Quantum Information Division
Fachverband Quanteninformation (QI)

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Overview of Invited Talks and Sessions

(Lecture halls B302, B305, and F428; Poster Empore Lichthof)

Invited Talks

QI 3.1	Mon	11:00–11:30	B305	**Characterising quantum device variability with machine learning** — •Natalia Ares
QI 5.1	Mon	11:00–11:30	F428	**Building Superconducting Quantum Hardware towards Error-Corrected Quantum Computing** — •Christopher Eichler
QI 10.1	Tue	11:00–11:30	B302	**Quantum information in minimal quantum thermal machines** — •Géraldine Haack
QI 11.1	Tue	11:00–11:30	B305	**Characterisation of multipartite entanglement beyond the single-copy paradigm** — •Nicolai Friis
QI 17.1	Wed	11:00–11:30	B305	**Self-testing with dishonest parties and entanglement certification in quantum networks** — •Gláucia Murta, Flavio Baccari
QI 19.1	Wed	11:00–11:30	F428	**Experimental quantum error correction with trapped ions** — •Philipp Schindler
QI 21.1	Wed	14:30–15:00	B305	**Qube and Qube-II – Towards Quantum Key Distribution with Small Satellites** — •Lukas Knips
QI 26.1	Thu	11:00–11:30	B305	**Quantum firmware: optimal control for quantum simulators** — •Tommaso Calarco
QI 28.1	Thu	11:00–11:30	F428	**Conveyor-mode single-electron shuttling in Si/SiGe for a scalable quantum computing architecture** — •Inga Seidler, Tom Struck, Ran Xue, Stefan Trellenkamp, Hendrik Bluhm, Lars R. Schreiber
QI 30.1	Thu	14:30–15:00	B305	**Adaptive constant-depth circuits for manipulating non-abelian anyons** — Sergey Bravyi, Isaac Kim, Alexander Kliesch, •Robert König

Invited Talks of the joint Symposium SAMOP Dissertation Prize 2023

See SYAD for the full program of the symposium.

SYAD 1.1	Mon	14:30–15:00	E415	**Quantum gas magnifier for sub-lattice resolved imaging of 3D quantum systems** — •Luca Asteria
SYAD 1.2	Mon	15:00–15:30	E415	**From femtoseconds to femtometers – controlling quantum dynamics in molecules with ultrafast lasers** — •Patrick Rupprecht
SYAD 1.3	Mon	15:30–16:00	E415	**Particle Delocalization in Many-Body Localized Phases** — •Maximilian Kiefer-Emmanouilidis
SYAD 1.4	Mon	16:00–16:30	E415	**Feshbach resonances in a hybrid atom-ion system** — •Pascal Weckesser

Prize Talks of the joint Awards Symposium

See SYAS for the full program of the symposium.

SYAS 1.1	Tue	14:35–15:05	E415	**The Reaction Microscope: A Bubble Chamber for AMOP** — •Joachim Ullrich
SYAS 1.2	Tue	15:05–15:35	E415	**Quantum Computation and Quantum Simulation with Strings of Trapped Ca+ Ions** — •Rainer Blatt

SYAS 1.3	Tue	15:35–16:05	E415	**Amplitude, Phase and Entanglement in Strong Field Ionization** — •Sebastian Eckart
SYAS 1.4	Tue	16:05–16:35	E415	**All-optical Nonlinear Noise Suppression in Mode-locked Lasers and Ultrafast Fiber Amplifiers** — •Marvin Edelmann

Invited Talks of the joint Symposium From Molecular Spectroscopy to Collision Control at the Quantum Limit

See SYCC for the full program of the symposium.

SYCC 1.1	Thu	11:00–11:30	E415	**The unity of physics: the beauty and power of spectroscopy** — •Paul Julienne
SYCC 1.2	Thu	11:30–12:00	E415	**Using high-resolution molecular spectroscopy to explore how chemical reactions work** — •Johannes Hecker Denschlag
SYCC 1.3	Thu	12:00–12:30	E415	**Monitoring ultracold collisions with laser light** — •Olivier Dulieu
SYCC 1.4	Thu	12:30–13:00	E415	**The birth of a degenerate Fermi gas of molecules** — •Jun Ye

Invited Talks of the joint PhD-Symposium – Many-body Physics in Ultracold Quantum Systems

See SYPD for the full program of the symposium.

SYPD 1.1	Thu	14:30–15:00	E415	**Entanglement and quantum metrology with microcavities** — •Jakob Reichel
SYPD 1.2	Thu	15:00–15:30	E415	**Many-body physics in dipolar quantum gases** — •Francesca Ferlaino
SYPD 1.3	Thu	15:30–16:00	E415	**Quantum Simulation: from Dipolar Quantum Gases to Frustrated Quantum Magnets** — •Markus Greiner
SYPD 1.4	Thu	16:00–16:30	E415	**Quantum gas in a box** — •Zoran Hadzibabic

Invited Talks of the joint Symposium Quantum Optics and Quantum Information with Rigid Rotors

See SYQR for the full program of the symposium.

SYQR 1.1	Fri	11:00–11:30	E415	**Femtosecond timed imaging of rotation and vibration of alkali dimers on the surface of helium nanodroplets** — •Henrik Stapelfeldt
SYQR 1.2	Fri	11:30–12:00	E415	**Quantum toolbox for molecular state spaces** — Eric Kubischta, Shubham Jain, Ian Teixeira, Eric R. Hudson, Wesley C. Campbell, Mikhail Lemeshko, •Victor V. Albert
SYQR 1.3	Fri	12:00–12:30	E415	**Coherent rotational state control of chiral molecules** — •Sandra Eibenberger-Arias
SYQR 1.4	Fri	12:30–13:00	E415	**Optically levitated rotors: potential control and optimal measurement** — •Martin Frimmer
SYQR 2.1	Fri	14:30–15:00	E415	**Rotational optomechanics with levitated nanodumbbells** — •Tongcang Li
SYQR 2.2	Fri	15:00–15:30	E415	**Quantum rotations of nanoparticles** — •Benjamin A. Stickler
SYQR 2.3	Fri	15:30–16:00	E415	**Quantum control of trapped molecular ions** — •Stefan Willitsch
SYQR 2.4	Fri	16:00–16:30	E415	**Full control over randomly oriented quantum rotors: controllability analysis and application to chiral observables** — •Monika Leibscher

Sessions

QI 1.1–1.8	Mon	11:00–13:00	A320	**Quantum Technologies I (joint session Q/A/QI)**
QI 2.1–2.8	Mon	11:00–13:00	B302	**Quantum Foundations**
QI 3.1–3.7	Mon	11:00–13:00	B305	**Quantum Machine Learning**
QI 4.1–4.8	Mon	11:00–13:00	E214	**Quantum Computing and Simulation (joint session Q/QI)**
QI 5.1–5.5	Mon	11:00–12:30	F428	**Superconducting Qubits and Hybrid Systems**
QI 6.1–6.49	Mon	16:30–19:00	Empore Lichthof	**Poster I (joint session QI/Q)**
QI 7.1–7.8	Mon	17:00–19:00	F342	**Quantum Technologies: Color Centers I (joint session Q/A/QI)**

QI 8.1–8.8	Mon	17:00–19:00	F442	**Quantum Communication I (joint session Q/QI)**
QI 9.1–9.8	Tue	11:00–13:00	A320	**Photonic Quantum Technologies (joint session Q/QI)**
QI 10.1–10.7	Tue	11:00–13:00	B302	**Quantum Thermodynamics and Open Quantum Systems I**
QI 11.1–11.7	Tue	11:00–13:00	B305	**Quantum Entanglement I**
QI 12.1–12.7	Tue	11:00–13:00	E001	**Integrated Photonics I (joint session Q/QI)**
QI 13.1–13.8	Tue	11:00–13:00	F428	**Quantum Simulation**
QI 14.1–14.8	Tue	11:00–13:00	F442	**Quantum Technologies: Color Centers II (joint session Q/QI)**
QI 15	Tue	13:15–14:00	B305	**Members' Assembly**
QI 16.1–16.8	Wed	11:00–13:00	B302	**Concepts and Methods I**
QI 17.1–17.6	Wed	11:00–12:45	B305	**Quantum Networks I (joint session QI/Q)**
QI 18.1–18.8	Wed	11:00–13:00	F342	**Quantum Technologies: Trapped Ions (joint session Q/QI)**
QI 19.1–19.7	Wed	11:00–13:00	F428	**Implementations: Ions and Atoms (joint session QI/Q)**
QI 20.1–20.8	Wed	14:30–16:30	B302	**Concepts and Methods II**
QI 21.1–21.7	Wed	14:30–16:30	B305	**Quantum Communication II (joint session QI/Q)**
QI 22.1–22.7	Wed	14:30–16:30	E214	**Quantum Technologies II (joint session Q/MO/QI)**
QI 23.1–23.65	Wed	16:30–19:00	Empore Lichthof	**Poster II (joint session QI/Q)**
QI 24.1–24.8	Wed	17:00–19:00	A320	**Integrated Photonics II (joint session Q/QI)**
QI 25.1–25.8	Thu	11:00–13:00	B302	**Quantum Entanglement II**
QI 26.1–26.7	Thu	11:00–13:00	B305	**Quantum Control (joint session QI/Q)**
QI 27.1–27.7	Thu	11:00–13:00	E001	**Precision Measurements with Optical Clocks (joint session Q/QI)**
QI 28.1–28.7	Thu	11:00–13:00	F428	**Spin Qubits**
QI 29.1–29.8	Thu	14:30–16:30	B302	**Quantum Thermodynamics and Open Quantum Systems II**
QI 30.1–30.7	Thu	14:30–16:30	B305	**Quantum Algorithms**
QI 31.1–31.7	Thu	14:30–16:30	E214	**Single Quantum Emitters (joint session Q/QI)**
QI 32.1–32.8	Thu	14:30–16:30	F102	**Quantum Optics and Quantum Information with Rigid Rotors (joint session MO/Q/QI)**
QI 33.1–33.8	Thu	14:30–16:30	F428	**Quantum Networks II (joint session QI/Q)**
QI 34.1–34.8	Fri	11:00–13:00	B302	**Concepts and Methods III**
QI 35.1–35.8	Fri	11:00–13:00	B305	**Quantum Computers: Algorithms and Benchmarking**
QI 36.1–36.8	Fri	11:00–13:00	F428	**Quantum Metrology (joint session QI/Q)**
QI 37.1–37.7	Fri	14:30–16:15	F428	**Quantum Many Body Systems**

Members' Assembly of the Quantum Information Division

Tuesday, 07/03/2023 13:15–14:00 B305

More information will be sent to the members of the division by e-mail.

QI 1: Quantum Technologies I (joint session Q/A/QI)

Time: Monday 11:00–13:00 Location: A320

QI 1.1 Mon 11:00 A320

Holography with single photons — •Hrvoje Skenderovic and Denis Abramovic — Institute of Physics, Bijenicka cesta 46, 10000 Zagreb, Croatia

Holography relies on interference between two beams, reference and object. Although single photon can not be divided, holograms with heralded single-photon source in a classical holographic setup were recorded, due to indistinguishable paths. The amplitude and phase reconstructions show quantum enhancement for heralded over non-heralded channel. Non-classical nature of heralded photons is verified by continuous measurement of g2(0) of the light source during hologram acquisition.

QI 1.2 Mon 11:15 A320

Three-Dimensional Imaging of Single Atoms in an Optical Lattice via Helical Point-Spread-Function Engineering — •Tangi Legrand[1], Falk-Richard Winkelmann[1], Wolfgang Alt[1], Dieter Meschede[1], Andrea Alberti[1], and Carrie Weidner[2] — [1]Institut für Angewandte Physik, Universität Bonn, Germany — [2]Quantum Engineering Technology Laboratories, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, United Kingdom

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 if the position is inferred from the defocus alone, although tomographic methods have been applied to extract this information [1]. However, phase-front engineering can be used to localize emitters in 3D with sub-micrometer resolution from a single experimental image [2]. The technique consists of shaping the imaging system's point spread function (PSF) such that it results in an axially rotating azimuthally asymmetric distribution. By means of a spatial light modulator, we create a double-helix PSF consisting of two lobes whose relative angle encodes an atom's axial position. We demonstrate 3D localization at the level of single lattice sites in a quantum gas microscope. As we show, the technique also features an increased depth of field. This method can find applications in other quantum gas experiments to extend the domain of quantum simulation from 2D to 3D. [1] O. Elíasson *et al.* Phys. Rev. A **102**, 053311 (2020), [2] S.R.P. Pavani *et al.* PNAS **106**, 2995 (2009).

QI 1.3 Mon 11:30 A320

Tomography of distant single Atoms — •Florian Fertig[1,2], Yiru Zhou[1,2], Pooja Malik[1,2], Anastasia Reinl[1,2], Tim van Leent[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

Entanglement of distant quantum memories forms the building block of quantum networks. Neutral atoms with long coherence times are possible candidates for such a quantum network link and can be entangled via the entanglement swapping protocol. Our experiment consists of two nodes, currently 400 m apart, employing single optically trapped Rubidium-87 atoms as quantum memories. A new collection setup allows for an increased entanglement event rate of 1/6 Hz allowing a state analysis and reconstruction of the entangled state.

Here, we use quantum state tomography for the first time on atom-atom entanglement and evaluate the influence of different kind of experimental improvements on the fidelity of the entangled state. We introduce time-filtering, a method to increase the atom-atom entanglement fidelity. At the cost of events we reach a fidelity $> 90\%$ well suited for demanding tasks like device-independent QKD.

QI 1.4 Mon 11:45 A320

Mid-Infrared Quantum Scanning Microscopy with Visible Light — •Josué R. León-Torres[1,2], Jorge Fuenzalida[1], Marta Gilaberte Basset[1], Sebastian Töpfer[1], and Markus Gräfe[1,2,3] — [1]Fraunhofer Institute of Applied Optics and Precision Engineering IOF, Albert-Einstein-Straße 7, D-07745 Jena, Germany — [2]Friedrich-Schiller-Universität Jena, Abbe Center of Photonics, Max-Wien-Platz 1, D-07745 Jena, Germany — [3]Technische Universität Darmstadt, Institute of Applied Physics, Hochschulstraße 6, D-64289 Darmstadt, Germany

Abstract: Laser scanning microscopy (LSM) is known to be the workhorse for modern life-science, it allows to get new insights into a variety of biological processes. LSM together with illumination in the mid infrared region (Mid-IR) permits to map the chemical composition of samples to a space frame. However, low-light observations in the Mid-IR spectrum are still challenging and a limiting factor for a faster development. A label-free quantum imaging system is presented here, capable of performing the detection in the visible regime, while illuminating the sample with undetected light in the Mid-IR region. Our quantum imaging with undetected light implementation aims to retrieve amplitude and phase images of biological samples containing a variety of functional groups that are present in the Mid-IR region. Due to the momentum correlations shared by the entangled photon-pair the illumination can take place in the Mid-IR spectrum and the detection can be carried out with silicon-based technology in the VIS spectrum.

QI 1.5 Mon 12:00 A320

GHz bandwidth four-wave mixing in a thermal rubidium vapor — •Max Mäusezahl[1], Felix Moumtsilis[1], Moritz Seltenreich[1], Jan Reuter[2,3], Hadiseh Alaeian[4], Harald Kübler[1], Matthias Müller[2], Charles Stuart Adams[5], Robert Löw[1], and Tilman Pfau[1] — [1]5. Physikalisches Institut, Universität Stuttgart, Germany — [2]Forschungszentrum Jülich GmbH, PGI-8, Germany — [3]Universität zu Köln, Germany — [4]Departments of Electrical & Computer Engineering and Physics & Astronomy, Purdue University, USA — [5]Department of Physics, Joint Quantum Centre (JQC), Durham University, UK

Fast coherent control of Rydberg excitations is essential for quantum logic gates and on-demand single-photon sources based on the Rydberg blockade as demonstrated for room-temperature rubidium atoms in a micro-cell. During our ongoing development of the next generation of this single-photon source we employ state-of-the-art 1010 nm pulsed fiber amplifiers to drive a Rydberg excitation via the 6P intermediate state.

Here we report on time resolved observations of nanosecond pulsed four-wave mixing and GHz Rabi cycling involving the 32S Rydberg state. Our results show oscillating dynamics of the mixed photons on the final transition of the FWM cycle. The MHz repetition rates and significantly higher photon yields allow us to study and optimize the antibuching through elaborate pulse shaping motivated by numerical simulations. Such excitation timescales also pave the way towards fast optimal control methods for high fidelity Rydberg logic gates.

QI 1.6 Mon 12:15 A320

Absorption sensing mode in radio frequency electrometry using Rydberg atoms in hot vapors — •Matthias Schmidt[1,2], Stephanie Bohaichuk[1], Chang Liu[1], Harald Kübler[2], and James P. Shaffer[1] — [1]Quantum Valley Ideas Laboratories, 485 Wes Graham Way, Waterloo, ON N2L 6R1, Canada — [2]5. Physikalisches Institut, Universität Stuttgart, Pfaffendwaldring 57, 70569 Stuttgart

We present theoretical work on atom-based RF E-field sensing using Rydberg atoms in hot vapors. There are two distinct strategies to detect the electric field strength of the RF wave, namely the Autler-Townes limit, where the splitting of the dressed states is proportional to the incident RF electric field strength and the amplitude regime, where we determine the electric field by measuring the difference of transmission in the presence of the RF electromagnetic field. We present theoretical calculations for the amplitude regime, using a two photon excitation scheme, that show how the scattering of the probed transition changes in the presence of the RF electromagnetic field. We find an analytical expression in the thermal limit with finite wave vector mismatch that yields an accurate approximation compared to full density matrix calculation in the strong coupling limit. Our work extends the understanding of the detection of weak RF E-fields with Rydberg-atom based RF sensors.

QI 1.7 Mon 12:30 A320

Light Filtration With Hot Atomic Vapor Cells — •Denis Uhland, Yijun Wang, Helena Dillmann, and Ilja Gerhardt — Institute of Solid State Physics, Light and Matter Group, Leibniz University Hannover

The interaction of light and atoms is one of the cornerstones to study quantum effects. Atomic vapor cells offer a convenient and robust framework to such studies. Not only can fundamental quantum effects be studied, but their robustness and ease of handling is beneficial for a vast array of applications in quantum technology. Examples are magnetometers, electrometers, atomic clocks, or laser frequency stabilization. We probe hot vapor cells with lasers and external magnetic fields to enable spectral narrow filtering and show their potential to improve confocal and wide-field imaging in microscopy [1]. Not only does this method efficiently suppress the undesired laser leakage of scattered excitation light, but it also enhances the detection efficiency by 15% compared to one of the best commercially available long-pass filters. Another flavor of such filters utilizes magnetic fields and founds on the Macaluso-Corbino effect. This allows to enable GHz-wide band-pass filters in a Faraday configuration.

[1] Uhland, D., Rendler, T., Widmann, M. et al. Single molecule DNA detection with an atomic vapor notch filter. EPJ Quantum Technol. 2, 20 (2015). https://doi.org/10.1140/epjqt/s40507-015-0033-1

QI 1.8 Mon 12:45 A320

Optimization and readout-noise analysis of a hot 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, 12489 Berlin, Germany.

Efficient, noise-free quantum memories are indispensable components of quantum repeaters, which will be crucial for the realization of a global quantum communication network [1, 2]. We have realized a technologically simple, in principle satellite-suited quantum memory in Cesium vapor, based on electromagnetically induced transparency (EIT) on the ground states of the Cs D1 line [3]. We simultaneously optimize the end-to-end efficiency and the signal-to-noise level in the memory, and have achieved light storage at the single-photon level with end-to-end efficiencies up to 13(2)% at a minimal noise level corresponding to $\bar{\mu}_1 = 0.07(2)$ signal photons. From varying the control laser power at different detunings we gain profound understanding of the physical origin of the readout noise, and thus determine strategies for further minimization.

[1] M. Gündoğan et al., npj Quantum Information 7, 128 (2021)
[2] J. Wallnöfer et al., Commun Phys 5, 169 (2022)
[3] L. Esguerra, et al., arXiv:2203.06151 (2022)

QI 2: Quantum Foundations

Time: Monday 11:00–13:00 Location: B302

QI 2.1 Mon 11:00 B302

Uncertainty relations from graph theory — •Kiara Hansenne, Carlos de Gois, and Otfried Gühne — Universität Siegen, Siegen, Germany

Quantum measurements are inherently probabilistic and quantum theory often forbids to precisely predict the outcomes of simultaneous measurements. This phenomenon is captured and quantified through uncertainty relations. Although studied since the inception of quantum theory, the problem of determining the possible expectation values of a collection of quantum measurements remains, in general, unsolved. By constructing a close connection between observables and graph theory, we derive uncertainty relations valid for any set of dichotomic observables. These relations are, in many cases, tight, and related to the size of the maximum clique of the associated graph. As applications, our results can be straightforwardly used to formulate entropic uncertainty relations, separability criteria and entanglement witnesses.

QI 2.2 Mon 11:15 B302

Many-particle coherence and higher-order interference — •Marc-Oliver Pleinert[1], Eric Lutz[2], and Joachim von Zanthier[1] — [1]Quantum Optics and Quantum Information, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 1, 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. 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.

QI 2.3 Mon 11:30 B302

What aspects of the phenomenology of interference witness nonclassicality? — •Lorenzo Catani[1], Matthew Leifer[2], Giovanni Scala[3], David Schmid[3], and Robert Spekkens[4] — [1]Technische Universitaet Berlin — [2]Chapman University — [3]University of Gdansk — [4]Perimeter Institute for Theoretical Physics

Interference phenomena are often claimed to resist classical explanation. However, such claims are undermined by the fact that the specific aspects of the phenomenology upon which they are based can in fact be reproduced in a noncontextual ontological model [Catani et al. arXiv:2111.13727]. This raises the question of what other aspects of the phenomenology of interference do in fact resist classical explanation. We answer this question by demonstrating that the most basic quantum wave-particle duality relation, which expresses the precise trade-off between path distinguishability and fringe visibility, cannot be reproduced in any noncontextual model. We do this by showing that it is a specific type of uncertainty relation, and then leveraging a recent result establishing that noncontextuality restricts the functional form of this uncertainty relation [Catani et al. arXiv:2207.11779]. Finally, we discuss what sorts of interferometric experiment can demonstrate contextuality via the wave-particle duality relation.

QI 2.4 Mon 11:45 B302

Contextuality as a precondition for entanglement — •Martin Plávala and Otfried Gühne — Universität Siegen, Siegen, Deutschland

Quantum theory features several phenomena which can be considered as resources for information processing tasks. Some of these effects, such as entanglement, arise in a non-local scenario, where a quantum state is distributed between different parties. Other phenomena, such as contextuality can be observed, if quantum states are prepared and then subjected to sequences of measurements. Here we provide an intimate connection between different resources by proving that entanglement in a non-local scenario can only arise if there is preparation & measurement contextuality in a sequential scenario derived from the non-local one by remote state preparation. Moreover, the robust absence of entanglement implies the absence of contextuality. As a direct consequence, our result allows to translate any inequality for testing preparation & measurement contextuality into an entanglement test; in addition, entanglement witnesses can be used to obtain novel contextuality inequalities.

QI 2.5 Mon 12:00 B302

Distribution of quantum incompatibility across subsets of multiple measurements — •Lucas Tendick, Hermann Kampermann, and Dagmar Bruss — Institute for Theoretical Physics, Heinrich Heine University Düsseldorf, D-40225 Düsseldorf, Germany

The incompatibility of quantum measurements, i.e., the impossibility of measuring two or more observable quantities simultaneously, is one of the most fundamental properties of quantum physics. Not only are incompatible measurements necessary to reveal nonlocal effects, such as quantum steering and the violation of Bell inequalities, but they are also valuable resources that provide advantages in various information processing tasks. It is generally known that increasing the number of distinct measurements can also increase the incompatibility. However, it is yet unknown how much incompatibility can be gained from adding more measurements to an existing measurement scheme and on what this gain depends. Here, we show how the maximal incompatibility that can be gained by increasing the number of measurements can be upper bounded by functions of the incompatibility of respective subsets of the available measurements. More generally, we show how to bound the incompatibility of a set of measurements using the properties of its subsets, which reveals a new notion of measurement incompatibility. We prove the relevance of our bounds by providing tight examples using noisy measurements based on mutually unbiased bases. Finally, we discuss the direct consequences of our results for the nonlocality that could be gained by increasing the number of measurements in a Bell experiment.

QI 2.6 Mon 12:15 B302

Simulability of Sets of Continuous and Infinite-Dimensional POVMs — •Sophie Egelhaaf[1], Juha-Pekka Pellonpää[2], and Roope Uola[1] — [1]Département de Physique Appliquée, Université de Genève, CH-1205 Genève, Switzerland — [2]Department of Physics and Astronomy, University of Turku, FI-20014 Turun yliopisto, Finland

When considering quantum information tasks such as steering and Bell non-locality, the statistics not only depend on the state(s) shared by the parties but also the set of POVMs available to them. A key feature for witnessing true quantum behaviour is the incompatibility of POVMs. If a set of POVMs is jointly measurable, i.e. not incompatible, it can be fully compressed. Hence Ioannou et al [1] use the compression dimension of a set of POVMs, named the simulability, to quantify the incompatibility of the set. However, so far many findings only apply to finite-dimensional and discrete POVMs. We are working on adapting these findings such that they also hold for infinite-dimensional and continuous POVMs. In this context we are interested in finding the most incompatible and least compressible pair of continuous and infinite-dimensional POVMs, examples potentially being position and momentum as well as number and phase.

[1] M. Ioannou et al. Simulability of high-dimensional quantum measurements. arXiv preprint arXiv:2202.12980 (2022)

QI 2.7 Mon 12:30 B302

Causality and signalling in a quantum information space-time — •Leonardo Silva Vieira Santos — Universitat Siegen, Siegen, Germany

In recent years, there has been a growing interest and effort in understanding causality in the quantum domain. Much of this is due to the tension between the two most successful scientific theories of modern physics: quantum mechanics and Einstein's general relativity. On the one hand, quantum mechanics is a probabilistic theory whose application typically takes place in contexts with a fixed and well-defined causal structure. General relativity, on the other hand, is deterministic but has a dynamical causal structure. We propose a framework to study space-time causal structures from the point of view of quantum information theory. In our approach, the causal constrains of a space-time determines the possible deterministic transformations between states of quantum systems called quantum causal probes. As a result, we demonstrate how well-known processes with indefinite causal order and indefinite time direction emerge from the formalism.

QI 2.8 Mon 12:45 B302

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], Eric Meyer[4], Harald Weinfurter[1,2,3], Alexander Szameit[4], 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 (MCQST), Munich, Germany — [4]Institute of Physics, University of Rostock, Germany

Quantum walks are the quantum mechanical analogue of classical random walks. While in classical mechanics each particle follows a definite trajectory, in standard quantum mechanics (QM) no such description of the coherent propagation of the quantum walker is possible. 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 to visualize particle trajectories.

For photons these Bohmian trajectories correspond to energy flow lines given by the Poynting vector in classical electrodynamics and can be reconstructed from weak measurements. We report on the simulation and first measurement results of such energy flow lines of a quantum walk, realized in an integrated waveguide array written into fused silica substrate. By analyzing different time steps of the quantum walk evolution we are able to reconstruct the trajectories giving information about the energy flow in quantum walk structures.

QI 3: Quantum Machine Learning

Time: Monday 11:00–13:00 Location: B305

Invited Talk QI 3.1 Mon 11:00 B305

Characterising quantum device variability with machine learning — •Natalia Ares — University of Oxford

Machine learning is proving to be essential in the tuning and characterization of quantum devices. The search for operation conditions, which often requires navigating large and complex parameter spaces, can now be fully automated, with performances superior to those achieved by human experts. Now these machine learning approaches are not only enabling scalability by automating qubit control, but also by providing us with unprecedented insight into quantum device variability.

We can use machine learning algorithms for automatic tuning across different semiconductor platforms. This demonstrates not only the robustness of these algorithms against the differences in the characteristics of the material system and device architecture, but that they can provide a tool for their comparison and analysis. I will show that by using a physics-aware machine learning algorithm we are able to infer the disorder potential affecting the operation of quantum dot devices, revealing a hidden characteristic of such devices, and thus narrowing the gap between simulation and reality.

QI 3.2 Mon 11:30 B305

The application of quantum neural networks in function approximation — •David Kreplin and Marco Roth — Fraunhofer IPA, Nobelstraße 12, 70569 Stuttgart, Deutschland

Approximating functions by parameterized quantum circuits is a promising application for quantum computing, since the repetitive encoding of the input data can result in an exponentially growing complexity of the function. In the literature, this approach is often described as Quantum Neural Networks (QNNs), since it can be similarly utilized as classical artificial neural networks.

In this talk, we show how an efficient and general function approximation can be realized by a QNN. We discuss the construction, training, and the application of the QNN with the example of solving a differential equation based model of a hydrogen electrolyzer and benchmark the results against classical neural networks.

A particular focus in this talk will be on the unavoidable noise that results from the finite sampling of the quantum state. This so-called shot noise strongly degrades the training process and yields a noisy outcome of the QNN. We discuss how that shot noise can be strongly reduced during the training of the QNN by an additional regularization term. This not only reduces the noise in the final function but also simplifies the training process on shot based simulators or real devices. Finally, we present results from the real quantum computing hardware and we reflect on the obstacles that we currently face in training such QNNs on the real backends.

QI 3.3 Mon 11:45 B305

Parameterized quantum circuits for reinforcement learning of classical rare dynamics — Alissa Wilms[1,2], •Laura Ohff[2,3], Andrea Skolik[4,5], David A. Reiss[1], Sumeet Khatri[1], and Jens Eisert[1,6,7] — [1]Dahlem Center for Complex Quantum Systems, Freie

Universität Berlin, Berlin, Germany — [2]Porsche Digital GmbH, Ludwigsburg, Germany — [3]Otto-Friedrich Universität Bamberg, Bamberg, Germany — [4]Leiden University, Leiden, The Netherlands — [5]Volkswagen Data:Lab, Munich, Germany — [6]Fraunhofer Heinrich Hertz Institute, Berlin, Germany — [7]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany

In the study of non-equilibrium or industrial systems, rare events are crucial for understanding the systems' behavior. Since they are atypical, one requires specific methods for sampling and generating rare event statistics in an automated and statistically meaningful way. We propose two quantum reinforcement learning (QRL) approaches to study rare dynamics of time-dependent systems and investigate their benefits over classical approaches based on neural networks. We investigate how architectural choices influence the successful learning by QRL agents and demonstrate that a QRL agent is capable of learning the rare dynamics of a random walker with using just a single qubit. Furthermore, we are able to numerically demonstrate an improved environment exploration during learning and a better performance in coping with environment scaling by the quantum agents in comparison to their classical counterparts.

QI 3.4 Mon 12:00 B305

Optimal storage capacity of quantum Hopfield neural networks — •Lukas Bödeker[1,2], Eliana Fiorelli[1,2,3], and Markus Müller[1,2] — [1]Institute for Theoretical Nanoelectronics (PGI-2), Forschungszentrum Jülich, 52428 Jülich, Germany — [2]Institute for Quantum Information, RWTH Aachen University, 52056 Aachen, Germany — [3]Instituto de Fisica Interdisciplinar y Sistemas Complejos (IFISC), CSIC UIB Campus, Palma de Mallorca, E-07122, Spain

Quantum neural networks form one pillar of the emergent field of quantum machine learning. Here, quantum generalisations of classical networks realizing associative memories - capable of retrieving patterns, or memories, from corrupted initial states - have been proposed. It is a challenging open problem to analyze quantum associative memories with an extensive number of patterns, and to determine the maximal number of patterns the quantum networks can reliably store, i.e. their storage capacity. In this work, we propose and explore a general method for evaluating the maximal storage capacity of quantum neural network models. As an example, we apply our method to an open-system quantum associative memory formed of interacting spin-1/2 particles realizing coupled artificial neurons. The system undergoes a Markovian time evolution resulting from a dissipative retrieval dynamics that competes with a coherent quantum dynamics. We map out the non-equilibrium phase diagram and study the effect of temperature and Hamiltonian dynamics on the storage capacity. Our method opens an avenue for a systematic characterization of the storage capacity of quantum associative memories.

QI 3.5 Mon 12:15 B305

Quantum kernel methods for regression — •Jan Schnabel — Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA, Center for Cyber Cognitive Intelligence (CCI), Stuttgart, Germany

It was shown in Refs. [1,2] that encoding data into a quantum state and interpreting the respective expectation value when measuring w.r.t. an observable as machine learning model, links quantum computing to the rich framework of classical kernel theory. Hence, these theoretical tools can now be used to understand quantum models. Here, the inherent structure of quantum kernel methods is particularly suited for NISQ applications. As a result, these facts caused constantly growing research activities in this field, where little attention has been hitherto paid to quantum kernel regression problems.

