111.15526 (2021)

Q 60.19 Thu 16:30 P

Robust Qubit Encoding for a Single-Atom Quantum Network Link — •Yiru Zhou[1,2], Tim van Leent[1,2], Florian Fertig[1,2], Pooja Malik[1,2], Anastasia Reinl[1,2], Wei Zhang[1,2], and Harald Weinfurter[1,2,3] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Max-Planck-Institut für Quantenoptik, Garching, Germany

The most fundamental task for a quantum network node is to serve as light-matter entanglement interface. For high-quality entanglement distribution over long distances, the quantum memories in such nodes need a quantum storage, i.e, coherence time that is much longer than the travel time of the photons used to distribute the entanglement. Here we represent the improvement of the coherence time of a single-atom quantum memory from 300 μs to more than 5 ms. This is realized via coherently transferring the initial qubit states $\{|F = 1, m_F = -1>, |F = 1, m_F = +1>\}$ to a magnetic-field-insensitive encoding states $\{F = 1, m_F = -1>, |F = 2, m_F = +1>\}$

by a state-selective Raman transfer [1]. Even longer coherence time should become possible by implementing spin-echo and Raman sideband cooling. With these measurement coherence time can increase the reach of our quantum network link from 33 km [2] to hundreds of kilometers.

[1] M. Körber et al., Nat. Photonics 12, 18 (2018)
[2] T. van Leent et al., arXiv: 2111.115526 (2021)

Q 60.20 Thu 16:30 P

Quantum Memories based on Spin Exchange between Alkali Metal and Noble Gas Vapours at Room Temperature — •Norman Vincenz Ewald[1], Luisa Esguerra[1,2], and Janik Wolters[1,2] — [1]German Aerospace Center (DLR), Institute of Optical Sensor Systems, Berlin — [2]Technische Universität Berlin, Institut für Optik und Atomare Physik, Berlin

Quantum memories with optical interfaces and storage times well beyond 1 s will spawn manifold applications in quantum communication, e.g. as quantum tokens for authentication. Compactness and technological simplicity are key parameters for the memory platform to achieve large-scale applicability. Our goal is to realise such a quantum memory in atom vapours at room temperature. We present our approach to use a mixture of a noble gas—with its well isolated nuclear spins that remain coherent for hours [1] serving as long-term memory—and an alkali metal providing the optical interface based on EIT [2]. The optically inaccessible nuclear spins of the noble gas will be addressed by coherent, collisional spin exchange with the alkali metal atoms [3]. Compatibility with existing telecommunication infrastructure may be established by employing bi-chromatic sources of entangled photon pairs with one photon on the alkali atom's storage transition and one photon suitable for telecom fibres [4].

[1] C. Gemmel et al., *Eur. Phys. J. D* **57**, 303–320 (2010).
[2] J. Wolters et al., *Phys. Rev. Lett.* **119**, 060502 (2017).
[3] O. Katz et al., arXiv:2007.08770v2 (2020).
[4] D. Rieländer et al., *New J. Phys.* **18**, 123013 (2016).

Q 60.21 Thu 16:30 P

Towards coherent single praseodymium ion quantum memories in optical fiber microcavities — •Sören Bieling[1], Evgenij Vasilenko[1], Roman Kolesov[2], and David Hunger[1] — [1]Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany — [2]Universität Stuttgart, 70569 Stuttgart, Germany

Rare earth ions doped into solids show exceptional quantum coherence in their ground-state hyperfine levels. These spin states can be efficiently addressed and controlled via optical transitions and are thus ideally suited to serve as quantum memories and nodes of quantum networks. However, while long storage times, high storage efficiencies and storage on the single photon level have all been demonstrated separately, they could not yet be achieved simultaneously.

We aim to demonstrate both long and efficient single quantum storage in the ground-state hyperfine levels of single Pr^{3+} ions doped into yttrium orthosilicate (YSO) by integrating them as membrane into optical high-finesse fiber-based Fabry-Pérot microcavities. This allows for efficient addressing and detection of individual ions. In order to prolong the storage times, we aim to increase their hyperfine coherence times further by operating under a zero first-order Zeeman (ZEFOZ) shift magnetic field as well as by employing dynamical decoupling sequences. Together with the Purcell enhanced emission and ultrapure Pr^{3+}:YSO membranes this strives to realize efficient and coherent spin-photon interfaces that are suitable for deployment in scalable quantum networks.

Q 60.22 Thu 16:30 P

Quantum repeater node for unconditionally secure quantum key distribution — Stefan Langenfeld, •Philip Thomas, Olivier Morin, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

In classical communications a measure-and-resend strategy is used to amplify signals and overcome the exponential losses in optical fibers. In the quantum case this does not work due to the no-cloning theorem. An alternative concept which became known as the quantum repeater [1] aims at dividing a link into shorter segments across which entanglement is created independently. This leads to an effective increase in attenuation length by a factor equal to the number of segments.

Here, we demonstrate an elementary quantum repeater link consisting of a single repeater node and two classical end nodes, Alice and Bob. The repeater node is realized using two ^{87}Rb atoms in a high-finesse optical cavity [2]. Photons which are entangled with atom A are sent to Alice until she registers a detection event. Then, the same procedure is carried out on atom B and Bob, while the qubit on atom A is being stored. When Bob registers a photon, a Bell-state measurement is performed for entanglement swapping. We show an enhanced rate vs. distance scaling and thus the key signature of a quantum repeater. Furthermore, we demonstrate an error rate below 11 % which is essential for unconditional security in quantum key distribution protocols.

[1] H.-J. Briegel *et al.*, Phys. Rev. Lett. **81**, 5932 (1998)
[2] S. Langenfeld *et al.*, Phys. Rev. Lett. **126**, 230506 (2021)

Q 60.23 Thu 16:30 P

Portable warm vapor memory — •Martin Jutisz[1], Mustafa Gündoğan[1], Elisa Da Ros[1], Markus Krutzik[1], Janik Wolters[2,3], and Leon Messner[1,3] — [1]Humboldt-Universität zu Berlin, Berlin, Germany — [2]Technische Universität Berlin, Berlin, Germany — [3]Deutsches Zentrum für Luft- und Raumfahrt, Berlin, Germany

Warm vapor memories have seen significant progress in terms of efficiency and storage time in recent years. Their low complexity makes them a promising candidate for operation in non-lab environments including space-based applications. As necessary element of quantum repeaters, memories operating in space could advance global quantum communication networks [1].

We will present the overall design and status of a portable system with an emphasis on the miniaturized laser system. The implementation of the optical memory is based on electromagnetically induced transparency on the Cesium D1 line at 895nm. A distributed Bragg reflector laser is frequency stabilized by saturated absorption technique. Automated locking is realized via a FPGA-based tool for laser frequency stabilization.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50RP2090.

[1] M. Gündoğan et. al., npj Quantum Information 7, 128 (2021)

Q 61: Quantum Optics (Miscellaneous)

Time: Thursday 16:30–18:30 Location: P

Q 61.1 Thu 16:30 P

Generating multi-photon graph states in the telecom wavelength regime using sagnac single-photon sources — •Nico Hauser, Simone d'Aurelio, Matthias Bayerbach, Shreya Kumar, and Stefanie Barz — Institute for Functional Matter and Quantum Technologies and IQST, University of Stuttgart, 70569 Stuttgart, Germany

Graph states with multiple qubits are important resources for quantum computation and quantum communication. In particular, multipartite communication protocols between three and more parties can benefit from maximally entangled N-qubit states. Examples are quantum secret sharing protocols, quantum conference key agreement and secure quantum e-voting - all of which require a reliable generation of entangled N-qubit states. Therefore, the experimental generation of such states is of great importance, in particular, in the telecom wavelength regime in order to use existing and well established fiber networks. In this work, we investigate the generation of multipartite entangled states using single photon sources based on spontaneous parametric down-conversion in ppKTP-crystals. The sources are operated in a sagnac interferometer type scheme that allows generating two-photon Bell states. Fusing multiple of those states at beam splitters then creates multipartite entangled states. These can then serve as the basis for implementing multipartite communication protocols.

Q 61.2 Thu 16:30 P

Tracking Rydberg state dynamics to study the effect of long-range dipole-dipole interactions on Superradiance — •Elmer

Suarez, Philip Wolf, Patrizia Weiss, and Sebastian Slama — Center for Quantum Science and Physikalisches Institut, Eberhard-Karls Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

We report on the real-time detection of internal-state dynamics of cold Rubidium atoms being excited to the $30D_{5/2}$ Rydberg state via two-photon excitation. The atoms are overlapped with the mode of an optical cavity and excited by two laser beams transverse to the cavity axis. The excitation changes the collective atom-cavity coupling, which we detect by measuring the cavity transmission. We observe not only the excitation dynamics, but also the transfer of population from the Rydberg state to other neighbouring states due to black-body radiation, and the decay back to the ground state. Moreover, we find a superradiant enhancement of this decay and a density-dependent mitigation of superradiance which we attribute to dipole-dipole interactions between atoms in neighbouring Rydberg states. The findings contribute to resolve a recent controversy on the role of BBR-induced superradiance in cold atomic gases.

Q 61.3 Thu 16:30 P

Waveguide QED with Rydberg superatoms — •Lukas Ahlheit[1], Nina Stiesdal[1], Hannes Busche[1], Kevin Kleinbeck[2], Jan Kumlin[2], Hans-Peter Büchler[2], and Sebastian Hofferberth[1] — [1]Institute for Applied Physics, University of Bonn — [2]Institute for Theoretical Physics III, University of Stuttgart

A Rydberg superatom is a model 2-level system formed by thousands of atoms sharing a single excitation to a Rydberg state. Only a single excitation is allowed in the system due to the Rydberg blokade, and due to the collectivity of the excitation, the system couples strongly to a driving coherent field of few photons, and features directionality defined by this driving mode.

On this poster we discuss how we experimentally implement a 1D chain of Ryderg superatoms, and how we use this system to study the dynamics of emitter-light-couplings. In particular, the directed emission of the superatoms makes our free-space chain of superatoms very similar to a chain of emitters coupled to a 1D optical waveguide. This has recently allowed us to realize a multi-photon subtractor, which we present here. We have also studied the collective internal dynamics of many-atom-systems with a single, shared excitation. We discuss how these internal dynamics can be included in a 1D waveguide model.

Q 61.4 Thu 16:30 P

Nanophotonic fiber-coupled silicon carbide quantum interface — •Lukas Niechziol, Raphael Nold, Marcel Krumrein, Jonathan Körber, Izel Gediz, Jonas Zatsch, Florian Kaiser, and Jörg Wrachtrup — 3rd Institute of Physics, University of Stuttgart, 70569 Stuttgart, Germany

In the field of quantum sensing, quantum cryptography and quantum computing silicon vacancy centers in silicon carbide have recently quickened the interest of many research groups, due to its availability, spin configuration, integratabilty and more. Until now most publications focus on color centers in bulk material. This results in collecting efficiencies between 0.1% and 1%. In our experiment we will use waveguides with photonic crystal cavities to enhance the photon flux of the color centers. These photons will travel to a taper of the waveguide to be transferred to a tapered fiber. We used FTDT simulations to find optimal parameters for single-mode waveguide geometries as well as for the fiber. The simulation showed that the waveguides we plan to use achieve a transmission of a color center (dipole) of 42.4% into the desired TE fundamental mode of the waveguides. Additionally a transmission efficiency over the quantum interface of about 99.0% resulting in a total collecting efficiency of 41.9% of the light of a color center into a fiber. Our goal is to translate the results of our simulations towards highly efficient quantum interface including a photonic crystal cavity with a deposited color center.

Q 61.5 Thu 16:30 P

Generation of GHZ-states using Symmetric Bell Multiport Beam Splitters — •Daniel Bhatti and Stefanie Barz — Institute for Functional Matter and Quantum Technologies & IQST, University of Stuttgart, Germany

Symmetric Bell multiport beam splitters, with N input and output modes, have been found useful for investigating the indistinguishability of multiple photons [1,2] and also for generating post-selected, highly entangled multi-photon states [3]. Interestingly, when employing polarization encoding varying the indistinguishability of the N independent input photons leads to different classes of entangled states [4]. In the case of N=3 and N=4 the generation of polarization encoded W-states and GHZ-states has been analyzed theoretically and in the case of W-states it has even been generalized to arbitrary N [5]. Choosing a particular set of polarization states for the N independent partially distinguishable input photons we, here, present a generalization for the generation of polarization encoded GHZ-states. This leads to different results for even and odd numbers of photons.

[1] A. J. Menssen, et al., PRL 118, 153603 (2017).
[2] A. E. Jones, et al., PRL 125, 123603 (2020).
[3] S. Paesani, et al., PRL 126, 230504 (2021).
[4] Y. L. Lim and A. Beige, Phys. Rev. A 71, 062311 (2005).

Q 61.6 Thu 16:30 P

Towards realizing an optical Racetrack memory — •Parvez Islam and Patrick Windpassinger — Institut für Physik, JGU, Mainz

Long distance quantum communications require the storage and on demand retrieval of the quantum qubits. Quantum memories with light stored in cold atomic ensembles is an established light storage platform towards scalable quantum networks. Controlled transport and manipulation of the stored light gives further control and opens new opportunities in quantum communication. Additionally, multiple storage sites or spatially separated hubs of storage sites can help realize novel devices like optical racetrack memories and quantum repeaters. We present our ongoing work on realizing an optical racetrack memory. An optical racetrack memory, in principle, consists of a multisegmented array of atomic ensembles which are individually addressable with a perpendicular Write/Read head. Light storage is achieved using EIT and transport by an optical conveyor belt as demonstrated in our previous work [1]. With individually addressable multiple storage sites which can be shifted spatially after storage and subsequently retrieved on demand, this work will serve as a proof of principle for realizing an optical racetrack memory. Furthermore, we plan to investigate the splitting and merging of stored polaritons. The stored light pulses are mapped into a collective excitation of the storage medium, forming strongly coupled light-matter quasiparticles called Dark state polaritons. Controlled splitting/merging of stored polaritons will provide more insight on light-matter interactions. [1] W.Li et al., Phys. Rev. Lett. 125, 150501

Q 61.7 Thu 16:30 P

Construction of a new type of room-temperature single-photon source based on two-photon interferences — •Lucas Pache, Martin Cordier, Francisco Crespo, Charlotta Gurr, Max Schemmer, Philipp Schneeweiss, Jürgen Volz, and Arno Rauschenbeutel — Department of Physics, Humboldt-Universität zu Berlin, 10099 Berlin, Germany

Single-photon sources are a key component for future quantum technologies. Here, we report on the progress in implementing a new type of single-photon source. This source relies on a two-photon interference effect which has been recently demonstrated in a proof-of-principle experiment with cold atoms [1]. The mechanism relies on engineering destructive two-photon interference, in order to transform a coherent laser field into a stream of single photons [2]. The physical origin of this effect is the collectively enhanced non-linear response of many weakly coupled atoms. Now, we transfer this concept to a vapor cell experiment with ^{85}Rb atoms and circumvent Doppler broadening by a two-color excitation scheme. This allows to generate indistinguishable single photons from a compact room-temperature source. The scheme can be readily adapted to the telecom range (1529nm).

[1] Prasad, et. al, Nature Phot. (2020).
[2] European patent pending (PCT/EP2019/075386).