In this talk, I briefly introduce the core theoretical concepts of different approaches for computing quantum kernels before discussing associated challenges. The latter includes the role of classical data pre-processing and selection, data redundancies as well as the design of quantum feature maps. These aspects are discussed based on project-specific use cases from hydrogen production research. Beyond that, I attempt to provide a systematic comparison of different quantum kernel regression approaches and show results from real backend runs. This also incorporates demonstrating effects of proper error mitigation techniques.

[1] M. Schuld and N. Killoran. Phys. Rev. Lett. 122, 040504 (2019)
[2] M. Schuld, arXiv:2101.11020v2 (2021)

QI 3.6 Mon 12:30 B305

Renormalisation through the lens of QCNNs — •Nathan A. McMahon, Petr Zapletal, and Michael J. Hartmann — Friedrich-Alexander-Universität Erlangen- Nürnberg

The cluster-Ising model is an example of a quantum model with a symmetry protected topological (SPT) phase. For this model, the efficiency of performing phase recognition has recently been improved over measuring string order parameter (SOP) by the use of a particular quantum convolutional neural network (QCNN), which was motivated by renormalisation theory.

Unlike most neural networks, the function of the QCNN used here is relatively straightforward to explain. First, each layer of the QCNN performs a process analogous to both renormalisation/quantum error correction. Second, the remainder of the circuit simply determines if we are in the ground state of a stabiliser Hamiltonian. If the energy is sufficiently low we consider the input state to be in the target phase.

This QCNN also has a second feature, it is exactly equivalent to a constant depth quantum circuit + post-processing. Beyond just providing a cheaper circuit, this also points to the generalisation of phase recognising QCNNs beyond the cluster-Ising model. Combining these with the fidelity view of quantum phases, I will discuss the potential of QCNNs as a quantum information theory construction of renormalisation.

QI 3.7 Mon 12:45 B305

Quantum Gaussian Processes for Bayesian Optimization — •Frederic Rapp and Marco Roth — Fraunhofer IPA, Stuttgart 70569, Nobelstrasse 12

An important aspect of machine learning is finding the best possible hyperparameters for a given model. Bayesian optimization is one often used algorithm when tackling this task. It requires a surrogate model where Gaussian processes can be used. Gaussian processes are a method based on the evaluation of kernel matrices that serve as covariance functions. These matrices can be evaluated using a quantum computer by encoding the data into the quantum Hilbert space. We study Gaussian processes using quantum kernels based on parameterized quantum circuits, and their application to regression tasks, as well as their usage as a surrogate model for Bayesian optimization. We show that the method can solve a regression of a one-dimensional function under the influence of different quantum computing noise sources. We discuss the important aspects of the model and provide an example of the optimization of the method when solving a multi-dimensional regression task. Finally, we perform a hyperparameter tuning using Bayesian optimization based on quantum Gaussian process regression. We show that the quantum version of the algorithm is able to find suitable hyperparameter settings of a given problem that are comparable to applying the classical counterpart and even better than using a random search based algorithm.

QI 4: Quantum Computing and Simulation (joint session Q/QI)

Time: Monday 11:00–13:00 Location: E214

QI 4.1 Mon 11:00 E214

An energy estimation benchmark for quantum computers — •Andreas J C Woitzik[1], Edoardo Carnio[1,2], and Andreas Buchleitner[1,2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104 Freiburg im Breisgau, Federal Republic of Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, 79104 Freiburg im Breisgau, Federal Republic of Germany

While quantum-mechanical measurements yield intrinsically stochastic outcomes, the fluctuations in the output of current noisy intermediate-scale quantum (NISQ) devices are caused, for the large part, by imperfections in the hardware components and operations. We propose a simple energy estimation benchmark and use it to gauge noise-induced fluctuations in the output of IBM Quantum System One in Ehningen. We find that the errors we measure in our benchmark correlate only weakly with the reported calibration data of the machine. Moreover, a time-resolved analysis of the benchmark measure reveals periodic oscillations and unpredictable outliers that cannot be mildened by measurement error mitigation. We conclude that we cannot rely on single realizations of circuit outcomes, but rather on appropriately sampled ensembles.

QI 4.2 Mon 11:15 E214

Effects of particle losses in two photon quantum walks — •Federico Pegoraro, Philip Held, Sonja Barkhofen, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS) Warburger Str. 100, 33098, Paderborn, Germany

In real photonic quantum systems losses are an unavoidable factor limiting the scalability to many modes and particles, restraining their application in fields as quantum information and communication. A considerable amount of engineering effort has been taken in order to improve the quality of particle sources and system components. At the same time, data analysis and collection methods based on post-selection have been used to mitigate the effect of particle losses. This has allowed for investigating experimentally multi-particle evolutions where the observer lacks knowledge about the system's intermediate propagation states. Nonetheless, the fundamental question how losses affect the behaviour of the surviving subset of a multi-particle system has not been investigated so far. For this reason, with this contribution we study the impact of particle losses in a quantum walk of two photons reconstructing the output probability distributions for one photon conditioned on the loss of the other in a known mode and temporal step of our evolution network. We present the underlying theoretical model that we have devised in order to model controlled particle losses, we describe a platform capable of implementing our theory and in the end we show how localized particle losses change the output distributions without altering their asymptotic spreading properties.

QI 4.3 Mon 11:30 E214

Realization of a photonic ultra-fast free space discrete-time quantum walk. — •Jonas Lammers, Syamsundar De, Nidhin Prasannan, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Straße 100, 33098 Paderborn, Germany

Recent developments in quantum systems based on time-multiplexed techniques have shown high potential for quantum communication and information processing protocols. The time-multiplexed architecture has already been used in experiments demonstrating exponential increase in GHZ state generation and quantum advantage based on Gaussian boson sampling. Here we demonstrate an ultra-fast free space discrete-time quantum walk. With the newest generation of SNSPDs enabling higher than ever timing resolutions, we were able to overcome the need for long optical delay paths - typically optical fibers - in time-multiplexed systems. The resulting free space architecture enables us to increase measurement repetition rates by multiple orders of magnitude and promises increased stability. Furthermore, we can expect an increase in efficiency which would lead to an exponential increase in observable step numbers. We performed a full polarization resolved quantum walk characterization using coherent light and heralded single photons, observing up to twenty quantum walk steps with high similarity to theory. The demonstrated ultra-fast quantum walk is a promising platform for quantum simulations and opens up a path for large-scale quantum photonic networks utilizing time-multiplexing.

QI 4.4 Mon 11:45 E214

Multiphoton entangled graph states from a single atom — •Philip Thomas, Leonardo Ruscio, Olivier Morin, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching

Optical photons interact very weakly with their environment, making them robust qubit carriers suitable for numerous protocols in quantum information science. Many experiments on photonic entanglement that were carried out over the last decades relied on the well-established toolbox of non-linear optics. However, the underlying process is intrinsically probabilistic and thus poses a practical limit on the size of entangled states one can generate. In order to avoid this obstacle, we use a single Rubidium atom in an optical cavity as an efficient photon source [1]. Single photons are emitted sequentially while the atomic spin qubit mediates entanglement between them. We show that by tailored single-qubit operations on the atomic state we generate Greenberger-Horne-Zeilinger (GHZ) states of up to 14 photons and linear cluster states of up to 12 photons. A combined source-to-detection efficiency of 43% leads to coincidence rates orders of magnitude higher than the previous state-of-the-art [2]. Our work represents a step towards scalable measurement-based quantum computing and communication.

[1] P. Thomas *et al.*, Nature **608**, 677-681 (2022).
[2] H.-S. Zhong *et al.*, Phys. Rev. Lett. **121**, 250505 (2018).

QI 4.5 Mon 12:00 E214

Multi-photon coherence and interference — •Sholeh Razavian[1,2], Klaus Mølmer[3], Jasmin Meinecke[1,2], and Harald Weinfurter[1,2] — [1]Department fur Physik, Ludwig-Maximilians-Universitat, Munich, Germany — [2]Max-Planck-Institute for quantum optics, Garching, Germany — [3]Niels Bohr Institute, Copenhagen, Denmark

The Hong-Ou-Mandel(HOM) effect is a prime example of photon interference in quantum optics and forms the basis for many quantum applications. While HOM interference is a two-photon effect, we are lifting it to the general case, considering multi-photon interference including decoherence effects.

Here we are analyzing polarized photons propagating in integrated waveguide arrays with polarization dependent coupling. With two observables, one for path and one for polarization. The output is a superposition of all the different configurations in a possibly non-classical state.

We analyze multiphoton coincidence measurements and samples from the probability distribution in order to investigate polarization-dependent decoherence of the total quantum state.

QI 4.6 Mon 12:15 E214

Physical computing with a superfluid — Maurus Hans[1], •Elinor Kath[1], Marius Sparn[1], Nikolas Liebster[1], Felix Draxler[2], Helmut Strobel[1], and Markus Oberthaler[1] — [1]Kirchhoff-Institut für Physik, Universität Heidelberg, Germany — [2]Interdisziplinäres Zentrum für Wissenschaftliches Rechnen, Universität Heidelberg, Germany

We report on the implementation of a hybrid neural network with a physical system. As a proof-of-concept we implement the regression and interpolation of a non-linear, one-dimensional function. A digital micromirror device is used to prepare an elongated atomic cloud and encode input values by imprinting a phase profile onto the superfluid. Its non-linear response is detected by the observation of the density distribution, from which the output value is generated by a trained linear layer. We compare the performance of this hybrid neural network for different parameters and give an outlook for further directions.

QI 4.7 Mon 12:30 E214

A novel quantum simulation platform for ultracold ytterbium atoms using hybrid optical potentials — •Etienne Staub[1,2], Tim O. Höhn[1,2], Guillaume Brochier[1,3], Clara Z. Bachorz[1,2,4], David Gröters[1,2], Bharath Hebbe Madhusudhana[1,2,5], Nelson Darkwah Oppong[1,2,6], and Monika Aidelsburger[1,2] — [1]Ludwig-Maximilians-Universität München, München, Germany — [2]Munich Center for Quantum Science and Technology, München, Germany — [3]École normale supérieure de Lyon, Lyon, France — [4]Max-Planck-Institut für Quantenoptik, Garching, Germany — [5]Los Alamos National Laboratory, Los Alamos, USA — [6]JILA, University of Colorado at Boulder, Boulder, USA

We report on our recent progress constructing a novel experimental platform for ytterbium atoms. Our approach combines optical lattices and optical tweezers, providing a versatile, robust and scalable environment for both analog and digital quantum simulation. A central ingredient of our implementation are optical potentials at the magic and tune-out wavelengths for the ground and meta-stable clock state of ytterbium. Leveraging high-resolution optical clock spectroscopy, we present preliminary results from our efforts to experimentally determine two new magic wavelengths and the ground-state tune-out wavelength near the narrow cooling transition at 556nm. Furthermore, we demonstrate loading, cooling and imaging of individual atoms in our tweezer array. Possible avenues of research include the simulation of lattice gauge theories and the implementation of quantum computing schemes by means of collisional gates.

QI 4.8 Mon 12:45 E214

Robust localization effects in dipolar systems with positional

disorder — •Adrian Braemer and Martin Gärttner — University Heidelberg, Germany

We study a Heisenberg XXZ model with disordered couplings arising from power-law interactions between randomly positioned sites. This type of system is realized naturally in a large range of quantum simulation platforms. We numerically find indications of a localization transition and derive a simple, effective model for the local integrals of motion based on strongly interacting pairs. By systematically taking into account higher order resonances, we find a strong renormalization flow towards a pure Ising model. This might explain the numerically observed robustness of the localization transition, which in this system does not drift towards strong disorder strength as the system size is increased. One may even conjecture that the localized phase could be stable in this type of systems.

QI 5: Superconducting Qubits and Hybrid Systems

Time: Monday 11:00–12:30 Location: F428

Invited Talk QI 5.1 Mon 11:00 F428

Building Superconducting Quantum Hardware towards Error-Corrected Quantum Computing — •Christopher Eichler — Department of Physics, FAU Erlangen, Germany

Quantum Computers will ultimately rely on near-perfect logical gates, implemented while correcting errors at the physical level. The need for developing quantum hardware optimized for performing fast, repeatable, and high-fidelity syndrome measurements in quantum error-correcting codes such as the surface code therefore becomes increasingly important. In my talk, I will present advances in performing qubit readout and two-qubit gates in multi-qubit superconducting quantum processors, which enabled the recent experimental demonstration of repeated quantum error correction in surfaces codes. I will show how quantum processors optimized for quantum error correction can also serve as a testbed to explore noisy intermediate-scale quantum algorithms. The talk will conclude with a discussion about open challenges and opportunities to advance the speed and fidelity of syndrome detection in scalable device architectures by exploiting tunable coupling elements.

QI 5.2 Mon 11:30 F428

Towards High-Fidelity Fluxonium Quantum Processors — •Florian Wallner[1,2], Johannes Schirk[1,2], Ivan Tsitsilin[1,2], Christian Schneider[1,2], Niklas Bruckmoser[1,2], Leon Koch[1,2], and Stefan Filipp[1,2] — [1]Technical University of Munich, TUM School of Natural Sciences, Physics Department, Garching, Germany — [2]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany

To solve real-world problems on error-corrected quantum computers it is estimated that multiple hundreds to thousands of physical qubits have to be combined to build one logical qubit. This results in an impractical large overhead in the number of qubits and demands new types of qubits with orders of magnitude improvements in performance.

Here, we report on our recent advances to build superconducting fluxonium qubits that offer distinct advantages compared to the widespread transmons-type qubits. We show high coherence times and fast high-fidelity single qubit gates, realized through the flux bias line, which significantly reduces the control line overhead associated with flux qubits. Furthermore, we demonstrate a dispersive readout with assignment fidelity greater than 96%. Since these qubits have low transition frequencies a significant thermal population needs to be removed at the start of each experiment. We achieve this by employing an unconditional active reset and a conditional real-time feedback-assisted reset that can later enable dynamical circuits. In addition, we provide an outlook on our efforts to build multi-qubit devices and multi-qubit gates.

QI 5.3 Mon 11:45 F428

High-impedance resonators based on granular aluminum — •Mahya Khorramshahi[1], Martin Spiecker[1], Patrick Paluch[2], Thomas Reisinger[1], and Ioan Pop[1] — [1]Institute for Quantum Materials and Technology, Karlsruher Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany — [2]Physikalisches Institut, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Superconductors with characteristic impedance larger than the resistance quantum are a valuable resource in superconducting circuits. They enable the design of protected qubits such as Fluxoniums or 0-pi qubits and can improve the coupling to small-dipole-moment objects, which may be useful for interfacing with spin-qubits, donor spins, etc. Here we present compact resonators in the lower GHz regime with a high characteristic impedance given by a high-kinetic-inductance material, namely granular aluminum, with spurious modes above 10GHz. We fabricated the resonators with an electron-beam lithography lift-off process, and we coupled them using a 50 Ohm coplanar waveguide architecture. Measurements performed in a dilution cryostat reveal that the resonators maintain high-quality factors in the single photon regime, a valuable resource for future quantum hardware implementations

QI 5.4 Mon 12:00 F428

Rare earth ions in molecular crystals for quantum information application — •Jannis Hessenauer[1], Evgenij Vasilenko[1], Weizhe Li[1], Christina Ioannou[1], Kumar Senthil Kuppusamy[2], Mario Ruben[2], and David Hunger[1,2] — [1]Karlsruher Institut für Technologie (KIT), Physikalisches Institut — [2]Karlsruher Institut für Technologie (KIT), Institut für Quantenmaterialen

Rare-earth ions in solid state hosts are promising candidates for optically addressable spin qubits, owing to their long optical and spin coherence times in the solid state [1]. Recently, rare earth ions in organic molecules have demonstrated outstanding coherence properties, while also promising a large parameter space for optimization by chemically engineering of the host molecule [2]. We characterize the optical properties of novel rare earth ion based molecular materials at low temperature using techniques such as photoluminescence excitation spectroscopy, absorption spectroscopy and spectral hole burning. We observe narrow homogenous and inhomogeneous linewidths and long-lived spin polarization, confirming the great potential of molecular rare earth materials for quantum information applications.

[1] Kinos, Adam, et al. "Roadmap for rare-earth quantum computing." arXiv preprint arXiv:2103.15743 (2021).

[2] Serrano, Diana, et al. "Ultra-narrow optical linewidths in rare-earth molecular crystals." Nature 603.7900 (2022): 241-246.

QI 5.5 Mon 12:15 F428

Schrödinger cat states of a 16-microgram mechanical oscillator — •Marius Bild[1,2], Matteo Fadel[1,2], Yu Yang[1,2], Uwe von Lüpke[1,2], Phillip Martin[1,2], Alessandro Bruno[1,2], and Yiwen Chu[1,2] — [1]Department of Physics, ETH Zürich, 8093 Zürich, Switzerland — [2]Quantum Center, ETH Zürich, 8093 Zürich, Switzerland

While the principle of superposition in quantum physics is routinely validated for microscopic systems, it is still unclear why we do not observe macroscopic objects to be in superpositions of states that can be distinguished by some classical property. I will present our experiments, that harness the resonant Jaynes-Cummings interaction between a high overtone resonator mode of a bulk acoustic wave resonator and a superconducting qubit, to demonstrate the preparation of Schrödinger cat states of motion. In such a state, the constituent atoms oscillate in a superposition of two opposite phases with an effective oscillating mass of 16μg. Making use of the circuit quantum acoustodynamics toolbox we have developed, we furthermore show control over amplitudes and phases of the created Schrödinger cat states, and investigate their decoherence dynamics by observing the disappearance of Wigner negativities. Our results can find applications in continuous variable quantum information processing and in fundamental investigations of quantum mechanics in massive systems.

QI 6: Poster I (joint session QI/Q)

Time: Monday 16:30–19:00 Location: Empore Lichthof

QI 6.1 Mon 16:30 Empore Lichthof

Towards multi-photon tests of hyper-complex quantum mechanics — •Ece Ipek Saruhan, Marc-Oliver Pleinert, and Joachim von Zanthier — Quantum Optics and Quantum Information, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 1, 91058 Erlangen, Germany

Axioms of quantum mechanics do not tell much about the structure of the Hilbert space such as, e.g., the number system, which could be real, complex, or hyper-complex. Probabilities are amplitude squares of wave functions, which are defined on a complex space in general. Can one consider the result of a dot product to be a hyper-complex number? Asher Peres proposed a way to test hyper-complex quantum mechanics with a single particle scattered from 3 different scatterers [1]. We adapt this test to a 3-slit interference setup and extend it to multi-slit and multi-particle scenarios. We construct Peres-like functions to see if the multitude of paths and particles show different sensitivity to, still hypothetical, hyper-complex phases.

[1] A. Peres, Phys. Rev. Lett. 42, 683 (1979).

QI 6.2 Mon 16:30 Empore Lichthof

An analysis on the almost quantum correlation set — •Vitor Sena and Rafael Rabelo — University of Campinas, Brazil

A good way to investigate the foundations of quantum theory is through the correlations it allows between results of measurements performed on spatially separated systems. These correlations may present some known nonclassical phenomena such as Bell nonlocality, but, interestingly, the set of nonlocal correlations allowed by quantum theory is quite specific and, in some sense, limited. There is a set of correlations slightly larger than this, known as the almost quantum correlations set, which presents similarities and differences with the set of quantum correlations. In this work, we study the relationship between these sets by numerically estimating their relative volumes in different scenarios. In doing so, we seek to understand the kind of correlations allowed by each one and how their differences can be shown quantitatively.

QI 6.3 Mon 16:30 Empore Lichthof

Reducing Bias in Quantum State Tomography — •Yien Liang[1,2] and Matthias Kleinmann[1] — [1]Universität Siegen, Walter-Flex-Straße 3, D-57068 Siegen, Germany — [2]Peking University, Beijing 100871, China

Quantum state tomography aims to estimate the quantum state of a system using quantum measurements. It is well known that such an estimate cannot be perfect, that is, the procedure may yield an operator with negative eigenvalues or the mean reconstructed state deviates from true state. This is the dilemma of having a nonphysical reconstruction or a biased estimator. It also has been shown that any unbiased estimator has to yield rather large negative eigenvalues. We ask the complementary question: What is the minimum bias of an estimator, even if one is willing to accept an increased variance of the estimator? We show that the bias can indeed be improved by orders of magnitude, but at the price of being rather pathological. We furthermore discuss the behavior of estimators with low bias compared to canonical estimators for large sample sizes and many qubits.

QI 6.4 Mon 16:30 Empore Lichthof

Witnessing non-Markovianity in quantum Brownian motion by quasi-probability distributions in phase-space — •Irene Ada Picatoste Fernández[1], Moritz Ferdinand Richter[1], and Heinz-Peter Breuer[1,2] — [1]Physikalisches Institut, Universität 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 theory of open quantum systems aims to describe the dynamics of a quantum system coupled to an environment using a limited number of degrees of freedom. The Caldeira-Leggett model of quantum Brownian motion represents a physically interesting example of such systems showing strong memory effects, i.e., non-Markovian dynamics, in certain parameter regimes. Recently, a witness for non-Markovianity has been developed which is based on the Kolmogorov distance between quasi-probability distributions of two states [1]. Additionally, for Gaussian dynamics, a new measure of non-Markovianity can be defined using exclusively the Glauber-Sudarshan P-function. Here, we apply this witness to the Caldeira-Leggett model and show the behaviour of the non-Markovianity measure in different scenarios, while studying where the witness works best.

[1] M. F. Richter, R. Wiedenmann and H.-P. Breuer, arXiv:2210.06058 [quant-ph].

QI 6.5 Mon 16:30 Empore Lichthof

Photon-number resolved model for multimode quantum optical setups based on Gaussian states — •Florian Niederschuh, Erik Fitzke, and Thomas Walther — Institute for Applied Physics, TU Darmstadt, Darmstadt, Germany

Experiments in quantum optics and photonic quantum information protocols regularly employ multimode states with low photon numbers. While early setups used single photon avalanche diodes, recent advances aim at the realization of photon-number resolving detectors. Consequently, mathematical models for the prediction of photon-number resolved detection probabilities may provide valuable insight and aid in experimental design. Here, a formalism for simulating the photon statistics of Gaussian states is presented. It is based on the construction of suitable generating functions, which are further processed by software for automatic differentiation. This allows the extraction of various statistical quantities, e.g. the photon number distribution, cumulative probabilities and statistical moments. The model considers an array of experimental imperfections and agrees with recent measurement results of an entanglement-based phase-time coding setup for quantum key distribution [Fitzke et al. (2022). PRX Quantum, 3, 020341].

QI 6.6 Mon 16:30 Empore Lichthof

Entanglement classification schemes : comparison between Majorana representation and algebraic geometry approaches — •Tom Weelen[1], Naïm Zénaïdi[2], Pierre Mathonet[2], and Thierry Bastin[1] — [1]Institut de Physique Nucléaire, Atomique et de Spectroscopie, Université de Liège, BE-4000 Liège, Belgium — [2]Département de Mathématique, Université de Liège, BE-4000 Liège, Belgium

Quantum entanglement can be of different kinds [1] and classifying the quantum states in this respect may represent a difficult challenge in general multipartite systems. In particular, entanglement classes that are inequivalent under stochastic local operations and classical communication (SLOCC) are of fundamental importance. For N-qubit systems with $N > 3$, there is an infinity of such SLOCC entanglement classes [1] and it makes sense to gather them into a finite number of families, as was done for symmetric states in Refs. [2,3] using two distinct approaches (Majorana representation and algebraic geometry tools, respectively). Here, we compare these two structures and identify whether they can be embedded into one another or not. To do so, we formulate the structure of Ref. [2] in terms of k-secants and k-tangents (k a positive integer) of the Veronese variety [3] and we prove that only the k-tangent structuration provides a coherent structure compatible with that of Ref. [3].

[1] W. Dür et al., Phys. Rev. A **62**, 062314 (2000). [2] T. Bastin et al., Phys. Rev. Lett. **103**, 070503 (2009). [3] M. Sanz et al., J. Phys. A: Math. Theor. **50**, 195303 (2017).

QI 6.7 Mon 16:30 Empore Lichthof

What channels can be implemented without a reference frame? — •Fynn Otto — University of Siegen, Germany

Quantum reference frames are needed for communication tasks for which the method of information encoding matters. In contrast to – for example – sending integers, reference frames are needed for communicating, e.g. quantum phases or directional information. Even if a classical communication link between two parties is established, it is not possible to send a *direction in space*.

Lacking a reference frame limits the set of operations that can be performed deterministically. Changing reference frames is equivalent to the passive evolution of a state under the unitary operator $U(g)$, representing the transformation g. The transformations between reference frames form a group G, and allowed frame-agnostic channels turn out to be G-covariant: the channel $\mathcal{E}$ must commute with every $U(g)$.

Here we investigate the reachable states for two important cases: lacking a phase reference (corresponding to the group $G = U(1)$) and lacking a Cartesian frame alignment ($G = SU(2)$). Examples of G-covariant state transformation are provided along with possible classification and interpretation of the reachability structure.

QI 6.8 Mon 16:30 Empore Lichthof

Leveraging noisy physical observables with machine learning.
— •Adisorn Panasawatwong, Ulf Saalman, and Jan-Michael Rost — Max-Planck-Institute for the Physics of Complex Systems

A noisy light pulse containing many frequencies leads to deterministic electron dynamics in the illuminated target, whose response will also look noisy. At first glance, it cannot be distinguished from a random signal which results from fully chaotic dynamics. While the latter contains little information, the former contains valuable information about the target system, even more than its (linear) response to a Fourier-limited single-frequency pulse.

We are developing a machine learning-based approach which can distinguish the two kinds of noisy signals according to their actual information content: their complexity. Without using entropy, we show emergence of information by interpreting the result from auto-encoder.

Knowing the degree of complexity in the signal enables us to develop networks tailored to extract the amount of information about the target which is contained in the noisy observable due to its complexity.

QI 6.9 Mon 16:30 Empore Lichthof

Entanglement in free fermion systems
— Lexin Ding[1,2], •Gesa Dünnweber[1,2], and Christian Schilling[1,2] — [1]Faculty of Physics, Arnold Sommerfeld Centre for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstr. 37, 80333 Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, 80799 Munich, Germany

Entanglement is becoming an increasingly important resource for the realisation of quantum information tasks. Several measures of mode entanglement have been proposed for fermionic systems.

We consider a spinful free fermion chain under nearest neighbour hopping and determine an analytic measure of the resulting site-site entanglement. Including in particular the restrictions imposed by parity or particle number superselection rules, we study how various factors affect the accessible entanglement. This approach is extended to a model that includes an additional hopping term where we investigate the evolution of entanglement across a Lifshitz-type transition. Relating orbital entanglement to the concept of locality within a molecule, we present numerical results for a hydrogen chain.

Finally, we are interested in protocols for extracting entanglement from fermionic systems such as entanglement swapping, where superselection rules demand modifications to the established protocols for qubits.

QI 6.10 Mon 16:30 Empore Lichthof

Quantum Key Distribution from Bound Entanglement
— •Zeynab Tavakoli[1] and Gláucia Murta[2] — [1]Institut für Theoretische Physik, Universität zu Köln, Zülpicher Str. 77, D-50937 Köln, Germany — [2]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, D-40225 Düsseldorf, Germany

Quantum key distribution (QKD) aims to secure communication and establish a secret key between two honest parties. A secret key is a string of independent and random bits known to both parties. Key distillation in QKD is related to entanglement distillation; by distilling a maximally entangled state, one can get the key by measuring it. The belief was that achieving security is equivalent to distilling maximally entangled states. However, Authors of [Phys.Rev.Lett.80,5239,(2005)] show bound entangled states are usable to obtain key. Bound entangled states are quantum states that no maximally entangled states can be distilled from them using LOCC. Bound entangled states used in QKD have entanglement, which protects correlations from the environment. However, the entanglement is so twisted that it cannot be brought into a maximally entangled state. In this work, we studied known examples of bound entangled states useful for QKD. In particular, we investigate the noise tolerance of the corresponding QKD protocol, construct new bound entangled states around the original examples, and investigate their achievable key rates. Finally, we investigate if bound entangled states can be used in a simple QKD protocol where a single copy of the state is distributed and measured each round.

QI 6.11 Mon 16:30 Empore Lichthof

Randomness Certification for Multipartite Arbitrary Dimensional Systems
— Yu Xiang[1,2], •Yi Li[1], and Qiongyi He[1,2,3] — [1]State Key Laboratory for Mesoscopic Physics, School of Physics, Frontiers Science Center for Nano-optoelectronics, and Collaborative Innovation Center of Quantum Matter, Peking University, Beijing 100871, China — [2]Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China — [3]Peking University Yangtze Delta Institute of Optoelectronics, Nantong, Jiangsu 226010, China

We first present a method to certify the randomness generated in multipartite arbitrary dimensional systems, closely to the actual situation where some of the untrusted sides are measured locally. The proposed method also provides a hierarchy of upper and lower bounds of randomness with different assumptions. Comparing with the bipartite scenario, our result shows more randomness can be certified in this asymmetric network. Surprisingly, for some systems, we find that there exists nonzero certified randomness on the untrusted parties together, even though no randomness can be induced in either mode individually, which implies randomness in the multipartite network can be used for some security tasks in the future. The ease of our method is also demonstrated by adopting some existing experimental data. Finally, we prove that multipartite steering is necessary for generating randomness in the asymmetric network.

QI 6.12 Mon 16:30 Empore Lichthof

Markovian master equations beyond the adiabatic and inertial limit
— •Josias Langbehn[1], Roie Dann[2], Raphael Menu[3], Giovanna Morigi[3], Ronnie Kosloff[2], and Christiane Koch[1] — [1]Freie Universität Berlin, Berlin — [2]Institute of Chemistry, Hebrew University, Jerusalem — [3]Universität des Saarlandes, Saarbrücken

Markovian master equations in Gorini-Kossakowski-Sudarshan-Lindblad (GKLS) form can accurately describe the dynamics of many open quantum systems ranging from optical to solid state systems. Adding a drive to the system complicates the derivation of any such master equation. The Markovian framework has been extended to drives in the adiabatic regime [1] and beyond that to inertial drives within the "non-adiabatic master equation" (NAME) [2]. The aim of this work is to extend this framework to drives that go even beyond the inertial limit by introducing a numerical scheme for finding an eigenoperator basis. In principle this allows for arbitrary drives, going as far as Markovian master equations in GKLS form remain valid. Moreover, the numerical scheme allows treating situations where no inertial solution can be found analytically. This opens the door for optimal control tasks where the time-dependency of the optimal drives may not be adiabatic/ inertial. We observe significant deviations between the NAME and the adiabatic/ inertial limit in multiple exemplary systems considered.

[1] Albash, T., Boixo, S., Lidar, D. A. & Zanardi, P. New J. Phys. 14, 123016 (2012). [2] Dann, R., Levy, A. & Kosloff, R. Phys. Rev. A 98, 052129 (2018).

QI 6.13 Mon 16:30 Empore Lichthof

Mimicking non-Markovian dynamics using the stochastic surrogate Hamiltonian
— •Jonas Fischer and Christiane Koch — Freie Universität Berlin

Some control tasks, like qubit reset, demand interaction between the system and environment. In order to perform these tasks quickly, it is beneficial if this coupling is as strong as possible. Typically, this leads to non-Markovian dynamics, for which there is no unified propagation method so far.

One possible candidate is the surrogate Hamiltonian. The real environment is substituted by a collection of two-level systems that capture the influence of the real environment on the system. This allows for the propagation of the full Hilbert space, allowing for the description of non-Markovian dynamics.

Due to the truncation of the Hilbert-space, this method is limited to short timescales. At a certain point in time, the environmental modes will saturate and recurrences in the system dynamics will occur. The stochastic surrogate Hamiltonian is aiming to resolve this issue by randomly resetting the environmental modes into a thermal state. These resets should be performed in such a way that the recurrences get suppressed, but at the same time, they should destroy as few correlations as possible. We present a reset method that reproduces the correct reduced density matrices for both the reset mode and the other environmental modes.

QI 6.14 Mon 16:30 Empore Lichthof

Quantum transport in noisy networks of coupled harmonic oscillators — •Emma King, Raphael Menu, and Giovanna Morigi — Theoretische Physik, Universitat des Saarlandes, D-66123 Saarbruecken, Germany

In recent years rapid progress has been made towards the realisation of scalable quantum computers. While devices with an increasing number of qubits are being realised, the present size does not yet allow for the efficient implementation of error-correction schemes. This highlights the importance of understanding the role of an environment on the target quantum coherent dynamics. In this work we address the question as to which properties of an external environment are detrimental, and, in contrast, which properties can be used as resources for quantum transport. For this purpose we consider two chains of coupled harmonic oscillators with long range interactions that decay in a power law fashion. The one chain acts as the system while the other is the environment. In this setting we derive a quantum master equation starting from the Liouville-von Neumann equation and identify the requirements on the environment for which the master equation has the Lindblad form. We then analyse transport in the chain as a function of the environment characteristics, identifying the regime(s) in which it leads to faster propagation of information along the chain.

QI 6.15 Mon 16:30 Empore Lichthof

Engineering a heat engine purely driven by quantum coherence — •Stefan Aimet — Imperial College London, London, United Kingdom — FU Berlin, Berlin, Germany

The question of whether quantum coherence is a resource beneficial or detrimental to the performance of quantum heat engines has been thoroughly studied but remains undecided. To isolate the contribution of coherence, we analyse the performance of a purely coherence-driven quantum heat engine, a device that does not include any heat flow during the thermodynamic cycle. The engine is powered by the coherence of a multi-qubit system, where each qubit is charged via interaction with a coherence bath using the Jaynes-Cummings model. We demonstrate that optimal coherence charging and hence extractable work is achieved when the coherence bath has an intermediate degree of coherence. In our model, the exctractable work is maximised when four copies of the charged qubits are used. Meanwhile, the efficiency of the engine, given by the extractable work per input coherence flow, is optimised by avoiding coherence being stored in the system-bath correlations that is inaccessible to work. We numerically find that the highest efficiency is obtained for slightly lower temperatures and weaker system-bath coupling than those for optimal coherence charging.

QI 6.16 Mon 16:30 Empore Lichthof

Design of a 4-party active base choice phase-coding quantum key distribution multi-user hub — •Adrian Klute, Maximilian Tippmann, Lucas Bialowons, Erik Fitzke, and Thomas Walther — TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt

In the developing field of secure quantum communication, several quantum key distribution (QKD) systems have been tested with various protocols. However, building scalable QKD systems with more than 2 parties is a challenging task. We recently presented a 4-party star-shaped quantum hub system, which is based on time-bin entanglement. The crucial part in this setup is the precise building of interferometers. Precise building methods with sufficient reliability are needed to exchange keys with low quantum bit error rate between all user pairs of the hub. Not only the building method but also a suitable design choice of the interferometer can reduce uncertainties in the building process. In that sense we are discussing the technological challenges of two known interferometer designs for an active phase-coding protocol, a Sagnac-Michelson and a Sagnac-Mach-Zehnder configuration. We present first results to assess the success of the building method that we used.

QI 6.17 Mon 16:30 Empore Lichthof

Towards a city-wide quantum key distribution network with a multi-user phase-time coding quantum key hub — •Maximilian Tippmann, Erik Fitzke, Till Dolejsky, Florian Niederschuh, and Thomas Walther — TU Darmstadt, Institute of Applied Physics, 64289 Darmstadt

Quantum key distribution (QKD) paves a way to make today's IT-infrastructure resilient against future attacks e.g. from quantum computers. Various QKD protocols and setups have been tested over the last decades. However, most experiments focus on two-user systems, thus not allowing an easy scaling to multiple users. Here, we report on a quantum key hub implementing the phase-time protocol with a central untrusted node for simultaneous pairwise key exchange, tested with four users, but readily scalable to more than 100 users. The central untrusted node consists of an entangled photon pair source, and provides high-flexibility, allowing plug-and-play reconfiguration of the connected parties. Furthermore, the setup has been tested with real-world deployed fiber demonstrating the practicability of our approach. Going towards a city-wide deployment, we look into setup specific issues, including post-processing and alignment of the setup, arising from the distribution of the communicating parties to a city-wide scale.

QI 6.18 Mon 16:30 Empore Lichthof

System Components for Single-Photon Quantum Key Distribution in the Telecom C-band — •Timm Gao, Mareike Lach, and Tobias Heindel — Institut für Festkörperphysik, Technische Universität Berlin, 10623 Berlin, Germany

We report on the evaluation of system components for single-photon based quantum communication in the telecom C-band. We evaluate the performance of different hardware components for quantum key distribution. Special emphasis lies here on the receiver module, where free-space and fiber-based approaches are comparatively discussed.

QI 6.19 Mon 16:30 Empore Lichthof

Night Sky Background Measurement for Quantum Key Distribution — •Rengaraj Govindaraj[1,2], Michael Auer[1,2,3], Adomas Baliuka[1,2], Peter Freiwang[1,2], Lukas knips[1,2,4], and Harald Weinfurter[1,2,4] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, 80799, München, Germany — [2]Munich Center for Quantum Science and Technology, 80799, München, Germany — [3]Universität der Bundeswehr, 85577 Neubiberg, Germany — [4]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Free-space satellite-to-ground quantum key distribution (QKD) enables two authenticated parties - potentially separated by global distances - to exchange a secret key that can be used for symmetric cryptography. However, the performance of free-space QKD crucially depends on the quantum bit error ratio (QBER) and hence on the contributions of background light sources such as light from natural sources as the sun or stars as well as from artificial light sources. As those noise contributions vary with time of day, season, weather and location, their study is important for estimating future QKD missions. We here present our experimental method to map the night sky background in terms of its brightness in the spectral bands around 850nm and 1550nm and discuss the implications for satellite-based QKD.

QI 6.20 Mon 16:30 Empore Lichthof

Designing versatile and performant DM-CV QKD systems 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[1,2], and Christoph Marquardt[1,2] — [1]Chair of Optical Quantum Technologies, Department of Physics, Friedrich Alexander University Erlangen-Nuremberg, Erlangen, Germany — [2]Quantum Information Processing Group, MPI for the Science of Light, 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 a key technology for guarding critical communication links against the rapidly growing threat of large-scale quantum computers. We present our progress in implementing a versatile and performant CV-QKD system designed for metropolitan fiber optical networks. Important performance indicators estimated during a public technology demonstration in August 2021 and recent improvements will be discussed. We also highlight special design aspects and challenges of the implementation, in particular with regard to stability and error correction requirements.

QI 6.21 Mon 16:30 Empore Lichthof

Night Sky Background Measurement for Quantum Key Distribution — •Rengaraj Govindaraj[1,2], Michael Auer[1,2,3], Adomas Baliuka[1,2], Peter Freiwang[1,2], Lukas Knips[1,2,4], and Har-

ald Weinfurter[1,2,4] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, 80799, München, Germany — [2]Munich Center for Quantum Science and Technology, 80799, München, Germany — [3]Universität der Bundeswehr, 85577 Neubiberg, Germany — [4]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Free-space satellite-to-ground quantum key distribution (QKD) enables two authenticated parties - potentially separated by global distances - to exchange a secret key that can be used for symmetric cryptography. However, the performance of free-space QKD crucially depends on the quantum bit error ratio (QBER) and hence on the contributions of background light sources such as sun or stars as well as artificial light sources. As those noise contributions vary with time of day, season, weather and location, their study is important for planning the location and performance of ground station's future QKD missions. We here present our experimental method and device to map the night sky background in terms of its brightness in the spectral bands around 850nm and 1550nm and discuss the implications for satellite-based QKD.

QI 6.22 Mon 16:30 Empore Lichthof

Towards quantum communication over intercity optical fiber link — •Ali Hreibi, Ann-Kathrin Kniggendorf, Harald Schnatz, and Stefan Kück — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig

We report on the status of the PTB's work to establish a quantum communication test bed between Braunschweig and Hanover (the "Niedersachsen Quantum Link"). In this context, we present an overview of the quantum key distribution (QKD) system based on the BBM92 protocol set up at PTB and the test of quantum communication via optical fiber up to 90 km in length. The QKD system generates Polarization-entangled photon pairs using the nonlinear optical process of spontaneous parametric down-conversion, and transmits the entangled photon pairs (signal, and idler) to a local and a remote location through the optical fiber. Photons are detected on both sides and measurement data is processed by the system in order to generate a secure quantum encryption key. The Communications security relies on the laws of quantum mechanics and the non-cloning theorem which prevents a quantum state from being copied or measured without disturbing it.

QI 6.23 Mon 16:30 Empore Lichthof

The Ideal Wavelength for Daylight Free-Space Quantum Key Distribution — •Mostafa Abasifard[1], Chanaprom Cholsuk[1], Roberto G. Pousa[2], Anand Kumar[1], Ashkan Zand[1], Daniel K. L. Oi[2], and Tobias Vogl[1,3] — [1]Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, 07745 Jena, Germany — [2]Computational Nonlinear and Quantum Optics, SUPA Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom — [3]Fraunhofer-Institute for Applied Optics and Precision Engineering IOF, 07745 Jena, Germany

Quantum key distribution (QKD) has matured from proof-of-principle demonstrations in the lab to commercial systems. Intercontinental quantum communication distances have been bridged with satellites. Satellite-based quantum links can only operate during the night, as the sunlight would otherwise saturate the detectors used to measure the quantum states. For high data rates and continuous availability, operation during daylight is desirable.

We model a satellite-to-ground quantum channel for the BB84 protocol in order to determine the optimal wavelength for daytime free-space QKD. We look at the 400 nm to 1700 nm wavelength range and find extractable secret bits per signal for several light sources. As expected, the Fraunhofer lines appear as peaks in the spectrum of the secure data rate. For the ideal wavelength, we also propose a true single photon source, based on a resonator coupled color center in hexagonal boron nitride.

QI 6.24 Mon 16:30 Empore Lichthof

Dynamic Polarization State Preparation for Single-Photon Quantum Cryptography — •Koray Kaymazlar, Tim Gao, Daniel Vajner, Lucas Rickert, and Tobias Heindel — Institut für Festkörperphysik, Technische Universität Berlin, 10623 Berlin, Germany

Quantum key distribution (QKD) systems using polarization encoding require fast modulation of the polarization states of single-photon pulses. Here, we present a setup for preparing the polarization of single photons dynamically. The system consists of electronics based on a field programmable gate array (FPGA) and a digital to analog converter (DAC) driving a free space electro optic modulator (EOM) with 500 MHz bandwidth. We characterize and optimize the performance of this setup in terms of extinction ratio and repetition rate and discuss its suitability for applications in QKD experiments.

QI 6.25 Mon 16:30 Empore Lichthof

Investigation of the phase-space distribution of the BPSK-encoded optical coherent signal from a geostationary satellite — •Hüseyin Vural[1], Conrad Rössler[1], Andrew Reeves[2], Bastian Hacker[1], Thomas Dirmeier[1], Karen Saucke[3], and Christoph Marquardt[1] — [1]Max-Planck Institut für die Physik des Lichts (MPL) — [2]Deutsches Zentrum für Luft- und Raumfahrt (DLR) - Institut für Kommunikation und Navigation — [3]Tesat Spacecom

Coherent optical communication between a satellite and a terrestrial ground station can facilitate classical as well as quantum-limited communication. In a recent paper, we demonstrated quantum limited signals from a geostationary satellite in a homodyning measurement, that indicate the viability of long-distance quantum key distribution (QKD) and global secure communication. Here, we investigate the phase-space distribution of the BPSK-encoded coherent signal from the same satellite, however at an optical ground station in an urban area and by heterodyning the quantum signal with a free running commercial laser. Our results indicate that scalable solutions for quantum-limited signals may be in reach.

QI 6.26 Mon 16:30 Empore Lichthof

Single atoms in optical cavities as source for multiphoton graph states — •Leonardo Ruscio, Philip Thomas, Olivier Morin, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Generating multiphoton entangled states is an essential step for the development of quantum information protocols such as measurement based quantum computation. Thanks to their weakly interacting nature, entangled photons are in fact ideal qubit carriers. So far, the most successful source of entangled photons has been spontaneous parametric down conversion, where scaling up is dramatically limited by its intrinsically probabilistic nature. We experimentally demonstrate the feasibility of a single Rubidium atom in an optical cavity as an efficient source of multiphoton graph states [1]. We use the atom as a memory mediating the entanglement generation between the photons and we efficiently grow GHZ states of up to 14 photons and linear cluster states of up to 12 photons. With an overall efficiency of 43%, our experiment opens a way towards scalable measurement-based quantum computation and communication, where this scheme could be for example extended to two atoms in a cavity to generate higher-dimensional cluster states.

[1] P.Thomas et al., Nature 608, 677-681 (2022)

QI 6.27 Mon 16:30 Empore Lichthof

Driven Gaussian Quantum Walks — •Philip Held[1], Melanie Engelkemeier[1], Syamsundar De[1], Sonja Barkhofen[1], Jan Sperling[2], 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, Theoretical Quantum Science, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098, Paderborn, Germany

Quantum walks function as essential means to implement quantum simulators, allowing one to study complex and often directly inaccessible quantum processes in controllable systems. In this contribution, the new notion of a driven Gaussian quantum walk is presented. Here, instead of a unitary operation, a nonlinear map is used to describe the operation of the quantum walk in optical settings. Including nonlinear elements as core components, this type of quantum walk introduces quantumness of the dynamic itself, regardless of the input state. A parametric down-conversion is chosen as the nonlinear operation, introducing new walkers and squeezing during the evolution. To characterize nonlinear, quantum, and quantum-nonlinear effects following from this evolution, a full framework for driven Gaussian quantum walks is developed. In particular, the generation and amplification of highly multimode entanglement, squeezing, and other quantum effects are studied over the duration of the nonlinear walk.

QI 6.28 Mon 16:30 Empore Lichthof

Quantum Simulation of Biased Open System Dynamics —

•Marcel Cech[1], Federico Carollo[1], and Igor Lesanovsky[1,2] — [1]Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany — [2]School of Physics and Astronomy and Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems, The University of Nottingham, Nottingham, NG7 2RD, United Kingdom

We present a protocol for the generation of rare quantum jump trajectories on a digital quantum simulator. Our approach allows to bias open system dynamics with regard to any, even non-linear, function, e.g. it can increase or decrease the likelihood of trajectories with specific emission patterns and correlation properties. We derive the dynamical map of the corresponding biased process. Moreover, we show how the biased open systems dynamics can be implemented on an IBM quantum processor. Using as an example an open two-level system we discuss challenges and current limitations of this approach.

QI 6.29 Mon 16:30 Empore Lichthof

Preparing ground states of the Fermi-Hubbard model with shallow quantum circuits — •Tobias Schmale[1], Bence Temesi[1], Hamed Saberi[1], and Hendrik Weimer[2,1] — [1]Institut für Theoretische Physik, Hannover, Germany — [2]Institut für Theoretische Physik, TU Berlin, Germany

The 2D Fermi-Hubbard model is a paradigmatic model in condensed matter physics, potentially holding the key to understanding high-temperature superconductivity. We turn to digital quantum simulations of the model, as classical simulation methods remain prohibitively challenging. We investigate a strategy for adiabatic preparation of the ground state by shallow quantum circuits running in constant time on a highly parallelized architecture. Additionally, we consider a simplified architecture consisting of a single computing register in a trapped-ion architecture based on ion shuttling, where we find that a single auxiliary qubit is sufficient to implement the mapping from fermions to qubits. We show that these architectures naturally allow for the realization of extensions to the Hubbard model such as next-nearest-neighbor hopping, which might be crucial to stabilize d-wave superconductivity.

QI 6.30 Mon 16:30 Empore Lichthof

Quantum Simulations: Endeavours with trapped ions in a 2D array and a Linear Paul trap — •Apurba Das, Deviprasath Palani, Florian Hasse, Maharshi Pran Bora, Lucas Eisenhart, Tobias Spanke, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, Freiburg, Deutschland

Individual ions, trapped in a customised trap architecture offer one of the most promising platforms for quantum simulations[1]. In our lab, applying suitable local and global control fields on the trapped ions, we set up and tune increasingly complex quantum systems with a high level of control in a 2D array on a Surface electrode radio frequency trap and in a linear Paul trap. In our 2D array, we realize the Floquet-engineered coupling of adjacent sites through local manipulation of trapping potentials[2] and tuning of the system in real-time and interference of coherent states over large amplitudes[3]. Here, we also demonstrate the relocation of ions in a deterministic manner. In the Linear Paul Trap, we show the preparation of two ions in a squeezed state of motion featuring entanglement of the ions' motional degrees. This leads to the realization of an experimental analogue of the particle pair creation during cosmic inflation in the early universe[4]. In addition, we move towards the transfer of entanglement of motional degrees of freedom to internal degree of freedom.

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

QI 6.31 Mon 16:30 Empore Lichthof

Programmable cooling on noisy quantum computers: Implementation and error analysis — •Imane El Achchi[1], Anne Matthies[1], Achim Rosch[1], Mark Rudner[2], and Erez Berg[3] — [1]Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany — [2]University of Washington, Seattle, WA 98195-1560, US — [3]Weizmann Institute of Science, Rehovot, 76100, Israel

Recent advances in quantum computing provide a vast playground for the application of quantum algorithms on noisy intermediate-scale quantum devices. Here, we test the performance of the programmable adiabatic demagnetization protocol proposed in Ref. [1] on IBM's quantum devices. The cooling protocol prepares low-energy states for any gapped Hamiltonian independently of the system's initial state. Half the qubits simulate the system, and the other a bath in a strong Zeeman field, initialized in the polarized state. Entropy is transferred from the system to the bath by slowly decreasing the Zeeman field. Finally, the bath spins are measured and reset to the polarized state. The process is repeated throughout the protocol until a low-energy state of the system is reached. Cooling protocols are generally stable against low noise, making them a promising application for near-term quantum computers. We experimentally observe a cooling effect for the available small system size and limited gate depth on the IBM quantum device using quantum optimal control. Furthermore, we analytically analyze the dynamics of the cooling protocol to find a dark state of the corresponding quantum channel.

[1] arxiv: 2210.17256

QI 6.32 Mon 16:30 Empore Lichthof

Treating finite system-bath coupling using the hierarchy-of-pure-states approach — •Johann Assmus, Tobias Becker, and André Eckardt — Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstrasse 36, 10623 Berlin, Germany

Open quantum system dynamics can be described by master equations for the system's reduced density matrix, however, the derivation of these equations often requires some assumptions like the Born-Markov-approximation. The hierarchy-of-pure-states approach is an alternative to master equations where the system is described by a stochastic ensemble of pure states and additional auxiliary states [1]. Since the dynamics of these pure states can be derived without any approximations, this approach is numerically exact. However, an approximation is made, by allowing for a finite number of auxiliary states. We compare the solutions of this method with the exact dynamics of a damped harmonic oscillator to examine its behaviour in regards to the number of hierarchies and other parameters.

[1] D. Süß, A. Eisfeld, W.T. Strunz, Phys. Rev. Lett. 113, 150403 (2014)

QI 6.33 Mon 16:30 Empore Lichthof

Quantisation and breakdown of topological transport in the Hubbard-Thouless pump — •Marius Gächter, Zijie Zhu, Anne-Sophie Walter, Konrad Viebahn, Stephan Roschinski, Joaquín Minguzzi, Kilian Sandholzer, and Tilman Esslinger — ETH, Zurich, Switzerland

Predicting the fate of topologically protected transport in the strongly correlated regime represents a central challenge within condensed matter physics. On the one hand, free-fermion energy bands and their geometric properties give rise to quantised transport phenomena, such as the quantum Hall effect and its dynamic analogon, the Thouless pump. The quantisation in these systems is considered robust against perturbations that commute with a protecting symmetry. On the other hand, interparticle interactions support strongly correlated states of matter, which often preclude particle transport, exemplified by the Mott transition in the Hubbard model. Will topology prevail in the presence of strong correlations? Here, we systematically probe the response of a topological Thouless pump to Hubbard interactions in an ultracold-atom experiment. We identify three distinct regimes, that is, pair pumping for strongly attractive interactions, quantised pumping for weak and moderate interactions, as well as the breakdown of transport for strong repulsive Hubbard U. Our experiments pave the way for investigating edge effects in interacting topological insulators, as well as interaction-induced topological phases with no counterpart in free-fermion systems.

QI 6.34 Mon 16:30 Empore Lichthof

Switching Topological State via Ferroelectric Polarization Field — •Jiabao Yang and Niels B. M. Schröter — Max-Planck-Institute of Microstructure Physics, Weinberg 2, 06120 Halle(Saale), Germany

The quantum spin hall insulator (QSHI) has shown great potential in low-dissipation spintronics and topological quantum computing, most of which highly rely on the emergency of topological edge state. Two common achieving methods, electric gating and strain effect are both challenging though the former requires continuous energy consumption and the latter needs precise control of strain. Two-dimensional(2D) ferroelectric material (FE), a kind of material with spontaneous and switchable charging polarization, can bring out a controllable topological order of 2D heterostructure when stacked with a heavy-element trivial insulator. The built-in electric field leads to new band alignment of the heterostructure, and band inversion occurs at the conduction band minimum of 2D FE and valence band maximum of TI. With the help of the robust interlayer spin-orbit coupling effect, the band gap can be opened. α-In2Se3, a typical ferroelectric material with a quite large polarizing built-in electric field(1.35eV), is an ideal substrate for monolayer WTe2. What is expected is the new topological state occurs in the van der Waals heterostructure around the gamma point and new non-volatile control of topological states.

QI 6.35 Mon 16:30 Empore Lichthof

Noise-assisted adiabatic quantum search algorithm: a study via quantum trajectories — •Raphaël Menu[1], Christiane P. Koch[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, D-66123 Saarbr *ucken, Germany — [2]Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin, Germany

Adiabatic quantum computing offers a precious alternative to quantum circuits for the implementation of quantum search algorithms. Indeed, while circuits require an oracle, namely a black box, to test whether the algorithm converged towards the target state, adiabatic quantum search algorithms performs the calculation via the adiabatic preparation of the ground state of a simple effective two-level system. Yet, such an approach is not flawless since it requires a large annealing time so that transitions out of the ground state are suppressed, and therefore one may reach time scales when the effects of the environment become relevant.

In this work, we study by the means of the framework of quantum trajectories (Monte Carlo wavefunction) the adiabatic implementation of the Grover search algorithm, and investigate how one can improve the performance of the search via the coupling of the computation qubit to an ancilla, leading to a shortest annealing time and a correction of the computational errors.

QI 6.36 Mon 16:30 Empore Lichthof

Microwave quantum memory based on rare earth doped crystal — •Jianpeng Chen[1,2,3], Ana Strinic[1,2,3], Achim Marx[1,2], Kirill G. Fedorov[1,2], Hans Huebl[1,2,3], Rudolf Gross[1,2,3], and Nadezhda Kukharchyk[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]Physik department, Technische Universität München, 85748 Garching, Germany — [3]Munich Center for Quantum Science and Technology, 80799 Munich, Germany

Quantum memory is essential in future quantum technologies, such as quantum computing circuits and quantum communication links. Specifically, Crystals doped with rare earth ions are promising competitive candidates due to their long coherence times [1] and potential multiplexing capability [2]. Here, we use a transmission line to couple microwave signals to rare earth ion dopants in yttrium orthosilicate crystals (Y2SiO5) at 10 mK. We present experimental results on storing coherent microwave states using the spin echo protocol. We will discuss the resulting coherence time and the impact of the transmission line design on the efficiency of the quantum information storage and its multimodality potential. We acknowledge financial support from the Federal Ministry of Education and Research of Germany (project number 16KISQ036). [1] Zhong, M, Nature 517, 177*180 (2015). [2] Antonio Ortu et al.Quantum Sci. Technol. 7 035024 2022.

QI 6.37 Mon 16:30 Empore Lichthof

Towards on-chip microwave-to-telecom transduction based on erbium-doped silicon — •Daniele Lopriore[1,2] and Andreas Reiserer[1,2] — [1]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany — [2]TU München and Munich Center for Quantum Science and Technology, 85748 Garching, Germany

The development of a device that converts microwave to optical photons at a telecommunication wavelength would be a key enabler for the communication between remote quantum computers. In this context, we are investigating erbium ensembles doped into nanophotonic silicon waveguides. This novel hardware platform features a unique combination of a small inhomogeneous broadening and an exceptional optical coherence even in nanostructured materials [1]. In an external magnetic field, the ground and excited states are split into doublets, which allows the erbium ensemble to act as the nonlinear medium mediating an efficient conversion process [2,3]. To this end, we plan to enhance both the microwave and the telecom transitions with resonators of high quality factor, fabricated on the same silicon chip. By optimizing the resonator geometries in order to maximize the overlap between the resonating fields and the erbium dopants, we aim to achieve transduction efficiencies approaching unity [3]. This would pave the way for the entanglement of superconducting qubits in remote cryostats.

[1] A. Gritsch, et al. Phys.Rev.X 12, 041009 (2022).
[2] L. Williamson, et al. Phys.Rev.Lett. 113, 203601 (2014).
[3] C. O'Brien, et al. Phys.Rev.Lett. 113, 063603 (2014).

QI 6.38 Mon 16:30 Empore Lichthof

Towards an efficient Quantum Network - Silicon Vacancy Color Centers in Diamond — •Donika Imeri[1,2], Tuncay Ulas[1], Sunil Kumar Mahato[1,2], and Ralf Riedinger[1,2] — [1]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg

Quantum networks combine a high level of security and the ability to scale up the qubit number which is crucial for quantum information processing. These networks contain nodes that store information. Quantum communication can be enabled by linking these nodes via entanglement. Silicon vacancy color centers in diamonds are promising components for optically connected quantum processors. The point defects establish an efficient optical interface and display a protective inversion symmetry. Therefore, the incorporation of nanophotonic structures, as well as coherent resonators, is possible. This can be used to generate entanglement between spin and photonic qubits. Long coherence times are a benefit, however, this includes the challenge of working in a cryogenic environment. Here, we present a platform to generate efficient and secure quantum communication by connecting multiple quantum processors.

QI 6.39 Mon 16:30 Empore Lichthof

Towards active stabilization of magnetic fields for trapped ions — •Lucas Eisenhart, Deviprasath Palani, Fabian Thielemann, Florian Hasse, Apurba Das, Ulrich Warring, Tobias Spanke, and Tobias Schaetz — Physikalisches Institut, Freiburg, Deutschland

When experimenting with trapped ions, it can be of great importance to generate magnetic fields that are highly stable, for example, when exploiting the electron degree of freedom in quantum applications. For this we characterize magnetic field sensors, with the help of which we may be able to adapt the coil current in our experiments to reduce field fluctuations. For magnetic field amplitudes in a range from 0.1G to 10^5G we use a Hall sensor with a sensitivity of 0.02mV/G and and a bandwidth that reaches up to 200kHz. For smaller magnetic field amplitudes in a range from 60μG to 10G we use a fluxgate sensor module that has a sensitivity of 1V/G and a bandwidth of up to 1kHz. We present our benchmark results of the hall- and fluxgate-sensor within our test environment.

QI 6.40 Mon 16:30 Empore Lichthof

High-order series expansions and crystalline structures for Rydberg atom arrays — •Duft Antonia, Jan Koziol, Matthias Mühlhauser, Patrick Adelhardt, and Kai Phillip Schmidt — Friedrich-Alexander-Universität Erlangen-Nürnberg

We investigate a model of hardcore bosons on the links of a Kagome lattice subject to a long-range decaying van-der-Waals interaction. This model is known to be the relevant microscopic description of Rydberg atom arrays excited by a detuned laser field which has been realized in experiments recently. Particular interest lies on this system as it is an engineerable quantum platform which has been predicted to to host a topological phase. We investigate the quantum phase diagram for different limiting cases with a main focus on the low interaction-strength limit where we apply high-order linked cluster expansions.

QI 6.41 Mon 16:30 Empore Lichthof

Numerical investigation of the Ising model in a light-induced quantized transverse field — •Anja Langheld and Kai Phillip Schmidt — Lehrstuhl für Theoretische Physik I, Staudtstraße 7, Friedrich-Alexander Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

We investigate the Ising model in a light-induced quantized transverse field [1] with a particular focus on antiferromagnetic, potentially frustrated Ising interactions. Using exact diagonalization, we provide data for the antiferromagnetic chain in a longitudinal field that is inconsistent with earlier results coming from mean-field considerations [2]. In order to study the model on frustrated, two-dimensional lattice geometries, we extend the mean-field calculation and develop a quantum Monte Carlo update based on the recently introduced wormhole update [3], for which the photons are integrated out. By this means, the photons induce a retarded spin-spin interaction in imaginary time that is also non-local in space in contrast to the Ising interaction inherent to the model.

[1] J. Rohn et al., Phys. Rev. Research 2, 023131 (2020)
[2] Y. Zhang et al., Sci Rep 4, 4083 (2014)
[3] M. Weber et al., Phys. Rev. Lett. 119, 097401 (2017)

QI 6.42 Mon 16:30 Empore Lichthof

Luttinger's Theorem in the One-Dimensional tJ-model — •Annika Böhler[1,2], Henning Schlömer[1,2], and Fabian Grusdt[1,2] — [1]Ludwig-Maximilians University, Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany

The Hubbard model in one dimension is known to exhibit spin charge separation, which has recently been observed in settings of ultracold fermions in optical lattices. Another signature of spin-charge separation in a lattice, that has not been directly observed thus far, is constituted by a change of the Fermi momentum. Luttinger's theorem relates the volume of the Fermi surface - and therefore the Fermi momentum - to the underlying particle density of the system. Here we discuss a proof of the theorem [M. Oshikawa, Phys. Rev. Lett. 84 (2000), 3370] in the presence of spin charge separation and evaluate whether it provides a tool to distinguish between qualitatively distinct spin-1/2 liquids and spinless chargon liquids via their different Fermi momenta. We show that Friedel oscillations of the density at the edge of a system can be used to directly observe the change of Fermi momentum, reflecting a qualitative change in the nature of charge carriers which we associate with an emergent U(1) symmetry corresponding to the total number of holes in the large-U limit of the Hubbard model.

QI 6.43 Mon 16:30 Empore Lichthof

Guided variational quantum algorithm for time evolution in dynamical mean field theory — •Stefan Wolf[1], Michael J. Hartmann[1], and Martin Eckstein[2] — [1]Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg — [2]I. Institute of Theoretical Physics, Department of Physics, University of Hamburg

Dynamical mean-field theory (DMFT) is a useful tool to treat models of strongly correlated fermions like the Hubbard model. The lattice of the model is replaced by a single-impurity site embedded in an effective bath. The resulting single impurity Anderson model (SIAM) can then be solved self-consistently with a quantum-classical hybrid algorithm. This procedure involves repeatedly preparing the ground state on a quantum computer and evolving it in time. We propose an approximation of the time evolution operator by a Hamiltonian variational ansatz. The parameters of the ansatz are obtained via a variational quantum algorithm that utilizes a small number of Trotter steps, given by the Suzuki-Trotter expansion of the time evolution operator, to guide the evolution of the parameters. The cost function is evaluated by measuring a single ancilla qubit using the Hadamard test, thus reducing the required number of measurements compared to other approaches. The resulting circuit for the time evolution is shallower than a comparable Suzuki-Trotter expansion. We show results for two-site DMFT with half-filling. We further looked into the possibility to extend the approach for the impurity model with more than one bath site and away from half-filling.

QI 6.44 Mon 16:30 Empore Lichthof

Measurement Induced State Preparation — •Daniel Alcalde Puente — PGI8, Wilhelm-Johnen-Straße 52428 Jülich

This work explores the protocol proposed in (Roy, Sthitadhi, et al. "Measurement-induced steering of quantum systems." Physical Review Research 2.3 (2020): 033347) for state preparation outside of the Lindblad limit. In this protocol, a system is coupled to ancillas with a time-independent Hamiltonian, with the ancillas being periodically reset. The protocol exploits the frustration-free nature of the parent Hamiltonian, enabling the writing of local operators that map from locally excited states to locally unexcited states. The full dynamics of this protocol are simulated using Matrix Product States and quantum trajectories, and the behavior of the protocol is analyzed for different measurement intervals. In particular, our study explores the case of preparing the spin-1 Affleck-Kennedy-Lieb-Tasaki state and discusses the protocol's resilience to errors. The results show that the dynamics of the protocol match the dynamics of the Lindblad limit for relatively large measurement intervals, that the optimal measurement interval is close to the expected ideal measurement interval, and that the protocol converges even for large measurement intervals, though only slowly.

QI 6.45 Mon 16:30 Empore Lichthof

Portfolio Optimization using a Quantum Computer — •Matthias Hüls and Daniel Braun — Institut für Theoretische Physik, Eberhard Karls Universität Tübingen, Deutschland

Entering the era of Noisy Intermediate-Scale Quantum (NISQ) devices, hopes are raising to already make practical use of the existing quantum processors. While deep algorithms still fail on the error prone hardware, variational algorithms show error resilience to some extend. This makes them well suited for the NISQ technology. Therefore, popular candidates like the Quantum Approximate Optimization Algorithm (QAOA), designed to solve combinatorial optimization problems, attracted much attention in recent years. In a case study, we benchmark the performance of the QAOA for the portfolio optmimization problem. We focus on how the characteristics of a given problem instance influence the algorithms performance and deduce a criterion for distinguishing between 'easy' and 'hard' instances.