Q 61.8 Thu 16:30 P

Superradiance and multilevel interference in an atomic chain — •Aleksei Konovalov and Giovanna Morigi — Universität des Saarlandes

We analyse the properties of the light coherently scattered by a chain of atomic dipoles. We develop a model of coherent dipoles which accounts for the effect of vacuum-induced interference in a multilevel structure [1] and analyse its effect of the coherently scattered light for a chain of Na 23 and a chain of Rb 87 atoms.

[1] Aleksei Konovalov and Giovanna Morigi Phys. Rev. A 102, 013724 (2020)

Q 61.9 Thu 16:30 P

Machine learning Lindblad dynamics — •Francesco Carnazza[1], Federico Carollo[1], Sabine Andergassen[1], Dominik Zietlow[2], Georg Martius[2], and Igor Lesanovsky[1] — [1]Institut für Theoretische Physik and Center for Quantum Science, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany — [2]Max Planck Institute for Intelligent Systems, Max-Planck-Ring 4, 72076 Tübingen, Germany

Even if full knowledge of the wave-function of a quantum system is unattainable, important information can still be retrieved by observing local degrees of freedom. Typically, it is possible to single out and measure just a subsystem, while regarding the rest as a bath. In the simplest case, the evolution of the reduced quantum state obtained by tracing out the environment is governed by a Markovian, i.e. time independent, quantum master equation, also known as Lindblad master equation. Here we investigate if it is possible to train a fully interpretable neural network which learns the parameters of a Lindblad generator [1]. We test this idea in a class of spin models, and investigate in which certain situations the network can indeed provide good predictions.

[1] P. Mazza *et al*. Phys. Rev. Research **3**, 023084 (2021)

Q 61.10 Thu 16:30 P

Collective phenomena in a system of two interacting qubits — •Robin Rüdiger Krill, Tom Schmit, and Giovanna Morigi — Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany

Collective phenomena play a fundamental role in classical physics as well as quantum physics. A prominent classical collective phenomenon is synchronization, where the constituents of an interacting many-body system move in unison. Recently, efforts were made to extend the notion of synchronization to quantum systems [1]. Drawing from a recent work [2], we analyse the relation between superradiance [3], subradiance, and synchronization, focussing in particular on the timescale characterizing the onset of these phenomena.

[1] R. H. Dicke, Phys. Rev. **93**, 99 (1954).
[2] F. Galve, G. L. Giorgi, and R. Zambrini, Quantum Science and Technology. Springer, Cham. pp. 393-420 (2017).
[3] B. Bellomo, G. L. Giorgi, G. M. Palma, and R. Zambrini, Phys. Rev. A **95**, 043807 (2017).

Q 61.11 Thu 16:30 P

Quantum fluctuations and correlations in open quantum Dicke models — •Mario Boneberg, Igor Lesanovsky, and Federico Carollo — Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

In the vicinity of ground-state phase transitions quantum correlations can display non-analytic behavior and critical scaling. This signature of emergent collective effects has been widely investigated within a broad range of equilibrium settings. However, under nonequilibrium conditions, as found in open quantum many-body systems, characterizing quantum correlations near phase transitions is challenging. Moreover, the impact of local and collective dissipative processes on quantum correlations is not broadly understood. This is, however, indispensable for the exploitation of quantum effects in technological applications, such as sensing and metrology. We consider as a paradigmatic setting the superradiant phase transition of the open quantum Dicke model and characterize quantum and classical correlations across the phase diagram [1]. We develop an approach to quantum fluctuations which allows us to show that local dissipation, which cannot be treated within the commonly employed Holstein-Primakoff approximation, rather unexpectedly leads to an enhancement of collective quantum correlations, and to the emergence of a nonequilibrium superradiant phase in which the bosonic and spin degrees of freedom of the Dicke model are entangled.

[1] M. Boneberg, I. Lesanovsky, and F. Carollo, arXiv:2110.13191 (2021).

Q 61.12 Thu 16:30 P

Coherent spectroscopy of Europium-doped materials — •Christina Ioannou[1], Jannis Hessenauer[1], Evgenij Vasilenko[1], Phillipe Goldener[2], Diana Serrano[2], Mario Ruben[1], Senthil Kuppusamy[1], and David Hunger[1] — [1]Karlsruhe Institute of Technology — [2]Institut de Recherche de Chimie Paris

Solid state crystals doped with rare earth ions (REI) such as Europium have been demonstrated to be excellent candidates for optically addressable spin qubits. The coherence properties of REI within the partially filled 4f shell are exceptional due to their immunity against fluctuations of their environment as a result of the shielding effect of the outer filled electronic shells. Still, the host material affects the properties of the ions, such as the optical and spin coherence time. We use ensemble spectroscopy techniques such as spectral hole burning and photon echo techniques to investigate the optical coherence time of Europium in promising host materials. These techniques allow the measurement of the homogeneous linewidth of particular ion classes in spite of the significant inhomogeneous broadening of the ensemble. The host materials that we investigate are Y2SO3 nanocrystals and specifically designed molecular complexes [1]. Furthermore, we demonstrate our newly developed fiber based setup used for these measurements. This setup is compact and only needs very small amounts of sample. It is easily installed inside a cryostat, without the need of free-space optical access, while still maintaining good collection efficiency.

[1] Serrano et al., arXiv:2105.07081, in print at Nature

Q 61.13 Thu 16:30 P

A Novel Setup for Coupling Diamond Color Centers to Open Fiber-based Microcavities — •Yanik Herrmann[1,2], Julius Fischer[1,2], Laurens Feije[1,2], Matthew Weaver[1,2], Maximilian Ruf[1,2], Julia Brevoord[1,2], Matteo Pasini[1,2], and Ronald Hanson[1,2] — [1]QuTech, Delft University of Technology, P.O. Box 5046,2600 GA Delft, Netherlands — [2]Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 5046,2600 GA Delft, Netherlands

Quantum networks [1,2] are promising both for applications like secure communication and for basic science tests of quantum mechanics at a large scale. The Nitrogen-Vacancy (NV) center in diamond is an excellent node candidate, because of its long spin coherence and accessible local qubit registers, but it has limited collectible coherent photon emission. Integration into an optical cavity can boost collection via the Purcell effect [3], but the sensitivity of open cavities to vibrations from the environment has so far been a major roadblock for developing the system further into a quantum network node, capable of entanglement generation [4]. Here we present a new low temperature setup, which is in particular designed to provide a low vibration level while maintaining high flexibility over the cavity and fiber control. [1] S. Wehner et al., Science 362, 6412 (2018), [2] M. Pompili et al., Science 372, 6539 (2021), [3] E. Janitz et al., Optica 7, 1232-1252 (2020), [4] M. Ruf et al., Phys. Rev. Applied 15, 024049 (2021),

Q 61.14 Thu 16:30 P

Light-induced correlations in cold dysprosium atoms — •Marvin Proske[1], Ishan Varma[1], Niels Petersen[1,2], Nico Bassler[4], Claudiu Genes[3,4], Kai Phillip Schmidt[4], and Patrick Windpassinger[1,2] — [1]QUANTUM, Institut für Physik, JGU Mainz — [2]Graduate School Materials Science in Mainz — [3]Max Planck Institute for the Science of Light, Erlangen — [4]Department of Physics, FAU Erlangen-Nuremberg

With the evergrowing interest in quantum cooperativity, comes an ongoing effort to study light-induced correlations in atomic media. In these typically extreme dense regimes, with atomic distances below the scattering lights wavelength, a direct matter-matter coupling is introduced by electric and magnetic interactions. We intend to study light-matter interactions in dense dipolar media with large magnetic moments to explore the impact of magnetic dipole-dipole interactions onto the cooperative response of the sample. With the largest ground-state magnetic moment in the periodic table (10 Bohr-magneton), dysprosium is the perfect choice for these experiments.

This poster reports on our recent work to generate dense ultracold dysprosium clouds utilizing a microscopic optical dipole trap. Further, we give a perspective on future adaptations of this technique with a self-built science cell, that serves as a highly accessible platform to manipulate the atomic cloud. The small dimensions of the cell allow for extremely tight optical dipole trapping and precise magnetic field control at the position of the atoms.

Q 61.15 Thu 16:30 P

Master equation for ultracold atoms in an optical cavity — •Tom Schmit[1], Carlos Máximo[2], Tobias Donner[2], and Giovanna Morigi[1] — [1]Theoretical Physics, Department of Physics, Saarland University, 66123 Saarbrücken, Germany — [2]Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, 8093 Zürich, Switzerland

The recent progress in the control of ultracold quantum gases in optical cavities enabled the realization of quantum simulators to study collective phenomena, such as self-organization. The theoretical description of these systems, however, still poses a big challenge due to the exponential scaling of the Hilbert space in the number of particles, making the full solution of the system's dynamical equations inaccessible, both analytically and numerically. Suitable approximations, most prominently adiabatic and mean-field approximations, are typically the way to tackle this problem, effectively reducing the dimension of the Hilbert space. In this work, we employ projector based techniques [1,2] to derive a description of self-organization of ultracold atoms in an optical cavity including first-order mean-field corrections. The effect of these corrections is then analyzed by comparing to the mean-field model, i.e., the lowest-order approximation.

[1] C. R. Willis and R. H. Picard, Phys. Rev. A **9**, 3 (1974).
[2] P. Degenfeld-Schonburg and M. J. Hartmann, Phys. Rev. B **89**, 245108 (2014).

Q 61.16 Thu 16:30 P

Design and fabrication of metalenses — •Shan Song[1] and Andreas Schell[2] — [1]Institut für Festkörperphysik, Leibniz Universität Hannover, Hannover, Deutschland — [2]Institut für Festkörperphysik, Leibniz Universität Hannover, Hannover, Deutschland

Recently, researchers have shown an increased interest in tailoring light by metasurfaces. A metasurface is a two-dimensional ultra-thin layer, artificially fabricated by planar structures on a sub-wavelength scale. By interaction with the planar structure, the transmitted light can be phase-shifted. Compared to conventional optical elements, metasurfaces are capable to manipulate the light wavefront accurately by specific nanostructures and they can be fabricated using microfabrication processes. The imaging of quantum emitters by metalenses in optical quantum technologies is the focus of interest. We are designing and fabricating a high numerical aperture metasurface lens, which is composed of polysilicon nanodiscs on a quartz glass substrate. By variation of discs diameter and periodicity, the full 2π phase shift and the high numerical aperture are achieved. It consists of multiple steps in the fabrication process, mainly including the deposition of a thin polysilicon layer by low-pressure chemical vapor deposition, the pattern determination by application of hydrogen silsesquioxane negative resist in electron beam lithography and the pattern transfer on polysilicon layer by reactive ion etching. After the fabrication of nanostructures, the structures will be covered with a polydimethylsiloxane layer, which ensures a homogeneous environment of light propagation.

Q 61.17 Thu 16:30 P

Squeezing and Correlations in an Atom Chain — •Kasper Kusmierek[1], Sahand Mahmoodian[2], and Klemens Hammerer[1] — [1]Institute for Theoretical Physics and Institute for Gravitational Physics (Albert-Einstein-Institute), Leibniz University Hannover, Germany — [2]ARC Future Fellow, University of Sydney, Australia

We study squeezing and correlations in an atomic array weakly coupled to a waveguide at large optical depth. The atoms are treated as two level atoms with a ground and excited state. The waveguide supports just modes traveling in one direction such that the whole system constitutes a cascaded system. Properties of light, like squeezing, can be derived via correlations of atoms. Since the degrees of freedom scale exponentially with the number of atoms, at large optical depth the system can not be solved exactly. We use the cumulant expansion method to cut correlations at arbitrary order and compare the resulting properties of the light field at different truncation orders.

Q 61.18 Thu 16:30 P

Implementation of a sub 10ps RMS jitter TDC in Xilinx 7-series FPGAs — •Verena Leopold[1], Yury Prokazov[2], Evgeny Turbin[2], Stefan Richter[1], and Joachim von Zanthier[1] — [1]FAU, Erlangen, Germany — [2]Photonscore, Magdeburg, Germany

For many experiments in quantum optics, it is crucial to detect photon arrival times from (multiple) detectors. Usually a TDC (Time-to-Digital-Converter) is used for recording of this time stream. However for low-contrast, long-running measurements, available TDCs show disadvantages. The main challenges are high quality analog inputs and non-linearities on short ps-timescales. We successfully implemented a TDL (Tapped-Delay-Line) TDC inside an FPGA. Communication with the CPU is established by PCIe. Using Xilinx 7-series silicon, a RMS jitter of (3.24 ± 0.03) ps was obtained with non-linearities in the regime of 0.32%.

Q 62: Ultra-cold atoms, ions and BEC (joint session A/Q)

Time: Thursday 16:30–18:30 Location: P

Q 62.1 Thu 16:30 P

Quantum degenerate Fermi gas in an orbital optical lattice — •Yann Kiefer — Luruper Chaussee 149, 22761 Hamburg

Spin-polarized samples and spin mixtures of quantum degenerate fermionic atoms are prepared in selected excited Bloch bands of an optical chequerboard square lattice. For the spin-polarized case, extreme band lifetimes above 10 s are observed, reflecting the suppression of collisions by Pauli*s exclusion principle. For spin mixtures, lifetimes are reduced by an order of magnitude by two-body collisions between different spin components, but still remarkably large values of about one second are found. By analyzing momentum spectra, we can directly observe the orbital character of the optical lattice. The observations demonstrated here form the basis for exploring the physics of Fermi gases with two paired spin components in orbital optical lattices, including the regime of unitarity. Furthermore access to a broad Feshbach resonance enables to study the role of interaction and pairing of ultracold molecular orbital optical lattices.

Q 62.2 Thu 16:30 P

non-equilibrium dynamics of a bose-einstein condensate populating higher bands of an optical lattice — •josé vargas[1,3] and andreas hemmerich[1,2,3] — [1]Institut für Laserphysik, Universität Hamburg, 22761 Hamburg, Germany — [2]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg, Germany — [3]The Hamburg Center for Ultrafast Imaging, Luruper Chaussee 149, Hamburg 22761, Germany

We present the realization of diverse experiments on non-equilibrium dynamics of a Bose-Einstein condensate populating higher bands of a bipartite square optical lattice. We experimentally investigate single- and many-body phenomena such as Bloch oscillations along different paths over each addressable Brillouin zones, and Josephson oscillations in the second Bloch band of the lattice. In addition, by exciting the atomic sample into different initial quasi-momenta of the lattice, we study instabilities of the system together with the characterization of re-condensation dynamics towards the energy minimum of the Bloch band.

Q 62.3 Thu 16:30 P

Optically trapping single ions in a high-focused laser beam — •Wei Wu[1], Fabian Thielemann[1], Joachim Welz[1], Pascal Weckesser[1,2], Daniel Hönig[1], Amir Mohammadi[1], Thomas Walker[1], and Tobias Schätz[1] — [1]Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Hermann-Herder-Straße 3, 79104 Freiburg, Germany — [2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Ions stored in Paul traps are well suited to design few-particle systems with high-fidelity control over electronic and motional degrees of freedom and individual addressability., alongside long-range interactions. It is challenging, however, to extend this control to two- or higher-dimensional systems. This is partly due to the existence of driven motion, which intrinsically leads to decoherence and heating. Ions confined in optical traps, on the other hand, constitute a system which is free of driven motion but still benefits from long-range interaction. For example, ions in optical traps could be used to study and control quantum structural phase transitions from 1D (linear) to 2D (zigzag) crystals. Additionally, optical traps offer scalability, flexibility and nanoscale potential geometries which are not easily accessible with Paul traps. Optical traps for ions also feature state-dependent trapping due to the different potentials seen by the ion when in different electronic states. In this poster, we present a method to deterministically prepare a single ion or string of ions, making use of state dependent potentials in optical traps to eject selected ions from the trap.

Q 62.4 Thu 16:30 P

Feshbach Resonances in a hybrid Atom-Ion System — •Joachim Welz[1], Fabian Thielemann[1], Wei Wu[1], Thomas Walker[1], Pascal Weckesser[1,2], Daniel Hönig[1], Amir Mohammadi[1], and Tobias Schätz[1] — [1]Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Hermann-Herder-Straße 3, 79104 Freiburg, Germany — [2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

We present the observation of Feshbach resonances between neutral atoms and ions [1,2]. These resonances - a quantum phenomenon only observable at ultracold temperatures - allow the interaction rate between particles to be tuned with the perspective to even switch them off. While Feshbach resonances are commonly utilized in neutral atom experiments, reaching the ultracold regime in hybrid rf-optical traps is challenging, as the driven motion of the ion by the rf trap limits the achievable collision energy [3]. By immersing a single Ba ion in an ultracold cloud of Li, we demonstrate the enhancement of both two-body and three-body interactions through changes in the ion's internal and motional energy. This paves the way for all-optical trapping of both species, circumventing the fundamental rf-heating, and for new applications, such as the coherent formation of molecular ions and simulations of quantum chemistry [4].

[1] WECKESSER, Pascal, et al. arXiv:2105.09382, 2021.
[2] SCHMIDT, J., et al. Phys.Rev.Lett. 2020, 124-5.
[3] CETINA, Marko et al. Phys.Rev.Lett. 2012, 109-25.
[4] BISSBORT, Ulf, et al. Phys.Rev.Lett. 2013, 111-8.

Q 62.5 Thu 16:30 P

A dipolar quantum gas microscope — •Paul Uerlings, Kevin Ng, Jens Hertkorn, Jan-Niklas Schmidt, Ralf Klemt, Sean Graham, Tim Langen, and Tilman Pfau — 5. Physikalisches Institut and Center for Integrated Quantum Science and Technology IQST, Universität Stuttgart

We present the progress towards constructing a dipolar quantum gas microscope. This new apparatus combines the long-range interactions found in dipolar quantum gases with the single-site resolution of a quantum gas microscope, allowing for detailed studies of quantum phases in strongly correlated systems. Fermionic atoms trapped in optical lattices can model the behaviour of electrons in complex solid materials. By implementing a quantum gas microscope, microscopic details such as site occupation and site correlations will be observable, providing new insights into elusive quantum phases. We plan to do this using dysprosium atoms trapped in an ultraviolet optical lattice with a lattice spacing of about 180 nm. Combined with the long-range dipole interaction, the short lattice spacing will significantly increase the nearest-neighbour interaction strength to be on the order of 200 Hz (10 nK). This will allow us to study the regime of strongly interacting dipolar Bose- and Fermi-Hubbard physics where even next-nearest-neighbour interactions could be visible.

Q 62.6 Thu 16:30 P

Compact device for painting blue-detuned time-averaged optical potentials for space application — •Kai Frye[1,2], Marius Glaeser[1], Christian Schubert[1,2], Waldemar Herr[1,2], Ernst Rasel[1], and BECCAL Team[1,2,3,4,5,6,7,8,9,10] — [1]Leibniz Universität Hannover — [2]DLR-SI, Hannover — [3]Universität Ulm — [4]FBH Berlin — [5]HU, Berlin — [6]JGU, Mainz — [7]ZARM, Universität Bremen — [8]DLR-QT, Ulm — [9]DLR-SC, Braunschweig — [10]Universität Hamburg

The Bose-Einstein and Cold Atom Laboratory (BECCAL) will be a multi-user and -purpose facility onboard the International Space Station. It will provide ultacold ensembles of Rb and K atoms for experiments on fundamental research and sensor applications. For this, BECCAL will support the confinement of atoms in optical flat-bottom traps of arbitrary shapes.

Here, we present a design of a compact and robust setup for creation of blue-detuned time-averaged optical potentials. We utilize a dual-axis acousto-optical deflector and characterize the setup in terms of efficient use of light power, light extinction in the center of the optical trap and smoothness of the potential.

BECCAL is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under the grant numbers 50 WP 1431 and 1700. Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany*s Excellence Strategy * EXC-2123 QuantumFrontiers * 390837967.

Q 62.7 Thu 16:30 P

Trapping Ions And Ion Coulomb Crystals In Optical Lattices — •Daniel Hoenig[1], Fabian Thielemann[1], Joachim Welz[1], Wei Wu[1], Thomas Walker[1], Leon Karpa[2], Amir Mohammadi[1], and Tobias Schaetz[1] — [1]Albert-Ludwigs-Universität, Freiburg, Deutschland — [2]Leibniz-Universität, Hannover, Deutschland

Optically trapped ion Coulomb crystals are an interesting platform for quantum simulations due to the long range of the Coulomb interaction as well as the state dependence of the optical potential. Optical lattices expand the possible application of this platform by trapping the ions in seperate potential wells as well as giving optical confinement along the axis of the beam. In the past we reported the succesfull trapping of a single ion in a one dimensional optical lattice as well as of ion coulomb crystals in a single beam optical dipole trap.

In this Poster, we present recent advancements in trapping of Ba138+ ions in an one dimensional optical lattice at a wavelength of 532nm and report the first successfull trapping of small ion coulomb crystals ($N \leq 3$) in a lattice. We compare trapping results between the lattice and a single-beam optical dipole trap and investigate the effect of axial electric fields on the trapping probability of a single ion to demonstrate the axial confinement of the ion by the lattice structure. Additionally we show preliminary results on the measurement of the vibrational modes of a single ion in the optical lattice.

Q 62.8 Thu 16:30 P

Vortex motion quantifies strong dissipation in a holographic superfluid — Paul Wittmer[1,2], Christian-Marcel Schmied[2,3], •Martin Zboron[3], Thomas Gasenzer[1,2,3], and Carlo Ewerz[1,2] — [1]Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg — [2]ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany — [3]Kirchhoff-Institut für Physik, Universität Heidelberg, Im Neuenheimer Feld 227, 69120 Heidelberg

Gauge-gravity duality establishes a connection between strongly correlated quantum systems and higher-dimensional gravitational theories at weak coupling. In general, finding the quantitative parameters of the quantum system thus described is challenging. We numerically simulate dynamics of generic vortex configurations in the holographic superfluid in two and in three spatial dimensions and match to these the corresponding dynamics resulting from the dissipative Gross-Pitaevskii equation. Excellent agreement between the vortex core profiles and their trajectories in both frameworks is found, both in two and three dimensions. Comparing our results to phenomenological equations for point- and line-like vortices allows us to extract friction parameters of the holographic superfluid. The parameter values suggest the applicability of two-dimensional holographic vortex dynamics to strongly coupled Bose gases or Helium at temperatures in the Kelvin range, effectively enabling experimental tests of holographic far-from-equilibrium dynamics.

Q 62.9 Thu 16:30 P

Accordion lattice set-up for trapping Dysprosium ultra-cold gases in two dimensions — •Valentina Salazar Silva, Jianshun Gao, Karthik Chandrashekara, Joschka Schöner, Christian Gölzhäuser, Lennart Hoenen, Shuwei Jin, and Lauriane Chomaz — Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Ultracold quantum gases offer an excellent platform to study few- and many-body quantum phenomena with a remarkable level of control.

At the new group of Quantum Fluids in Heidelberg we are designing a novel experimental set-up focused on highly magnetic dysprosium atoms, with the aim to study the effect of competing long- and short-range interactions at the many-body level and in lower dimensional settings. With our unique combination of 2D and 3D magneto-optical traps, magnetic field coils, and various optical traps, we intend to achieve large quantum degenerate samples and to be able to adjust their confinement geometry and their interaction properties at will.

In order to achieve a 2-dimensional sample in the main experimental chamber, we plan to implement a dynamical optical trap - the accordion lattice. The interference pattern of two laser beams at a shallow angle, theta, creates a spatially periodic potential. Varying theta allows us to adjust both the fringe spacing and the confinement strength in the modulated direction. This scheme makes it possible to achieve a 2D regime with high efficiency and tuneability. At the Erlangen 22 conference, I will present the design and implementation of this accordion lattice.

Q 62.10 Thu 16:30 P

Towards simulation of lattice gauge theories with ultracold ytterbium atoms in hybrid optical potentials — •Tim Oliver Hoehn[1,2], Etienne Staub[1,2], Guillaume Brochier[1,2], Clara Zoe Bachorz[1,2,3], David Gröters[1,2], Bharath Hebbe Madhusudhana[1,2], Nelson Darkwah Oppong[1,2], and Monika Aidelsburger[1,2] — [1]Ludwig-Maximilians-Universität München — [2]Munich Center for Quantum Science and Technology, München — [3]MPI für Quantenoptik, Garching

Gauge theories play a fundamental role for our understanding of nature, ranging from high-energy to condensed matter physics. Their formulation on a regularized periodic lattice geometry, so-called lattice gauge theories (LGTs), has proven invaluable for theoretical studies. However, as numerical simulations are limited in their capability to simulate, e.g., the real-time dynamics, there have been sustained efforts to develop quantum simulators for LGTs. We report on our recent progress on constructing a novel experimental platform for ytterbium atoms, which employs optical lattices and optical tweezers to engineer and probe LGTs. In contrast to other experimental realizations, this approach allows for a robust and scalable implementation of local gauge invariance. A central component enabling this favorable property are optical tweezer potentials operated at the tune-out wavelengths for the ground and clock state of ytterbium. Notably, optical potentials generated from light at these wavelengths could also find applications for digital quantum computation. We present our efforts towards precisely determining these wavelengths experimentally.

Q 62.11 Thu 16:30 P

Investigating ultracold chemical processes with NaK molecules — •Jakob Stalmann, Jula Simone Morich, Kai Konrad Voges, and Silke Ospelkaus — Institute of Quantum Optics, Leibniz University Hannover

Ultracold ground-state molecular quantum gases yield highly complex and mostly unknown scattering behavior, ranging from the formation of long-lived collisional complexes to subsequent chemical reactions, photo-excitation or spontaneous spin relaxation.

Here, we present our approach for the detection of such quantum chemical reaction pathways by state-selective product ionization and VMI mass spectroscopy [1] with ultracold ^{23}Na^{39}K ground-state molecules. The chemically stable, lightweight NaK molecule is ideally suited for such investigations. Alongside deeper studies of ultracold collisions and reaction pathways, this approach will allow us to develop and implement new quantum control techniques for chemical reactions.

[1] Phys. Chem. Chem. Phys., 2020,22, 4861-4874

Q 62.12 Thu 16:30 P

A moveable tuneout optical dipole trap for ultracold ^{6}Li in a ^{133}Cs BEC — •Robert Freund, Binh Tran, Eleonora Lippi, Michael Rautenberg, Tobias Krom, Manuel Gerken, Lauriane Chomaz, and Matthias Weidemüller — Physikalisches Institut, Ruprecht Karls University of Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

The ultracold Bose-Fermi mixture of ^{133}Cs and ^{6}Li is an interesting system which can be used to study different few- and many-body phenomena. By immersing fermionic ^{6}Li impurities into a ^{133}Cs Bose-Einstein Condensate (BEC) the energy spectrum of quasiparticles namely Bose polaron can be mapped out. The large mass imbalance between Caesium and Lithium atoms is expected to give a signature of 3-body Efimov effect in the polaron spectrum. In order to obtain a clear polaron signal the optimization of the overlap between the two species in space and momentum is crucial. The Lithium is going to be trapped in a tightly confined optical dipole trap with a beam waist of around 10 μm to adapt to the size of the BEC. Moreover the trap is translatable both to compensate for the gravitational sag due to the large mass difference of the species and to store Lithium far away from Caesium during the preparation and cooling procedures. The trap runs at a tune-out wavelength of Caesium to reduce the influence of the trap on the potential landscape of the BEC as much as possible.

Q 62.13 Thu 16:30 P

Towards Quantum Simulation of Light-Matter Interfaces with Strontium Atoms in Optical Lattices — •Valentin Klüsener[1,2], Jan Trautmann[1,2], Dimitry Yankelev[1,2], Annie J. Park[1,2], Immanuel Bloch[1,2,3], and Sebastian Blatt[1,2] — [1]MPQ, Hans-Kopfermann-Str. 1, 85748 Garching, Germany — [2]MCQST, Schellingstr. 4, 80799 München, Germany — [3]LMU, Schellingstr. 4, 80799 München, Germany

In the last two decades, quantum simulators based on ultracold atoms in optical lattices have successfully emulated strongly correlated condensed matter systems. With the recent development of quantum gas microscopes, these quantum simulators can now control such systems with single-site resolution. Within the same time period, atomic clocks have also started to take advantage of optical lattices by trapping alkaline-earth-metal atoms such as Sr, and interrogating them with unprecedented precision and accuracy. Here, we report on progress towards a new quantum simulator that combines quantum gas microscopy with optical lattice clock technology. We have developed in-vacuum buildup cavities with large mode volumes that will be used to overcome the limits to system sizes in quantum gas microscopes. In addition, we present precision spectroscopy of the ultra-narrow magnetic quadrupole transition $^1S_0 - {}^3P_2$ in Sr, which enables spatially selective addressing in an optical lattice. By combining these techniques with state-dependent lattices, we aim to emulate strongly-coupled light-matter-interfaces.

Q 62.14 Thu 16:30 P

Magnetic-field-coils and 3D-MOT for novel dysprosium quantum gas experiment — •Joschka Schöner, Lennart Hoenen, Jianshun Gao, Christian Gölzhäuser, Karthik Chandrashekara, Valentina Salazar Silva, Shuwei Jin, and Lauriane Chomaz — Physikalisches Institut, Heidelberg, Germany

Ultra-cold atoms are one of the major platforms to study novel quantum phenomena due to their outstanding level of controllability. Highly magnetic atoms like Dysprosium show a long-range, anisotropic dipolar interaction, comparable in strength to the short-range contact interaction. These interactions can be precisely tuned by controlling the direction and strength of the applied magnetic fields.

At our new Quantum Fluids group in Heidelberg we aim to produce ultracold quantum gases of Dy to study exotic physical phenomena like supersolidity, topological ordering, and out-of-equilibrium physics emerging from competing dipolar and contact interactions and restricting the system to 2D. Our novel experimental platform relies on transferring Dy atoms from a 2D- to a 3D-MOT before loading them into an accordion lattice combined with an in-plane trap of tailorable geometry and a highly controllable magnetic-field environment.

I will report on our 3D-MOT and coil setup. The latter is made of 5 pairs of coils used to generate (1) gradient fields for the MOT, (2) homogeneous magnetic fields at the required strengths and orientations with fast response times. This is central to our quest to realize the promise of the outstanding level of controllability of the ultra-cold atom platform to investigate novel quantum phenomena.

Q 62.15 Thu 16:30 P

Dipolar Supersolid States of Matter with Dysprosium — •Kevin Ng[1], Jan-Niklas Schmidt[1], Jens Hertkorn[1], Mingyang Guo[1], Sean Graham[1], Paul Uerlings[1], Ralf Klemt[1], Tim Langen[1], Martin Zwierlein[2], and Tilman Pfau[1] — [1]5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart — [2]MIT-Harvard center for Ulatracold Atoms, Research Laboratory of Electronics, and Department of Physics, MIT

Ultracold dipolar gases are an established platform to realize exotic states of matter due to the anisotropic and long-range dipolar interaction between atoms. Recently, supersolid states of matter which have both a superfluid nature and crystal-like periodic density modulation have been realized with ultracold dysprosium.