QI 6.46 Mon 16:30 Empore Lichthof

Performance of Grover's Algorithm on IBM Quantum Processors — •Yunos El Kaderi[1,2], Andreas Honecker[1], and Iryna Andriyanova[2] — [1]LPTM UMR CNRS 8089, CY Cergy Paris Université, France — [2]ETIS UMR CNRS 8051, CY Cergy Paris Université, France

This work tests the performance of Grover search circuits on the available IBM superconducting quantum devices that are accessible on the IBMQ cloud. Ideally, we expect to get a probability distribution that is clearly peaked at the targeted state. However, the quantum circuit executed on NISQ devices is vulnerable to noise which leads to fluctuations in the expected results. This depends on the quality of the device which is defined by a Quantum Volume parameter and on the depth of the circuit. Some previous works reached results that are completely noisy with no useful information, see for example Ref. [1] for 4 qubits (16 elements). Here we show that suitable implementations on concurrent IBMQ devices can actually yield useful results and explore the limitations.

[1] Y. Wang, P.S. Krstic, Phys. Rev. A **102**, 042609 (2020)

QI 6.47 Mon 16:30 Empore Lichthof

QVLS Q1 supporting experiment for development of techniques for ion transport and sympathetic cooling — •Christian Joohs[1,2], Markus Duwe[1,2], Yannick Hermann[1,2], Ludwig Krinner[1,2], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]PTB, Bundesallee 100, 38116 Braunschweig

Within the ongoing development of the ion-based quantum computer Q1 carried out by QVLS (**Q**uantum **V**alley **L**ower **S**axony), a supporting experiment is being built and used for research and development of transport and cooling techniques. The trap is experimentally realised by a surface electrode Paul trap, which allows movement of trapped ions in a two-dimensional space above the trap. This possibility is used to realise the computer in a register-like fashion (termed QCCD architecture [1,2]) by having different zones on the trap chip that account for different tasks including storage, readout, and quantum logic gate application. A key aspect therefore is the development of ion transport techniques between said zones while maintaining a low heating rate and without interruption of the ion's electronic quantum state. Furthermore, we study the possibility to sympathetically cool two logic ions with a single cooling ion of significantly heavier mass. We report on previous progress and goals.

[1] D.J. Wineland *et al.*, J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)
[2] D. Kielpinski, C. Monroe, and D. J. Wineland, Nature **417**, 709 (2002)

QI 6.48 Mon 16:30 Empore Lichthof

Towards a fault tolerant microwave-driven two qubit quantum processor — •Markus Duwe[1,2], Hardik Mendpara[1,2], Nicolas Pulido-Mateo[1,2], Ludwig Krinner[1,2], Giorgio Zarantonello[3], Amado Bautista-Salvador[1,2], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover — [2]Physikalisch-Technische Bundesanstalt, Braunschweig — [3]National Institute of Standards and Technology, Boulder, USA

A universal quantum gate set can be realized by the combination of single-qubit gates and one entangling operation. In this work, we realize such a gate set using the microwave near field approach [1]. We trap two 9Be+ ions in a radio-frequency surface electrode trap and perform the quantum logic operations with embedded microwave conductors. The individual qubits are addressed by micromotion sidebands [2] and the entangling gate is performed via a Mølmer-Sørensen type interaction. We approach an infidelity of 10^{-4} with single qubit gates and 10^{-3} with entangling gates using partial tomography [3]. We report on challenges and solutions for further improving the gate fidelities and to characterize gate errors.

[1] C. Ospelkaus *et al.*, Phys. Rev. Lett. **9**, 090502 (2008)
[2] U. Warring *et al.*, Phys. Rev. Lett. **17**, 173002 (2013)
[3] M. Duwe *et al.*, Quantum Sci. Technol. **7**, 045005 (2022)

QI 6.49 Mon 16:30 Empore Lichthof

Next generation platform for implementing fast gates in ion trap quantum computation — •Donovan Webb, Sebastian Saner, Oana Bazavan, Mariella Minder, and Christopher Ballance — University of Oxford

Scalable trapped-ion quantum computation relies on the development of high-fidelity fast entangling gates in a many ion crystal. Conventional geometric phase gates either suffer from scattering errors or off-resonant carrier excitations. A potential route to achieve fast entanglement is creating a standing wave which can suppress the unwanted carrier coupling [Mundt 2003].

We present the roadmap to our next-generation platform tailored for fast gates in the ~1μs regime where gate speeds become comparable to the secular trap frequency. The quadrupole transitions between S1/2 and D5/2 levels in Calcium 40 will be driven to perform Molmer-Sorenson gates with a standing wave rather than a typical travelling wave. The off-resonant carrier excitation may be strongly suppressed by placing ions at the nodes of the optical lattice. This new platform has scope for a multi-ion chain and a corresponding array of optical lattices which each address a single ion. The lattice array is created by a set of counter-propagating beams which are tightly focused by a symmetric setup of high-NA lenses. Control of the optical phase at the ion site will be achieved by actively stabilising the counter-propagating beam interferometer and feedbacking on the ion signal.

QI 7: Quantum Technologies: Color Centers I (joint session Q/A/QI)

Time: Monday 17:00–19:00 Location: F342

QI 7.1 Mon 17:00 F342

NMR-fingerprinting of biomolecules on the picoliter level — •Nico Striegler, Thomas Unden, Jochen Scharpf, Stephan Knecht, Christophoros Vassiliou, Jochen Scheuer, Michael Keim, John Blanchard, Martin Gierse, Mohammad Usman Qureshi, Ilai Schwartz, and Philipp Neumann — NVision Imaging Technologies GmbH

A standard method for diagnostics and analytics is nuclear magnetic resonance (NMR). Conventional NMR only function well for large enough samples and is inherently limited by the low thermal spin polarisation. The combination of nuclear spin hyperpolarisation with a microscale quantum sensor enables study of metabolism on the single-cell level. This can be used for evaluating the treatment effectiveness from tumor biopsies using only a few cells. In this study the combination of a Nitrogen-Vacancy-based quantum sensor and a hyperpolarized Fumarate solution enables heteronuclear magnetic resonance spectroscopy of liqudis in picoliter volumes. The NMR probe is based on an ensemble of negatively charged Nitrogen-Vacancy (NV) centers in a ten micrometer thick diamond layer. Hyperpolarization of the solution is based on parahydrogen induced polarization (PHIP) methods, which is done in house and then transferred to the detection volume of the quantum sensor. Microwave pulse sequences brings the NV electron spins into adjustable frequencies for detection of AC magnetic fields generated by the nuclear spins of interest.

QI 7.2 Mon 17:15 F342

Impact of Charge Conversion on NV-Center Relaxometry — •Isabel Barbosa, Jonas Gutsche, and Artur Widera — Physics Department and State Research Center OPTIMAS, RPTU Kaiserslautern, Erwin-Schroedinger-Str. 46, 67663 Kaiserslautern, Germany

Relaxometry schemes employing nitrogen-vacancy (NV) centers in diamonds are essential in biology and physics to detect a reduction of the color centers' characteristic spin relaxation (T_1) time caused by, e.g., paramagnetic molecules in proximity. However, while only the negatively-charged NV center is to be probed in these pulsed-laser measurements, an inevitable consequence of the laser excitation is the conversion to the neutrally-charged NV state, interfering with the result for the negatively-charged NV centers' T_1 time or even dominating the response signal. In this work, we perform relaxometry measurements on an NV ensemble in nanodiamond combining a 520 nm excitation laser and microwave excitation while simultaneously recording the fluorescence signals of both charge states via independent beam paths. Correlating the fluorescence intensity ratios to the fluorescence spectra at each laser power, we monitor the ratios of both charge states during the T_1 measurement and systematically disclose the excitation-power-dependent charge conversion. Even at laser intensities below saturation, we observe charge conversion, while at higher intensities, charge conversion outweighs spin relaxation. These results underline the necessity of fluorescence normalization during the measurement to accurately determine the T_1 time and characterize paramagnetic species close to the sensing diamond.

QI 7.3 Mon 17:30 F342

SiV center in nanodiamonds as a potential source for a hybrid quantum network node — •Marco Klotz[1], Richard Waltrich[1], Niklas Lettner[1], Lukas Antoniuk[1], Viatcheslav Agafonov[2], and Alexander Kubanek[1] — [1]Institut für Quantenoptik, Universität Ulm — [2]Universite Francois Rabelais de Tours

Combining conventional photonic systems with the good optical and spin properties of group IV defects in diamond puts a platform for quantum technologies into reach. Here, we present measurements of characteristic properties of SiV centers in nanodiamond in comparison with bulk diamond. This reveals key benefits of a nanostructured defect host for future integration into photonic-enhancing structures, e.g. cavities.

QI 7.4 Mon 17:45 F342

Vector Magnetometry Based on Polarimetric Optically Detected Magnetic Resonance — Philipp Reuschel[1], Mario Agio[1,2], and •Assegid M. Flatae[1] — [1]Laboratory of Nano-Optics, University of Siegen, Siegen (Germany) — [2]National Institute of Optics (INO), National Research Council (CNR), Sesto Fiorentino (Italy)

Vector magnetometry has various applications in navigation systems, spintronics and life sciences. So far, different sensitive magnetic field sensors exist, for example, superconducting quantum interference devices and alkali vapor cells magnetometers. However, they suffer from high technical complexity and low spatial resolution. Recently, negatively charged nitrogen-vacancy (NV-) color centers in diamond have been developed as sensitive magnetic field sensors based on the optically detected magnetic resonance (ODMR). However, these approaches require knowledge of the crystal axes and need an external magnetic bias field or they rely on the use of single NV- centers. Recently, by combining ODMRs of ensembles of NV- color centers with polarimetry, we have been able to determine the magnitude and direction of an unknown magnetic field [1]. A longitudinal laser polarization component enables the unequivocal distinction of the four crystal axes containing NV- centers, allowing high sensitivity and robust vector magnetometry without a bias field. Our approach is general for other spin-1 color centers with C3v symmetry, and it is compatible with standard microscopy methods. Reference [1] P. Reuschel, M. Agio, A. M. Flatae, Adv. Quantum Technol. 2200077 (2022).

QI 7.5 Mon 18:00 F342

Coherent optical spectroscopy on ensembles of Silicon-vacancy color centers in diamond — •Anna Fuchs and Christoph Becher — Universität des Saarlandes, Saarbrücken 66123, Germany

Spectral hole burning (SHB) and coherent population trapping (CPT) are important techniques both in spectroscopy to characterize an ensemble of emitters in terms of their coherence times and in coherent control experiments to realize e.g. quantum memories or sensors. Single negatively charged silicon-vacancy (SiV^-) color centers in diamond are of the leading candidates for qubit systems in quantum communication [1] based on their long spin coherence and narrow optical emission lines. In addition, ensembles of SiV centers show strong coherent light-matter interaction [2], enabling applications as Raman-based optical quantum memories or for realizing single photon nonlinearities. However, the spin coherence of SiV ensembles so far remains unexplored. In this talk, we report our results of SHB and CPT measurements on two different SiV^-- ensembles in an external magnetic field. The SHB measurements reveal in both samples an additional narrow resonance of a few MHz linewidth, which we attribute to coherent population oscillations (CPO) due to the beat frequency between the two independent input laser fields. The CPT measurements allow us to determine the Zeeman splittings not resolvable in excitation or emission spectroscopy due to inhomogeneous line broadening.

[1] Stas et al., Science 378, 557 (2022)
[2] Weinzetl et al., Phys. Rev. Lett. 122, 063601 (2019)

QI 7.6 Mon 18:15 F342

Probing the Orbital Coherence of a Tin-Vacancy Center in a Diamond Nanopillar via Coherent Population Trapping — •Cem Güney Torun[1], Joseph H. D. Munns[1], Franziska M. Herrmann[1], Gregor Pieplow[1], Tommaso Pregnolato[1,2], and Tim Schröder[1,2] — [1]Humboldt-Universität zu Berlin, Department of Physics, Berlin, Germany — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany

Tin-vacancy color center in diamond (SnV) has gained much attention in recent years as a promising spin-photon interface. This is mainly due to its excellent optical properties resulting from the inhibited first-order coupling to external electric fields via DC Stark Shifts [1] and millisecond spin coherence through decreased phononic coupling by the large ground state splitting of 850 GHz [2]. Here, we analyze the coherence properties of the ground state orbital levels under zero magnetic field. This is implemented via a coherent population trapping experiment where two optical transitions in a lambda scheme are simultaneously driven and a reduction in the fluorescence signal is observed. Working in the spectral domain enables the extraction of a rapid 5 ps phononic decay time after analyzing the data; showing that the orbital degree of freedom is not particularly suitable for most quantum information processing applications. Finally, implications of orbital coherence times on the spin levels are considered. These experiments lay the basis for the coherent control of SnV spin states.

[1] J. Görlitz, et al. *npj Quan. Inf.* 8.1 (2022): 1-9.
[2] R. Debroux, et al. *Phy. Rev. X* 11.4 (2021): 041041.

QI 7.7 Mon 18:30 F342

Optical Microcavity with Coupled Single SiV- Centers in a Nanodiamond for a Quantum Repeater Platform — •Robert Berghaus[1], Gregor Bayer[1], Selene Sachero[1], Andrea B Filipovski[1], Lukas Antoniuk[1], Niklas Lettner[1], Richard Waltrich[1], Marco Klotz[1], Patrick Maier[1], Viatcheslav Agafonov[2], and Alexander Kubanek[1] — [1]Institute for Quantum Optics, Ulm University, Germany — [2]Tours University, France

A quantum repeater node requires a long-lived memory that can be addressed coherently. Additionally, efficient writing and reading of quantum states with high rates are crucial. Optical cavities can be used as spin-photon platforms to accomplish such requirements. By coupling silicon vacancy defect centers (SiV-) in a nanodiamond to an open Fabry-Pérot cavity, our work paves the way for a light-matter interface with efficient coherent control. Our fully tunable cavity formed by two Bragg mirrors allows short cavity lengths down to $\approx 1\mu$m and provides efficient coupling of the quantum emitter at liquid helium temperatures.
Here, we perform photoluminescence measurements of SiV- centers and power-dependent photoluminescence excitation of single SiV centers by collecting the cavity modulated sideband. We observe spectrally stable emitters and measure a linewidth close to the Fourier limit below $\Delta\nu = 200$ MHz. With the Purcell-enhanced cavity signal we demonstrate coherent optical driving and access the electron spin all-optical in a strong external magnetic field. The electron spin can be initialized within 67 ns and a lifetime of 350 ns is reached.

QI 7.8 Mon 18:45 F342

Entanglement in a disordered chain of coupled qubits — •Alexander Michael Minke[1], Edoardo Carnio[1,2], and Andreas Buchleitner[1,2] — [1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104, Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104, Freiburg, Germany

Nitrogen-Vacancy (NV) centers in diamond are promising candidates for quantum computation due to their long coherence times. However, the robust implementation of scalable quantum registers composed of suitably coupled NV centers remains a challenge, due to limited control of their assembly. We therefore investigate the entanglement properties of arrays of dipole-coupled NV centers, the robustness of these properties against positional disorder and the dependence of the registers' resilience on their size. We find that, for chains with an even number of components, some manifolds of eigenstates show resilient entanglement properties when scaling up the system.

QI 8: Quantum Communication I (joint session Q/QI)

Time: Monday 17:00–19:00 Location: F442

QI 8.1 Mon 17:00 F442

Eavesdropper location inside quantum channel using nonlinear optics — •Alexandra Popp[1,2], Birgit Stiller[1,2], and Christoph Marquardt[1,2] — [1]Max Planck Institute for the Science of Light (MPL), Erlangen, Germany. — [2]Department of Physics, University of Erlangen-Nürnberg (FAU), Erlangen, Germany.

Secure communictation is highly important in today's information age. Quantum key distribution uses the laws of quantum mechanics to offer secure key exchange between two parties. A key feature of this is the notice of eavesdropping through changes to the quantum bit error rate or excess noise of the quantum channel. Once the eavesdropper is detected, it however needs to be localized and removed from the communication channel. In a quantum channel, this can be especially challenging. We present a novel idea for localizing eavesdroppers on the cm level within quantum as well as classical communication channels using localized acoustic waves created by a correlation-based technique. Amongst other interception techniques, we show that our setup is capable of detecting interception by evanescent outcoupling with as low as 1% outcoupling.

QI 8.2 Mon 17:15 F442

Hacking QKD Sender Electronics Using Deep Learning — •Adomas Baliuka[1,2], Markus Stöcker[1,2], Michael Auer[1,2,3], Peter Freiwang[1,2], Harald Weinfurter[1,2,4], and Lukas Knips[1,2,4] — [1]Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 München — [2]Munich Center for Quantum Science and Technology, 80799 München — [3]Universität der Bundeswehr, 85577 Neubiberg — [4]Max-Planck-Institut für Quantenoptik, 85748 Garching

Quantum key distribution (QKD) promises provably secure communication. However, the proofs make assumptions which have to be met carefully in practical implementations. Violations of the assumptions open up *side channels*, which enable an eavesdropper to obtain secret information. For a QKD sender, imperfections in quantum state preparation can lead to *quantum side channels* by encoding secret information in degrees of freedom (e.g., frequency, spatial mode) not protected by the QKD protocol. On the other hand, information can also leak via *classical side channels*, such as acoustic vibrations or classical electromagnetic emissions.

We analyze electromagnetic emissions from the electronics of our home-built BB84 QKD sender at a distance of a few centimeters. We are able to extract virtually all information about the secret key using a neural network and even observe traces of electromagnetic radiation at distances of up to a few meters. We discuss countermeasures and evaluate a revised electronics design, showing a significant reduction of emissions and attack performance.

QI 8.3 Mon 17:30 F442

Atomic arrays based on optical tweezers at the center of an optical cavity — •Lukas Hartung, Matthias Seubert, Stephan

Welte, Emanuele Distante, and Gerhard Rempe — Max-Planck Institut für Quantenoptik, Hans-Kopfermann-Str.1, 85748 Garching

Future quantum networks require multi-qubit network nodes that are capable to manipulate and process quantum information locally and distribute entanglement over the entire network. Therefore, a variety of fundamental qubit-operations and quantum gates are necessary and were already demonstrated, e.g. single qubit-rotations, local [1] and remote qubit-gates [2] and efficient atom-photon entanglement [3]. However, scaling up to many qubits at one node remains an outstanding challenge.

In this talk, we present the generation of arrays of rubidium 87 atoms in an optical cavity. The atoms are loaded and trapped in an optical lattice probabilistically and are then rearranged within the lattice with the help of optical tweezers. In this way, we increase the rate of generation of atomic arrays by orders of magnitudes and, in principle, preserve the capabilities already demonstrated in the past.

[1] Welte, Stephan, et al., Photon-Mediated Quantum Gate between Two Neutral Atoms in an Optical Cavity, Phys. Rev. X 8, 011018 (2018)

[2] Daiss, Severin, et al., A quantum-logic gate between distant quantum-network modules, Science 371, 614 (2021)

[3] Thomas, Philip, et al., Efficient generation of entangled multiphoton graph states from a single atom, Nature 608, 677-681 (2022)

QI 8.4 Mon 17:45 F442

Quantum communication protocols over a 14 km urban fiber link — •Stephan Kucera, Elena Arenskötter, Christian Haen, Jonas Meiers, Tobias Bauer, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

The application of existing telecom-fiber infrastructure for quantum communication protocols enables efficient development of quantum networks [1]. It also entails multiple challenges, since existing infrastructure in an urban region is often underground, or paired with the electrical overhead power line.

We report on the implementation of entanglement distribution and quantum-state teleportation over a 14 km polarization-stabilized urban dark-fiber link, which is partially underground, partially overhead, and patched in several stations. Using a type-II cavity-enhanced SPDC photon-pair source, a $^{40}Ca^{+}$ single-ion quantum memory whose transition matches the source, and quantum frequency conversion to the telecom C-band of one photon of a pair [2], we demonstrate photon-photon entanglement, ion-photon entanglement, and teleportation of a qubit state from the ion onto the remote telecom photon, all realized over the urban fiber link.

[1] H. Kimble, Nature 453, 1023*1030 (2008)

[2] E. Arenskötter et al., arXiv:2211.08841 (2022)

QI 8.5 Mon 18:00 F442

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 Kopff[3], René Berlich[3], Matthias Goy[3], Daniel Rieländer[3], Fabian Steinlechner[3], Florian Kanitschar[4,5], 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.

QI 8.6 Mon 18:15 F442

Atom-Photon Entanglement over 101 km Telecom Fiber — •Yiru Zhou[1,2], Pooja Malik[1,2], Florian Fertig[1,2], Matthias Bock[3], Tim van Leent[1,2], 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

The crucial task for future quantum networks is to share entanglement over large distances. For that, quantum systems are required which provide an efficient light-matter interface, long coherence times and the possibility to connect to low-loss quantum channels.

Here we present the distribution of entanglement between an atom and a photon. Spontaneous emission of a photon at 780 nm from a single, trapped Rb-87 atom is employed to obtain entanglement between the polarization of the photon and the respective Zeeman state of the atom. Raman state transfer is used to change the encoding of the atomic qubit in a combination of F=1 & F=2 hyperfine states [1]. The reduced sensitivity to magnetic fields enables one to increase the coherence time to 7 ms. Together with efficient polarization-preserving quantum frequency conversion to telecom wavelengths minimizing the photon loss [2], we demonstrate the distribution of atom-photon entanglement over 101 km telecom fiber with a fidelity ≥70.8%.

[1] M. Körber et al., Nat. Photonics 12, 18 (2018)

[2] T. van Leent et al., Nature 607, 69-73 (2022)

QI 8.7 Mon 18:30 F442

A 3km free-space link in the munich quantum network — •Michael Auer[1,2,3], Adomas Baliuka[1,2], Fabian Farina[3], Peter Freiwang[1,2], Swantje Kastrup[3], Hedwig Körfgen[3], Hanns Zimmermann[3], Nils gentschen Felde[3], Lukas Knips[1,2,4], Udo Helmbrecht[3], 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 paired with underlying infrastructure and proper key management.

The MuQuaNet aims to build, test and operate a secure quantum communication network with multiple nodes by employing a heterogeneous framework using various manufacturers and provide this network as a transparent service to other institutes, authorities and offices.

Here, we focus on a 3km optical free-space link using a small-size, low-power, FPGA-controlled decoy-state BB84 QKD sender operating at 850nm and 100MHz. With a modulated 1550nm beacon laser, active beam stabilization using two fast steering mirrors, synchronization as well as classical communication is achieved. This will show how to integrate individual QKD links into a network or key management solution and will yield insights to long-term effects and maintainability of QKD devices outside a well controlled environment.

QI 8.8 Mon 18:45 F442

Development and characterization of a high-rate receiver for satellite-based QKD — •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-Universität Erlangen-Nürnberg, Staudstr. 7/A3, 91058 Erlangen, Germany

Since the famous BB84 protocol was proposed in 1984, QKD has evolved to a very mature and promising quantum technology. While classical communication is being threatened by the approach of quantum computers, QKD offers an information theoretical secure way to share a key between two parties. Our high-rate receiver is designed and tested for phase-encoded satellite-based QKD. We present the corresponding discrete variable QKD protocol as well as the concept and characterization of our photon-detection-based phase locking and time synchronization of sender and receiver.

QI 9: Photonic Quantum Technologies (joint session Q/QI)

Time: Tuesday 11:00–13:00 Location: A320

QI 9.1 Tue 11:00 A320

Fluorescence Excitation of Quantum Dots by Entangled Two-Photon Absorption — •Tobias B. Gäbler[1,2], Patrick Hendra[1,2], Nitish Jain[1], Erik Prenzel[1], and Markus Gräfe[1,2,3] — [1]Fraunhofer Institute of Applied Optics and Precision Engineering IOF, Albert-Einstein-Straße 7, D-07745 Jena, Germany — [2]Friedrich-Schiller-Universität Jena, Abbe Center of Photonics, Max-Wien-Platz 1, D-07745 Jena, Germany — [3]Technische Universität Darmstadt, Institute of Applied Physics, Hochschulstraße 6, D-64289 Darmstadt, Germany

Fluorescence excited by absorption of entangled light becomes a prominent candidate to tackle the challenges in the state-of-the-art two-photon imaging techniques, such as the requirement of bright excitation light and fast photobleaching. However, due to the low brightness of entangled photon pair sources used in most studies, fluorescence measurements were not feasible.

Our work addresses this issue by optimization of several experimental parts. Initially, a setup of an efficient entangled photon pair source based on nonlinear waveguides was assembled. Secondly, quantum dots were used to maximize the absorption cross sections and thus the probability to detect fluorescence photons. Additionally, we performed coherence measurements to observe influences of single-photon effects.

Our measurements of fluorescence demonstrate that obstacles like disruptive single-photon effects or insufficient photon pair rates can be handled. These results represent the next step towards an experimental realization of entangled light fluorescence microscopy.

QI 9.2 Tue 11:15 A320

Nonclassical states of light via high harmonic generation in semiconductors — •René Sondenheimer[1], Ivan Gonoskov[2], Christian Hünecke[2], Daniil Kartashov[3], Ulf Peschel[4], and Stefanie Gräfe[1,2] — [1]Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Strasse 7, 07745 Jena, Germany — [2]Institute of Physical Chemistry, Friedrich Schiller University Jena, Helmholtzweg 4, 07743 Jena, Germany — [3]Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, Max-Wien-Platz 1, 07743 Jena, Germany — [4]Institute of Solid State Theory and Optics, Friedrich Schiller University Jena, Max-Wien-Platz 1, 07743 Jena, Germany

I will discuss the generation of higher-order harmonics from a quantum optics perspective via the interaction of a semiconductor with a coherent pump field focusing on the regime where strong-field intraband excitations dominate. While the fundamental mode undergoes intricate but sufficiently mild modifications due to nonlinear interactions, the harmonic modes can be described by coherent displacements depending on the position quadrature component of the driving laser field within our approximations. Similar to high-harmonic generation in atoms, all radiation field modes are entangled, allowing for potential novel protocols for quantum information processing with high photon numbers over a large range of frequencies.

QI 9.3 Tue 11:30 A320

Interfacing a quantum memory based on warm atomic vapour with single photons from a semiconductor quantum dot — •Benjamin Maass[1,2,3], Avijit Barua[3], Norman Vincenz Ewald[2], Leon Messner[1,2,3], Jin-Dong Song[4], Stephan Reitzenstein[3], and Janik Wolters[2,3] — [1]Optische Systeme, Humboldt Universität zu Berlin, Germany — [2]German Aerospace Center (DLR), Institute of Optical Sensor Systems, Berlin, Germany — [3]Institut für Festkörperphysik, Technische Universität Berlin, Germany — [4]Center for Opto-Electronic Materials and Devices, Korea Institute of Science and Technology, Korea

The complexity of modern quantum applications demands for heterogeneous technological solutions. In particular, the excellent controllability and robustness of atomic quantum memories and the effectiveness of single photon generation with solid state emitters can serve as a cornerstone for future applications in quantum optics, e.g. synchronization and buffering of optical networks.

We present prospects of using a warm caesium vapour as storage medium for single photons at the caesium D1 line (894nm). Our quantum memory is based on electromagnetically induced transparency (EIT) in a ladder-type configuration and allows for on-demand storage and retrieval of few-photon light pulses with 20 MHz repetition rate. We achieve 1/e storage times of 20 ns and an end-to-end efficiency of 1%. The high storage bandwidth of the memory and the low read-out noise promise compatibility with single photons from deterministically fabricated quantum light sources based on InGaAs quantum dots.

QI 9.4 Tue 11:45 A320

Room-temperature quantum memory: Interfacing atomic vapours and semiconductor quantum dots — •Esteban Gómez-López[1], Quirin Buchinger[2], Tobias Huber[2], and Oliver Benson[1] — [1]Humboldt-Universität zu Berlin, 12489 Berlin — [2]University of Würzburg, 97074 Würzburg

Quantum repeaters are a key element for scalable quantum networks, where quantum memories can substantially increase the efficiency of long-distance communications [1]. Quantum memories based on warm atomic ensembles constitute an attractive platform as they can store high-bandwidth photons [2] up to the second range [3]. Here we show an Electromagnetically Induced Transparency (EIT) quantum memory hosted in warm cesium vapour. Storage of faint coherent light pulses shows high readout efficiency. A measured bandwidth in the order of 200 MHz makes the memory compatible with the Fourier-limited emission of semiconductor Quantum Dots (QD) embedded in micropillar cavities [4]. We also present the first attempts to interface the emission from a QD-micropillar with our quantum memory by fine-tuning the emission wavelength of the emitters to the hyperfine transitions of the Cs D1 line, where the EIT memory takes place. This work sets the base for a hybrid quantum memory for single photons from a semiconductor single-photon source based on warm atomic ensembles. [1] P. van Loock et al., Adv. Quantum Technol. 3, 1900141 (2020). [2] N. Sangouard et al., Rev. Mod. Phys. 83, 33 (2011). [3] O. Katz and O. Firstenberg, Nat. Commun. 9, 2074 (2018). [4] H. Wang et al., Phys. Rev. Lett. 116, 213601 (2016).

QI 9.5 Tue 12:00 A320

Raman control for ultrahigh fidelity spin gates for the generation of large entangled photonic states with group-IV vacancies — •Gregor Pieplow[1], Joseph H. D. Munns[2], Mariano I. Monsalve[1], and Tim Schröder[1,3] — [1]Department of Physics, Humboldt-Universität zu Berlin, 12489 Berlin, Germany — [2]Psi Quantum, 94304 California Palo Alto, USA — [3]Ferdinand-Braun-Institut, 12489 Berlin, Germany

Large photonic entangled states such as multiphoton Greenberger-Horne-Zeilinger (GHZ) states or cluster states (CS) play a crucial role as a resource in two key photonic quantum information applications: measurement-based quantum computing, and one-way quantum repeaters. Here, we focus on theoretically investigating the deterministic generation of photonic resource states by employing a promising class of optically active spin defects in diamond: group-IV color centers. Specifically, we investigate the generation of linear cluster states and GHZ states. Because the generation of a large entangled photonic state comprised of single photons requires many iterations of the same coherent operations on a quantum emitter, they have to be of ultra high fidelity or otherwise the quality of the state degrades exponentially. This work provides a highly detailed investigation of the optical coherent control that facilitates single and two qubit gates, which are used for the deterministic generation of highly entangled states. We also introduce an original GHZ and CS quality measure, which will underline the importance of ultrafast and high fidelity control techniques for creating large time-bin entangled photonic qubit states.

QI 9.6 Tue 12:15 A320

Ideal Single Photon Sources at Telecom Wavelengths — •Jonas Grammel[1], Julian Maisch[2], Simone Luca Portalupi[2], Peter Michler[2], and David Hunger[1] — [1]Physikalisches Institut, Karlsruher Institut für Technologie — [2]Institut für Halbleiteroptik und Funktionelle Grenzflächen, Univer- sität Stuttgart

Semiconductor single photon sources are fundamental building blocks for quantum information applications. The current limitations of such quantum dot sources are the emitting wavelength and insufficient collection efficiency in fiber-based implementations. In the project *Telecom Single Photon Sources* we aim to realize high brightness, fiber coupled sources of single and indistinguishable photons at the telecom wavelength for the upcoming realization of fiber-based quantum networks. We employ open cavities realized with fiber-based mirrors, in combination with InGaAs quantum dots emitting in the telecom O-band and C-band. To achieve Fourier-limited photons we utilize the lifetime reduction of the emitters via the Purcell effect. We optimize the mode matching between the cavity mode and the guided fiber mode by introducing a fiber-integrated mode-matching optics that can basically reach near-unity collection efficiency.

QI 9.7 Tue 12:30 A320

Spatially and spectraly indistinguishable single mode photons from domain-engineered crystal — •Baghdasar Baghdasaryan[1,2], 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

Pure single-photon sources are currently one of the most important goals of photonic quantum technologies. A heralded single photon from spontaneous parametric down-conversion (SPDC) is a good candidate for a pure single-photon source. However, the photons from SPDC occur in pairs, that are highly correlated in space and frequency. This correlation reduces the purity of the heralded photons. Domain-engineered crystals with a Gaussian nonlinear response have been successfully used to minimize spectral correlations and enhance spectral purity in SPDC. However, a general approach, which minimizes both, spectral and spatial correlations, is still lacking. We go beyond the ansatz of the Gaussian nonlinear response and find a general nonlinear response that maximizes both the spatial and spectral purity of the SPDC emission.

QI 9.8 Tue 12:45 A320

Towards time-multiplexed pseudo-on-demand generation of single-photons in the C-band based on SPDC — •Xavier Barcons Planas[1,2,3], Leon Messner[1,2,3], Helen Chrzanowski[2], and Janik Wolters[2,3] — [1]Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany — [2]Institute of Optical Sensor Systems, German Aerospace Center (DLR), Berlin, Germany — [3]Institut für Optik und Atomare Physik, Technische Universität Berlin, Berlin, Germany

The deterministic generation of single photons is crucial for photonic quantum technology applications. Spontaneous parametric down-conversion (SPDC) is one of the most prominent processes for the generation of single-photons, where a classical pump beam can spontaneously convert into (entangled) pairs of signal and idler photons. Despite significant advantages in the versatility and the possibility of room-temperature operation, photon-pairs are emitted probabilistically because of the spontaneous nature of the process. We present first results of our efforts to overcome this limitation through temporal multiplexing [1]. We herald the presence of the signal photon from a monolithic cavity SPDC source [2] by detecting the corresponding idler, and store the signal in a highly-efficient storage loop [3]. The synchronization of the source with the memory provides a pseudo-on-demand single-photon source.