With a self-organized array of dipolar quantum droplets in one dimension, we demonstrate supersolidity of the droplet array from the coherent nature of these droplets and have observed the low energy goldstone mode that exists as a consequence of the systems superfluidity. We map out the elementary excitations of droplet arrays in one and two dimensions and study in-situ the density fluctuations at the superfluid-supersolid phase transition. A peak in the extracted static structure factor identifies the transition region and allows us to connect the crystallization mechanism of the droplet array to the emergence of low-lying angular roton modes. Furthermore, we theoretically predict supersolid phases beyond droplets in two dimensions at higher densities, where density saturation favours honeycomb and stripe phases.

Q 62.16 Thu 16:30 P

Towards dark energy search using atom interferometry in microgravity — •Magdalena Misslisch[1], Holger Ahlers[2], Maike Lachmann[1], and Ernst Rasel[1] — [1]Institute of Quantum Optics,

Hanover, Germany — [2]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) Institut für Satellitengeodäsie und Inertialsensorik, Hanover, Germany

Dark energy is estimated to represent around 70 % of the universe energy budget, yet its nature remains unknown. A possible solution for this problem is the proposed scalar chameleon field whose effects are hidden from usual high density probe particles due to a screening effect.

The project DESIRE (Dark energy search by atom interferometry in the Einstein-Elevator) aims to detect chameleon dark energy by atom interferometry in microgravity. In this experiment multi-loop interferometry with Rb-87 Bose-Einstein condensates will be performed to search for phase contributions induced by chameleon scalar fields shaped by a changing mass density in their vicinity [1]. Atoms traverse a periodic test mass designed in cooperation with the JPL while accumulating the signal within a multi-loop interferometer over several seconds. To reach these long interaction times the experiment will be performed in microgravity in the Einstein-Elevator, an active drop tower in Hanover.

[1] Sheng-wey Chiow und Nan Yu. "Multiloop atom interferometer measurements of chameleon dark energy in microgravity" doi: 10.1103/PhysRevD.97.044043, 2018

Q 62.17 Thu 16:30 P

Excitation Spectra of Homogeneous Ultracold Fermi Gases — •René Henke, Hauke Biss, Niclas Luick, Jonas Faltinath, Lennart Sobirey, Thomas Lompe, Markus Bohlen, and Henning Moritz — Institute of Laserphysics, University of Hamburg, Luruper Chaussee 149, Gebäude 69, 22761 Hamburg, Germany

Understanding the origins of unconventional superconductivity has been a major focus of condensed matter physics for many decades. While many questions remain unanswered, experiments have found that the systems with the highest critical temperatures tend to be layered materials where superconductivity occurs in two-dimensional (2D) structures. However, to what extent the remarkable stability of these strongly correlated 2D superfluids is related to their reduced dimensionality is still an open question. In our experiment, we use dilute gases of ultracold fermionic atoms as a model system to directly observe the influence of dimensionality on strongly interacting fermionic superfluids. This poster presents our most recent work, where we measured the superfluid gap of a strongly correlated quasi-2D Fermi gas over a wide range of interaction strengths and compares the results to recent measurements in 3D Fermi gases as well as theoretical predictions.

Q 62.18 Thu 16:30 P

RF and MW coils for experimental quantum simulators — •Hüseyin Yildiz, Tobias Hammel, Maximilian Kaiser, Keerthan Subramanian, Matthias Weidemüller, and Selim Jochim — Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg (Germany)

To manipulate the spin degree of ultracold atoms we apply radio frequency (RF) and microwave (MW) magnetic fields. In current experiments it is challenging to realize magnetic field amplitudes that realize sufficiently large Rabi frequencies. It is therefore a major challenge to optimize magnetic field coil designs.

We present optimized and frequency-variable RF and MW coils for the excitation of different states in the Paschen-Back regime of ultracold Lithium-6 atoms and molecules. Fast and controlled changes in resonance frequency of RF and MW coils enable more flexible sequences and shorter sequence times.

Q 62.19 Thu 16:30 P

A new apparatus for trapping single strontium atoms in arrays of optical microtraps — Tobias Kree, •Felix Rönchen, Jonas Schmitz, and Michael Köhl — Physikalisches Institut Bonn

We present the design and implementation of the vacuum system featuring a custom designed titanium vacuum chamber with optical access along six different axes. The apparatus offers space to incorporate two high-NA objectives (NA > 0.65) to manipulate and read out atoms cooled to the motional ground state. One of the two objectives is characterized and currently being installed. In addition we describe the sequence of cooling steps we implemented to rapidly cool thermal Strontium atoms to microkelvin temperatures. To produce optical dipole traps we set up and characterized a liquid-crystal based spatial light modulator. We are able to produce highly uniform one-, two- and three-dimensional geometries of hundreds of optical foci. The system will be integrated into the main experiment in the upcoming months. In the future the experiment will be used as a quantum simulator profiting from the powerful combination of high imaging efficiency and arbitrary arrangements of single atoms.

Q 62.20 Thu 16:30 P

Quantum simulation of many-body non-equilibrium dynamics in tilted 1D fermi-hubbard model. — •Bharath Hebbe Madhusudhana[1,2], Sebastian Scherg[1,2], Thomas Kohlert[1,2], Immanuel Bloch[1,2], and Monika Aidelsburger[1] — [1]Ludwig-Maximilians-Universitat Munchen, Germany — [2]Max-Planck-Institut fur Quantenoptik, Garching, Germany

Thermalization of isolated quantum many-body systems is deeply related to redistribution of quantum information in the system. Therefore, a question of fundamental importance is when do quantum many-body systems fail to thermalize, i.e., feature non-ergodicity. A useful test-bed for the study of non-ergodicity is the tilted Fermi-Hubbard model. Here we experimentally study non-ergodic behavior in this model by tracking the evolution of an initial charge-density wave over a wide range of parameters, where we find a remarkably long-lived initial-state memory [1]. In the limit of large tilts, we identify the microscopic processes which the observed dynamics arise from. These processes constitute an effective Hamiltonian and we experimentally show its validity [2]. We show that in these simulations, our experiment surpasses the present-day computational limitation with $L_{exp} =$ 290 lattice sites and evolution times up to 700 tunneling times. We use our experiment to benchmark a new efficient numerical technique to solve for the dynamics of many-body systems [3].

[1.] Sebastian Scherg et al. Nature Communications 12 (1), 1-8 [2.] Thomas Kohlert et al. arXiv:2106.15586 [3.] Bharath Hebbe Madhusudhana et. al. PRX Quantum 2, 040325.

Q 62.21 Thu 16:30 P

Tunable Beyond-Ising Interactions in Tweezer Arrays by Rydberg Dressing — Lea Steinert, •Philip Osterholz, Arno Trautmann, and Christian Gross — Physikalisches Institut, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany

We report on a new experimental platform leveraging the long coherence times of a spin-1/2 encoded in the potassium-39 ground-state manifold and the tunability and versatility of interactions between atoms excited to Rydberg-states. We utilize an SLM to prepare an arrangement of optical tweezers, each occupied by a single atom. By off-resonantly coupling to the Rydberg manifold via a single photon transition, we are able to map tuneable angular- and distance-dependent XYZ-type interactions onto the spin-1/2 system. This approach paves the way not only to novel types of quantum magnets but together with the fast cycling time of ~1s it holds the promise to enable the measurement of new entanglement witnessing observables.

Q 62.22 Thu 16:30 P

Multiloop functional renormalization group study of the Fermi polaron problem — •Marcel Gievers — Max Planck Institute for Quantum Optics, Garching, Germany

Imbalanced mixtures of strongly correlated fermions have been investigated both theoretically and experimentally for several decades. A single impurity immersed in a Fermi gas is subject to a transition from a bound molecule of two different fermion species to a so-called Fermi polaron where the impurity forms a quasiparticle with the surrounding fermions. We study the Fermi polaron problem theoretically in three dimensions in an experimentally more realistic setup where there is a finite density of the impurity particles. For this, we apply multi-loop functional renormalization group (mfRG) which is an extension of the conventional functional renormalization group equivalent to the diagrammatic parquet formalism. With this elaborate numerical method, we aim to provide more reliable theoretical predictions such as the lifetime of the polaron.

Q 63: Matter Wave Optics

Time: Friday 10:30–12:30 Location: Q-H10

Q 63.1 Fri 10:30 Q-H10

Bragg diffraction of large organic molecules — Christian Brand[1,2], Filip Kiałka[1,3], Stephan Troyer[1], Christian Knobloch[1], •Ksenija Simonović[1], Benjamin A. Stickler[3,4], Klaus Hornberger[3], and Markus Arndt[1] — [1]University of Vienna, Faculty of Physics — [2]German Aerospace Center (DLR), Institute of Quantum Technologies — [3]Faculty of Physics, University of Duisburg-Essen — [4]QOLS, Blackett Laboratory, Imperial College London

We present the first experimental realization of Bragg diffraction for polar and non-polar molecules [1]. Using a thick laser grating at 532 nm, we diffract a molecular beam and observe Bragg diffraction in the far-field. We study this effect for the dye molecule phthalocyanine and the antibiotic ciprofloxacin and observe a pronounced angular dependence and asymmetry in the pattern, characteristic for Bragg diffraction. We can thus realize an effective mirror and a large-momentum molecular beamsplitter with a momentum transfer of up to 18 grating photon momenta $\hbar k$. This is an important step towards gaining control over the manipulation of functional, complex molecules.

[1] Brand et al. Phys. Rev. Lett. 125, 033604

Q 63.2 Fri 10:45 Q-H10

Efficient aberration analysis of Bose-Einstein condensates — •Jan Teske and Reinhold Walser — Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstraße 4A, Darmstadt, D-64289, Germany

Matter-wave interferometry with ultracold atoms is paving the way to a new era of quantum technologies. Recent milestones of space application are space-borne Bose-Einstein condensates [1] and BECs in Earth's orbit on ISS [2]. These achievements require precision modeling of matter-wave optics. In photonic optics, aberrations are efficiently described by Zernike's orthogonal “Kreisflächenpolynome” representing the optical path difference between light waves and a reference wavefront [3].

In this contribution, we present a (3+1)-dimensional aberration analysis for matter-wave optics with Bose-Einstein condensates. Motivated by the intrinsic properties of an interacting condensate, we use a set of orthogonal basis functions to perform a multipole expansion to quantify distortions of the atomic cloud. The resulting aberration coefficients encode the relevant information of the condensate wave function leading to efficient data compression of realistic 3D simulations.

[1] D. Becker et al., Nature 562, 391 (2018)
[2] D. C. Aveline et al., Nature 582, 193 (2020)
[3] F. Zernike, Physica 1, 689 (1934)

Q 63.3 Fri 11:00 Q-H10

Matter-wave Gravimetry Based on Tunneling — •Patrik Schach and Enno Giese — Institut für Angewandte Physik, Technische Universität Darmstadt

One promising candidate for high-precision gravimetry is atom interferometry. In contrast to light in optical interferometers, matter waves consisting of massive particles couple strongly to gravity, making them a tool suitable for gravimetry. In addition to gravity, the motion of atomic wave packets is manipulated by optical potentials that trap, guide or diffract the atoms. Contrary to classical waves, quantum physics allows for tunneling through forbidden regions and thus offers an additional tool to influence the atomic motion.

The combination of quantum tunneling and atom interferometers leads to gravimeters based on an analogue to optical Fabry-Pérot cavities. In this contribution, we theoretically study the transmission spectrum of matter-wave Fabry-Pérot interferometers, present their sensitivity to accelerations and discuss their applicability to gravimetry. Similar to optical Fabry-Pérot cavities that act as monochromators, matter-wave devices introduce a velocity filtering, allowing to select specific momenta of the atomic wave packet. In addition to this effect, we study the preparation of a quantum gas inside the cavity and its asymmetry in tunneling, an effect that has no direct optical analogue.

Q 63.4 Fri 11:15 Q-H10

Chip-based manipulation of guided electrons with auto-ponderomotvie potentials — •Michael Seidling, Franz Schmidt-Kaler, and Peter Hommelhoff — Department Physik, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen

Recent advances in free electron beam guiding and beam splitting for electrons from the eV to the keV range are reported [1, 2]. Electron beam guiding and splitting is based on auto-ponderomotive forces generated by the motion of charged particles through electrostatic electron optics on planar substrates. In the co-moving frame of the electron, the electrostatic fields transform into an alternating potential, and thus the electrons are subject to the same transverse restoring forces as in a conventional linear Paul trap driven with oscillating fields. The confinement of electrons in the two directions perpendicular to the direction of motion is determined by the electrodes* layout. In the future coherent electron beam splitting should be feasible using auto-ponderomotive potentials, enabling new coherent charged matter wave experiments. [1] Zimmermann, R., Seidling, M. & Hommelhoff, P. Charged particle guiding and beam splitting with auto-ponderomotive potentials on a chip. Nat Commun 12, 390 (2021). https://doi.org/10.1038/s41467-020-20592-4 [2] M. Seidling, R. Zimmermann, and P. Hommelhoff, "Chip-based electrostatic beam splitting of guided kiloelectron volt electrons", Appl. Phys. Lett. 118, 034101 (2021) https://doi.org/10.1063/5.0030049

Q 63.5 Fri 11:30 Q-H10

Bragg-Josephson effect in matter-wave beamsplitters — •Oleksandr Marchukov and Reinhold Walser — Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstraße 4A, Darmstadt, D-64289, Germany

The Josephson effect is one of the few known macroscopic quantum effects. While initially predicted and observed in superconductors, it has been shown in externally trapped Bose-Einstein condensates (BECs), as well as internally prepared superpositions of hyperfine levels [1, 2]. In the QUANTUS collaboration [3] matter-wave Bragg beamsplitters are a central tool. Here we demonstrate the Josephson effect between two macroscopic occupied momentum states $-k_L \to +k_L$ coupled by a Bragg beamsplitter [4] in interacting BECs.

We construct an analytical model and demonstrate how the competition between the Bragg diffraction and mean-field interaction leads to the Josephson-like equations. We compare our analytical calculations with numerical simulations and find good agreement. Finally, we evaluate the experimental parameters that would allow for the observation of the effect, based on the realistic experimental set-ups.

[1] S. Raghavan et al., Phys. Rev. A 59, 620 (1999)
[2] J. Williams et al., Phys. Rev. A 59, R31 (1999)
[3] https://www.zarm.uni-bremen.de/en/research/space-science/experimental-gravitation-and-quantum-optics/projects/quantus-2.html
[4] A. Neumann et al., Phys. Rev. A 103, 043306 (2021)

Q 63.6 Fri 11:45 Q-H10

Atomic diffraction through single-layer graphene — •Christian Brand[1,2], Maxime Debiossac[2], Toma Susi[2], Francois Aguillon[3], Jani Kotakoski[2], Philippe Roncin[3], and Markus Arndt[2] — [1]German Aerospace Center, Institute of Quantum Technologies — [2]University of Vienna, Faculty of Physics — [3]Université Paris Saclay, Institut des Sciences Moléculaires d' Orsay

We discuss the prospect of diffracting fast atomic matter waves through atomically thin membranes, such as graphene. Using hydrogen atoms with a velocity of up to 120'000 m/s, we predict a high probability of coherently diffracting the matter wave through the crystalline grating. As the atom-membrane interaction is encoded in the matter wave, interaction microscopy on the pm-scale might be possible. The natural lattice constant of 246 pm furthermore leads to unusual wide diffraction angles in the regime of mrad, which are interesting for novel applications in atom interferometry.

[1] Brand et al., New J. Phys **21**, 033004 (2019)

Q 63.7 Fri 12:00 Q-H10

Double Bragg atom interferometry with BECs in microgravity — •Julia Pahl[1], Merle Cornelius[2], Peter Stromberger[3], Laura Pätzold[2], Waldemar Herr[4,5], Sven Herrmann[3], Patrick Windpassinger[3], Christian Schubert[5], Ernst M. Rasel[4], Markus Krutzik[1,6], and The QUANTUS Team[1,2,3,4,7,8] — [1]HU

Berlin — [2]U Bremen — [3]JGU Mainz — [4]LU Hannover — [5]DLR-SI — [6]FBH Berlin — [7]U Ulm — [8]TU Darmstadt

QUANTUS-2 is a high-flux Bose-Einstein condensate (BEC) experiment operating in microgravity at the ZARM drop tower in Bremen. Its functionality is extended with a rubidium atom interferometry setup based on double Bragg diffraction. We present our latest results on the performance of open interferometer archtictures (Ramsey-type and Mach-Zehnder) in free fall. In combination with a magnetic lens, we are able to enhance the atomic signal on longer time scales. By studying the resulting fringe pattern, we can further spatially resolve the velocity distribution of the ensembles.

This project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy under grant number DLR 50WM1952-1957.

Q 63.8 Fri 12:15 Q-H10

Quantum state engineering of quantum gases in orbit — •Annie Pichery[1], Matthias Meister[2], Nicholas P. Bigelow[3], Naceur Gaaloul[1], and the CUAS Team[1] — [1]Institut für Quantenoptik, Leibniz University Hannover, Hannover, Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany — [3]The Institute of Optics, University of Rochester, New York, USA

Ensembles of cold atoms behave as matter-waves and are routinely used for quantum sensing experiments. Space provides an environment where atoms can float for extended times, but the free expansion and the inherent atomic density drop make the signal detection difficult. By analogy with light, it is possible to collimate the clouds with atomic lenses, using the delta-kick collimation technique. In this contribution, we present a protocol for controlling the expansion of condensed Rb clouds applied to experiments in the NASA Cold Atom Laboratory (CAL) on board of the International Space Station that led to expansion energies at the tens of picokelvin level. This is made possible thanks to an accurate quantum state preparation of the atomic source that makes it compatible with the most stringent requirements of precision atom interferometry experiments.

We acknowledge financial support from NASA/JPL RSA No. 1616833 and the German Space Agency (DLR) with funds provided by the Federal Ministry of Economic Affairs and Energy (BMWi) due to an enactment of the German Bundestag under Grant No. 50WP1705 and No. 50WM1861/2.

Q 64: Nano-Optics III

Time: Friday 10:30–12:30 Location: Q-H11

Q 64.1 Fri 10:30 Q-H11

Extinction spectroscopy of ellipsoidal nanoparticles — •Mathis Noell and Carsten Henkel — Universität Potsdam, Institut für Physik und Astronomie

Plasmonic nanostructures provide an interesting platform to enhance the spectroscopy of molecules. If a nanoparticle is covered with a thin absorbing layer, theory predicts certain resonances that are not seen in experimental extinction spectra [1, 2]. To understand this issue, we analyse the distribution of electric fields and of energy dissipation in and around an ellipsoidal nanoparticle. Calculations are done for gold particles covered with a few nm thick layer. At the spurious resonance, the field is highly localised in this layer, suggesting that strong coupling to the molecular exciton is possible at the few-photon level. We compare the impact of different effective medium approaches on the calculated spectra.

[1] F. Stete et al., “Vacuum Induced Saturation in Plasmonic Nanoparticles,” arXiv:2008.09395.

[2] T. J. Antosiewicz, S. P. Apell, and T. Shegai, “Plasmon–Exciton Interactions in a Core–Shell Geometry: From Enhanced Absorption to Strong Coupling,” ACS Photonics **1**, 454 (2014).

Q 64.2 Fri 10:45 Q-H11

Theory of radial oscillations in metal nanoparticles driven by optically induced electron density gradients — •Robert Salzwedel[1], Andreas Knorr[1], Dominik Hoeing[2], Holger Lange[2], and Malte Selig[1] — [1]Institut für Theoretische Physik, Nichtlineare Optik und Quantenelektronik, Technische Universität Berlin, Berlin, Germany — [2]The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany

Radial breathing modes can be excited in metallic nanoparticles by optical excitations. In current classical theory, these oscillations are thought to be driven by the thermalization of hot electrons, which impulsively heat the lattice [1,2]. We provide a quantum hydrodynamic theoretical approach for the optical excitation of the electron gas in metal nanoparticles and the associated electron-phonon interaction.

We find that the ultrafast dynamics of electron occupation and the coherent phonon amplitude are responsible for the size oscillations of the nanoparticle. The optical excitation induces spatial gradients in the electron density that directly drive coherent phonon oscillations. Therefore, our results show a more direct coupling mechanism between the field and phonons compared to the established interpretation of experiments [3,4], and it is shown that thermalization is of reduced importance in the early stages of the oscillation.

[1] Hartland, G. V. et al., JCP, 116, 8048 (2002)
[2] Hodak, J. H. et al., JCP, 111, 8613 (1999)
[3] Del Fatti, N. et al., JCP, 110, 11484 (1999)
[4] Ng, M. Y. et al., JCP, 134, 094116 (2011)

Q 64.3 Fri 11:00 Q-H11

Room-temperature strong coupling of a single quantum dot to a tunable plasmonic nanogap antenna using a novel scanning probe technique — •Michael A. Becker[1], Hsuan-Wei Liu[1], Korenobu Matzusaki[1], Randhir Kumar[1], Stephan Götzinger[2,1], and Vahid Sandoghdar[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander University of Erlangen-Nürnberg, Erlangen, Germany

Scanning probe techniques offer a workhorse for optical investigations of structures smaller than the diffraction limit. In particular, scanning near-field optical microscopy (SNOM) can be used to probe light-matter interactions at the nanometer scale. However, the mechanical stability of the tip and its nanometric distance to the sample pose severe challenges for routine and robust measurements. Here, we report on a novel and simple tip-free scanning probe technique capable of carrying out high-precision near-field optical studies on single emitters. We utilize this technique to create an open and tunable nanogap antenna that can be tuned in resonance with the exciton transition of a single semiconductor quantum dot. With nanometer precision and a remarkable mechanical stability, the single emitter is positioned at the antenna hotspot, tuning the system between the weak and strong light-matter coupling regimes. We present spectral splitting and a characteristic anticrossing behavior.

Q 64.4 Fri 11:15 Q-H11

On the usage of fluorescent nanodiamonds in modern nanoscopy — •Philipp Kellner[1], Max Haase[1], Tanja Weil[3], and Christian Eggeling[1,2] — [1]Institut für angewandte Optik und Biophysik, Friedrich-Schiller-Universität, Philosophenweg 7, 07743 Jena — [2]Leibniz-Institut für photonische Technologien, Albert-Einstein-Straße 9, 07745 Jena — [3]Max-Planck-Institut für Polymerchemie, Ackermannweg 10, 55128 Mainz

Fluorescent correlation spectroscopy (FCS) is a widely used microscopy-based, non-invasive technique for measuring mechanical and chemical properties like diffusion coefficient and concentration of specific molecules in solution, biological tissue and soft matter samples. This talk will present the basics of fluorescence correlation spectroscopy and newest insights in FCS in combination with modern Stimulated Emission Depletion (StED-) Nanoscopy using fluorescent nanodiamonds, a bright, stable, biocompatible nanoparticle as a probe. We will elaborate on the usage of the method, the nanoparticle and their combination for dynamical measurements on length-scales far below the diffraction limit. A special focus will be on the question: Are StED-FCS experiments biased by optical tweezer effects?

Q 64.5 Fri 11:30 Q-H11

Coincidence gated imaging using free electrons and photons

— Armin Feist[1,2], Guanhao Huang[3], •Germaine Arend[1,2], Yujia Yang[3], Jan-Wilke Henke[1,2], Arslan Sajid Raja[3], F. Jasmin Kappert[1,2], Rui Ning Wang[3], Hugo Lourenco-Martins[1,2], Junqiu Liu[3], Ofer Kfir[1,2], Tobias J. Kippenberg[3], and Claus Ropers[1,2] — [1]Georg-August Universität Göttingen, Germany — [2]Max Planck Institute for Biophysical Chemistry, Göttingen, Germany — [3]Swiss Federal Institute of Technology, Lausanne, Switzerland

Electron microscopy can probe optical modes at the nanoscale with the light generated by a focused electron beam. In this the photonic density of states and optical transitions are mapped, while photon statistics reveal the properties and lifetime of excitations. However, current methods largely disregard correlated properties of the single electrons involved.

In this work, we demonstrate the generation of photons in a Si_3N_4 high-Q resonator and characterize their temporal and energetic correlation with the inelastically scattered electrons. We also show how photonic mode mapping using correlated events allows for a two-order of magnitude contrast enhancement for extremely low-intensity signals.

Q 64.6 Fri 11:45 Q-H11

Nanoscale Imaging of Live Cells with Confocal Interferometric Scattering (iSCAT) Microscopy — •David Albrecht[1], Michelle Küppers[1,3], Anna Kashkanova[1], Jennifer Lühr[1], and Vahid Sandoghdar[1,2,3] — [1]Max Planck Institute for the Science of Light, 91058 Erlangen, Germany — [2]Max-Planck-Zentrum für Physik und Medizin, 91058 Erlangen, Germany — [3]Friedrich-Alexander University Erlangen-Nürenberg, 91058 Erlangen, Germany

Light microscopy methods are widely used in biomedical research to investigate cellular structure and dynamics in live specimen. Label-free approaches are of particular interest to circumvent problems such as phototoxicity, functional impairment or insufficient signal that may be imposed by the label. Here, we present nanoscale imaging with confocal interferometric scattering (iSCAT) microscopy for recording label-free information from subcellular processes. iSCAT is a shot-noise limited homodyne interferometry technique, which has been extensively used for tracking nanoparticles with exquisite performance. However, application of iSCAT for cellular imaging has been hampered by a strong speckle-like background. By employing a pinhole in a confocal arrangement, we show that one can reject a large portion of the background scattering from the complex environment of a live cell. We, thus, identify cellular organelles and confirm our findings through the molecular specificity of concomitant fluorescence microscopy measurements. We also investigate the interaction of nanoscopic matter such as intracellular vesicles, lipid droplets and viruses in a cellular context at a high spatial and temporal resolution.

Q 64.7 Fri 12:00 Q-H11

Nanoscopic Charge Fluctuations in a Gallium Phosphide Waveguide Measured by Single Molecules — •Alexey Shkarin[1], Dominik Rattenbacher[1,3], Jan Renger[1], Simon Hönl[2], Tobias Utikal[1], Paul Seidler[2], Stephan Götzinger[3,1], and Vahid Sandoghdar[1,3] — [1]Max Planck Institute for the Science of Light, D-91058 Erlangen, Germany — [2]IBM Research Europe, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland — [3]Department of Physics, Friedrich Alexander University Erlangen-Nuremberg, D-91058 Erlangen, German

Nanometer-scale electric field fluctuations can shed light on material properties of technological interest such as crystal defects and charge distributions. However, nanoscopic characterization of these features is challenging because there exist not many probes that combine the necessary sensitivity, size, and vicinity to the location of interest. In our work [1], we study local electric field fluctuations via the Stark shift induced in single quantum emitters. Specifically, we examine the field at several points directly next to a GaP waveguide (< 50 nm away) using individual dibenzoterrylene molecules embedded in para-dichlorobenzene as nanoscopic probes. We discuss a series of experiments for investigating the spatial and temporal correlations of the electric field to confirm that the observed fluctuations originate in GaP and are photoinduced. Furthermore, we analyze the statistics of the fluctuations and show that it is consistent with fluctuations being induced by very few (< 50) charges jumping under the influence of light.

[1] A. Shkarin et al., Phys. Rev. Lett. 126, 133602 (2021)

Q 64.8 Fri 12:15 Q-H11

Ultrafast Field Microscopy of Terahertz Near-field Waveforms — •Moritz B. Heindl[1], Nicholas Kirkwood[2], Tobias Lauster[3], Julia A. Lang[1], Markus Retsch[3], Paul Mulvaney[2], and Georg Herink[1] — [1]Experimental Physics VIII, University of Bayreuth, Germany — [2]ARC Centre of Excellence in Exciton Science, School of Chemistry, University of Melbourne, Australia — [3]Physical Chemistry I, University of Bayreuth, Germany

Access to high-frequency electric waveforms is critical to the understanding of ultrafast plasmonic and field-driven nonlinear phenomena, yet, microscopic measurements still present a grand challenge. Here, we present a fluorescence-based field microscope for imaging ultrafast THz near-field evolutions using quantum dots. The Quantum-probe Field Microscopy (QFIM) scheme is enabled by the quantum-confined Stark-effect encoding the local field evolution in the luminescence yield of semiconductor nanocrystals [1,2]. QFIM allows for the spatio-temporal detection of THz sub-wavelength fields in the optical far-field using conventional fluorescence microscopy. We demonstrate the spatio-temporal tracking of propagating wavepackets confined to sub-wavelength THz waveguides, and we investigate the near-field evolutions inside single THz antennas with sub-cycle resolution [3]. QFIM paves a new route towards in-operando nanoscopy of nonlinear interactions and ultrafast nanodevices.

[1] Hoffmann, M. C. et al. Appl. Phys. Lett. 97, 231108 (2010).
[2] Pein, B. C. et al. Nano Lett. 17, 5375-5380 (2017).
[3] Heindl, M. B. et al. Light Sci. Appl. (in press).

Q 65: Quantum Information (Miscellaneous)

Time: Friday 10:30–12:15 Location: Q-H12

Q 65.1 Fri 10:30 Q-H12

Bi-photon correlation time measurement with a two-colour broadband SU(1,1) interferometer — •Franz Roeder, Matteo Santandrea, René Pollmann, Michael Stefszky, Victor Quiring, Raimund Ricken, Christof Eigner, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Department of Physics, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Straße 100, 33098 Paderborn, Germany

SU(1,1) interferometers have been investigated intensively lately for applications such as spectroscopy or imaging with undetected photons. These interferometers are mostly utilising engineered broadband non-degenerate PDC sources as active elements to achieve broad spectral coverage. Being pumped with a narrow bandwidth CW laser, these PDC sources exhibit strong frequency correlations and simultaneous correlation times between the photons down to below 100 fs. In general, such short correlation times are hard to measure. Nevertheless, knowledge about this quantity is essential for further applications such as entangled two-photon absorption.

In this contribution, we show that the fringing pattern, measured in terms of single photon numbers and coincidence counts, of a SU(1,1) interferometer is directly connected to the correlation time.

We will present measurements from an interferometer consisting of a broadband integrated Type-II PDC source operating at wavelengths of 830 nm and 1370 nm. We are able to deduce the correlation time of the bi-photons within the interferometer and discuss its significance for applications.