[1] E. Meyer-Scott *et al.*, Rev. Sci. Instrum. **91**, 041101 (2020).
[2] R. Mottola *et al.*, Opt. Express **28**, 3159 (2020).
[3] T. Pittman *et al.*, Phys. Rev. A **66**, 042303 (2002).

QI 10: Quantum Thermodynamics and Open Quantum Systems I

Time: Tuesday 11:00–13:00 Location: B302

Invited Talk QI 10.1 Tue 11:00 B302

Quantum information in minimal quantum thermal machines — •Géraldine Haack — University of Geneva, Switzerland

Minimal models for quantum thermal machines are central to understand energy exchanges at the quantum scale and the intimate connection between quantum thermodynamics and quantum information theory. In particular, one would like to determine whether quantum features, like entanglement, interactions and quantum statistics, can be beneficial to the efficiency of a thermal machine made of few quantum constituents. This research direction becomes even more fascinating in view of recent experimental progresses towards manipulating out-of-equilibrium multi-partite quantum systems, allowing for new designs and investigations of quantum thermal machines. In this talk, I will present some of our latest results concerning the advantages that open quantum systems can offer towards heat and quantum information management at the nanoscale, including storing energy, generation of quantum correlations and optimization of dissipative flows. References: Khandelwal et al., PRX Quantum 2, 040346 (2021) Seah et al., PRL 127, 100601 (2021) Brask et al., Quantum 6, 672 (2022)

QI 10.2 Tue 11:30 B302

Quantum optomechanical thermodynamics — •David Edward Bruschi — Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, Germany

Quantum Thermodynamics extends the notions from classical thermodynamics to the quantum regime. Novel features appear, and processes acquire intrinsic probabilistic nature, in the sense that classically forbidden processes can statistically occur at least in principle. Given the advances in quantum technologies, it remains an open question to develop and characterize quantum systems as potential quantum thermal machines.

We propose an extension of the concepts of quantum thermodynamics to optomechanical systems. We study their properties and characterize them as quantum thermal machines. Applications and extensions are discussed in light of quantum technological applications.

QI 10.3 Tue 11:45 B302

Catalytic Gaussian thermal operations — •Benjamin Yadin[1], Hyejung Jee[2], Carlo Sparaciari[2,3], Gerardo Adesso[4], and Alessio Serafini[3] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany — [2]Department of Computing, Imperial College London, London SW7 2AZ, UK — [3]Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK — [4]School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK

We examine the problem of state transformations in the framework of Gaussian thermal resource theory in the presence of catalysts. To this end, we introduce an expedient parametrisation of covariance matrices in terms of principal mode temperatures and asymmetries, and consider both weak and strong catalytic scenarios. We show that strong catalysts (where final correlations with the system are forbidden) are useless for a single mode, in that they do not expand the set of states reachable from a given initial state. We then go on to prove that weak catalysts (where final correlations with the system are allowed) are capable of reaching more final system states, and determine exact conditions for state transformations of a single mode in their presence. Next, we derive necessary conditions for Gaussian thermal state transformations holding for any number of modes, for strong catalysts and approximate transformations, and for weak catalysts with and without the addition of a thermal bath. We discuss the implications of these results for devices operating with Gaussian elements.

QI 10.4 Tue 12:00 B302

Which Bath-Hamiltonians Matter for Thermal Operations? — •Frederik vom Ende — Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany

We explore the set of thermal operations from a mathematical and topological point of view. We introduce the concept of Hamiltonians with resonant spectrum with respect to some reference Hamiltonian, followed by proving that when defining thermal operations it suffices to only consider bath Hamiltonians which satisfy this resonance property. Moreover we find a semigroup representation of the (enhanced) thermal operations in two dimensions by characterizing any such operation via three real parameters, thus allowing for a visualization of this set. This allows us to specify all qubit thermal operations (without the closure). This talk is based on the article J. Math. Phys. 63, 112202 (2022)

QI 10.5 Tue 12:15 B302

Thermodynamics of a many-body three level maser —

•Julia Boeyens, Benjamin Yadin, and Stefan Nimmrichter — Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen 57068, Germany

Many-body systems that are invariant under permutation of particles display interesting effects like superradiance due to their collective dynamics. These effects are apparent even in systems of particles that are, in principle, distinguishable but are permutation invariant from the perspective of the bath. It was recently demonstrated that multi-level systems that are collectively coupled to a thermal environment have thermodynamic properties that are different from collective spin systems and collections of distinguishable particles [1]. The thermodynamic effects of interactions between the multi-level systems are, however, yet to be investigated. Interactions should heighten the differences observed between the non-thermal steady states obtained by multi-level systems and the already well studied spin systems. In this work we study a three level maser coupled collectively to two thermal reservoirs. The performance is compared to an equivalent engine that is made up of the same number of three level systems that are distinguishable from the perspective of the baths.

[1] B. Yadin, B. Morris, K. Brandner arXiv:2206.12639 (2022)

QI 10.6 Tue 12:30 B302

A Trapped Ion Anharmonic Oscillator — •Bo Deng, Moritz Göb, Max Masuhr, Daqing Wang, and Kilian Singer — Experimentalphysik I, Universität Kassel, Heinrich Plett Str. 40, 34132 Kassel, Germany

In a tapered trap used for the realization of a single ion heat engine, the coupling of radial and axial modes implements an anharmonic mechanical oscillator. In this talk, we show that this coupling can be approximately described by the radiation-pressure Hamiltonian in the context of optomechanics. We further characterize the nonlinearity of this oscillator and the resulting mechanical bi-stability. Finally, we will discuss possible applications for thermal machines in the quantum regime.

QI 10.7 Tue 12:45 B302

Probing coherent quantum thermodynamics using a trapped ion — •Oleksiy Onishchenko[1], Giacomo Guarnieri[2], Pablo Rosillo-Rodes[3], Daniël Pijn[1], Janine Hilder[1], Ulrich G. Poschinger[1], Martí Perarnau-Llobet[4], Jens Eisert[2], and Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Universität Mainz, Staudingerweg 7, Mainz, Germany — [2]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Berlin, Germany — [3]Institute for Cross-Disciplinary Physics and Complex Systems, Campus Universitat de les Illes Balears, Palma, Spain — [4]Department of Applied Physics, University of Geneva, Geneva, Switzerland

We report an experimental measurement of the genuine quantum correction to the classical fluctuation-dissipation relation (FDR) [1] in a trapped ion platform. We employ a single qubit and perform thermalization and coherent drive via laser pulses to implement a quantum coherent work protocol [1]. Using the excellent degree of control of trapped ions, we find agreement with the theory of quantum FDR and violate any classical explanation by more than 10.9 standard deviations [2]. This work opens the path to further experimental exploration of quantum thermodynamics, in particular to measurements of non-Markovian evolution, where the state of the qubit would not be reset between single experiments.

[1] M. Scandi *et al.*, Phys. Rev. Research **2**, 023377 (2020).
[2] O. Onishchenko *et al.*, arXiv:2207.14325 (2022).

QI 11: Quantum Entanglement I

Time: Tuesday 11:00–13:00 Location: B305

Invited Talk QI 11.1 Tue 11:00 B305

Characterisation of multipartite entanglement beyond the single-copy paradigm — •Nicolai Friis — Institute of Atomic and Subatomic Physics - Atominstitut, TU Wien, Vienna, Austria

Scenarios with multiple parties such as one would imagine will be encountered in future large-scale quantum networks present complex challenges for the characterisation of entanglement. One of the most basic insights in the theory of multipartite entanglement is the fact that some mixed states can feature entanglement across every possible bipartition of a multipartite system, yet can be biseparable, i.e., can be produced as mixtures of partition-separable states. To distinguish biseparable states from those states that genuinely cannot be produced from mixing partition-separable states, the term genuine multipartite entanglement was coined. The premise for this distinction is that only a single copy of the state is distributed and locally acted upon. However, advances in quantum technologies prompt the question of how this picture changes when multiple copies of the same state become locally accessible. In this talk I will discuss recent work [Yamasaki et al., Quantum 6, 695 (2022), Palazuelos & de Vicente, Quantum 6, 735, (2022)] which demonstrates that multiple copies unlock genuine multipartite entanglement from partition-separable states, even from undistillable ensembles. These results show that a modern theory of entanglement in multipartite systems, which includes the potential to locally process multiple copies of distributed quantum states, exhibits a rich structure that goes beyond the convex structure of single copies.

QI 11.2 Tue 11:30 B305

Entanglement in quantum hypergraph states — •Jan Nöller[1] and Mariami Gachechiladze[2] — [1]Technische Universität Darmstadt — [2]Technische Universität Darmstadt

Hypergraph states are the natural generalization of well-known graph states, capturing multipartite entanglement between three or more parties.

We investigate how local Pauli stabilizers of symmetric hypergraph states can be used to quantify their geometric entanglement measures, and to explain exponentially increasing violation of local realism.

Specifically, we recover some known results for states with low hyperedge cardinalities and extend these further to infinitely many classes of hypergraph states.

Finally, we derive some results on robustness for the violation of separability inequalities against particle loss.

QI 11.3 Tue 11:45 B305

Bound Entanglement in Generalized Grid States — •Robin Krebs — Technical University Darmstadt, Germany

Quantum grid states are mixed quantum states introduced to study bound entanglement. They are defined by graphs on a regular grid, allowing for graph theoretical separability criteria.

Recently a generalization including hyperedges was proposed by Ghimire et al. In our work, we extend the graphical range and PPT criterion to allow treatment of hyperedges to deepen the understanding of entanglement in generalized grid states and study the behaviour of the Schmidt number under this generalization.

QI 11.4 Tue 12:00 B305

Quantifying electron entanglement faithfully — Lexin Ding[1,2], Zoltan Zimboras[3,4,5], and •Christian Schilling[1,2] — [1]Ludwig Maximilian University of Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Germany — [3]Theoretical Physics Department, Wigner Research Centre for Physics, Budapest, Hungary — [4]Algorithmiq Ltd., Helsinki, Finland — [5]Eötvös Loránd University, Budapest, Hungary

Entanglement is one of the most fascinating concepts of modern physics. In striking contrast to its abstract, mathematical foundation, its practical side is, however, remarkably underdeveloped. Even for systems of just two orbitals or sites no faithful entanglement measure is known yet. By exploiting the spin symmetries of realistic many-electron systems, we succeed in deriving a closed formula for the relative entropy of entanglement between electron orbitals. Its broad applicability in the quantum sciences is demonstrated: (i) in light of the second quantum revolution, it quantifies the true physical entanglement by incorporating the crucial fermionic superselection rule (ii) an analytic description of the long-distance entanglement in free electron chains is found, refining Kohn's locality principle (iii) the bond-order wave phase in the extended Hubbard model can be confirmed, and (iv) the quantum complexity of common molecular bonding structures could be marginalized through orbital transformations, thus rationalizing zero-seniority wave function ansatzes.

QI 11.5 Tue 12:15 B305

Constructing entanglement witnesses based on the Schmidt decomposition of operators — •Sophia Denker[1], Chengjie Zhang[2], Ali Asadian[3], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany — [2]School of Physical Science and Technology, Ningbo University, Ningbo, 315211, China — [3]Department of Physics, Institute for Advanced Studies in Basic Sciences (IASBS), Gava Zang, Zanjan 45137-66731, Iran

Characterizing entanglement is an important issue in quantum information, as entanglement is considered to be a resource for quantum key distribution or quantum metrology. One useful tool to detect and quantify entanglement are witness operators. A standard way to design entanglement witnesses for two or more particles is based on the fidelity of a pure quantum state; in mathematical terms this construction relies on the Schmidt decomposition of vectors. In this contribution, we present a method to build entanglement witnesses based on the Schmidt decomposition of operators. Our scheme works for the bipartite and the multipartite case and is found to be strictly stronger than the concept of fidelity-based witnesses. We discuss in detail how to improve known witnesses for genuine multipartite entanglement for various multipartite quantum states. Finally, we demonstrate that our approach can also be used to quantify quantum correlations as well as characterize the dimensionality of entanglement.

QI 11.6 Tue 12:30 B305

Maximally entangled symmetric states of two qubits — •Eduardo Serrano-Ensástiga[1,2] and John Martin[2] — [1]Centro de Nanociencias y Nanotecnología, Universidad Nacional Autónoma de México, Ensenada, Baja California, México — [2]Institut de Physique Nucléaire, Atomique et de Spectroscopie, CESAM, University of Liège, Liège, Belgium

The problem studied by Verstraete, Audenaert and De Moor [1] -about which global unitary operations maximize the entanglement of a bipartite qubit system- is revisited and solved when permutation symmetry between the qubits is taken into account. This condition appears naturally in bosonic systems or spin-1 systems [2]. Our results [3] allow us to characterize the set of symmetric absolutely separable states (SAS) for two qubits. In particular, we calculate the maximal radius of a ball of SAS states around the maximally mixed state in the symmetric sector, and the minimum radius of a ball that includes the set of SAS states. For symmetric 3-qubit systems, we deduce a necessary condition for absolute separability and bounds for the radii of similar balls studied in the two-qubit system. [1] F. Verstraete, K. Audenaert, and B. De Moor, Phys. Rev. A, 64, 012316, (2001). [2] O. Giraud, P. Braun, and D. Braun, Phys. Rev. A, 78, 042112, (2008). [3] E. Serrano-Ensástiga, and J. Martin, ArXiv:2112.05102 (2021).

QI 11.7 Tue 12:45 B305

Geometry of the state space of two qubits — •Simon Morelli[1], Christopher Eltschka[2], Marcus Huber[3], and Jens Siewert[4,5] — [1]Basque Center for Applied Mathematics (BCAM), 48009 Bilbao, Spain — [2]Istitut für Theoretische Physik, Universität Regensburg, 93053 Regensburg, Germany — [3]Atominstitut, Technische Universität Wien, 1020 Vienna, Austria — [4]University of the Basque Country UPV/EHU, 48080 Bilbao, Spain — [5]IKERBASQUE, Basque Foundation for Science, 48011 Bilbao, Spain

The quantum marginal problem and related questions have received considerable attention recently. We investigate an even simpler question for which there is no answer so far: Given the purities of the two local states of a bipartite system, what is the maximum purity the global state can achieve? We derive an exact solution for two qubits. Together with previous findings [1], this result gives rise for a new representation of the state space – the Bloch ball – of two qubits. We show that this visualization has various interesting properties regarding geometry, majorization, and entanglement.

[1] S. Morelli, C. Kloeckl, C. Eltschka, J. Siewert, and M. Huber, Lin. Alg. App. **584**, 294 (2020).

QI 12: Integrated Photonics I (joint session Q/QI)

Time: Tuesday 11:00–13:00 Location: E001

Invited Talk QI 12.1 Tue 11:00 E001

Thin-film lithium niobate waveguides for integrated quantum photonic technologies — •Francesco Lenzini[1], Emma Lomonte[1], and Wolfram Pernice[1,2] — [1]University of Muenster, 48149 Muenster, Germany — [2]Heidelberg University, 69120 Heidelberg, Germany

Lithium-Niobate-On-Insulator (LNOI) has emerged in recent years as a promising platform for integrated quantum photonic technologies because of its high-index contrast, enabling the realization of waveguides with a compact footprint, large second-order optical nonlinearity, and high electro-optic coefficient. In the first part of my talk I will give a general overview about our fabrication process for the realization of low-loss LNOI waveguide circuits, with a special focus on the development of efficient fiber-to-chip interconnects based on the use of grating couplers with a metal back-reflector. In the second part of my talk, I will instead discuss some applications in integrated quantum photonic technologies of the developed LNOI circuits. Specifically, I will present the first demonstration of an electro-optically tunable LNOI waveguide network integrated on-chip with superconducting nanowire single-photon detectors (SNSPDs), as well as the realization of high-speed programmable circuits specially designed for operation with single photons emitted by a Quantum Dot source.

QI 12.2 Tue 11:30 E001

Duty cycle errors in periodically poled $LiNbO_3$ waveguides — •Sebastian Brauner, Christof Eigner, Harald Herrmann, Lara Padberg, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics,Institute for Photonic Quantum Systems (PhoQS), Warburgerstr. 100, 33098 Paderborn, Germany

Photon pair generation and quantum frequency conversion are fundamental in quantum communication. Waveguides and specifically tailored quasi-phase matching have shown an amazing potential for future quantum communication technologies, which established material platforms as $LiNbO_3$ are about to explore. However, one often observes deviations from the expected performance, i.e. a low efficiency and distorted spectral phase-matching curves. We attribute these distortions to imperfections of the period poling. To gather a profound understanding, how such imperfections impact on the device performance, we conduct theoretical and experimental studies how duty cycle errors affect the conversion characteristic.

QI 12.3 Tue 11:45 E001

Ultrabright and narrowband intra-fiber biphoton source at ultralow pump power — •Alexander Bruns[1], Chia-Yu Hsu[1,3], Sergiy Stryzhenko[1,2], Enno Giese[1], Leonid Yatsenko[2], Ite Yu[3,4], Thomas Halfmann[1], and Thorsten Peters[1] — [1]TU Darmstadt, Germany — [2]National Academy of Science of Ukraine, Kyiv, Ukraine — [3]National Tsing Hua University, Hsinchu, Taiwan — [4]Center for Quantum Technology, Hsinchu, Taiwan

Nonclassical photon sources of high brightness are key components of quantum communication technologies. We here demonstrate the generation of narrowband, nonclassical photon pairs by employing spontaneous four-wave mixing in an optically-dense ensemble of cold atoms within a hollow-core fiber.

The brightness of our source approaches the limit of achievable generated spectral brightness at which successive photon pairs start to overlap in time. For a generated spectral brightness per pump power of up to 2×10^9 pairs/(s MHz mW) we observe nonclassical correlations at pump powers below 100 nW and a narrow bandwidth of $2\pi\times6.5$ MHz. In this regime we demonstrate that our source can be used as a heralded single-photon source. By further increasing the brightness we enter the regime where successive photon pairs start to overlap in time and the cross-correlation approaches a limit corresponding to thermal statistics.

Our approach of combining the advantages of atomic ensembles and waveguide environments is an important step toward photonic quantum networks of ensemble-based elements.

QI 12.4 Tue 12:00 E001

Realisation of an integrated source for Gaussian boson sam-

pling — Laura Padberg, •Simone Atzeni, Michael Stefszky, Kai Hong Luo, Harald Herrmann, Benjamin Brecht, Christof Eigner, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

Photonic quantum computing based on Gaussian Boson Sampling (GBS) is a quickly emerging research field, whose first implementations have demonstrated the role of single-mode squeezed states at telecom wavelength as key resources. Generally, the generation of these states relies on the process of parametric down-conversion in a nonlinear crystal, where care has to be taken to ensure that spectral correlations in the source do not lead to the generation of undesired multi-mode squeezed states. Due to its unique dispersion properties, bulk potassium titanyl phosphate (KTP) is typically employed for the generation of single-spectral-mode squeezed states at telecom wavelength. However, the performance of KTP sources will benefit from the enhanced light-matter interaction of a waveguide approach.

Here, we present the modelling, characterisation, and fabrication of a waveguide in periodically poled rubidium-doped KTP (ppRb:KTP). This system can act as a high-quality integrated source of single-mode squeezed states at telecom wavelength and can be readily employed in a GBS photonic processor.

QI 12.5 Tue 12:15 E001

Development of micro-integrated optical systems for atom-based quantum sensors — •Conrad Zimmermann, Marc Christ, and Markus Krutzik — Ferdinand-Braun-Institut (FBH), Berlin, Germany

Compact and mobile quantum sensors enable a broad range of applications in e.g. navigation and field-sensing with high sensitivity. The size and weight requirements derived from these applications place high demands on the degree of miniaturization, integration and robustness of all subsystems of such a device. Working on the physics package, we develop and qualify necessary integration technologies to realize miniaturized, ultra-stable optical systems and increase their functionality. Using these techniques, we set up a micro-integrated optical distribution system with a volume of ~25 ml to generate a crossed beam optical dipole trap. The two high-power laser beams precisely overlap in their focal points ($\omega_0 = 32\ \mu$m), and the system exhibits a high mechanical and thermal alignment stability. We present initial results from its operation in a cold atom experiment.

One approach to further reduce the overall size of a cold-atom based quantum sensor is to integrate optical setups within the vacuum system. We show development and qualification efforts for future in-UHV optical systems for atom trapping and manipulation.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant numbers 50RK1978 and 50WM1949.

QI 12.6 Tue 12:30 E001

Design and Simulation of Photonic Integrated Ion Traps — •Guochun Du[1], Elena Jordan[1], Carl-Frederik Grimpe[1], Anastasiia Sorokina[2,3], Steffen Sauer[2,3], Pascal Gehrmann[2,3], Stefanie Kroker[2,3], and Tanja E. Mehlstäubler[1,4,5] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Institut für Halbleitertechnik, Technische Universität Braunschweig, Braunschweig, Germany — [3]Laboratory for Emerging Nanometrology, Braunschweig, Germany — [4]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — [5]Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover, Hannover, Germany

Ion traps are a promising platform for realizing high-performance quantum computers and atomic clocks. To make these systems scalable, integrated photonic components for guiding and manipulating laser light on a chip scale are important. We will report on finite element simulations of our integrated ion traps. In the simulations, we examined the distortion of the potential at the position of the ion due to the openings in the electrodes for the outcouplers. Our simulations indicate that a transparent conductive coating can help to smoothen the potential. Further, we study how our traps can benefit from grating outcouplers designed with shallow angles.

QI 12.7 Tue 12:45 E001

Integrated photonics for the ATIQ quantum computer demonstrator — •Carl-Frederik Grimpe[1], Guochun Du[1], Anastasiia Sorokina[2,3], Pascal Gehrmann[2,3], Steffen Sauer[2,3], Elena Jordan[1], Tunahan Gök[4,5], Radhakant Singh[4,5], Maxim Lipkin[4,5], Pragya Sah[4,5], Stephan Suckow[4], Babita Negi[5], Stefanie Kroker[1,2,3], and Tanja E. Mehlstäubler[1,6,7] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Institut für Halbleitertechnik, Technische Universität Braunschweig, Braunschweig, Germany — [3]Laboratory for Emerging Nanometrology, Braunschweig, Germany — [4]AMO GmbH, Advanced Microelectronic Center Aachen, Aachen, Germany — [5]Chair of Electronic Devices, RWTH Aachen University, Aachen, Germany — [6]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — [7]Laboratorium für Nano- und Quantenengineering, Hannover, Germany

The BMBF project "ATIQ" aims to develop reliable trapped-ion quantum computer demonstrators with more than 40 qubits and with multi-qubit gate fidelities larger than 99.5%. To make the trapped ion systems scalable, we are developing integrated photonic systems for guiding and manipulating the laser light at the chip level. In this talk, we will discuss some design considerations to make when integrating photonics in surface ion traps. Furthermore, we will discuss the characterization of the photonic elements and benchmarking of the ion trap performance.

QI 13: Quantum Simulation

Time: Tuesday 11:00–13:00 Location: F428

QI 13.1 Tue 11:00 F428

Quantum simulation of graph complexity problems — •Durga Dasari and Joerg Wrachtrup — 3. Physics Institute, ZAQUANT, University of Stuttgart, 70569,Stuttgart, Germany

Finding the perfect matchings that cover the entire graph is known to be a computationally hard ($\#P$) problem in graph theory. A similar analogy exists for spin-lattices, where the coverings of lattice by dimers is a hard combinatorial problem. Dimer models are well studied in statistical physics and in many-body physics. We show here how to simulate such computationally complex problems using a simple model system comprising of a single quantum probe interacting with a rectangular spin-lattice. We identify different configurations for complete lattice filling using dimers through the quantum probe coherence, and use it further to obtain the pairing statistics, that confirm the previously known results for planar graphs. We highlight here the new role of quantum sensor that allows it to go beyond its conventional sensing applications towards resolving computational complexity in graph theory.

QI 13.2 Tue 11:15 F428

Quantum simulations of infinite spin transverse field Ising model using the variational quantum eigensolver algorithm — •Sumeet Sumeet, Max Hörmann, and Kai P. Schmidt — Institut für Theoretische Physik I Friedrich-Alexander-Universität Erlangen-Nürnberg

With the advancements in quantum technologies it has become inevitable to investigate the potential existence of quantum advantage for the paradigmatic models of quantum-many body physics. One of the very basic models is the transverse field Ising model that can be simulated on a quantum computer to compute properties such as the ground-state energy of a spin system. This problem, when tackled on a classical computer, leads to an exponential surge in the cost of computation with increasing system size. The advent of classical-quantum hybrid algorithms has shifted the focus to investigate the solution to this problem with algorithms such as the variational quantum eigensolver (VQE) which is considered reasonably good for obtaining the ground-state energies of quantum many-body systems in the NISQ era. In this work, we exploit the Hamiltonian variational ansatz for calculating the ground-state energy and fidelity of the transverse-field Ising model on one- and two-dimensional geometries. We devise strategies to compute the ground-state energy in the thermodynamic limit on quantum computers. In that regard, we apply numerical linked cluster expansions (NLCE) to VQE in order to simulate infinite spin systems using calculations on finite graphs. Further, we extend this approach to geometrically frustrated systems.

QI 13.3 Tue 11:30 F428

Toolbox for the digital twin of a Rydberg atom QPU — •Daniel Jaschke[1,2,3], Alice Pagano[1,2,3], Sebastian Weber[4], and Simone Montangero[1,2,3] — [1]Institute for Complex Quantum Systems, Ulm University — [2]Dipartimento di Fisica e Astronomia "G. Galilei" & Padua Quantum Technologies Research Center, Università degli Studi di Padova — [3]INFN, Sezione di Padova — [4]Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart

The many-body simulation of a QPU at the level of the Hamiltonian and pulses requires the integration of different tools leading to a simulation that encompasses different aspects and their interplay. In the example of a Rydberg atom QPU, we demonstrate how tensor network simulations can be used to gain insight into the system. Therefore, we employ an integration of an effective description of strontium-88 atoms, optimal control methods, a dedicated compiler, and tree tensor networks. To show the power of this tool, we focus on how benefits from parallelization of a quantum algorithm scale with the system size.

QI 13.4 Tue 11:45 F428

Accessing entanglement phase transitions from fluctuations — •Teemu Ojanen, Ali Moghaddam, and Kim Pöyhönen — Physics Unit, Faculty of engineering and natural sciences, Tampere University, Tampere Finland

Entanglement phase transitions in driven unitary quantum circuits subject to projective measurements provides an example of new type of critical phenomena in quantum information platforms. While the random unitary two-qubit gates drive the system rapidly into a volume-law entangled phase, the projective measurements of a finite fraction of qubits after each cycle try to freeze the proliferation of entanglement and drive the system to an area-law entangled phase. At critical measurement rate, the system undergoes a phase transition between the volume and area law phases. I will show how this phenomenon can be accessed directly via fluctuations of conserved quantities, circumventing the need to measure entanglement entropies. Remarkably, this could exponentially reduce the required number of measurements to observe entanglement phase transitions in experiments.

QI 13.5 Tue 12:00 F428

Signatures of MBL in a dilute gas of ultracold polar molecules in a 2D optical lattice — •Timothy J. Harris[1,2,3], Andrew J. Groszek[1], Arghavan Safavi-Naini[4,5], and Matthew J. Davis[1] — [1]ARC CoE EQUS, University of Queensland, Brisbane, Australia — [2]LMU Munich, Munich, Germany — [3]MCQST, Munich, Germany — [4]QuSoft, Amsterdam, the Netherlands — [5]University of Amsterdam, Amsterdam, the Netherlands

We present our work exploring many-body localization (MBL) in systems of ultracold polar molecules in two-dimensional (2D) optical lattices. We characterize a novel ergodicity breaking mechanism that emerges in molecular quantum simulators when a fraction of the lattice sites are left unoccupied. We consider a system of diatomic polar molecules pinned in a deep 2D optical lattice with at most one molecule per site. The system is well described by a dipolar spin-1/2 Hamiltonian, with effective on-site disorder arising from the dilute, randomised configurations of molecules in the lattice. We perform extensive exact diagonalisation simulations to explore non-equilibrium dynamics and eigenstate properties for systems of up to 16 molecules at 50% lattice filling. We observe several essential signatures of MBL, including retention of initial state memory in the system's long-time dynamics, logarithmic growth of bipartite entanglement entropy, divergent entanglement fluctuations and a transition to Poissonian level-spacing statistics. Our results are realisable in current molecular quantum gas microscope experiments, and open exciting new avenues to explore non-equilibrium many-body physics with ultracold polar molecules.

QI 13.6 Tue 12:15 F428

Confinement and phase diagrams of one-dimensional $\mathbb{Z}_2$ lattice gauge theory — •Matjaž Kebrič[1,2], Jad C. Halimeh[1,2], Christian Reinmoser[1,2], Ulrich Schollwöck[1,2], Luca Barbiero[3], Annabelle Bohrdt[4,5], and Fabian Grusdt[1,2] — [1]Department of Physics and ASC, LMU München, Theresienstr. 37, München D-80333, Germany — [2]MCQST, Schellingstr. 4, D-80799 München, Germany — [3]DISAT, Politecnico di Torino, I-10129 Torino, Italy — [4]ITAMP, Cambridge, MA, USA — [5]Department of Physics, Harvard University, Cambridge, MA 02138, USA

We present our work on confinement in a one-dimensional $\mathbb{Z}_2$ lattice gauge theory (LGT), where dynamical matter is coupled to gauge fields. This results in a non-local confining potential among pairs of individual particles, which bind into mesons. This is a notoriously difficult problem to tackle when the density of matter is finite and dynamical. We solve the confinement problem in the 1D $\mathbb{Z}_2$ LGT, by relating confinement to translational symmetry breaking in a non-local basis. We study the mechanism and effect of confinement in a broad context. Our model is already within the reach of existing cold-atom experiments. We thus consider the manifestation of confinement in the context of quantum simulation experiments and study the effect of finite temperature. In addition, we map out phase diagrams at different fillings and uncover rich physic driven by the interplay of non-local confining potential and purely local interactions. Furthermore, we develop a mean-field description of the LGT and explore the possibility to use the LGT formalism to describe mixed dimensional spin systems.

QI 13.7 Tue 12:30 F428

Time Evolution of Matrix Product States Using Adaptive Subspace Expansion — •Tizian Blatz, Sebastian Paeckel, and Martin Grundner — Arnold Sommerfeld Center of Theoretical Physics, Department of Physics, University of Munich, Theresienstrasse 37, 80333 Munich, Germany

Today's advances in experimentally realizable ultracold-atom-based quantum simulators are tied to the evolution of computational methods ranging from phenomenological approaches to full quantum state descriptions. Matrix product states (MPS) are a prominent numerical state class that has gained popularity due to the success of density-matrix renormalization group (DMRG) algorithms for ground state search. Beyond the ground state, accessing dynamic quantities and finite-temperature states realized in experiments requires methods for a state's evolution in time. Here, we present recent advances in MPS time-evolution methods based on the time-dependent variational principle (TDVP) accompanied by a subspace expansion prescription. Compared to the current state of the art, this method excels in describing challenging initial conditions, global quenches, and long (effective) interaction ranges, which are common, in particular, in (quasi) two-dimensional ultracold-atom setups. We highlight both technical aspects of the method as well as prospective use cases in the cold-atom context.

QI 13.8 Tue 12:45 F428

Confinement in doped $\mathbb{Z}_2$ lattice gauge theories — •Simon Linsel[1,2], Lukas Homeier[1,2,3], Annabelle Bohrdt[3,4], and Fabian Grusdt[1,2] — [1]Ludwig-Maximilians-Universität München, Munich. Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany — [3]Harvard University, Cambridge, MA, USA — [4]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

In proof-of-principle experiments, ultracold atoms have demonstrated that $\mathbb{Z}_2$ lattice gauge theories with dynamical matter can be studied in quantum simulators, and realistic proposals for large-scale realizations exist. Here we study the deconfinement of charges in such models, with a strong focus on observables directly accessible from snapshots generated by quantum simulators. We demonstrate that in the $\hat{\tau}^x$-basis the confined phase is characterized by localized hole pairs connected by (short) strings while deconfinement implies a global net of strings spanning over the entire lattice: We probe deconfinement with Monte Carlo simulations using percolation-inspired order parameters. Moreover, we simulate a Hamiltonian in two dimensions that is experimentally realistic. For small doping, there is a thermal deconfinement phase transition. For large doping, charges are always confined in the thermodynamic limit. For a related three-dimensional model, a thermal deconfinement phase transition exists for arbitrary doping. We map out the phase diagram and calculate the critical exponents. We speculate whether the use of percolation-inspired order parameters can be extended to the Fradkin-Shenker model and related models.