Q 65.2 Fri 10:45 Q-H12

Engineering of Kerr squeezing of light — •Nikolay A. Kalinin[1,2], Arseny A. Sorokin[1,2], Thomas Dirmeier[2,3], Elena A. Anashkina[1,4], Gerd Leuchs[1,2,3], and Alexey Andrianov[1] — [1]Institute of Applied Physics, RAS, Nizhny Novgorod, Russia — [2]Max Planck Institute for the Science of Light, Erlangen, Germany — [3]Department of Physics, Friedrich-Alexander-University Erlangen-Nürnberg, Germany — [4]Advanced School of General and Applied Physics, Lobachevsky State University of Nizhny Novgorod, Russia

We report on a new experimental study and a modified set-up, allowing for reliably generating 5dB of two-mode Kerr squeezing. Manipulating the two-mode squeezed state using standard linear optic unitary transformations, we also demonstrate the enhancement of the sensitivity of an interferometer. In addition, we are studying different glasses with higher Kerr effect coefficient [A.A. Sorokin et al., Photonics 8, 226 (2021)]. Squeezing coherent states of light using the optical Kerr effect requires no phase matching condition. The effect is observable, if the incoming coherent light is intense enough, the interaction is long enough and losses are small enough. Therefore, experimental studies concentrated on optical waveguides, such as fibers of several meter length, using pulses in the soliton domain to enhance the overall effect. The Kerr nonlinear phase shift results in an elliptical distribution in phase space, tilted with respect to amplitude quadrature. Squeezing cannot be seen in intensity detection directly out of the waveguide, so that demonstrating sensitivity enhancement of an interferometer is challenging. (RFBR 19-29-11032; Megagrant 075-15-2021-633)

Q 65.3 Fri 11:00 Q-H12

Sensing with few photons: beating the Standard Quantum Limit in lossy SU(1,1) interferometers — •Matteo Santandrea, Kai Hong Luo, Michael Stefszky, Jan Sperling, Harald Herrmann, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Department of Physics, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburgerstr. 100, D-33098 Paderborn, Germany

SU(1,1) interferometers have been shown to be able to beat the Standard Quantum Limit (SQL), since their uncertainty in phase estimation scales as $\sim 1/\langle n\rangle$, in the limit of $\langle n\rangle \gg 1$, where $\langle n\rangle$ indicates the mean photon number inside the interferometer. However, in recent years, these systems have been used more and more often in the low photon number regime ($\langle n\rangle \ll 1$) for spectroscopy and microscopy applications, where the scaling properties are not considered. In this regime, it is not obvious whether they can beat the SQL or in which cases - in particular when losses inside and outside the interferometer are considered.

In this contribution, we investigate lossy SU(1,1) interferometers in the low photon number regime. We show that concidence measurement can drastically help in beating the SQL and that it is still possible to beat the SQL even in the presence of moderate losses inside the setup.

The results of this work are fundamental in understanding the behaviour of SU(1,1) interferometers in the low photon number regime and provides the foundations for improved low-photon-number interferometric schemes.

Q 65.4 Fri 11:15 Q-H12

Engineering Organic Molecules with Long-Lived Quantum Coherence — •Burak Gurlek[1], Vahid Sandoghdar[1], and Diego Martin-Cano[2] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center, Universidad Autónoma de Madrid, Madrid, Spain

Some organic molecules in the solid state offer remarkable coherent properties at liquid helium temperatures and flexibility in their chemical synthesis [1]. However, the excited state associated with the strong Fourier-limited zero-phonon lines of these systems decay within nanoseconds, posing a challenge for practical applications in quantum technologies. In this theoretical work, we propose a new molecular system with quantum coherences up to millisecond time scales. Here, we exploit the inherent optomechanical character of organic molecules in a solid organic crystal [2]. The proposed scheme consists of a single organic molecule in a host matrix with a structured phononic environment. By suppressing phononic decay channels, we realize and exploit long optomechanical coherence times up to milliseconds for storing and retrieving information. We show that the resulting long-lived vibrational states facilitate reaching the strong optomechanical regime at the single photon level. The proposed system shows the promise of organic molecules for achieving unexplored optomechanical phenomena and long-lived quantum memories. References: [1] C. Toninelli et al., Nat. Mater. 20, 1615-1628 (2021). [2] B. Gurlek et al., Phys. Rev. Lett. 127, 123603 (2021).

Q 65.5 Fri 11:30 Q-H12

Quantum interference and spectral properties of single photons generated from a single $^{40}Ca^+$ ion — •Matthias Kreis, Jelena Ritter, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

Generation of single photons by Raman scattering is a way of realizing an atom-photon quantum interface [1]. For quantum communication applications, well-controlled temporal and spectral properties are important, for example for the indistinguishability of photons from different senders.

We record spectra of single photons generated on the 393 nm ($P_{3/2} \rightarrow S_{1/2}$) and 854 nm ($P_{3/2} \rightarrow D_{5/2}$) transitions of a single trapped $^{40}Ca^+$ ion, using frequency stabilized Fabry-Perot cavities as single-photon spectrometers. The temporal single-photon wave packets are recorded simultaneously.

We report comprehensively on the observed properties, including the time-bandwidth product, in dependence of the excitation parameters. We demonstrate the generation of photons narrower than the natural linewidth of the $P_{3/2}$ state. We further discuss quantum interference effects in absorption and emission leading to an enhancement and suppression of the emission into certain frequency modes. For all cases, measured spectra are compared to model calculations extended from the theory in [2] and [3].

[1] C. Kurz et al., Phys. Rev. A **93**, 062348 (2016).
[2] P. Müller et al., Phys. Rev. A **96**, 023861 (2017).
[3] S. Zhu et al., Phys. Rev. A **52**, 4791 (1995)

Q 65.6 Fri 11:45 Q-H12

Optimal control design of preparation pulses for higher contrast imaging — •Amanda Nicotina and Steffen Glaser — Technische Universität München, Munich, Germany

Magnetic Resonance Imaging (MRI) is an imaging technique that has gained a lot of attention in the medical community for its ability to visualize the internal body in a non-invasive manner. This visualization is achieved based on the contrast originating from intrinsic tissue properties, such as relaxation times (T1 and T2). This contrast can be emphasized via additional acquisition parameters (for example, flip angles/RF pulses), the standard acquisition strategies being T1 and T2 weighting. However, these do not always generate the optimal contrast. This work proposes a more tailored approach, where we present how to find an optimal sequence of flip angles based on optimal control theory for the contrast between specific tissues. In addition, it allows for robust control pulses even when introducing B0- and B1-inhomogeneities. More precisely, we employ the Pontryagin Maximum Principle to numerically find optimal solutions to the underlying Bloch equations implementing the GRadient Ascent Pulse Engineering (GRAPE) algorithm. In particular, we focus on the theoretical and experimental limits of the optimizations.

Q 65.7 Fri 12:00 Q-H12

Incompatibility of energy conservation and fluctuation theorems for quantum work — •Karen Hovhannisyan[1] and Alberto Imparato[2] — [1]University of Potsdam, Institute of Physics and Astronomy, 14476 Potsdam, Germany — [2]Aarhus University, Department of Physics and Astronomy, Ny Munkegade 120, 8000 Aarhus, Denmark

Characterizing the fluctuations of work in coherent quantum systems is a notoriously elusive problem. Aiming to reveal the ultimate source of this elusiveness, we demand of a work measurement the sheer minimum and check if those demands can be met at all. We require (A) energy conservation for arbitrary initial states of the system and (B) the Jarzynski equality for thermal initial states. By energy conservation we mean that the average work must be equal to the difference of initial and final average energies, and that untouched systems must exchange deterministically zero work. Requirement B encapsulates the second law of thermodynamics and the quantum–classical correspondence principle. We prove that work measurement schemes that do not depend on the system's initial state satisfy B if and only if they coincide with the famous two-point measurement scheme, thereby establishing that state-independent schemes cannot simultaneously satisfy A and B. Expanding the scope to the realm of state-dependent schemes allows for more compatibility between A and B. However, merely requiring the state-dependence to be continuous still effectively excludes the possibility of coexistence of A and B.

Q 66: Quantum Effects IV

Time: Friday 10:30–12:15 Location: Q-H13

Q 66.1 Fri 10:30 Q-H13

Generalized expression for full characterization of spectral and spatial properties of the two-photon state in Laguerre-Gaussian basis — •Baghdasar Baghdasaryan[1,2,3], Carlos Sevilla[2], Fabian Steinlechner[3,4], and Stephan Fritzsche[1,2,4] — [1]Theoretisch-Physikalisches Institut, Friedrich-Schiller-University Jena, 07743 Jena, Germany — [2]Helmholtz-Institut Jena, 07743 Jena, Germany — [3]Fraunhofer Institute for Applied Optics and Precision Engineering IOF, 07745 Jena, Germany — [4]Abbe Center of Photonics, Friedrich-Schiller-University Jena, 07745 Jena, Germany

We present a semi-analytical expression for the two-photon state that describes quantitatively both spatial and spectral properties of down-converted photons. The expression has been derived independently of the phase-matching condition. Moreover, the pump field is a pulsed Laguerre-Gaussian (LG) beam that can be easily extended to an arbitrary laser field. The expression can be used to model and predict most SPDC experiments. As an important application, we consider the engineering of high-dimensional entangled states in spatial degree of freedom. Hereby, we focus on the decoupling of spatial and spectral degrees of freedom in the broadband regime, which is crucial for the efficient generation of entangled photons.

Q 66.2 Fri 10:45 Q-H13

Many-body coherence and entanglement from randomized correlation measurements — •Eric Brunner[1,2], Andreas Buchleitner[1,2], and Gabriel Dufour[1,2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg, Deutschland — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg, Deutschland

We show that k-point correlation measurements on output of a non-interacting, multimode random unitary allow to quantify the k-particle coherence of $N \geq k$ identical (bosonic or fermionic) particles. We establish a strictly monotonic relationship between k-particle coherence, the interference contrast in the experimentally accessible counting statistics, and the degree of the particles' mutual distinguishability, as controlled by their internal degrees of freedom, given separable many-particle input states. Non-separability on input can be unveiled by comparison of correlation measurements of different orders.

Q 66.3 Fri 11:00 Q-H13

Investigation of incoherent-seeding effects on performance of nonlinear interferometers — •Björn Haase[1,2], Joshua Hennig[1,2], Mirco Kutas[1,2], Georg von Freymann[1,2], and Daniel Molter[1] — [1]Fraunhofer Institute for Industrial Mathematics, Kaiserslautern, Germany — [2]Department of Physics and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

In the last decade, measurement techniques with undetected photons have undergone remarkable improvements and their potential has been demonstrated for various spectral ranges like the infrared or terahertz frequency range. This effect is based on the interference of biphotons which are generated in nonlinear crystals. In those interferometers solely the interference of the signal photons generated in one of the crystals is detected while the correlated idler radiation interacts with a sample. If both the signal and idler are aligned the sample's information can be transferred from the idler to the signal photons which are easier to detect. Yet, if the idler photon energy is very small thermal idler radiation present at room temperature has to be considered. To simulate this kind of radiation we added an incoherent seed to a nonlinear Mach-Zehnder interferometer setup used in the original work [Lemos *et al.*, Nature **512**, 409, (2014)] to evaluate its influence on the performance of nonlinear interferometers. Here, 532-nm pump photons decay into signal and idler photons at 810 nm and 1550 nm due to DFG with the incoherent seed or SPDC with vacuum fluctuations. I will present the findings, that might be useful to enhance the applicability in spectral regions suffering from insufficient sensor sensitivity.

Q 66.4 Fri 11:15 Q-H13

Dynamics of partially distinguishable particles — •Gabriel Dufour, Eric Brunner, Christoph Dittel, and Andreas Buchleitner — Physikalisches Institut, Albert-Ludwigs-Universität Freiburg

A complete description of bosonic and fermionic many-body systems should include any degree of freedom which could, in principle, allow to distinguish the particles. Indeed, even if they do not participate in the dynamics, the existence of such "labels" leads to a degradation of many-particle interference in the dynamical degrees of freedom. We show that partial distinguishability can be described in terms of entanglement between dynamical and label degrees of freedom, conditioned by the overall symmetry of the many-particle state. This entanglement suppresses interference contributions to expectation values of many-body observables, which are governed by the coherences of the reduced state of the dynamical degrees of freedom.

Q 66.5 Fri 11:30 Q-H13

Non-Markovian Stochastic Schrödinger Equation: Matrix Product State Approach to the Hierarchy of Pure States — Xing Gao[1], Jiajun Ren[2], Zhigang Shuai[2], and •Alexander Eisfeld[3] — [1]Sun Yat-sen University, Shenzhen, Guangdong, China — [2]Tsinghua University, Beijing, China — [3]MPI-PKS, Dresden

We derive a stochastic hierarchy of matrix product states (HOMPS) for non-Markovian dynamics in open quantum system at finite temperature, which is numerically exact and efficient. HOMPS is obtained from the stochastic hierarchy of pure states (HOPS) by expressing HOPS in terms of formal creation and annihilation operators. The resulting stochastic first order differential equation is then formulated in terms of matrix product states and matrix product operators. In this way the exponential complexity of HOPS can be reduced to scale polynomial with the number of particles. The validity and efficiency of HOMPS is demonstrated for the spin-boson model and long chains where each site is coupled to a structured, strongly non-Markovian environment.

[1] arXiv:2109.06393 [quant-ph]

Q 66.6 Fri 11:45 Q-H13

Decoherence of Nanorotors due to Heat Radiation — •Jonas Schäfer, Benjamin A. Stickler, and Klaus Hornberger — Faculty of Physics, University of Duisburg-Essen, Duisburg

Recent breakthroughs in levitated optomechanics with aspherical nanoparticles open the door to observing and exploiting rotational quantum interference for fundamental tests of quantum physics and for sensing applications [1]. This talk presents a theory of spatio-orientational decoherence of arbitrarily shaped dielectrics due to thermal emission of radiation. It will be shown that the orientational coherences decay gradually even for isotropic particles due to the vector character of phononic dipole transitions. We quantify the decoherence and discuss its impact for upcoming lab and space-based quantum superposition tests.

[1] Stickler et al., Nat. Rev. Phys. 3, 589-597 (2021)

Q 66.7 Fri 12:00 Q-H13

Certification of High-Dimensional Entanglement in Ultracold Atom Systems — •Niklas Euler[1,2] and Martin Gärttner[1,2,3] — [1]Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany — [2]Kirchhoff-Institut für Physik, Universität Heidelberg, Heidelberg, Germany — [3]Institut für Theoretische Physik, Universität Heidelberg, Heidelberg, Germany

Quantum entanglement has been identified as a crucial concept underlying many intriguing phenomena in condensed matter systems. Recently, instead of considering mere quantifiers of entanglement like entanglement entropy, the study of entanglement structure in terms of the entanglement spectrum has shifted into focus, leading to new insights into topological phases and many-body localization, among others. What remains a challenge is the experimental detection of such fine-grained properties of quantum systems. Here we present a method to bound the width of the entanglement spectrum or entanglement dimension of cold atoms in lattice geometries, requiring only measurements in two experimentally accessible bases and utilizing ballistic time-of-flight (ToF) expansion. Building on previous proposals for entanglement certification for photon pairs, we first consider entanglement between two atoms of different atomic species and later generalize to higher numbers of atoms per species and multispecies configurations showing multipartite high-dimensional entanglement. Through numerical simulations of a Fermi-Hubbard system we demonstrate that our method is robust against typical experimental noise effects and that the required measurement statistics is manageable.

Q 67: Rydberg Systems (joint session Q/A)

Time: Friday 10:30–11:45 Location: Q-H14

Q 67.1 Fri 10:30 Q-H14

Trapped Rydberg Ions in Motional States for Quantum Computation and Sensing — •Jonas Vogel[1], Alexander Schulze-Makuch[1], Marie Niederländer[1], Bastien Gely[2], Arezoo Mokhberi[1], and Ferdinand Schmidt-Kaler[1,3] — [1]QUANTUM, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany — [2]ENS Paris-Saclay, 91190 Gif-sur-Yvette, France — [3]Helmholtz-Institut Mainz, D-55128 Mainz, Germany

Cold and controlled atoms and ions are currently of great interest for applications in quantum information processing, simulation and sensing. Excitation of trapped ions to their Rydberg states offers a unique opportunity for combining advantages of precisely controllable trapped-ion qubits with long-range and tunable Rydberg interactions [1]. Intrinsically large polarizabilities of Rydberg states result in enhanced electric field sensitivity to generate entanglement in sub-μs timescales [2]. Here, we present two-photon spectroscopy on high lying Rydberg states of $^{40}Ca^{+}$ ions for precise determination of the second ionization energy as well as principal quantum number scaling for blackbody induced ionization and depopulation rates [3]. We introduce a model to simulate the transition lineshape and study phonon number induced frequency shifts. Finally, we excite large coherent states of motion to extract the Rydberg state polarizability, a prerequisite for using Rydberg ions as electric field sensors.

[1] Mokhberi et al., Adv. At., Mol., Opt. Phys. Ch.4, 69 (2020)
[2] Vogel et al., Phys. Rev. Lett. 123, 153603 (2019)
[3] Andrijauskas et al., Phys. Rev. Lett. 127, 203001 (2021)

Q 67.2 Fri 10:45 Q-H14

Structure and dynamics of cesium long-range Rydberg molecules — •Michael Peper, Ali-Dzhan Ali, Martin Trautmann, and Johannes Deiglmayr — Leipzig University, Department of Physics and Geosciences, 04103 Leipzig, Germany

Long-range Rydberg molecules (LRMs) are exotic bound states of a Rydberg atom and a ground-state atom within its orbit. Because their structure is very sensitive to the elastic electron–ground-state-atom scattering phase shifts, precision measurements and accurate theoretical modelling may provide a unique possibility to test quantum scattering theories for such systems at extremely low collision energies [1]. A detailed understanding of the structure of LRMs is also a prerequisite for the proposed creation of ultracold neutral plasmas with equal-mass charges via photoassociation (PA) and stimulated charge-transfer of LRMs [2,3].

In this talk I will present recent results on the modelling of experimental PA spectra using an accurate Hamiltonian [4] and optimized scattering phase shifts. I will discuss in detail the characterization of molecular decay processes and the role of Stark-facilitated excitation of Rydberg atoms at molecular PA resonances.

[1] M. Peper, J. Deiglmayr, Phys. Rev. Lett. 126, 013001 (2021) [2] M. Peper, J. Deiglmayr, J. Phys. B 53, 064001 (2020) [3] F. Hummel *et al.*, New J. Phys. 22, 063060 (2020) [4] M. Eiles, C. Greene, Phys. Rev. A 95, 042515 (2017)

Q 67.3 Fri 11:00 Q-H14

Hamiltonian Engineering of a many-body Rydberg-spin system — •Sebastian Geier[1], Nithiwadee Thaicharoen[1,2], Clément Hainaut[1,3], Titus Franz[1], Andre Salzinger[1], Annika Tebben[1], David Grimshandl[1], Gerhard Zürn[1], Matthias Weidemüller[1], Pascal Scholl[4], Hannah J. Williams[4], Guillaume Bornet[4], Loic Henriet[5], Adrien Signoles[5], Florian Wallner[4], Daniel Barredo[4], Thierry Lahaye[4], and Antoine Browaeys[4] — [1]Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany — [2]Physikalisches Institut, Im Neuenheimer Feld 226 — [3]Université Lille, CNRS, UMR 8523 -PhLAM- Physique des Lasers, Atomes et Molécules, Lille, France — [4]Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127 Palaiseau Cedex, France — [5]Pasqal, 2 avenue Augustin Fresnel, 91120 Palaiseau, France

Using time-periodic driving, we present how a naturally given many-body Hamiltonian of a quantum system can be transformed into an effective target Hamiltonian. We demonstrate such Floquet engineering with a Rydberg-spin system in different spatial geometries. Applying a sequence of spin manipulations, we change the interaction parameters of the effective XYZ Hamiltonian. In a 3D disordered configuration with hundreds of spins, we explore the conservation laws associated to engineered symmetries. In complementary experiments, we apply the engineering to a 1D array of ordered atoms and benchmark the technique for the case of two atoms. Furthermore, we explore the transport behavior of a domain wall state for tunable XXZ Hamiltonians.

Q 67.4 Fri 11:15 Q-H14

Controlled Dephasing and Unequal Time Correlations in Rydberg Qubits — •Andre Salzinger[1], Kevin T. Geier[2,3], Titus Franz[1], Sebastian Geier[1], Nithiwadee Thaicharoen[4], Annika Tebben[1], Clément Hainaut[5], Robert Ott[3], Martin Gärttner[1], Gerhard Zürn[1], Philipp Hauke[2], and Matthias Weidemüller[1] — [1]Physikalisches Institut Heidelberg — [2]University of Trento — [3]Institut für Theoretische Physik Heidelberg — [4]Chiang Mai University — [5]Université Lille

Engineering open system dynamics relies on restricted degrees of freedom of a larger system. Equivalently, master equations can be derived by averaging over realisations of stochastic processes. We present experimental results for qubit rotations subjected to random phase walks, which are sampled from 1D Brownian motion. The observed realisation average follows a Lindblad description with decay parameter γ given by the variance of sampled phase walks. We use this controlled dephasing in a linear-response scheme to extract the unequal-time anticommutator in an ensemble of driven two-level systems by coupling to an ancilla level. This acts as a first benchmark for future measurements in many-body systems far from equilibrium, where unequal-time commutator and anticommutor probe fluctuation-dissipation relations.

Q 67.5 Fri 11:30 Q-H14

Quantum transport enabled by non-adiabatic transitions — Ajith Ramachandran[1], Alexander Eisfeld[2], •Sebastian Wüster[1], and Jan-Michael Rost[2] — [1]Indian Institute of Science Education and Research, Bhopal — [2]Max Planck Institute for the Physics of Complex Systems, Dresden

Quantum transport of charge or energy in networks with discrete sites is a core feature of diverse prospective quantum technologies, from molecular electronics over excited atoms to photonic metamaterials. In many of these examples, transport can be affected by motion of the sites or coupling to phonons.

The Born-Oppenheimer surfaces of the hybrid Rydberg chain with side-unit (Fano-Anderson chain), are shown to inherit characteristics from both constituents: A dense exciton band from the regular chain with added avoided crossings or conical intersections. Using time dependent quantum wave packets, we demonstrate that these features enable a setting in which only a mobile, symmetric side unit permits quantum transport on the regular chain, while transport is blocked without motion or for a distorted side unit [1]. This provides an example for functional synthetic Born-Oppenheimer surfaces with possible uses for temperature sensing in molecular electronics, through the sensitive linkage between molecular motion and quantum transport [2].

[1] A. Ramachandran, A. Eisfeld, S. Wüster, J. M. Rost; ArXiv (2022).
[2] A. Ramachandran, M. Genkin, A. Sharma, A. Eisfeld, S. Wüster, J. M. Rost; PRA 104 (2021) 042219.

Q 68: Quantum Cooperativity (joint session Q/SYQC)

Time: Friday 10:30–12:30 Location: Q-H15

Q 68.1 Fri 10:30 Q-H15

Interplay of periodic dynamics and noise: insights from a simple adaptive system — •Frederic Folz[1], Kurt Mehlhorn[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — [2]Algorithms and Complexity Group, Max-Planck-Institut für Informatik, Saarland Informatics Campus, 66123 Saarbrücken, Germany

We study the dynamics of a simple adaptive system in the presence of noise and periodic damping. The system is composed by two paths connecting a source and a sink, the dynamics is governed by equations that usually describe food search of the paradigmatic Physarum polycephalum. In this work we assume that the two paths undergo damping whose relative strength is periodically modulated in time and analyse the dynamics in the presence of stochastic forces simulating Gaussian noise. We identify different responses depending on the modulation frequency and on the noise amplitude. At frequencies smaller than the mean dissipation rate, the system tends to switch to the path which minimizes dissipation. Synchronous switching occurs at an optimal noise amplitude which depends on the modulation frequency. This behaviour disappears at larger frequencies, where the dynamics can be described by the time averaged equations. Here, we find metastable patterns that exhibit the features of noise-induced resonances.

Q 68.2 Fri 10:45 Q-H15

A software pipeline for simulating and evaluating incoherent diffraction imaging — •Sebastian Karl[1], Stefan Richter[1], Fabian Trost[2], Henry Chapman[2], Ralf Röhlsberger[3], and Joachim von Zanthier[1] — [1]University of Erlangen-Nuremberg, Staudtstr. 1, 91058 Erlangen — [2]Center for Free-Electron Laser Science, Notkestraße 85, 22607 Hamburg — [3]Helmholtz-Institute Jena, Max-Wien-Platz 1, 07743 Jena

Conventional x-ray crystallography relies on coherent scattering for high resolution structure determination. However often the predominant scattering mechanism is an incoherent process like fluorescence, introducing severe background in the coherent diffractogram. Incoherent diffractive imaging (IDI) aims to use this incoherently scattered light for structure determination by measuring second order correlations n the far field [1]. While in theory single shot 3d imaging would be possible using IDI, careful theoretical examinations place thresholds on its feasibility in both the high [2] and low [3] photon limit. We present a software pipeline facilitating simulation and evaluation of IDI images of structures ranging from crystals to mircometer-size masks. Since this pipeline is able to account for mode mixing identified as the main obstacle in [3], it enables realistic estimations of necessary photon fluxes and image shot numbers for IDI experiments.

[1] A. Classen et al, PRL 119, 053401, 2017
[2] F. Trost et al., New J. Phys. 22, 083070, 2020
[3] L. M. Lohse, Acta Cryst. A 77, 480-496, 2021

Q 68.3 Fri 11:00 Q-H15

Twisted matter waves and reference frame motions. — •Alexey Okulov — Russian Academy of Sciences, 119991, Moscow, Russia

When superfluid is loaded in helical trap the external disturbances affect translational and rotational dynamics in nontrivial way. The conventional approach is to consider reference frame transformations corresponding to translations, rotations and linear accelerations. In mean-field Gross-Pitaevskii equation with a weakly modulated linear velocity, rotation and free-fall acceleration it is possible to obtain exact solutions which connect linear displacements of reference frame $\vec{V}$ to rotations of atomic ensemble and vise versa rotations of reference frame $\vec{\Omega}_{\oplus}$ are the cause of linear displacements of ensemble. Linear accelerations being equivalent to gravitational force induce phase modulation of macroscopic wavefunction.

Q 68.4 Fri 11:15 Q-H15

Quantum criticality of the long-transverse-field Ising model extracted by Quantum Monte Carlo simulations — •Jan Alexander Koziol, Anja Langheld, Sebastian C. Kapfer, and Kai Phillip Schmidt — Lehrstuhl für Theoretische Physik I, Staudtstraße 7, Friedrich-Alexander Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

The quantum criticality of the ferromagnetic transverse-field Ising model with algebraically decaying interactions is investigated by means of stochastic series expansion quantum Monte Carlo, on both the one-dimensional linear chain and the two-dimensional square lattice. Utilizing finite-size scaling (FSS), we extract the full set of critical exponents as a function of the decay exponents of the long-range interactions. We resolve the three different regimes predicted by field theory, ranging from the nearest-neighbor Ising to the long-range Gaussian universality classes with an intermediate regime giving rise to a continuum of critical exponents. Focusing on the non-trivial intermediate regime, we verify our study by the well-known limiting regimes. In the long-range Gaussian regime, we treat the effect of dangerous irrelevant variables on the homogeneity laws by means of a modern FSS formalism.

Q 68.5 Fri 11:30 Q-H15

Measuring the temperature of laser-cooled ions via resonance fluorescence — •Marvin Gajewski[1], Giovanna Morigi[1], Walther Hahn[2,3], Sebastian Wolf[4], Wenbing Li[2,4], Christoph Düllmann[2,4,5], Dmitry Budker[2,4,6], and Fedinand Schmidt-Kaler[4,2] — [1]Saarland University, Saarbrücken, Germany — [2]Helmholtz-Institut, Mainz, Germany — [3]IQOQI, Innsbruck, Austria — [4]Johannes Gutenberg-Universität, Mainz, Germany — [5]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany — [6]University of California, Berkeley, USA

The fluorescence light emitted by atoms and ions carries information about their mechanical motion. We show how the temperature of an ion crystal could be inferred from the resonance fluorescence: By means of a theoretical formalism we identify the optimal conditions on saturation and detuning at which this thermometry is most efficient. We then argue that this theory is not only relevant for experimental identification of intruder ions traversing or captured in a large ion crystal, but also for investigating the heat capacity of such mesoscopic systems.

Q 68.6 Fri 11:45 Q-H15

Finite-Size Scaling at Quantum Phase Transitions Above the Upper Critical Dimension — •Anja Langheld, Jan Alexander Koziol, Patrick Adelhardt, Sebastian C. Kapfer, and Kai Phillip Schmidt — Lehrstuhl für Theoretische Physik I, Staudtstraße 7, Friedrich-Alexander Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

We present a modern formalism for finite-size scaling (FSS) at quantum phase transitions (QPT) above the upper critical dimension. The upper critical dimension becomes experimentally accessible, for instance, in systems with long-range interactions such as the long-range transverse-field Ising model, which can be realized in systems of trapped ions. In general, FSS at phase transitions above the upper critical dimension requires a special treatment as dangerous irrelevant variables (DIV) lead to modifications in the homogeneity laws, thereby causing the breakdown of hyperscaling and standard FSS. Following the recently developed Q-FSS formalism addressing this issue for thermal phase transitions, we transfer the idea to QPT while stressing the subtle differences and connections to the classical version. By relaxing the long-standing belief that the correlation length is unaffected by DIV, the presented FSS formalism fixes the aforementioned issues above the upper critical dimension and recovers a generalized hyperscaling relation. The influence of DIV on the correlation length is explicitly confirmed using numerical calculations of the long-range transverse-field Ising model.

Q 68.7 Fri 12:00 Q-H15

Cavity-induced long-range interactions in strongly correlated systems — •Paul Fadler[1], Jiajun Li[2], Kai Phillip Schmidt[1], and Martin Eckstein[1] — [1]Friedrich-Alexander Universität Erlangen-Nürnberg — [2]Paul Scherrer Institut

In recent years, the coupling of optical cavity modes to solid states systems has emerged as a possible way to control material properties. Here we investigate cavity-induced long-range interactions between spins in a Mott insulator, which are a new feature of the coupling to the quantized cavity field and are absent in the control of magnetism by classical light. In detail, we show that coupling a cavity mode to the Fermi-Hubbard model at half filling leads to long-range four-spin terms in the effective low spin model at large onsite-interaction U, in addition to the conventional local antiferromagnetic Heisenberg exchange interaction. To obtain these long-range interactions, we compare exact diagonalization, a perturbative approach based on the effective spin-photon Hamiltonian description of the system, and fourth-order perturbation theory in the Hubbard model. We show that knowing the phenomenologically determined spin-photon matrix elements is not sufficient to derive the photon-mediated spin-interactions; instead, long-range interactions are additionally mediated via virtual intermediate states, that involve multiple excitations in the charge sector. A similar point should be kept in mind for deriving photon-mediated long-range interactions between emergent low-energy degrees of freedom in interacting systems in general.