QI 14: Quantum Technologies: Color Centers II (joint session Q/QI)

Time: Tuesday 11:00–13:00 Location: F442

QI 14.1 Tue 11:00 F442

Purcell-Enhanced Emission from Individual SiV^- Center coupled to a Photonic Crystal Cavity — •Niklas Lettner[1,2], Lukas Antoniuk[1], Konstantin Fehler[1,2], Anna P. Ovvyan[3], Nico Gruhler[3], Viatcheslav N. Agafonov[4], Wolfram H.P. Pernice[3], and Alexander Kubanek[1,2] — [1]Institute for Quantum Optics, Ulm University, Germany — [2]Center for Integrated Quantum Science and Technology (IQst), Ulm University, Germany — [3]Institute of Physics and Center for Nanotechnology, University of Münster, Germany — [4]Universite F. Rabelais, 37200 Tours, France

The combination of classical integrated photonic structures with color centers in diamond, like the Silicon Vacancy (SiV^-) Center, offer a promising platform for on-chip quantum optics experiments. We functionalize classical silicon nitride photonic crystal cavities with SiV^- color centers in nanodiamonds in a hybrid approach. We show the experimental results coupling SiV^- centers efficiently to a photonic crystal cavity mode and the Purcell enhanced emission of individual SiV^- transitions [1]. By utilizing two mode coupling we achieved lifetimes of 460 ps [2].

[1] Fehler, Konstantin G., et al. Nanophotonics 9.11 (2020): 3655-3662.

[2] Fehler, Konstantin G., et al. ACS Photonics 8.9 (2021): 2635-2641.

QI 14.2 Tue 11:15 F442

Fabrication and characterization of μm-thin color center enriched diamonds for an open microcavity quantum network node — •Colin Sauerzapf[1,2], Julia Brevoord[1], Julius Fischer[1], Yanik Herrmann[1], Leonardo Wienhoven[1], Matteo Pasini[1], Laurens Feije[1], Matthew Weaver[1], Maximilian Ruf[1], Jörg Wrachtrup[2], and Ronald Hanson[1] — [1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft 2628 CJ, Netherlands — [2]3. Physikalisches Institut, University of Stuttgart, 70569 Stuttgart, Germany

Quantum network nodes are an essential building block to realize a Quantum Internet [1]. Color centers in diamond, like the established Nitrogen-Vacancy (NV) with its long spin coherence and spin register capabilities or the emerging Tin-Vacancy (SnV) centers, are promising candidates to realize such quantum nodes [2]. Integrating the color center into an open microcavity and therefore boosting the emission of coherent photons via the Purcell effect can significantly improve the entanglement rate of the system [3, 4]. Here we present a fabrication method for the required μm-thin color center enriched diamond platelets bonded to a Bragg mirror as well as the characterization of those samples in terms of emitter properties and performance in an open microcavity [5].

[1] S. Wehner et al., Science 362, 6412 (2018) [2] M. Ruf et al., J. Appl. Phys. 130, 070901 (2021) [3] M. Ruf et al., Phys. Rev. Applied 15, 024049 (2021) [4] E. Janitz et al., Optica 7, 1232-1252 (2020) [5] M. Ruf et al., Nano Lett. 19, 6, 3987*3992 (2019)

QI 14.3 Tue 11:30 F442

Overcoming spectral diffusion of NV defect centers in diamond nanostructures for enhanced entanglement generation — •Laura Orphal-Kobin[1], Kilian Unterguggenberger[1], Tommaso Pregnolato[1,2], Natalia Kemf[2], Mathias Matalla[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-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany

In large-distance quantum networks, quantum nodes are entangled by single photons. Using NV defect centers in diamond, network entanglement protocols were demonstrated in bulk-like microstructured samples. Performances could be significantly improved by coupling NVs to nanostructures, which increases the photon collection efficiency into a particular optical mode. However, ionization of surface defects leads to spectral diffusion of the NV zero-phonon-line resonance.

We demonstrate NVs in nanostructures that exhibit spectrally stable emission suited for entanglement generation [1]. Choosing a substrate with a high density of bulk nitrogen defects incorporates natural NVs and seems to screen fluctuating electric fields from the surface. Moreover, long ionization times allow for resonant control sequences in which high energy pulses can be circumvented for many entanglement attempt repetitions (optical π-pulses). By suppressing spectral diffusion, we propose spin-photon entanglement rates on the order of hundreds of kHz using NVs in nanostructures.

[1] L. Orphal-Kobin et al., arXiv:2203.05605 (2022).

QI 14.4 Tue 11:45 F442

High-precision localization of color centers in diamond for deterministic coupling to quantum photonic nanostructures — •Maarten H. van der Hoeven[1], Julian M. Bopp[1], Maximilian Kähler[1], Tommaso Pregnolato[1,2], Marco Stucki[1,2], and Tim Schröder[1,2] — [1]Humboldt-Universität zu Berlin, Department of Physics, Berlin, Germany — [2]Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Berlin, Germany

Quantum photonic circuits are fundamental building blocks for quantum information applications, like secure communication or quantum computing. In the past decades, it has been demonstrated that color centers in diamond have excellent properties to serve as qubits in such systems [1]. To create an efficient spin-photon interface, the color centers have to be coupled to quantum photonic nanostructures. The scalable fabrication of such devices with high yield and optimal performance requires deterministic alignment techniques [2]. This is achieved with high-precision localization of color centers in bulk diamond with uncertainties of a few tens of nanometers. Our approach is to determine the color center positions relative to alignment markers etched into the diamond's surface and subsequently fabricate nanostructures around them [3]. This technique allows for a pre-selection of the emitters and only the ones with the most suitable properties are chosen and integrated into a photonic device.

[1] M. Ruf et al., *Journal of Applied Physics* 130, 070901 (2021)

[2] S. Rodt et al., *J. Phys.: Condens. Matter* 32, 153003 (2020)

[3] T. Pregnolato et al., *APL Photon.* 5, 086101 (2020)

QI 14.5 Tue 12:00 F442

A novel open microcavity setup for an efficient spin-photon interface with diamond color centers — •Julius Fischer[1], Yanik Herrmann[1], Julia Brevoord[1], Colin Sauerzapf[1,2], Leonardo Wienhoven[1], Matteo Pasini[1], Laurens Feije[1], Matthew Weaver[1], Maximilian Ruf[1], and Ronald Hanson[1] — [1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft 2628 CJ, Netherlands — [2]3. Physikalisches Institut, University of Stuttgart, 70569 Stuttgart, Germany

Open microcavities are capable of equipping color centers in diamond with an efficient spin-photon interface [1,2] enabling their use as quantum nodes for quantum internet applications [3]. The well-established Nitrogen-Vacancy (NV) center with its long spin coherence times and spin register capabilities as well as the emerging Tin-Vacancy (SnV) center are two promising candidates. We recently showed Purcell enhancement under resonant excitation of NV centers in open microcavities [4]. However, the performance was limited by cavity length variations due to vibrations [4]. Here we present a new cryogenic low-vibration open microcavity setup including first measurements on defect center enriched μm-thin diamond samples.

[1] M. Ruf et al., Journal of Applied Physics 130, 070901 (2021) [2] E. Janitz et al., Optica 7, 1232-1252 (2020) [3] S. Wehner et al., Science 362, 6412 (2018) [4] M. Ruf et al., Phys. Rev. Applied 15, 024049 (2021)

QI 14.6 Tue 12:15 F442

Advances in Nanoscale Nuclear Magnetic Resonance with NV centers in diamond — •Marcel Martin[1], Nicolas Palazzo[2,3], Erik Knall[2], Daniel Kim[2,3], Nadine Meister[2], Ryan Gelly[2,3], Ryan Cimmino[2], Bartholomeus Machielse[2], Elana Urbach[2], Mikhail Lukin[2], Hongkun Park[2,3], and Nabeel Aslam[1] — [1]Institute of Condensed Matter Physics, Technische Universität Braunschweig, Braunschweig, Germany — [2]Department of Physics, Harvard University, Cambridge, USA — [3]Department of Chemistry and Chemical Biology, Harvard University, Cambridge, USA

Limitations of traditional nuclear magnetic resonance (NMR) can be overcome by using Nitrogen vacancy (NV) centers in diamond as local NMR probes which rely on statistical rather than thermal polarisation.

Proof-of-concept NMR measurements with NV centers have successfully been demonstrated in the past but revealed new challenges. One of them being the fast diffusion of molecules in liquids out of the detection volume, prohibiting NMR sensing by the NV centers. This can be solved by confining liquids in close proximity to the NV sensor. We realized this by structuring the diamond surface with nanowells, which function as traps for zeptoliter scale samples. In addition we demonstrated the controlled creation of NV centers underneath these nanostructures. We present NMR data measured with NV centers in such devices.

The promising technique of nanoscale NMR using NV centers is not restricted to liquids though but can be applied to a wide variety of materials. We will discuss a selection of potential applications.

QI 14.7 Tue 12:30 F442

Highly-efficient extraction of single photons from silicon vacancy in diamond using plasmonic nanoantenna — Ilya Fradkin[1], Mario Agio[2], and •Dmitry Fedyanin[1] — [1]Dolgopudny, Moscow, Russia — [2]University of Siegen, Siegen, Germany

Color centers in diamond and related wide-bandgap semiconductors are considered as one of the most promising quantum optoelectronic systems for single-photon sources and spin qubits. However, one of the major obstacles towards their practical exploitation is the high refractive index of diamond, which limits the maximum photon extraction efficiency to only a few percent for a horizontally oriented dipolar emitter, while for a vertically oriented emitter, the collection efficiency is even lower. At the same time, for practical applications, the efficiency of photon extraction of higher than 70% is typically required even at 100% quantum efficiency of the emitter. In this work, we develop a plasmonic nanoantenna that not only dramatically enhances the quantum efficiency of the silicon-vacancy (SiV) center in diamond but also improves the collection efficiency of the vertically oriented emitter by more than two orders of magnitude. We numerically demonstrate that the proposed nanoantenna allows to achieve the collection efficiency of more than 85%. Even more remarkable result is that the collection efficiency almost does not depend on the distance from the SiV center to the nanoantenna at distances from 10 to 100 nm and exceeds 80%, which is particularly beneficial for practical applications.

QI 14.8 Tue 12:45 F442

Fabrication of suspended "Sawfish" photonic crystal cavities in diamond — •Tommaso Pregnolato[1,2], Marco Stucki[1,2], Julian Bopp[1,2], Maarten van der Hoeven[2], and Tim Schröder[1,2] — [1]Ferdinand-Braun-Institut gGmbH, Berlin, Germany — [2]Department of Physics, Humboldt-Universität zu Berlin, Berlin, Germany

Color centers in diamond are a promising candidate for the development of quantum photonic applications: for example, their long spin-coherence times make them the optimal choice for building spin-based quantum networks [1]. Such networks will be formed by many nodes containing color centers that are all interconnected by photonic channels. An efficient interface between spin and photon is key for the success of such a system, as it enables the transfer of information from the stationary qubits (i.e. the spins) to the flying qubits (i.e. the propagating photons). Such interface can be achieved by coupling a defect center to a photonic crystal cavity [2]. Here, we report on our progress of fabricating such photonic crystal cavities, based on our recently proposed "sawfish" cavity design [3]. Our design is optimized for enhancing the interaction between tin-vacancy centers in diamonds and single-mode light fields. We present our fabrication procedure to obtain such suspended devices, our investigations on how different parameters affect the relevant etching rates and our first optical characterizations.

[1] M. Atatüre, et al., Nat. Rev. Mater. 3, 38-51 (2018) [2] T. Schröder, et al, J. Opt. Soc. Am. B 33, B65-B83 (2016) [3] J. Bopp, et al., arXiv:2210.04702 (2022)

QI 15: Members' Assembly

Time: Tuesday 13:15–14:00 Location: B305

All members of the Quantum Information Division are invited to participate.

QI 16: Concepts and Methods I

Time: Wednesday 11:00–13:00 Location: B302

QI 16.1 Wed 11:00 B302

Taming the Rotating Wave Approximation — •Daniel Burgarth[1,2], Paolo Facchi[3], Robin Hillier[4], and Marilena Ligabo[3] — [1]Macquarie University — [2]FAU Erlangen — [3]Bari University — [4]Lancaster University

The Rotating Wave Approximation (RWA) is one of the oldest and most successful approximations in quantum mechanics. It is often used for describing weak interactions between matter and electromagnetic radiation. In the semi-classical case, where the radiation is treated classically, it was introduced by Rabi in 1938. For the full quantum description of light-matter interactions it was introduced by Jaynes and Cummings in 1963. Despite its success, its presentation in the literature is often somewhat handwavy, which makes it hard to handle both for teaching purposes and for controlling the actual error that one gets by performing the RWA. Bounding the error is becoming increasingly important. Recent experimental advances in achieving strong light matter couplings and high photon numbers often reach regimes where the RWA is not great. At the same time, quantum technology creates growing demand for high-fidelity quantum devices, where even errors of a single percent might render a technology useless for error-corrected scalable quantum computation. I will report a conceptually simple way of explaining it and show how to tame it by providing non-perturbative error bounds, both for the semi-classical case and the full quantum case.

QI 16.2 Wed 11:15 B302

On the validity of the rotating wave approximation for interacting harmonic oscillators — •Paul Lageyre[1], Alessandro Ferreri[1], G. S. Paraoanu[2], Frank K. Wilhelm[1,3], Andreas W. Schell[4,5], and David Edward Bruschi[1,3] — [1]Forschungzentrum Jülich, 52425 Jülich, Germany — [2]Aalto University School of Science, FI-00076 AALTO, Finland — [3]Universität des Saarlandes, 66123 Saarbrücken, Germany — [4]Leibniz Universität Hannover, 30167 Hannover, Germany — [5]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

The rotating wave approximation (RWA) is widely used in the study of the dynamics of quantum systems. Within the interaction picture, terms in the Hamiltonian modelling two (or more) coupled quantum system acquire a phase factor. The RWA prescribes that terms rotating faster in phase with time tend to average out, and thus can be neglected in respect to slower rotating ones, which dominate the dynamics. The RWA is particularly easier to prove valid if the coupling is weak enough. Regardless of the success in applying this approximation, a deeper understanding of its domains of validity and the degree of error introduced otherwise would be greatly beneficial.

In this work we quantify the deviation from the full dynamics of coupled harmonic oscillators if the RWA is applied. We employ techniques from symplectic geometry and are able to directly relate the error introduced to the squeezing-like terms in the Hamiltonian that are dropped. We compute analytical expressions for the set of pure Gaussian states and discuss further applications.

QI 16.3 Wed 11:30 B302

Using beamsplitters as analogues for quantum mechanical joint spin measurements — •Hasan Ozgur Cildiroglu — Ankara University Dögol St. 06100 Ankara/Turkiye

Beamsplitters are optical and quantum mechanical components used to split incident light or particle beam at a designated ratio into two separate beams. The use of lossless beamsplitters with phase retarders reveals essential properties. In particular, they can be used as analogues to joint spin measurements in entangled quantum systems. In this study, after investigating this special property of beamsplitters, it will be tested in various hybrid gedanken experimental setups. Thus, a new method will be introduced for experimental testing of Bell-CHSH inequalities.

QI 16.4 Wed 11:45 B302

Quantum Correlations in Molecules: From quantum resourcing to chemical bonding — •Lexin Ding[1,2], Stefan Knecht[3,4], Zoltán Zimborás[3,5,6], and Christian Schilling[1,2] — [1]Ludwig Maximilian University of Munich, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), Germany — [3]Algorithmiq Ltd., Helsinki, Finland — [4]ETH Zurich, Switzerland — [5]Wigner Research Centre for Physics, Budapest, Hungary — [6]Eötvös Lorán University, Budapest, Hungary

The second quantum revolution is all about exploiting the quantum nature of atoms and molecules to execute quantum information processing tasks. To boost this growing endeavor and by anticipating the key role of quantum chemistry therein, our work establishes a framework for systematically exploring, quantifying and dissecting correlation effects in molecules. By utilizing the geometric picture of quantum states we compare – on a unified basis and in an operationally meaningful way – total, quantum and classical correlation and entanglement in molecular ground states. To unlock and maximize the quantum informational resourcefulness of molecules an orbital optimization scheme is developed, leading to a paradigm-shifting insight: A single covalent bond equates to the entanglement 2ln(2). This novel and more versatile perspective on electronic structure suggests a generalization of valence bond theory, overcoming deficiencies of modern chemical bonding theories.

QI 16.5 Wed 12:00 B302

Witnessing quantum non-Markovianity for high-entropy states using quasi-probability distributions — •Moritz Ferdinand Richter, Irene Ada Picatoste Fernández, and Heinz-Peter Breuer — Physikalisches Institut, Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

Memory effects in the dynamics of open quantum systems can be characterized by the flow of information between the open systems and its environment [1]. Quantum non-Markovian dynamics features a flow of information from the environment back to the open system. A commonly used measure quantifying this information backflow is based on the evaluation of the trace distance between two quantum states evolving in time according to a family of quantum dynamical maps. Yet, the computation of this measure becomes increasingly demanding in case of continuous variable systems with increasing entropy of the states at hand. We present a witness for quantum non-Markovianity which is based on the Kolmogorov distance between quasi-probability distributions [2]. Furthermore, we show that this witness is particularly efficient in high-entropy scenarios, and apply it to the determination of non-Markovianity in quantum Brownian motion [3].

[1] H.-P. Breuer, E.-M. Laine, J. Piilo and B. Vacchini, Rev. Mod. Phys. 88, 021002 (2016).

[2] M. F. Richter, R. Wiedenmann and H.-P. Breuer, arXiv:2210.06058 [quant-ph].

[3] S. Einsiedler, A. Ketterer and H.-P. Breuer, Phys. Rev. A 102, 022228 (2020).

QI 16.6 Wed 12:15 B302

Trajectory Representation of non-Markovian Quantum Dynamics — •Charlotte Bäcker, Konstantin Beyer, and Walter Strunz — Technische Universität Dresden, 01062 Dresden

The Markovian evolution of quantum systems can be described with the help of the well-known GKSL master equation. Quantum non-Markovianity is often associated with some backflow of information from the environment into the system. This backflow of information is closely related to the presence of memory effects and can result in negative decay rates in Lindblad-type master equations.

We address the question of whether such memory effects have to be quantum or if they can be modelled by classical memory only. We show how to obtain non-Markovian Lindblad-type master equations with time-dependent decay rates from trajectories described by consecutive classically conditioned measurements.

QI 16.7 Wed 12:30 B302

Optimizing the atom transport of neutral atoms between distant super-lattice sites — •Cristina Cicali[1,2], Robert Zeier[1], Felix Motzoi[1], and Tommaso Calarco[1,2] — [1]Forschungszentrum Jülich,Peter Grünberg Institute, Quantum Control (PGI-8), 52428 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, 50937 Köln, Germany

A variety of quantum platforms have demonstrated a capacity for efficiently manipulating quantum states to simulate macroscopic properties or to implement quantum gates. High-fidelity quantum operations rely on the precise control over the quantum system in order to minimize possible error sources such as decoherence. Within the BMBF project FermiQP, we are working together with the group of Christian Groß in Tübingen, on optimizing protocols to transport via optical tweezers the neutral atoms trapped in a two-dimensional super lattice. Optimized protocols aim at maximizing the transport velocity while considering error sources coming from excitation of the motional ground state of the atom, the non-deterministic imperfections in the optical apparatus, coming from aberrations and diffraction in the tweezers, as well as the presence of further atomic wells in the lattice. We present first numerically optimized example trajectories for the atom transport and discuss potential improvements to the protocols.

QI 16.8 Wed 12:45 B302

Optical cavities based on optical Tamm states for application in quantum optics — •Manuel Goncalves — Ulm University - Inst. of Experimental Physics, Ulm, Germany

Single optical Tamm states arise on junctions of one-dimensional binary photonic crystals of different Zak phase (a topological invariant). By stacking multiple crystals of alternating Zak phase multiple photonic modes arise in the band gap. Differently from Fabry-Perot cavities, structures based on multiple optical Tamm states exhibit more modes than the number of coupled cavities. An analysis of the optical properties of the modes is presented.

These cavities can achieve large quality factors, have small mode volume, due to the short cavity length (half-wavelength), and are tunable by varying the angle of incidence of external illumination. Due to these properties, they can be used in quantum optics applications and substitute the much larger Fabry-Perot cavities.

QI 17: Quantum Networks I (joint session QI/Q)

Time: Wednesday 11:00–12:45 Location: B305

Invited Talk QI 17.1 Wed 11:00 B305

Self-testing with dishonest parties and entanglement certification in quantum networks — •Gláucia Murta[1] and Flavio Baccari[2] — [1]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, D-40225 Düsseldorf, Germany — [2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, Garching 85748, Germany

Multipartite entanglement is a crucial resource for network cryptographic tasks, such as secret sharing and anonymous quantum communication. Here, we consider the task of entanglement verification in a quantum network. The goal is to certify entanglement of the distributed state even when some of the parties (an unknown subset of parties in the network) may act maliciously. Our main result is a device-independent verification protocol that can certify genuine multipartite entanglement in the presence of dishonest parties. Our protocol is based on the Svetlichny inequality, and we show that the maximal violation of the Svetlichny inequality can self-test the GHZ state even in the presence of dishonest parties.

QI 17.2 Wed 11:30 B305

Extracting maximal entanglement from linear cluster states — •Jarn de Jong[1], Frederik Hahn[1], Nikolay Tcholtchev[2], Manfred Hauswirth[2], and Anna Pappa[1,2] — [1]Electrical Engineering and Computer Science Department, Technische Universitaet Berlin, 10587 Berlin, Germany — [2]Fraunhofer Institute for Open Communication Systems - FOKUS, 10589 Berlin, Germany

Most quantum information processing architectures only allow for nearest-neighbour entanglement creation. In many cases, this prevents the direct generation of maximally entangled states, which are commonly used for many communication and computation tasks. Here we show how to obtain maximally entangled GHZ states between vertices initially connected by a minimum number of connections, which specifically allows them to share linear cluster states. We prove that the largest GHZ state that a linear cluster state on n qubits can be transformed into by means of local Clifford unitaries, local Pauli measurements and classical corrections, is of size $\lfloor(n+3)/2\rfloor$. We demonstrate exactly which qubit selection patterns are possible below this threshold and which are not, and implement the transformation on the `IBMQ Montreal` quantum device for linear cluster states of up to $n = 19$ qubits.

QI 17.3 Wed 11:45 B305

Aging effects in multiplexed quantum networks — •Lisa T. Weinbrenner[1], Lina Vandré[1], Tim Coopmans[2], and Otfried Gühne[1] — [1]Universität Siegen, Germany — [2]Universiteit Leiden, Netherlands

Aging is a well known problem which effects humans as well as technical devices. It is described by the effect that the probability for a failure in a given time interval increases with the life time of the biological or technological object. Different types of objects (e.g. humans and technical devices) age according to qualitatively different failure rates. The difference can be understood if these objects are modeled as systems of redundant parts with possibly initial defects [1].

Multiplexed quantum networks are quantum networks with multiple connections between two nodes, i.e., with redundancy in the edges of the network [2]. The functionality of the entire network depends on the functionality of the technical devices used. This leads to the question how the failure rates of the single devices lead to aging effects in the entire network. In this contribution we will apply the theory of aging to the technical devices used in a multiplexed quantum network. Our results rely on the analytical treatment of the underlying stochastic process of failure of the devices, as well as numerical simulations for different network structures.

[1] L. A. Gavrilov and N. S. Gavrilova, J. Theor. Biol. 213, 527-545 (2001)

[2] O. A. Collins et al., Phys. Rev. Lett 98, 060502 (2007)

QI 17.4 Wed 12:00 B305

Cavity-Assisted Entanglement Generation between Spins and Photon Pulses — •Ferdinand Omlor, Benedikt Tissot, and Guido Burkard — Department of Physics, University of Konstanz, D-78457 Konstanz, Germany

The reliable entanglement generation between distant nodes of a quantum network is a core challenge for the realization of quantum communication. Spin qubits contained in optical cavities are promising systems which can be interconnected by photons using fiber optics. So far the focus of theoretical studies was on single modes. We present a way to study multimode signals, in particular pulses of finite duration. This multimode character needs to be taken into account to correctly calculate the fidelity of entanglement generation between a single photon pulse and a spin qubit. We specifically study this with the network architecture proposed by K. Nemoto et al., Phys. Rev. X 4, 031022 (2014) in mind.

QI 17.5 Wed 12:15 B305

A Graphical Formalism for Entanglement Purification — •Lina Vandré and Otfried Gühne — Universität Siegen, Germany

Hypergraph states form an interesting family of multi-qubit quantum states which are useful for quantum error correction, non-locality and measurement-based quantum computing. They are a generalisation of graph and cluster states. The states can be represented by hypergraphs, where the vertices and hyperedges represent qubits and entangling gates, respectively.

For quantum information processing, one needs high-fidelity entangled states, but in practice most states are noisy. Purification protocols address this problem and provide a method to transform a certain number of copies of a noisy state into single high-fidelity state. There exists a purification protocol for hypergraph states [1]. In my talk, I will first reformulate the purification protocol in a graphical manner, which makes it intuitively understandable. Based on this, I will propose systematic extensions, which naturally arise from the graphical formalism.

[1] T. Carle et al., Phys. Rev. A 87, 012328 (2013)

QI 17.6 Wed 12:30 B305

Generation of multidimensional entanglement in quantum optical systems — •Felix Twisden-Peareth, Jan Sperling, and Polina Sharapova — Paderborn University, Warburger Str. 100 | 33098 Paderborn

Multidimensional entanglement is a key source for many quantum applications, such as quantum computing, quantum communication and quantum simulation [1].

In this work, we investigate a four-channeled quantum optical system, which is driven by two spontaneous parametric down-conversion (SPDC) sources (each emitting two photons), in order to find configurations that generate maximal entanglement. The entanglement is quantified by the Schmidt number $\mathrm{K} = \mathrm{Tr}[\rho_r^2]^{-1}$, which is applicable to both pure and mixed states [2]. In our system, to calculate the Schmidt number, we provide reductions regarding both frequencies and spatial channels. In order to affect the entanglement, the photons in the system are manipulated regarding their polarization and relative position by introducing a time delay. It was found that Schmidt numbers equal to the dimensionality of the system can be generated. For this, the generation of a coherent superposition of different polarizations is provided, which is followed by a temporal separation of its parts. All results are calculated for the material system $LiNbO_3$.

[1] J. Wang, et al., Multidimensional quantum entanglementwith large-scale integrated optics, Science **360**, 285*291 (2018).

[2] B. M. Terhal and P. Horodecki, Schmidt number for density matrices, Physical Review A **61**, 040301 (2000).

QI 18: Quantum Technologies: Trapped Ions (joint session Q/QI)

Time: Wednesday 11:00–13:00 Location: F342

QI 18.1 Wed 11:00 F342

Non-commuting dynamics in light-ion-interactions on an ion-trap system — •Sebastian Saner[1], Oana Bazavan[1], Donovan Webb[1], Gabriel Araneda[1], Mariella Minder[1], David Lucas[1], Raghavendra Srinivas[1], and Chris Ballance[1,2] — [1]University of Oxford, Oxford, UK — [2]Oxford Ionics, Oxford, UK

The interaction Hamiltonian that governs the dynamics between trapped ions and laser light [1] is well studied and understood in the limit of low laser powers, leading to simple dynamics. However, at high powers, off-resonant coupling to multiple carrier and motional transitions is not negligible, leading to more complex and richer dynamics, with Hamiltonians exhibiting non-commuting terms.

In quantum computing with trapped ions, fast and versatile interactions that require high laser powers are important. It is of interest to either suppress those off-resonant terms or harness them in a controlled way. In this talk, we present our experimental work on utilising non-commuting terms to create two-qubit entanglement [2]. Furthermore, we evaluate how to apply this idea in the context of hybrid spin-motion systems. Secondly, we will show how we employ a phase stable optical lattice to coherently suppress a non-commuting error source that appears in the conventional Molmer-Sorensen interaction. This approach has the potential to allow for fast and high-fidelity entangling gates which are not limited by scattering errors.

[1]: Wineland et al., J. Res. Natl. Inst. Stand. Technol. 103(3), 259-328, 1998

[2]: Bazavan, Saner et al., arXiv:2207.11193, 2022

QI 18.2 Wed 11:15 F342

Optimization methods for RF junctions in register-based surface-electrode ion traps — •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 RF junctions that allow the ions to move between the specialized zones of the quantum processor via ion transport. We discuss the design choices and optimization methods of such a junction and present an optimized symmetric RF X-junction feasible for through-junction ion transport of single $^{9}\mathrm{Be}^{+}$ ions and multilayer microfabrication.

QI 18.3 Wed 11:30 F342

Simultaneous super- and subradiant light emission of two stored ion in free space — •Stefan Richter[1], Sebastian Wolf[2], Joachim vom Zanthier[1], and Ferdinand Schmidt-Kaler[2] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, Staudtstraße 1, 91058 Erlangen — [2]QUANTUM, Institut für Physik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

Modification of spontaneous decay in space and time is a central topic of quantum physics. It has been predominantly investigated in cavity quantum electrodynamic systems. Altered spontaneous decay may equally result from correlations among the emitters in free space, as observed in super- and subradiance. Yet, preparation of an entangled quantum state and the resulting modified emission pattern has not been observed so far due to the lack of ultra-fast multi-pixelated cameras. Using two trapped ions in free space, we prepare their state via projective measurements and observe their corresponding collective photon emission. Depending on the direction of detection of the first photon, we record fundamentally different emission patterns, including super- and subradiance [1]. Our results demonstrate that the detection of a single photon may fundamentally determine the subsequent collective emission pattern of an atomic array, here represented by its most elementary building block of two atoms stored in an ion trap.

[1] arXiv:2202.13678

QI 18.4 Wed 11:45 F342

Quantum repeater node with two $^{40}\mathrm{Ca}^{+}$ ions — •Max Bergerhoff, Omar Elshehy, Stephan Kucera, Matthias Kreis, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

The quantum repeater cell according to [1] is a fundamental building block for large distance quantum networks. It serves for overcoming the exponential scaling of fiber transmission, by the division of a transmission fiber in two asynchronously driven segments and the use of quantum memories. Recent realizations with single atoms [2] in a cavity and ions in a large cavity [3] already demonstrate the advantage of this protocol. Here we report on the implementation of a free-space quantum repeater cell with two $^{40}\mathrm{Ca}^{+}$ ions in the same trap that act as memories.

We demonstrate ion-photon entanglement according to [4] by controlled emission of single photons from the individually addressed ions. The entanglement is swapped onto the photons via the Mølmer-Sørensen gate [5]. We discuss the rate scaling due to the asynchronous sequence and the fidelity of the final photon-photon state.

[1] D. Luong et al., Appl. Phys. B 122, 96 (2016)
[2] S. Langenfeld et al., Phys. Rev. Lett. 126, 30506 (2021)
[3] V. Krutyanskiy et al. arXiv preprint arXiv:2210.05418 (2022)
[4] M. Bock et al., Nat. Commun. 9, 1998 (2018)
[5] K. Mølmer and A. Sørensen, Phys. Rev. Lett 82, 1835-8 (1999)

QI 18.5 Wed 12:00 F342

Spin-dependent coherent light scattering from linear ion crystal — •Maurizio Verde[1], Benjamin Zenz[1], Stefan Richter[2], Zyad Shehata[2], Ferdinand Schmidt-Kaler[1], and Joachim von Zanthier[2] — [1]QUANTUM, Institut für Physik, Universität Mainz, Mainz, Germany — [2]Institut für Optik, Information und Photonik, Universität Erlangen, Erlangen, Germany

Linear crystals of ultracold ions are emerging platforms for quantum simulator thanks to their unique properties of long coherence times and high-fidelity optical manipulation. In this perspective, the development of new detection techniques based on photo-correlation measurements is of central interest in order to access structural and dynamical information. Following the ideas reported in [1] on light-crystal coherent scattering, we explored extensions of these phenomena and here we report on a new detection scheme to unveil the spin texture for linear chains of $^{40}\mathrm{Ca}^{+}$ ions. First, we initialize the crystal in the desired spin configuration, then we use the narrow transitions at 729nm and 854nm to perform spin-dependent coherent scattering and measure the background-free $g^{(1)}$ photo-correlation function by recording light near 393nm in the far field. The laser beam geometry is chosen to minimize the single-ion recoil and therefore the corresponding Debye-Waller factor. We use a high spatio-temporal resolution MCP camera and reveal from the spatial interference pattern the spin texture of the crystal. We discuss the efficiency of our new method for detecting magnetic phases and phase transitions.

[1]Wolf et al., Phys. Rev. Lett. 116, 183002 (2016)

QI 18.6 Wed 12:15 F342

Sideband Thermometry on Ion Crystals — •Ivan Vybornyi[1], Laura Dreissen[2], Daniel Vadlejch[2], Tanja Mehlstäubler[2], and Klemens Hammerer[1] — [1]Institut für theoretische Physik, Leibniz Universität Hannover, Appelstraße 2,30167 Hannover, Germany — [2]Physikalisch-Technische Bundesanstalt, Bundesallee 100,308116 Braunschweig, Germany

Crystals of ultracold trapped ions reach sizes of hundreds of individual particles and require high level of control over their motional temperature to account for the second-order Doppler shift in clocks and implement high-fidelity quantum gates in quantum computers. The existing thermometry tools fail to provide an accurate temperature estimation for large ground-state cooled crystals, either focusing only on the symmetric c.o.m. mode of motion or neglecting the involved spin-spin correlations between the ions.

To resolve the thermometry large-N bottleneck, we consider crystal many-body dynamics arising when motional sideband transitions are driven in a near ground-state regime, which is a widely used approach in thermometry of a single ion. To gain some valuable insights on the sideband thermometry method, we also address the single ion case and study it from the Fisher Information prospective.

Extending the approach further, we account for entanglement created between the ions in a crystal to derive a new reliable temperature estimator, insensitive to the number of ions, and field-test in experiments with 4- and 19-ion crystals done by colleagues from PTB and Innsbruck.

QI 18.7 Wed 12:30 F342

Mixed qubit types in registers of trapped barium ions — •Fabian Pokorny, Andres Vazquez-Brennan, Jamie Leppard, Ana Sotirova, and Chris Ballance — Department of Physics, University of Oxford, United Kingdom

Registers of mixed qubit types are a promising approach for scaling trapped-ion quantum computers. The insensitivity of one qubit type to the others' light fields eliminates scattering errors and enables advanced qubit control schemes.

Barium-ion qubits are uniquely suited for realising this approach. Their long-lived metastable states allow for the implementation of different qubit types using just one atomic species, which, combined with atomic transitions in the visible range, significantly reduces experimental complexity [1]. In our experiment we use $^{137}\mathrm{Ba}^{+}$, whose nuclear spin of 3/2 provides magnetic-field insensitive 'clock' qubits in both the stable ground-state manifold and the long-lived metastable $5D_{5/2}$ manifold. The ground and metastable level qubits are connected via a pair of 'clock' transitions, and both qubit types can be driven using a two-photon Raman process with 532 nm light and low scattering error.

We show an all-fiber Raman system capable of single-ion addressing in a large qubit register and further demonstrate simultaneous manipulation of ground-state and metastable-state qubits. These are prerequisites for working with long registers of mixed qubit types and for realising partial projective measurements and mid-circuit measurements.

[1] D. Allcock et al., Applied Physics Letters, vol. 119, 2021.

QI 18.8 Wed 12:45 F342

Introducing a surface ion trap with integrated photonics for Yb+ ions — •Markus Kromrey[1], Elena Jordan[1], Guochun Du[1], Carl-Frederik Grimpe[1], Gillenhaal Beck[2], Karan Metha[5], and Tanja Mehlstäubler[1,3,4] — [1]Physikalisch Technische Bundesanstalt, Braunschweig, Deutschland — [2]Eidgenössische Technische Hochschule Zürich, Zürich, Schweiz — [3]Laboratorium für Nano- und Quantenengineering, Hannover, Deutschland — [4]Leibniz Universität Hannover, Hannover, Deutschland — [5]Cornell University, Ithaca, USA

One of the main obstacles to the scalability of ion trap applications such as quantum computing and quantum sensing is the miniaturization and scalability of the optics required to provide the trapped ions with the light necessary to manipulate them. In this talk, we will present a surface ion trap with integrated optics that requires much less space than classical setups. Integrated optics also offer routes to eliminating important technical noise sources present in conventional setups. The integrated optics deliver all the lasers required for a Yb 172 clock experiment to the ion. One of the main features of the trap is a grating coupler that provides the ion with light in a Hermite-Gaussian mode to excite the narrow Yb 172 octupole transition.

QI 19: Implementations: Ions and Atoms (joint session QI/Q)

Time: Wednesday 11:00–13:00 Location: F428

Invited Talk QI 19.1 Wed 11:00 F428

Experimental quantum error correction with trapped ions — •Philipp Schindler — University of Innsbruck

For large-scale quantum computing, effective quantum error correction will be mandatory. Current, small-scale experiments can be used to validate assumptions on the physical errors in the system that are required for fault-tolerant operation. I will report on our experimental efforts towards fault-tolerant quantum information processing in our trapped-ion platform. In particular, I will discuss the implementation of a fault tolerant universal set of logical operations. The results from these experiments are used to inform the development of large scale ion-trap quantum devices.

QI 19.2 Wed 11:30 F428

Towards an entangling gate between bosonic qubits in trapped ions — •Stephan Welte, Martin Wagener, Moritz Fontbote-Schmidt, Hendrik Timme, Luca Hermann, Ralf Berner, Edgar Brucke, Paul Röggla, Ivan Rojkov, Florentin Reiter, and Jonathan Home — ETH Zurich, Zurich, Switzerland

Encoding quantum information in a harmonic oscillator provides a resource-efficient platform for quantum error correction. A promising code is Gottesman-Kitaev-Preskill (GKP) encoding [1], which has been realized both in trapped ions [2, 3] and superconducting qubits [4]. State preparation, single qubits rotations, readout, and error correction have been realized in both architectures. However, a universal two-qubit gate has not yet been realized. We will describe our work on such an entangling gate between GKP qubits prepared in the motional modes of calcium ions in a Paul trap. The modes are coupled via the Coulomb interaction approximating a beam splitter interaction. Together with squeezing operations, this interaction can realize the desired universal gate. In theoretical work, we investigate this gate for experimentally realistic parameters and finite energy states. In parallel, we are developing an apparatus for an experimental implementation, including the fabrication of a novel ion trap and the implementation of individual addressing with tightly focused laser beams.

[1] D. Gottesman, A. Kitaev, and J. Preskill. PRA 64, 012310 (2001) [2] C. Flühmann et al. Nature 566, 513(2019) [3] B. de Neeve et al. Nat. Phys. 18, 296 (2022) [4] V. Sivak et al. arXiv 2211.09116 (2022)

QI 19.3 Wed 11:45 F428

A universal two-qubit computational register for trapped-ion quantum processors — •Nicolas Pulido-Mateo[1,2], Hardik Mendpara[1,2], Markus Duwe[1,2], Giorgio Zarantonello[1,2,3], Amado Bautista-Salvador[1,2], Ludwig Krinner[1,2], 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

Here we report on the realization of a two qubit universal computational register compatible with the QCCD architecture [1]. Single qubit gates are performed by addressing each ion individually via a micromotion sideband [2]. The entangling operation is implemented using an MS-type interaction, where we measure an infidelity that approaches 10^{-3} [3] when using partial state tomography. To characterize the single qubit gates we use a randomized benchmarking protocol [4] and obtain an infidelity of $3.8(4) \times 10^{-3}$. We perform a characterization of the register by means of the cycle benchmarking protocol [5] obtaining, as a preliminary result, a composite process fidelity of 96.6(4) %. Finally we use simulation software for quantum open systems to model possible error sources and calculate an error budget.

[1] D. Kielpinski *et al.*, Nature **417**, 709 (2002).
[2] U. Warring *et al.*, Phys. Rev. Lett. **17**, 173002 (2013)
[3] M. Duwe *et al.*, Quantum Sci. Technol. **7**, 045005 (2022)
[4] C. Piltz *et al.*, Nature Communications **5**, 4679 (2014).
[5] A. Erhard *et al.*, Nat. Commun. **10**, 5347 (2019)

QI 19.4 Wed 12:00 F428

Coherent Control of Trapped Ion Qubits with Localized Electric Fields — •Raghavendra Srinivas[1,2], Clemens Löschnauer[1], Maciej Malinowski[1], Amy Hughes[1], Rustin Nourshargh[1], Vlad Negnevitsky[1], David Allcock[1,3], Steven King[1], Clemens Matthiesen[1], Thomas Harty[1], and Chris Ballance[1,2] — [1]Oxford Ionics — [2]University of Oxford — [3]University of Oregon, Eugene

We present a new method for coherent control of trapped ion qubits in separate interaction regions of a multi-zone trap by simultaneously applying an electric field and a spin-dependent gradient. Both the phase and amplitude of the effective single-qubit rotation depend on the electric field, which can be localised to each zone. We demonstrate this interaction on a single ion using both laser-based and magnetic field gradients in a surface-electrode ion trap, and measure the localisation of the electric field.

[1] arXiv:2210.16129

QI 19.5 Wed 12:15 F428

Entangling scheme for Rydberg ion crystals using electric kicks in radial direction — •Han Bao[1], Jonas Vogel[1], Alexander Schulze-Makuch[1], Ulrich Poschinger[1], and Ferdinand Schmidt-Kaler[1,2] — [1]QUANTUM, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany — [2]Helmholtz-Institut Mainz, D-55128 Mainz, Germany

Due to the strong dipole interaction between Rydberg atoms, fast entangling gates have been achieved both in neutral atoms [1] and trapped ions [2]. A second unique feature of Rydberg states is their high electric polarizability. For trapped ions, Rydberg states electric polarizability may lead to a change of the secular frequency [3]. Such state dependent secular frequency can establish entanglement [4]. Here, we show that using electric kicks in the radial direction demands a 100 times lower voltage, thus much more feasible for an experimental realization. Accordingly, as lower motional are transiently excited only, the scheme becomes more robust. We also show scaling the method up for larger ions crystals, using a complex sequence of electric kicks, such that finally the motion state is recovered back.

We discuss the status of the experimental realization the electric kick entanglement generation.

[1]Levine et al., *Phys. Rev. Lett.* **123**, 170503 (2019)
[2]Zhang et al., *Nature* **580**, 345 (2020)
[3]Schmidt-Kaler et al., *New J. Phys.* **13**, 075014 (2011)
[4]Vogel et al., *Phys. Rev. Lett.* **123**, 153603 (2019)

QI 19.6 Wed 12:30 F428

Coherent transfer of transverse optical momentum to the motion of a single trapped ion — •Felix Stopp[1], Maurizio Verde[1], Milton Katz[2], Martín Drechsler[2], Christian Schmiegelow[2], and Ferdinand Schmidt-Kaler[1] — [1]QUANTUM, Institut für Physik, Universität Mainz, Mainz, Germany — [2]CONICET, Instituto de Física de Buenos Aires (IFIBA), Universidad de Buenos Aires, Buenos Aires, Argentina

A structured light beam is carrying orbital angular momentum and we demonstrate the excitation of the center of mass motion of a single atom in the transverse direction to the beam's propagation. This interaction is achieved with a vortex beam carrying one unit of orbital angular momentum and one unit of spin angular momentum. Using a singly charged $^{40}Ca^+$ ion, cooled near the ground state of motion in the three-dimensional harmonic potential of a Paul trap, we probe the sidebands of the $S_{1/2}$ to $D_{5/2}$ transition near 729 nm to quantify the momentum transfer. Exchange of quanta in the perpendicular direction to the beam's wave vector k is observed in case of centered a vortex shaped beam, while parasitic carrier excitation is reduced by a factor 40. This is in sharp contrast to the vanishing spin-motion coupling at the center of Gaussian beam. We characterize the coherent interaction by an effective transverse Lamb-Dicke factor $\eta_{\perp}^{\rm exp} = 0.0062(5)$ which is in agreement with our theoretical prediction $\eta_{\perp}^{\rm theo} = 0.0057(1)$ [1]. Finally we discuss the application of our finding for quantum information processing with trapped ion crystals.

[1] accepted Paper 22 November 2022: Phys. Rev. Lett.

QI 19.7 Wed 12:45 F428

Lasersystem for Control of Magnsium Atoms — •Tobias Spanke, Lennart Guth, Philip Kiefer, Lucas Eisenhart, Deviprasath Palani, Apurba Das, Florian Hasse, Jörn Denter, Mario Niebuhr, Ulrich Warring, and Tobias Schätz — Physikalisches Institut, Albert-Ludwigs-Universität, Freiburg

Trapped ions present a promising platform for quantum simulations. Versatile and robust laser systems with narrow bandwidth and high power and intensity stability are required for reliable control of this platform. The latest systems for Mg^+, Be^+ ions are based on vertical external cavity surface emitting lasers (VECSEL)[1] in the near-infrared. We are testing new compact cooling systems with impact on short-term frequency stability using commercially available PC parts. With the goal of measuring magnesium ions at a frequency stability of 200 kHz ($\lambda \approx 1120$ nm, P=2 W) with high accuracy. We aim at further development of the VECSEL into a compact, stable and user-friendly "turnkey" system.

[1]Burd, S. et al.(2016), VECSEL systems for generation and manipulation of trapped magnesium ions, Optica Vol. 3, Issue 12, pp. 1294-1299 (2016)

QI 20: Concepts and Methods II

Time: Wednesday 14:30–16:30 Location: B302

QI 20.1 Wed 14:30 B302

Entropy and catalysis — •Henrik Wilming — Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany

I discuss the solution of the "catalytic entropy conjecture", showing that von Neumann entropy can be characterized in the following way: Non-decreasing entropy provides a necessary and sufficient condition to convert the state of a physical system into a different state by a reversible (unitary) transformation that acts on the system of interest and a further, finite-dimenaionsal, "catalyst" whose state has to remain invariant exactly under the unitary time-evolution.

QI 20.2 Wed 14:45 B302

Foundations of fermionic particle correlations — •Damiano Aliverti-Piuri, Kaustav Chatterjee, Lexin Ding, and Christian Schilling — LMU University, Faculty of Physics, Munich

Multipartite systems are an essential topic in Quantum information theory, and a comprehensive theory has been developed regarding the several kinds of correlations they can exhibit. Such correlations, especially entanglement, are both interesting on a theoretical level, and useful for quantum processing tasks. Our starting point is the well-established definitions of uncorrelated, classically correlated, and unentangled states of multipartite systems - for example, distinguishable particles. To these three sets of states correspond three correlation measures, based on geometric ideas: total correlation, quantum correlation, and relative entropy of entanglement. Inspired by recent work by other authors (Gigena and Rossignoli; Gottlieb and Mauser), we propose a systematic approach towards particle correlations in systems of *indistinguishable* particles, with an emphasis on fermions. We (i) give definitions of types of increasingly correlated fermionic states, and of the respective geometric correlation measures; (ii) motivate our definitions from the point of view of Resource theory; (iii) study some promising properties of these states and measures; (iv) obtain analytical formulas for 2-fermion systems and other simple cases.

QI 20.3 Wed 15:00 B302

Resource Theory of Fermionic Correlation — •Kaustav Chatterjee, Damiano Aliverti Piuri, Lexin Ding, and Christian Schilling — Faculty of Physics, Arnold Sommerfeld Centre for Theoretical Physics, Ludwig-Maximilian-University of Munich, Germany

Resource theories are a generic approach used to manage any valuable resource, such as entanglement, purity and asymmetry. Such settings provide a novel framework to discuss information theoretic tasks like quantum state transformations and characterizing the utility of quantum states with respect to some resource measure. Analogous to resource theories of correlations and entanglement for distinguishable parties, we establish a hierarchy of resource theories for indistinguishable fermionic systems where each theory corresponds to a specific resource involving fermionic total correlation, fermionic quantum correlation or fermionic entanglement. In our theory, easily implementable operations (the free operations) are related to the set of fermionic linear optics (FLO) operations and their extensions, which naturally selects out the subset of Gaussian states as a candidate for free states in particular case where the resource is fermionic total correlations. We also introduce monotones (based on quantum relative entropy) to quantify the hierarchy of resources and explore quantum state transformation properties under such theories. We further comment on efficient classical simulation of our free operations and reveal how non-free resource states can be connected to the idea of complexity of fermionic sampling

QI 20.4 Wed 15:15 B302

Continuity of robustness measures in quantum resource theories — Jonathan Schluck, Gláucia Murta, Hermann Kampermann, Dagmar Bruss, and •Nikolai Wyderka — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany

Robustness measures provide an intuitive and operational way to quantify resources in quantum resource theories, such as entanglement and coherence. Despite exhibiting useful mathematical properties like monotonicity, the use of robustness measures is hindered by the fact that some of their properties like continuity remain unclear, in particular when the set of resource-free states is non-convex. To that end, we investigate continuity properties of different robustness measures by showing that their continuity depends on the shape of the set of free states. In particular, we show that in many cases star-convexity is sufficient for Lipschitz-continuity, and we provide specific examples of sets leading to non-continuous robustness measures. Finally, we illustrate the applicability of our results by introducing the robustness of teleportation fidelity and by deriving bounds on the robustness of quantum discord.

QI 20.5 Wed 15:30 B302

Graph state preparation with noisy interactions — •Konrad Szymanski — Universität Siegen, Siegen, Germany

Graph states are regarded as a testing ground of various quantum information schemes – they are useful in analysis of e.g. cryptography, measurement-based quantum computation, error correction, and metrology. Their preparation relies on the interaction pattern provided by a graph – an Ising-like Hamiltonian $\hat{H}$ is built from it and the *graph state* is the result of evolution of the multiqubit $|+\rangle^{\otimes N}$ state under $\hat{H}$. Due to the simplicity, implementation is possible for a wide array of physical systems, including ion traps, nitrogen vacancies, and superconducting qubits.

However, such realizations invariably suffer from noise, which presents itself in a multitude of ways: the engineered interactions may have imperfect strengths, additional transitions may arise, and the systems rarely can be protected from coupling with the outside world.

All of these contribute to the reduced utility of the produced quantum states. Here, I investigate the effects of *preparation noise* in this context. In particular, imperfect interaction strengths effectively lead to an *ensemble* of graph states being prepared, which still possess some of the desirable qualities of the *perfectly prepared* state. Theoretical considerations are compared with real-world implementations of graph states.

QI 20.6 Wed 15:45 B302

Computational Complexity in Functional Theory — •Lukas Kienesberger, Julia Liebert, and Christian Schilling — University of Munich (LMU), Munich, Germany

Using tools from quantum information theory, we investigate the computational complexity of calculating the universal energy functional in functional theories. Firstly, we prove for the two-fermion Hubbard model that the space of density matrices constituting the functional's domain decomposes into exponentially many regions, separated by submanifolds where the functional fails to be analytic. As our second main result, we show that determining the functional itself on those cells is weakly np-complete. We demonstrate how these findings contradict the generally accepted assumption of a single analytic functional. Third, we analyze and quantify the relations between the number of subdomains and the spectrum of a generic interaction.

QI 20.7 Wed 16:00 B302

On a Matrix Ensemble for Arbitrary Complex Quantum Systems — William Salazar and •Javier Madroñero — Centre for Bioinformatics and Photonics (CIBioFi), Universidad del Valle, Cali, Colombia

We propose a specific system dependent matrix ensemble as an alternative to the unitary Haar one as a model for the study of the late time dynamics of correlation functions in arbitrary complex quantum systems. We show that for arbitrary systems this ensemble yields an unitary 1-design and for strongly chaotic systems it becomes an approximated 2-design. We are able to provide universal expressions for two- and four-point ensemble-averaged correlation functions. Additionally, we show that for small energy windows our ensemble reduces to the eigenstate thermalization hypothesis.

QI 20.8 Wed 16:15 B302

Exact Unification of Spacetime, Gravity and Quanta — •Hans-Otto Carmesin — Gymn. Athenaeum, Harsefelder Str. 40, 21680 Stade — Studienseminar Stade, Bahnhofstr. 5, 21682 Stade — Universität Bremen, Fachbereich 1, Postfach 330440, 28334 Bremen

Quantum physics, QP, and its relation to general relativity, GR, provide an exciting problem of physics [1]. That problem is solved as follows [2]: Firstly, a quadruple of four basic principles, the spacetime quadruple, SQ, is identified: Gaussian gravity, special relativity, the equivalence principle and the physical reality of cosmological vacuum. In particular, we introduce a measurement of a gravitational parallax distance r by using a pair of hand leads. So, that distance is an element of physical reality. Secondly, the dynamics of cosmological vacuum, VD, is derived from the SQ. Thirdly, the postulates [3] of quantum physics and GR are derived from VD. Fourthly, solutions for the essential paradoxes of QP are provided. In particular, consequences for quantum information are discussed.

[1] Einstein, A. and Podolski, B. and Rosen, N. (1935): Can the quantum-mechanical description of physical reality be considered complete? Phys. Rev., 47, pp. 777-780.

[2] Carmesin, H.-O. (December 2022): Unification of Spacetime, Gravity and Quanta. Berlin: Verlag Dr. Köster.

[3] Ballentine, L. (1998): Quantum Mechanics. London - Singapore: World Scientific Publishing.

QI 21: Quantum Communication II (joint session QI/Q)

Time: Wednesday 14:30–16:30 Location: B305

Invited Talk QI 21.1 Wed 14:30 B305

Qube and Qube-II – Towards Quantum Key Distribution with Small Satellites — •Lukas Knips for the Qube/Qube-II-Collaboration — Ludwig Maximilian University (LMU), Schellingstr. 4, D-80799 Munich, Germany — Max Planck Institute of Quantum Optics (MPQ), Hans-Kopfermann-Str. 1, D-85748 Garching, Germany — Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 Munich, Germany

Quantum Key Distribution (QKD) is a provably secure method for distributing secret keys between two trusted parties over a quantum channel for symmetric cryptography. As demonstrated by the Chinese satellite MICIUS, exchange of a secure key between a satellite and an optical ground station is possible, thereby indeed enabling QKD on a global scale. While this large satellite demonstrated its feasibility, the QUBE missions are focussing on a more economic solution for global key exchange.

In this talk, I will start with an overview of the first QUBE satellite, a so-called CubeSat with a size of only $30 \times 10 \times 10\,\mathrm{cm}^3$ and consequently with severe limitations on available power and space. The satellite includes two different quantum state sources and a quantum random number generator and is now ready for launch. QUBE will test performance and space readiness of those components. QUBE-II, a second satellite, is currently being designed and will be able to exchange a key mainly thanks to a much larger optical telescope with an optical aperture of about 80 mm and to a full QKD post-processing over an optical data communication channel.

QI 21.2 Wed 15:00 B305

Security of Time-Frequency Quantum Key Distribution — •Federico Grasselli, Nikolai Wyderka, Hermann Kampermann, and Dagmar Bruss — Heinrich-Heine-Universität Düsseldorf

One of the current drawbacks of Quantum key distribution (QKD) are the relatively low generation rates of secret keys, hindered by effects such as noise in the quantum channel and detector saturation. Such issues can be alleviated by increasing the dimension of the encoding space with time-frequency QKD, where log2(d) bits of information are encoded in 'd' time bins of a single photon, thereby increasing the efficiency of the communication.

We focus on a specific experimental implementation of time-frequency QKD that can be easily scaled to higher dimensions. For this setup, we discuss a method to prove its security by closing a critical loophole that has been often overlooked in QKD implementations based on the photons' temporal degree of freedom. Moreover, we provide preliminary experimental data demonstrating that our security method can be applied to practical time-frequency QKD setups.

QI 21.3 Wed 15:15 B305

Multipartite measurement device-independent quantum key distribution with quantum memories — •Julia Alina Kunzelmann, Hermann Kampermann, and Dagmar Bruss — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf

Quantum repeaters build a useful tool to increase the communication distance in quantum networks. To achieve higher repeater rates, multiplexing between quantum memories can be used. We generalize the multiplexing scheme for quantum repeaters to N parties where the station performs GHZ measurements. This setup is used for measurement device-independent conference key agreement. In this work, we present a protocol that allows the distribution of a secret key in a multipartite star network via one central repeater station. We analyze the secret key rate of the protocol depending on various protocol parameters.

QI 21.4 Wed 15:30 B305

Easy-to-compute local Clifford invariants for graph states — •Frederik Hahn[1] and Adam Burchardt[2,3,4] — [1]Technische Universität Berlin, Berlin, Deutschland — [2]Universität Amsterdam, Amsterdam, Niederlande — [3]QuSoft, Amsterdam, Niederlande — [4]CWI, Amsterdam, Niederlande

In this work, we study easy-to-compute LC-invariants of graph states. Although previous studies have already led to finite sets of invariants that fully characterize the LC-equivalence classes of graph states, these invariants are computationally inefficient. Their computation requires knowledge of the given state's full stabilizer set, which is exponential in the number of its qubits n.

In this paper, without the need to calculate this entire stabilizer set, we instead present an easy-to-calculate LC-invariant of order O(n^3). It is closely related to the so-called foliage of a graph and has a simple graphical interpretation in terms of leaves, axils, and twins: For any graph, we define a partition of the set of its vertices based on a simple equivalence relation and call it the foliage partition of this graph. We further show that foliage partitions remain invariant under any local complementation of the corresponding graph. Foliage partitions then represent simple LC-invariants for graph states, since there is a one-to-one correspondence between LC-operations on a graph state and local complementations of its graph. Finally, we generalize foliage partitions from qubits to qudits and prove their invariance under the generalized local complementation operations.

QI 21.5 Wed 15:45 B305

Towards consumer-level quantum-secure cryptography - Entanglement based short-range Quantum Key Distribution — •Henning Mollenhauer[1], Daniel Tippel[1], Pius Gerisch[1], Donika Imeri[1,2], and Ralf Riedinger[1,2] — [1]Zentrum für Optische Quantentechnologien, Universität Hamburg, 22761 Hamburg — [2]The Hamburg Centre for Ultrafast Imaging, 22761 Hamburg

Many schemes for Quantum Key Distribution (QKD) have been proposed and realized over the years. A common challenge that arises in experimental implementations is the exponential loss of photons in quantum channels over long distances. Solutions to this challenge like purification protocols with quantum repeaters have not to date been efficiently implemented. A different approach to QKD is the key distribution over a short distance- and therefore low-loss- quantum channel. QKD over short distances can be used to exchange an information-theoretically secure root-of-trust that is safely stored on two end modules. Based on the root-of-trust, keys for encryption are generated in re-keying schemes on each end module. With this approach, it is possible to spatially separate the end modules and communicate classically over already existing communication infrastructure. Since no quantum channel is involved in the actual process of communication, encrypted messages can be sent between end modules over arbitrary distances. We here present an experimental setup that aims to realize short-distance QKD with end modules that in the future could be made compact enough to be implemented on small silicone-based chips.

QI 21.6 Wed 16:00 B305

A theoretical and experimental analysis of the single-photon advantage in quantum coin flipping — •Fenja Drauschke[1,2], Daniel A. Vajner[1], Tobias Heindel[1], and Anna Pappa[2] — [1]Institut für Festkörperphysik, TU Berlin — [2]Institut für Softwaretechnik und Theoretische Informatik, TU Berlin

Quantum coin flipping is a prominent cryptographic primitive within the framework of non-collaborative models, where two or more distrustful parties want to perform a fair coin flip. The parties are separated by a distance and wish to agree on a random bit. Quantum coin flipping has raised much interest recently, as it has various applications and holds enormous potential for improving the security of secure communications. At the same time, the use of single-photon sources for quantum communication setups is also attracting a lot of attention as it promises further security advantages compared to the usage of weak coherent laser pulses. In this work, we investigate the advantage of using single-photon sources compared to weak coherent pulses for different quantum communication setups of coin flipping in a theoretical, as well as experimental approach.

QI 21.7 Wed 16:15 B305

Optimization and readout-noise analysis of a hot 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, 12489 Berlin, Germany.

Efficient, noise-free quantum memories are indispensable components for the realization of quantum repeaters, which will be crucial for long distance quantum communication [1, 2]. We have realized a technologically simple, in principle satellite-suited quantum memory in Cesium vapor, based on electromagnetically induced transparency (EIT) on the ground states of the Cs D1 line [3]. 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 13(2)%. Simultaneously we achieve a minimal noise level corresponding to $\bar{\mu}_1 = 0.07(2)$ signal photons, for which we present strategies for further minimization. Furthermore, improvements for the next implementation of the experiment are introduced.

[1] M. Gündoğan et al., npj Quantum Information 7, 128 (2021)
[2] J. Wallnöfer et al., Commun Phys 5, 169 (2022)
[3] L. Esguerra, et al., arXiv:2203.06151 (2022)

QI 22: Quantum Technologies II (joint session Q/MO/QI)

Time: Wednesday 14:30–16:30 Location: E214

Invited Talk QI 22.1 Wed 14:30 E214

BMBF-Förderprogramm: Wissenschaftliche Vorprojekte — •Bernhard Ihrig und Johannes Mund — VDI Technologiezentrum GmbH

Die zweite Quantenrevolution und die schnell voranschreitenden Entwicklungen in der Photonik bieten großes Potenzial für Anwendungen in Ökonomie, Ökologie und Gesellschaft. Zugleich sind neue Erkenntnisse aus der Grundlagenforschung in einem frühen Stadium hinsichtlich der Herausforderungen und Risiken bei der Umsetzung oftmals kaum zu beurteilen. Daher müssen wissenschaftlich-technische Vorarbeiten eine Grundlage schaffen, die es ermöglicht, das Potenzial einer neuen Erfindung bzw. der neuen wissenschaftlichen Erkenntnis zu bewerten.

Das Bundesministerium für Bildung und Forschung (BMBF) beabsichtigt daher, sogenannte Wissenschaftliche Vorprojekte (WiVoPro) im Bereich der Photonik und der Quantentechnologien auf Grundlage des Forschungsprogramms Quantensysteme zu fördern. Das Ziel dieser Vorprojekte besteht darin, wissenschaftliche Fragestellungen im Hinblick auf zukünftige industrielle Anwendungen in den Quantentechnologien und der Photonik zu untersuchen. Sie sollen die bestehende Forschungsförderung ergänzen und eine Brücke zwischen Grundlagenforschung und industriegeführter Verbundförderung schlagen.

Wir als Projektträger VDI Technologiezentrum GmbH möchten die Maßnahme in diesem Rahmen vorstellen, bewerben und Ihre Fragen für eine mögliche Förderung beantworten.

QI 22.2 Wed 15:00 E214

Mikrofabrikation von Ionenfallen für einen skalierbaren Quantencomputer — •Eike Iseke[1,2], Friederike Giebel[1,2], Nila Krishnakumar[1,2], Konstantin Thronberens[1,2], Jacob Stupp[1,2], Amado Bautista-Salvador[1,2] und Christian Ospelkaus[1,2] — [1]Leibniz Universität Hannover, Hannover, Deutschlad — [2]Physikalisch Technische Bundesanstalt, Braunschweig, Deutschland

Die Ionenfallentechnologie ist eine vielversprechende Option auf dem Weg zur Entwicklung eines skalierbaren Quantencomputers. Eine mögliche Realisierung stellt die Multilagen-Ionenfalle dar [1]. Durch multiple Lagen wird die Integrationsdichte entscheidend erhöht und es können neuartige Ionenfallendesigns realisiert werden.

Die zunehmende Komplexität der Fallen stellt neue Anforderungen an die Mikrofabrikationsmethoden. Forschung und Entwicklung in diesem Feld fokussieren sich unter anderem auf die Interposer-Technologie, das Thermokompressionsbonden und die Substratdurchkontaktierung mittels TSVs (through silicon vias).

Diese fortschrittlichen Fabrikationsmethoden ermöglichen die Skalierung der Plattform sowohl durch die Möglichkeit die Anzahl der geführten Signale zu erhöhen, als auch durch die gesteigerte Zuverlässigkeit der Verbindungstechnologie.

QI 22.3 Wed 15:15 E214

Squeezed States of Light for Future Gravitational Wave Detectors at a Wavelength of 1550 nm — •Fabian Meylahn[1,2], Benno Willke[1,2], and Henning Vahlbruch[1,2] — [1]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany — [2]Leibniz Universität Hannover, D-30167 Hannover, Germany

The generation of strongly squeezed vacuum states of light is a key technology for future ground-based gravitational wave detectors (GWDs) to reach sensitivities beyond their quantum noise limit. For some proposed observatory designs, an operating laser wavelength of 1550 nm or around 2 μm is required to enable the use of cryogenically cooled silicon test masses for thermal noise reduction. Here, we present the first the direct measurement of up to 11.5 dB squeezing at 1550 nm over the complete detection bandwidth of future ground-based GWDs ranging from 10 kHz down to below 1 Hz. Furthermore, we directly observe a quantum shot-noise reduction of up to 13.5 dB at megahertz frequencies. This allows us to derive a precise constraint on the absolute quantum efficiency of the photodiode used for balanced homodyne detection. These results hold important insight regarding the quantum noise reduction efficiency in future GWDs, as well as for quantum information and cryptography, where low decoherence of nonclassical states of light is also of high relevance.