Q 68.8 Fri 12:15 Q-H15

Quantum Criticality of the long-range antiferromagnetic Heisenberg ladder — •Patrick Adelhardt and Kai Phillip Schmidt — FAU Erlangen-Nürnberg, Germany

The Mermin-Wagner theorem excludes the breaking of a continuous symmetry in one-dimensional spin systems at zero temperature for sufficiently short-ranged interactions. Introducing algebraically decaying long-range couplings on the antiferromagnetic Heisenberg two-leg ladder, we show that a direct second-order quantum phase transition between the topologically ordered rung-singlet phase in the short-range limit and a conventionally Néel-ordered antiferromagnet can be realized in a one-dimensional system. We study the quantum-critical breakdown in the rung-singlet phase using the method of perturbative continuous unitary transformations (pCUT) on white graphs in combination with classical Monte Carlo simulations for the graph embedding in the thermodynamic limit supplemented with linear spin-wave calculations and exact diagonalization to extract the critical point. Exploiting (hyper-)scaling relations, the pCUT method is used to determine the entire set of canonical critical exponents as a function of the decay exponent. We find that the critical behavior can be divided into a long-range mean-field regime and a regime of continuously-varying exponents similar to the long-range transverse-field Ising model despite the presence of distinct orders on different sides of the critical point and the absence of criticality in the short-range limit.

Q 69: Ultra-cold atoms, ions and BEC IV (joint session A/Q)

Time: Friday 10:30–12:15 Location: A-H1

Invited Talk Q 69.1 Fri 10:30 A-H1

Cavity-enhanced optical lattices for scaling neutral atom quantum technologies — •Jan Trautmann[1,2], Annie J. Park[1,2], Valentin Klüsener[1,2], Dimitry Yankelev[1,2], Immanuel Bloch[1,2,3], and Sebastian Blatt[1,2] — [1]MPQ, 85748 Garching, Germany — [2]MCQST, 80799 München, Germany — [3]LMU, 80799 München, Germany

We present a solution to scale up optical lattice experiments with ultracold atoms by an order of magnitude compared to the state-of-the-art. We utilize power enhancement in optical cavities to create two-dimensional optical lattices with large mode waists using low input power. We test our system using high-resolution clock spectroscopy on ultracold Strontium atoms trapped in the lattice. The observed spectral features can be used to locally measure the lattice potential envelope and the sample temperature with a spatial resolution limited only by the optical resolution of the imaging system. The measured lattice mode waist is 489(8) μm and the trap lifetime is 59(2) s. We observe a long-term stable lattice frequency and trap depth on the MHz level and the 0.1% level. Our results demonstrate that large, deep, and stable two-dimensional cavity-enhanced lattices can be created at any wavelength and can be used to scale up neutral-atom-based quantum simulators, quantum computers, sensors, and optical lattice clocks.

[1] A. J. Park, J. Trautmann, N. Šantić, V. Klüsener, A. Heinz, I.Bloch, and S. Blatt. Cavity-enhanced optical lattices for scaling neutral atom quantum technologies, arXiv:2110.08073, (2021).

Q 69.2 Fri 11:00 A-H1

Ionic Polarons in a Bose-Einstein condensate — •Luis Ardila — Institut für Theoretische Physik, Leibniz Universität Hannover, Germany

The versatility and control of ultracold quantum gases opened up a plethora of theoretical predictions on polaronic physics using ultracold quantum gases, resulting in several experimental realizations. In his talk, we will discuss ionic polarons created as a result of charged particles interacting with a Bose-Einstein condensate. Here we show that even in a comparatively simple setup consisting of a charged impurity in a weakly interacting bosonic medium with tunable atom-ion scattering length, the competition of length scales gives rise to a highly correlated mesoscopic state. Using quantum Monte Carlo simulations, we unravel its vastly different polaronic properties compared to neutral quantum impurities. Moreover, we identify a transition between the regime amenable to conventional perturbative treatment in the limit of weak atom-ion interactions and a many-body bound state with vanishing quasi-particle residue composed of hundreds of atoms. Recent experiments on ionic impurities in quantum gases are promising platforms to study ionic polarons. Our work paves the way to understand how ions coupled a quantum gas which may be important for future applications in quantum technologies.

Q 69.3 Fri 11:15 A-H1

An Artificial Bosonic Atom in One Spatial Dimension — •Fabian Brauneis[1], Timothy Backert[1], Simeon Mistakidis[2], Mikhail Lemeshko[3], Hans-Werner Hammer[1,4], and Artem Volosniev[3] — [1]Technische Universität Darmstadt, Department of Physics, Institut für Kernphysik, 64289 Darmstadt, Germany — [2]ITAMP, Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138 USA — [3]Institute of Science and Technology Austria, Am Campus 1, 3400 Klosterneuburg, Austria — [4]ExtreMe Matter Institute EMMI and Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

We study an analogue of an atom realized by a one-dimensional Bose gas. Repelling bosons ("electrons") are attracted to an impurity, the "nucleus". The interplay between the attractive impurity-boson and repulsive boson-boson interaction leads to a crossover between different states of the system when the parameters are varied. For a non-interacting Bose gas, an arbitrary number of bosons can be bound to the impurity. In contrast, if they are impenetrable, the bosons fermionize and only one boson is bound. This observation implies that there is a critical number of bosons that can be bound to the impurity for finite values of the boson-boson interaction strength. We discuss the three resulting states of the system - bound, transition and scattering - within the mean-field approximation. In particular, we calculate the critical particle number supporting a bound state. To validate our mean-field results, we use the flow equation approach.

Q 69.4 Fri 11:30 A-H1

Pattern formation and symmetry breaking in a periodically driven 2D BEC — •Nikolas Liebster, Celia Viermann, Maurus Hans, Marius Sparn, Elinor Kath, Helmut Strobel, and Markus Oberthaler — Kirchhoff Institut für Physik, Heidelberg, Deutschland

Dynamical pattern formation is a ubiquitous phenomenon in nature, and has relevance in many fields in physics. The emergence of these patterns, as well as how symmetries are broken, remains an open field of research in quantum physical systems. By periodically driving the scattering length in a 2D potassium-39 Bose-Einstein condensate, we use parametric resonance to non-linearly populate specific momentum modes of trapped condensates. We show the emergence of randomly oriented standing waves with D4 symmetry and investigate these structures in real and momentum space, showing the growth of both primary and secondary momentum modes. Finally, we investigate the effects of trapping geometries on the formation of patterns on the condensate.

Q 69.5 Fri 11:45 A-H1

Quantum gas magnifier for sub-lattice-resolved imaging of 3D quantum systems — Luca Asteria, Henrik P. Zahn, •Marcel N. Kosch, Klaus Sengstock, and Christof Weitenberg — Universität Hamburg, Hamburg, Deutschland

Imaging is central for gaining microscopic insight into physical systems, but direct imaging of ultracold atoms in optical lattices as modern quantum simulation platform suffers from the diffraction limit as well as high optical density and small depth of focus. We introduce a novel approach to imaging of quantum many-body systems using matter wave optics to magnify the density distribution prior to optical imaging, allowing sub-lattice spacing resolution in three-dimensional systems. Combining the site-resolved imaging with magnetic resonance techniques for local addressing of individual lattice sites, we demonstrate full accessibility to local information and local manipulation in three-dimensional optical lattice systems. The method opens the path for spatially resolved studies of new quantum many-body regimes including exotic lattice geometries.

Q 69.6 Fri 12:00 A-H1

Resetting many-body quantum systems — •Gabriele Perfetto, Federico Carollo, Matteo Magoni, and Igor Lesanovsky — Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

We consider closed quantum many-body systems subject to stochastic resetting. This means that their unitary time evolution is interrupted by resets at randomly selected times. The study of the non-equilibrium stationary state that emerges from the combination of stochastic resetting and coherent quantum dynamics has recently raised significant interest. The connection between this non-equilibrium stationary state, an effective open dynamics and non-equilibrium signatures of quantum phase transitions is, however, not fully understood.

In the talk we provide a unified understanding of these phenomena by combining techniques from quantum quenches in closed systems and semi-Markov processes. We discuss as an application the paradigmatic quantum Ising chain. We show that signatures of its ground-state quantum phase transition are visible in the steady state of the reset dynamics as a sharp crossover.

Our findings show that stochastic resetting can be exploited to generate many-body quantum stationary states where incoherent effects, such as heating, can be hindered. These stationary states can be then used in quantum simulator platforms for sensing applications.

[1] G.Perfetto *et al.*, Phys. Rev. B **104**, L180302 (2021)

Q 70: Precision spectroscopy of atoms and ions IV (joint session A/Q)

Time: Friday 10:30–12:00 Location: A-H2

Invited Talk Q 70.1 Fri 10:30 A-H2

High-resolution DR spectroscopy with slow cooled Be-like Pb^{78+} ions in the CRYRING@ESR storage ring — •Sebastian Fuchs[1,2], Carsten Brandau[1,3], Esther Menz[3,4,5], Michael Lestinsky[3], Alexander Borovik Jr[1], Yanning Zhang[6], Zoran Andelkovic[3], Frank Herfurth[2], Christophor Kozhuharov[3], Claude Krantz[3], Uwe Spillmann[3], Markus Steck[3], Gleb Vorobyev[3], Regina Hess[3], Volker Hannen[7], Dariusz Banaś[8], Michael Fogle[9], Stephan Fritzsche[4,5], Eva Lindroth[10], Xinwen Ma[11], Alfred Müller[1], Reinhold Schuch[10], Andrey Surzhykov[12,13], Martino Trassinelli[14], Thomas Stöhlker[3,4,5], Zoltán Harman[15], and Stefan Schippers[1,2] — [1]JLU Gießen — [2]HFHF Campus Gießen — [3]GSI — [4]HI Jena — [5]FSU Jena — [6]Xi'an Jiaotong University — [7]WWU Münster — [8]JKU Kielce — [9]Auburn University — [10]Stockholm University — [11]IMPCAS Lanzhou — [12]TU Braunschweig — [13]PTB — [14]UPMC Paris — [15]MPIK

Dielectronic recombination (DR) collision spectroscopy is a very successful tool for studying the properties of ions. Due to its versatility and the high experimental precision, DR spectroscopy plays an important role in the physics program of the SPARC collaboration. CRYRING@ESR is particularly attractive for DR studies, since its electron cooler provides an ultra-cold electron beam promising highest experimental resolving power. Here, we report on the first DR experiment with highly charged ions in the heavy-ion storage ring CRYRING@ESR of the international FAIR facility in Darmstadt. The recent results are well in accord with our expectations and the theory.

Q 70.2 Fri 11:00 A-H2

Theory of the $^3He^+$ magnetic moments and hyperfine splitting — •Bastian Sikora, Zoltán Harman, Natalia S. Oreshkina, Igor Valuev, and Christoph H. Keitel — Max-Planck-Institut für Kernphysik, Heidelberg, Germany

In an external magnetic field, the ground state of the $^3He^+$ ion is split into four sublevels due to hyperfine and Zeeman effect. The bound electron's g-factor, the ground-state hyperfine splitting as well as the shielded magnetic moment of the nucleus can be determined by measurements of transition frequencies between these sublevels [1,2].

We present the theoretical calculation of the nuclear shielding constant, the ground-state hyperfine splitting and the bound-electron g-factor. The nuclear shielding constant is required to extract the magnetic moment of the bare nucleus with unprecedented precision, enabling new applications in magnetometry. Furthermore, one can extract the nuclear Zemach radius from the experimental hyperfine splitting value. The theoretical uncertainty of the bound-electron g-factor is dominated by the uncertainty of the fine-structure constant, allowing in principle an independent determination of α in future.

[1] A. Mooser et al., J. Phys.: Conf. Ser. 1138:012004 (2018)
[2] A. Schneider et al., submitted (2021)

Q 70.3 Fri 11:15 A-H2

Path integral formalism of Dirac propagators for atomic physics — •Sreya Banerjee and Zoltán Harman — Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

The very basic building blocks of perturbative calculations in atomic structure and collision theory are Green's functions. We extend this study of Green's functions, in the nonperturbative regime, using Feynman's path integral approach. As a first step, we derive the free Dirac propagator followed by the derivation of the Dirac-Coulomb Green's function (DCGF) in spherical coordinates, using this formalism.

For the free relativistic Dirac particle, the effective Hamiltonian for the iterated Dirac equation is constructed. The corresponding Green's function is expanded into partial waves in spherical coordinates. The radial part of this Green's function is then converted into a path integral, through reparametrisation of the paths by local time rescaling, followed by a one-to-one mapping of the radial variable with the local time parameter. This yields a closed form of the Green's function. Following the same procedure, the DCGF is diagonalised in Biedenharn's basis into a radial path integral, the effective action of which is similar to that of the non-relativistic hydrogen atom. We convert the radial path integral from Coulomb type to that of an isotropic harmonic oscillator through coordinate transformation along with local time rescaling. As such, an explicit path integral representation of the DCGF is obtained, along with the energy spectrum of the bound states.

Q 70.4 Fri 11:30 A-H2

Progress of the Laser Resonance Chromatography project — •EunKang Kim[1,2], Elisabeth Rickert[1,2,3], Elisa Romero Romer[1,2,3], Harry Ramanantoanina[1,2], Michael Block[1,2,3], Mustapha Laatiaoui[1,2], and Philipp Sikora[1] — [1]Department Chemie, Johannes Gutenberg-Universität, Fritz-Strassmann Weg 2, 55128 Mainz, Germany — [2]Helmholtz-Institut Mainz, Staudingerweg 18, 55128 Mainz, Germany — [3]GSI, Planckstraße 1, 64291 Darmstadt, Germany

Optical spectroscopy of superheavy elements is experimentally challenging as their production yields are low, half-lives are very short, and their atomic structure is barely known. Conventional spectroscopy techniques such as fluorescence spectroscopy are no longer suitable since they lack the sensitivity required in the superheavy element research. A new technique called Laser Resonance Chromatography (LRC) could provide sufficient sensitivity to study super-heavy ions and overcome difficulties associated with other methods. In this contribution, I will explain the LRC technique and the progress that we made towards LRC experiments. This work is supported by the European Research Council (ERC) (Grant Agreement No. 819957).

Q 70.5 Fri 11:45 A-H2

CREMA-Measuring the Ground State Hyperfine splitting of Muonic Hydrogen — •Siddharth Rajamohanan[1], Ahmed Ouf[1], and Randolf Pohl[2] — [1]QUANTUM, Institut für Physik & Exzellenzcluster PRISMA,Johannes Gutenberg Universität Mainz, 55099

Mainz, Germany — [2]Institut für Physik, QUANTUM und Exzellenzcluster PRISMA+, Johannes Gutenberg-Universität Mainz,55099 Mainz, Germany

Precision measurements on atoms and ions are a powerful tool for testing bound-state QED theory and the Standard Model [1]. Experiments done in the last decade by the CREMA collaboration on muonic Hydrogen and Helium have given a more accurate understanding of the lightest nuclei charge radius [2,3]. Our present experiment aims at a measurement of ground state Hyperfine Splitting in muonic hydrogen up to a relative accuracy of 1 ppm using pulsed laser spectroscopy. This allows us to determine the Zemach radius, which encodes the magnetic properties of the proton. A unique laser system, multi-pass cavity, and scintillation detection system are necessary for the experiment. We report the current status of our experiment and the recent developments.

[1] M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson Kimball, A. Derevianko, and Charles W. Clark, Rev. Mod. Phys. 90, 025008 (2018) [2] R. Pohl et al., Nature 466, 213 (2010) [3] A. Antognini, et al., Science, Vol. 339, 2013, pp. 417-420