QI 22.4 Wed 15:30 E214

A single-photon source based on hot Rydberg atoms — •Jan Reuter[1,2], Max Mäusezahl[3], Felix Moumtsilis[3], Tilman Pfau[3], Tommaso Calarco[1,2], Robert Löw[3], and Matthias Müller[1] — [1]Forschungszentrum Jülich GmbH — [2]Universität zu Köln — [3]Universität Stuttgart

The leading effects of a single-photon source based on Rydberg atoms are the strong van-der-Waals interaction between the atoms as well as the collective decay of the atom ensemble. Our setup is a vapor cell filled with Rubidium atoms which we excite via three different laser pulses. The decay of this excitation will then lead to the emission of a single photon. To ensure robustness, we investigated the behavior of moving Rydberg atoms and optimized the laser pulse sequence. For that, we simulated the transitions of Rubidium atoms from the ground state over the Rydberg state up to the singly-excited collective states. We can show that the collective decay of the single excitations leads to a fast and directed photon emission, while double excitations show no or only weak collective properties.

QI 22.5 Wed 15:45 E214

Resolving photon numbers using ultra-high-resolution timing single-channel electronic readout of a conventional superconducting nanowire single photon detector — •Gregor Sauer[1,2], Mirco Kolarczik[3], Rodrigo Gomez[1,2], Helmut Fedder[3], and Fabian Steinlechner[1,2] — [1]Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University, 07743 Jena, Germany — [2]Fraunhofer Institute for Applied Optics and Precision Engineering IOF, 07745 Jena, Germany — [3]Swabian Instruments GmbH, 70435 Stuttgart, Germany

Photon-number-resolving (PNR) detectors are indispensable building blocks for applications in quantum communications, computing, and sensing. PNR is commonly achieved by multiplexing onto several superconducting nanowire single-photon detectors (SNSPD) or using transition-edge sensors with energy- and photon-number resolution. This comes at the cost of resource overhead (for multiplexing) or long recovery times (for transition-edge sensors).

Here, we show how ultra-high-resolution timing measurements of the rising and falling edge of electrical pulses generated from the SNSPDs enable to distinguish photon numbers of up to 5 in a single-shot measurement. This provides a practical and comparably low-cost PNR detector, offering high detection efficiency and operational repetition rate. We present the implementation of such a PNR detector system (in the telecom C-band) and its characterization by measuring the photon-number statistics of a 300fs-pulsed coherent input source with tunable average photon number and repetition rate.

QI 22.6 Wed 16:00 E214

N00N-states for super-resolving quantum imaging and sensing — •Gil Zimmermann[1] and Fabian Steinlechner[1,2] — [1]Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University, 07743 Jena, Germany — [2]Fraunhofer Institute for Applied Optics and Precision Engineering IOF, 07745 Jena, Germany

Quantum measurement techniques can serve to improve precision imaging and sensing through entanglement. Employing N00N-states, i.e., maximally path-entangled photon-number states of two modes, the Heisenberg limit 1/N with N photons can be reached in precision phase measurements, thus overcoming the shot-noise limit. Furthermore, the Rayleigh diffraction limit can be overcome by a factor N. Therefore, the goal is to efficiently generate high N00N-states with N>2 to improve current sensing schemes achieving super-resolution and super-sensitivity. High-N00N states with N=5 photons have already been generated experimentally with high fidelity, as shown by Afek et al. This talk will focus on schemes with relatively low complexity to generate high N00N-states. In addition, applications of high-N00N states, e.g., in the context of quantum-enhanced lidar systems or quantum microscopy, are discussed, taking into account their high fragility due to interactions with the environment.

QI 22.7 Wed 16:15 E214

Non-destructive measurement of phonon number states using the Autler-Townes effect — •Marion Mallweger[1], Murilo de Oliveira[2], Robin Thomm[1], Harry Parke[1], Natalia Kuk[1], Gerard Higgins[1,3], Romain Bachelard[2,4], Celso Villas-Boas[2], and Markus Hennrich[1] — [1]Department of Physics, Stockholm University, Sweden — [2]Departamento de Física, Universidade Federal de São Carlos, Brazil — [3]Department of Microtechnology and Nanoscience (MC2), Chalmers University of Technology, Sweden — [4]Université Côte d'Azur, CNRS, Institut de Physique de Nice, France

Quantum technologies employing trapped ion qubits are currently some of the most advanced systems with regards to experimental methods in quantum computation, simulation and metrology. This is primarily due to the excellent control available over the ions' motional and electronic states. In this work we present a new method to measure the distribution of motional number states in a non-destructive manner. The technique can be applied to all platforms where a quantum harmonic oscillator is coupled to a three level system. We demonstrate the technique using a single trapped $^{88}Sr^{+}$ ion. The method relies on the Autler-Townes effect that arises when two levels are strongly coupled while being probed by a third level. If the two levels are coupled on a sideband transition, then the magnitude of the Autler-Townes splitting depends on the phonon number state. This new method provides a robust and efficient way of measuring motional states of quantum harmonic oscillators. It can even be applied to perform single shot measurements of phonon number states in a non-destructive way.

QI 23: Poster II (joint session QI/Q)

Time: Wednesday 16:30–19:00 Location: Empore Lichthof

QI 23.1 Wed 16:30 Empore Lichthof

New techniques to improve zero-noise extrapolation on superconducting qubits — •Kathrin Koenig[1,2], Thomas Wellens[1], and Finn Reinecke[1,2] — [1]Fraunhofer IAF, Freiburg, Germany — [2]University of Freiburg, Germany

Currently available quantum computing hardware suffers from errors due to environmental influences, nearest-neighbour interactions and imperfect gate operations. To achieve robust quantum computing, there are techniques like error mitigation by zero-noise extrapolation [1]. We propose a method for estimating the strength of the error occurring in a given quantum circuit in order to improve the result of this extrapolation. Furthermore, the impact of gate errors on observable expectation values can be reduced by noise tailoring, which converts arbitrary errors into stochastic Pauli errors [2]. Using these techniques, we elaborate on the implementation of error mitigation on a superconducting quantum computer and its impact on the computation of expectation values.

[1] He, A. et al., Zero-noise extrapolation for quantum-gate error mitigation with identity insertions, Phys. Rev. A 102, 012426 (2020)

[2] Wallman, J. J.; Emerson, J., Noise tailoring for scalable quantum computation via randomized compiling, Phys.Rev. A 94, 052325 (2016)

QI 23.2 Wed 16:30 Empore Lichthof

Introducing Non-Linear Activations into Quantum Generative Models — •Mykolas Sveistrys[1,2], Kaitlin Gili[2], and Chris Ballance[2] — [1]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany — [2]Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, U.K.

One prominent difference between most classical generative models and current quantum ones is linearity: classical neural-network-based models require non-linear activations for quality training, while embedding such activations in quantum models is challenging due to the linearity of quantum mechanics. We introduce a quantum generative model that adds non-linear activations via a neural network structure onto the standard Born Machine framework - the Quantum Neuron Born Machine (QNBM). We utilize a previously introduced Quantum Neuron subroutine, which is a repeat-until-success circuit with mid-circuit measurements and classical control. We then compare the QNBM to the linear Quantum Circuit Born Machine (QCBM). With gradient-based training, we show that while both models can easily learn a trivial uniform probability distribution, on a more challenging class of distributions, the QNBM achieves an almost 3x smaller error rate than a QCBM with a similar number of tunable parameters. We therefore provide evidence that suggests that non-linearity is a useful resource in quantum generative models, and we put forth the QNBM as a new model with good generative performance and potential for quantum advantage.

QI 23.3 Wed 16:30 Empore Lichthof

Quantum low-precision neural networks and their classical counterparts — •Felix Soest, Konstantin Beyer, and Walter Strunz — Institut für Theoretische Physik, Technische Universität Dresden, Dresden, Germany

With increasing accessibility of quantum computing devices and the successes of classical machine learning, efforts have been made to combine the two. Whether using quantum resources can provide an advantage to trainability or generalisability remains an open question, as the size of classical neural networks is much larger than what current quantum technologies can offer. Moreover, a clear indication of a quantum advantage is usually hard to identify. An often considered ansatz is that of parametrised unitaries, where the quantum machine learning model comprises multiple layers the parameters of which are trained classically. It has recently been shown that these models have classical surrogates [1], allowing for a classical benchmark to compare these models to. However, classical feed-forward neural networks can in general not be mapped to unitaries, in part due to the lack of irreversibility. Therefore we aim to construct a framework using intermediate measurements which has a classical counterpart. The resulting network is a parametrised quantum channel that allows us to reproduce classical low-precision networks as a special case. Allowing for quantum operations in this framework extends the classical regime, providing a good benchmark.

[1] Schreiber et al. arXiv:2206.11740

QI 23.4 Wed 16:30 Empore Lichthof

Learning Quantum Processes — Kerstin Beer[1], Dmytro Bondarenko[1,2], Terry Farelly[1], Younes Javanmard[1], Tobias J. Osborne[1], Debora Ramaciotti[1], Nils Renziehausen[1], Robert Salzmann[1,3], •Viktoria-Sophie Schmiesing[1], Robin Syring[1], Nils Zolitschka[1], and Ramona Wolf[1] — [1]Institut für theoretische Physik, Leibniz Universität Hannover — [2]Stewart Blusson Quantum Matter Institute, University of British Columbia — [3]Department of Applied Mathematics and Theoretical Physics, University of Cambridge

Machine learning and quantum computing are both emerging topics of research. In this poster, we tackle the issue of learning quantum processes. To do so, we use dissipative quantum neural networks.

QI 23.5 Wed 16:30 Empore Lichthof

Exact Qubit Resonance Calibration and Power Narrowing — •Ivo Mihov and Nikolay Vitanov — Department of Physics, St Kliment Ohridski University of Sofia, 5 James Bourchier blvd, 1164 Sofia, Bulgaria

At resonance, pulse shapes do not affect the population transfer; nevertheless, pulse shapes play a vital role in shaping the resonance response curves of a qubit. The response curves react differently to Rabi frequency increases, where some exhibit power broadening (e.g. rectangular pulses) but other ones do not change their width. In this work, the experimental frequency response curves of various pulse shapes were validated against theoretical predictions. Also, the effects of symmetrical truncation of Lorentzian-shaped pulses to different degrees were examined. More significantly, a solid power narrowing pattern was observed in Lorentzian pulses.

QI 23.6 Wed 16:30 Empore Lichthof

The QuMIC project - Towards a scalable ion trap with integrated high-frequency control — •Sebastian Halama[1] and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [2]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Ion traps are a promising candidate for a scalable quantum computer [1]. A major challenge is the integration of qubit control into the device. With the microwave near-field approach [2], qubit control realized by microwave conductors that are integrated into the ion trap naturally scale with the trap itself. However, the microwave signal generation currently takes place outside of the vacuum chamber in which the ion trap is located. The QuMIC project researches and develops novel highly integrated BiCMOS chips at high frequencies and their hybrid integration with quantum electronics like ion traps. This approach enables the scalability of a quantum computer to a large number of qubits and a drastic reduction in the number of required high-frequency lines, which also benefits the cooling capabilities of the cryostat used to cool down the ion trap to around 4 K. We describe the setup of a cryogenic ion trap apparatus for rapid testing of traps, such as the ion traps with integrated microwave sources developed for QuMIC. We will report on the current status of the project.

[1] Chiaverini et al., Quantum Inf Comput **5**, 419-439 (2005)
[2] Ospelkaus et al., Phys. Rev. Lett. **101**, 090502 (2008)

QI 23.7 Wed 16:30 Empore Lichthof

Tailored based composite pulses for NV-color centers towards the realization of ensembles-based quantum tokens — •Jan Thieme, Josselin Bernardoff, Ricky-Joe Plate, and Kilian Singer — Experimentalphysik I, Universität Kassel, Heinrich-Plett-Straße 40, 34132 Kassel

We present numerical and experimental results of the application of tailored composite pulses [1] to shape the excitation profile addressing only selected resonances of quantum states in the system. By using analytical methods applied to the Rosen-Zener excitation model [2], we derive excitation profiles for a broadband excitation profile with respect to detuning and pulse duration. Towards this goal we are using an arbitrary waveform generator to supply these pulses to single nitrogen-vacancy color centers [3]. In the outlook we will describe how this scheme is relevant for the realization of ensemble-based quantum tokens [4].

[1] B. T. Torosov and N. V. Vitanov, Phys. Rev. A 83, 053420 (2011). [2] N. Rosen and C. Zener, Phys. Rev. 40, 502 (1932). [3] A. Schmidt, J. Bernardoff, K. Singer, J. P. Reithmaier and C. Popov, Physica Status Solidi A, 216, 1900233 (2019). [4] https://www.forschung-it-sicherheit-kommunikationssysteme.de/projekte/diqtok

QI 23.8 Wed 16:30 Empore Lichthof

Quantum speed limit dependence on the number of controls in a qubit array. — •David Pohl, Fernando Gago-Encinas, and Christiane P. Koch — Arnimallee 14, 14195 Berlin

Qubit arrays form the basic unit of quantum computers. As such, it is desirable to be able to manipulate each qubit as needed. However, including a local control on every qubit is not scalable to a large number of qubits. On the other hand, reducing the number of controls might be sufficient for manipulation but slow down the implementation of quantum gates, bringing the system closer to the decoherence limit. Here, we investigate how quickly quantum gates can be implemented depending on the number of local controls. In particular, we show how the quantum speed limit (the shortest time to generate a quantum gate) increases when reducing the number of controls. We determine this limit for a universal set of gates for different 3-qubit systems using Krotov's optimization method.

QI 23.9 Wed 16:30 Empore Lichthof

Towards realizing an ultra-high vacuum chamber and experimental control of trapped ion systems using surface traps. — •Maharshi Pran Bora, Ulrich Warring, Florian Hasse, Deviprasath Palani, Phillip Kiefer, Apurba Das, Lucas Eisenhart, Tobias Spanke, and Tobias Schaetz — Physikalisches Institut, Freiburg, Albert-Ludwigs-Universität, Deutschland

Trapped ion systems are promising platforms for realizing quantum systems for quantum simulations and quantum information processing.The scalability and performance of these trapped ion systems depends crucially on the vacuum apparatus in which the trap is operated in and also on the efficiency and robustness of the experimental control of these systems. The project firstly aims at designing and characterizing an ultra-high vacuum chamber for the Phoenix surface trap produced at the Sandia National Laboratories . The Phoenix trap is a state of the art linear surface trap with high optical access. The scope of the project will include reaching an vacuum pressure of less than 10^{-9} Pa and consideration of an optimum design for the proper functioning of the trap . Secondly, to attain better experimental control, addressing of individual ions with a local beam using piezo devices will be also explored in this project . The calibration and characterization of the piezo driven platform will be reported. Hence, this project will aim at providing an improved understanding of the impact of UHV design and experimental control on the quality of operation of trapped ion systems.

QI 23.10 Wed 16:30 Empore Lichthof

Towards Quantum Control of Calcium Ions for the use in Molecular Spectroscopy — •Manika Bhardwaj, Josselin Bernardoff, Jan Thieme, Daqing Wang, and Kilian Singer — Experimentalphysik I, Universität Kassel, Heinrich-Plett-Str. 40, 34132 Kassel

We are building a measurement methodology for selective spectroscopy of long-lived states with a calcium ion. We want to use binary search on the $4^2S_{1/2}$-$3^2D_{5/2}$ transition of the calcium atom for the resonance search. Through the use of composite pulses techniques, we will change the narrow excitation profile with a passband pulse [1] for binary search. The final goal is to employ this method to identify the long-lived states of the lanthanoid molecular ions [2] targeting their use in molecular quantum information processing platforms.

References:

[1] B. T. Torosov, and N. V. Vitanov, Physical Review A 83, 053420 (2011).

[2] K. Groot-Berning, T. Kornher, G. Jacob, F. Stopp, S. T. Dawkins, R. Kolesov, J. Wrachtrup, K. Singer, and F. Schmidt-Kaler, Physical Review Letters 123, (2019).

QI 23.11 Wed 16:30 Empore Lichthof

Optimising gate performance of transmon qubits coupled by a central tunable bus — •Alexander Möller[1,2], Matthias G. Krauss[2], Daniel Basilewitsch[2,3], and Christiane P. Koch[2] — [1]Technische Universität Berlin, Berlin, Germany — [2]Freie Universität Berlin, Berlin, Germany — [3]Universität Innsbruck, Innsbruck, Austria

For transmon qubits coupled via a transmission line cavity, optimal control theory (OCT) has identified the quasi-dispersive regime to be optimal for universal quantum computing. For a single control driving the harmonic coupler, both local and entangling gates can be implemented with high fidelity and short gate durations [Goerz et al., *npj Quantum Information* **3**, 37 (2017)]. In an analogous manner we aim at exploring the transmon parameter landscape for a system of two transmons addressed by a third transmon acting as a tunable bus. We investigate how the anharmonicity of this central coupler affects the implemented gates and the OCT optimisation. Here we especially focus on the controllability of the two-transmon-subsystem as well as the achievable gates for different pulse durations and from this determine their respective quantum speed limit. Furthermore, we present an effective analytical model for the coupling between the outer transmons.

QI 23.12 Wed 16:30 Empore Lichthof

Single qubit gate optimization based on ORBIT cost functions — •Catharina Broocks[1,2], Max Werninghaus[1], Niklas Glaser[1,2], Federico Roy[1,3], and Stefan Filipp[1,2,4] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]Physik Department, Technische Universität München, Garching, Germany — [3]Theoretical Physics, Saarland University, Saarbrücken, Germany — [4]Munich Center for Quantum Science and Technologies (MCQST), Munich, Germany

Analytic control solutions for qubit gates are limited by the knowledge about modeled experimental hardware properties. To achieve high-fidelity gates for superconducting qubit devices, we optimize pulse parameters of analytic solutions with respect to experimental feedback loops. As cost function the ground state population after a net-identity series of Clifford gates is used. For small parameter sets, the parameter-landscape can serve as a reference to verify numerical system models and provide insight into the sensitivity and correlation of individual parameters. To find an optimal parameter configuration, we apply simultaneous multi-parameter optimization of single-qubit gates in form of CMA-ES closed-loop optimization. We analyze the behavior of the optimization algorithm when using features such as sensitivity adjustment, influence of various noise contributions and the design of the cost function to achieve a reliable and complete convergence of the algorithm. The optimization routine can then be used to verify and address various optimal control problems, such as robustness and avoidance of leakage out of the qubit subspace.

QI 23.13 Wed 16:30 Empore Lichthof

Predicting the minimum control time of quantum protocols with artificial neural networks — •Sofia Sevitz[1], Nicolás Mirkin[1], and Diego A. Wisniacki[1,2] — [1]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, Buenos Aires, Argentina — [2]CONICET - Universidad de Buenos Aires, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina

Quantum control relies on the driving of quantum states without the loss of coherence, thus the leakage of quantum properties onto the environment over time is a fundamental challenge. One work-around is to implement fast protocols, hence the Minimal Control Time (MCT) is of upmost importance. Here, we employ a machine learning network in order to estimate the MCT in a state transfer protocol. An unsupervised learning approach is considered by using a combination of an autoencoder network with the k-means clustering tool. The Landau-Zener (LZ) Hamiltonian is analyzed given that it has an analytical MCT and a distinctive topology change in the control landscape when the total evolution time is either under or over the MCT. We obtain that the network is able to not only produce an estimation of the MCT but also gains an understanding of the landscape's topologies. Similar results are found for the generalized LZ Hamiltonian while limitations to our very simple architecture were encountered.

QI 23.14 Wed 16:30 Empore Lichthof

Error Budget for the Sørensen-Mølmer Gate — •Susanna Kirchhoff[1,2], Frank Wilhelm-Mauch[1,2], and Felix Motzoi[3] — [1]Institute of Quantum Computing Analytics (PGI 12), Forschungszentrum Jülich, Germany — [2]Theoretical Physics, Saarland University, Saarbrücken, Germany — [3]Institute of Quantum Control (PGI-8), Forschungszentrum Jülich, Germany

The Sørensen-Mølmer gate is an entangling gate for ion qubits, where the entanglement is achieved by a bichromatic laser beam. The gate speed and fidelity are limited by leakage to other levels. We present a detailed expression for the fidelity including higher Lamb-Dicke orders and propose methods to improve gate speed and fidelity.

QI 23.15 Wed 16:30 Empore Lichthof

Optimizing for an arbitrary Schrödinger cat state — •Matthias G. Krauss[1], Anja Metelmann[2], Daniel M. Reich[1], and Christiane P. Koch[1] — [1]Freie Universität, Berlin, Germany — [2]Karlsruhe Institute of Technology, Karlsruhe, 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]. We present a set of cat state functionals which provide more freedom to the optimization algorithms, compared to state-to-state functionals. By using Krotov's method [Reich et al. *J. Chem. Phys.* **136**, 2012], we demonstrate their application by optimizing the dynamics of a Kerr-nonlinear system with two-photon driving and analyze the robustness of the cat state preparation under single and two-photon decay. In addition, we explore the generation of cat states in higher order Kerr systems. Furthermore, we show the versatility of the framework by applying it to a Jaynes-Cummings model and optimize towards arbitrary entangled cat states. We identify the strategy of the obtained control fields and determine the quantum speed limit as a function of the cat state's excitation. Finally, we extend the investigation to open quantum systems to analyze the benefit of reoptimization together with the changes in the control strategy induced by decay.

QI 23.16 Wed 16:30 Empore Lichthof

Operation of a microfabricated 2D trap array — •Marco Valentini[1], Matthias Dietl[1,2], Silke Auchter[1,2], Michael Dieter[1,2], Philip Holz[3], Clemens Rössler[2], Thomas Monz[1,3], Philipp Schindler[1], and Rainer Blatt[1,3,4] — [1]Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria — [2]Infineon Technologies Austria AG, Villach, Austria — [3]Alpine Quantum Technologies GmbH, 6020 Innsbruck, Austria — [4]Institute for Quantum Optics and Quantum Information, 6020 Innsbruck, Austria

We investigate scalable surface ion traps for quantum simulation and quantum computing. We have developed a microfabricated surface trap consisting of two parallel contiguous linear trap arrays with 9 trapping sites each. An interconnected three-metal-layer structure provides addressing of the DC electrodes across the chip and shielding of the silicon substrate. The trap fabrication is carried out by Infineon Technologies in an industrial facility, which allows for complex electrode designs and ensures high process reproducibility. We demonstrate trapping and shuttling of multiple ions in the trap array, and form square and triangular ion-lattice configurations with up to six ions. We characterize stray electric fields and measure ion heating rates between 131(13) and 470(50) ph/s in several trapping sites. Furthermore, we engineered our setup to control independently the RF voltage in between the two linear trap arrays, and we will make use of it to demonstrate motional coupling of ions across the lattice.

QI 23.17 Wed 16:30 Empore Lichthof

Engeneering of tin vacancies in diamond by lattice charging — •Vladislav Bushmakin[1,2], Oliver von Berg[1], Santo Santonocito[1], Sreehari Jayaram[1], Petr Siyushev[1], Rainer Stöhr[1,2], Andrej Denisenko[1,2], and Jörg Wrachtrup[1,2] — [1]Universität Stuttgart, 3. Physikalisches Institut, Allmandring, 13, 70569, Stuttgart, Germany — [2]Max-Plank-Institut für Festkörperforschung Heisenbergstraße 1, 70569 Stuttgart, Germany

Recent advances in the integration of spin-bearing solid-state defects in optical cavities for efficient spin-photon entanglement are mostly associated with silicon vacancy in diamond. Meanwhile, the implantation of diamond with heavier group IV ions promises similar performance but at elevated temperatures above 1 K, which contrasts with the stringent requirement of approximately 100 mK for the coherent manipulation of the SiV electron spin. However, the generation of defects involving heavier atoms, such as tin is accompanied by a high density of defects induced by ion implantation. Here we present a method of reduction of the implantation-induced density of defects by implanting through the Boron-doped charged lattice with a subsequent etching of the damaged layer. The given method is an extension of the conventional implantation technique and hence significantly less experimentally demanding than techniques relying on CVD overgrowth or HPHT annealing. Additionally, it provides better accuracy of implantation and allows for the efficient generation of tin vacancies with a narrow inhomogeneous zero-phonon line distribution.

QI 23.18 Wed 16:30 Empore Lichthof

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[1], Klaus Sengstock[2], and Patrick Windpassinger[1] — [1]Institut für Physik, JGU, Mainz — [2]Institut für Laserphysik, UHH, Hamburg — [3]Centre for Quantum Technologies, NUS, 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 the glass ceramic Zerodur in space borne atom interferometry experiments, e.g. FOKUS, KALEXUS and MAIUS.

On this poster, we present current developments of Zerodur to metal vacuum flanges, enabling 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.

Our work is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) under grant numbers 50WM2266B, 50WP1433 & 50WP2103.

QI 23.19 Wed 16:30 Empore Lichthof

Spin coherence control in an optically pumped magnetometer for space-borne magnetomyography — •Simon Nordenström[1], Victor Lebedev[1], Stefan Hartwig[1], Kirti Vardhan[2], Sascha Neinert[2,3], Jenichi Felizco[3], Martin Jutisz[2,3], Markus Krutzik[2,3], and Thomas Middelmann[1] — [1]Physikalisch-Technische Bundesanstalt, Berlin, Germany — [2]Humboldt-Universität zu Berlin, Berlin, Germany — [3]Ferdinand-Braun-Institut, Berlin, Germany

Detecting astronauts' neuromuscular degeneration with conventional methods such as surface or needle electromyography is inadequate or too detrimental. Optically pumped magnetometers (OPMs), on the other hand, allow for flexible handling and non-invasive measurements, utilizing the unique properties of alkali atom vapors interacting with external magnetic fields and laser light.

In this poster, we report on our progress in implementation of minimally necessary field control facilities to support the highest performance of the OPM, compatible with measurements on a space station. We investigate the balance between atomic spin coherence relaxation processes, anticipated dynamic range and response bandwidth in a magnetically perturbing environment. We present the anticipated system design and test results under lab conditions.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant numbers 50WM2168 and 50WM2069.

QI 23.20 Wed 16:30 Empore Lichthof

Miniaturized fiber-based endoscope with direct laser written antenna structures — •Stefan Dix[1], Jonas Gutsche[1], Erik Waller[1,2], Georg von Freymann[1,2], and Artur Widera[1] — [1]Department of Physics and State Research Center OPTIMAS, University of Kaiserslautern-Landau, 67663 Kaiserslautern, Germany — [2]Fraunhofer Institute for Industrial Mathematics ITWM, 67663 Kaiserslautern, Germany

Fiber-based endoscopic sensors are established and widely applied as local fluorescence detectors for various samples, replacing bulky microscopes. Such sensors require the integration of sensing objects, such as nitrogen-vacancy (NV) centers in diamond and microwave antennas on small scales. Here, the microwave (MW) field addresses a transition in the NV center for magnetic field sensing. The MW fields needed are usually created using thin conducting wires or chip-based antennas close to the diamond sample. These approaches either lead to fragile, bulky, or inefficient sensor tips.

Here, we present a robust fiber-based endoscope with a direct laser written silver antenna structure close to a 50 μm multimode fiber core for optimal efficiency. Using such an endoscope, we measure an ODMR sensitivity of $17.8\,\mathrm{nT}/\sqrt{\mathrm{Hz}}$ by probing 15 μm large diamonds entirely through the endoscope. Furthermore, we demonstrate a new method for measuring distances based on measurements of the Rabi frequency.

QI 23.21 Wed 16:30 Empore Lichthof

Status and perspective of a next generation, GHz bandwidth, on-demand single-photon source — •Felix Moumtsilis[1], Max Mäusezahl[1], Moritz Seltenreich[1], Jan Reuter[2,3], Hadiseh Alaeian[4], Harald Kübler[1], Matthias Müller[2], Charles Stuart Adams[5], Robert Löw[1], and Tilman Pfau[1] — [1]5. Physikalisches Institut, Universität Stuttgart, Germany — [2]Forschungszentrum Jülich GmbH, PGI-8, Germany — [3]Universität zu Köln, Germany — [4]Departments of Electrical & Computer Engineering and Physics & Astronomy, Purdue University, USA — [5]Department of Physics, Joint Quantum Centre (JQC), Durham University, UK

The ultimate challenge of coherent experiments in thermal vapors lies in the inevitable movement of atoms that must be overcome to profit from this highly scalable and miniturizable platform e.g. for high fidelity Rydberg logic gates. GHz interaction energies and nanosecond dephasing times in a thermal rubidium vapor demand equally fast coherent control of the atomic excitations, movement, and density.

Here we report on the current state, technical challenges, and the perspective of our next generation single photon source based on the Rydberg blockade. This involves an electronic pulse shaping system with sub-nanosecond jitter, two state-of-the-art 1010 nm pulsed fiber amplifiers, an ultra narrow yet high-contrast wavelength filtering of single photons, high NA focussing, and detection. Beyond our established micrometer thick wedged cells, we investigate novel glass cell geometries requiring a whole new set of manufacturing technologies.

QI 23.22 Wed 16:30 Empore Lichthof

Magnetometry with NV centers and Waveguide-Assisted Detection Channels — •Sajedeh Shahbazi[1], Michael Hoese[1], Michael K. Koch[1,2], Vibhav Bharadwaj[1,3], Johannes Lang[1], Argyro N. Giakoumaki[3], Roberta Ramponi[3], Fedor Jelezko[1,2], Shane M. Eaton[3], and Alexander Kubanek[1,2] — [1]Institute for Quantum Optics, Ulm University, Ulm, Germany — [2]Center for Integrated Quantum Science and Technology (IQst), Ulm University, Ulm, Germany — [3]Institute for Photonics and Nanotechnologies (IFN) - CNR, Milano, 20133, Italy

The negatively charged Nitrogen-Vacancy(NV) center in diamonds has shown great success in nanoscale, high-sensitivity magnetometry. Efficient fluorescence detection is crucial for improving sensitivity and for practical sensor-integrated devices. One way to approach such a goal is using ultrafast laser writing waveguides on the diamond to create such an on-chip integrated quantum sensor. Here, we present femtosecond laser-written type II waveguides on a diamond surface, integrated with NV centers a few nanometers below the diamond surface while covering the entire mode field of waveguides [1]. We experimentally verify the coupling efficiency and the detection of magnetic resonance signals through the waveguides to perform magnetic field sensing. In the future, our approach will enable the development of two-dimensional sensing arrays facilitating spatially and temporally correlated magnetometry.

[1] M. Hoese et al., Phys. Rev. Applied 15, 054059 (2021)

QI 23.23 Wed 16:30 Empore Lichthof

Experimentation platform towards a standardized characterization of ion traps for industrial and academic users — •Hemanth Kalathur[1], André P. Kulosa[1], Erik Jansson[1], Elena Jordan[1], Jan Kiethe[1], Nicolas Spethmann[1], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig — [2]Leibniz Universität Hannover, Hannover

Enabling technologies for quantum technologies (QT), such as ion traps, have become indispensable in the fields of quantum computing, quantum simulation, and quantum sensing. A successful commercialization of QT requires extensive knowledge exchange between research and industry.

The Quantum Technology Competence Center (QTZ) at PTB has the central goal of becoming the bridge between research and industry in Germany. The user facility "Ion Traps" of QTZ will provide a user-friendly experimentation platform for the standardized characterization of ion traps. In the long term, the performance of ion traps, e.g. ion micromotion and heating rates will be characterized. We will use incorporated automated routines to enable intuitive access to our measurement platform for collaborators even with a non-physics background. Here, we report about our experimentation platform in operation and the first comprehensive characterization of an ion trap as a cornerstone for the future standardization activities of QTZ.

QI 23.24 Wed 16:30 Empore Lichthof

Absorption sensing mode in radio frequency electrometry using Rydberg atoms in hot vapors — •Matthias Schmidt[1,2], Stephanie Bohaichuk[1], Chang Liu[1], Harald Kübler[2], and James P. Shaffer[1] — [1]Quantum Valley Idea Laboratories , 485 Wes Graham Way, Waterloo, ON N2L 6R1, Canada — [2]5. Physikalisches Institut, Universität Stuttgart, Pfaffendwaldring 57, 70569 Stuttgart

We present progress in atom-based RF E-field sensing using Rydberg atoms in hot vapors. There are two distinct strategies to detect the electric field strength of the RF wave, namely the Autler-Townes limit, where the splitting of the dressed states is proportional to the incident RF electric field strength and the amplitude regime, where we determine the electric field by measuring the difference of transmission in the presence of the RF electromagnetic field. We present theoretical calculations for the amplitude regime, using a two photon excitation scheme, that show how the scattering of the probed transition changes in the presence of the RF electromagnetic field. We find an analytical expression in the thermal limit with finite wave vector mismatch that yields an accurate approximation compared to full density matrix calculation in the strong coupling limit. Our work extends the understanding of the detection of weak RF E-fields with Rydberg-atom based RF sensors. Furthermore, we present a three photon excitation scheme, with which residual Doppler broadening is suppressed. This enables a spectral resolution comparable to the Rydberg state decay rate, the spectral bandwith limitation.

QI 23.25 Wed 16:30 Empore Lichthof

Measurement of the phase-matching function in PPKTP waveguides — •Jan-Lucas Eickmann, Florian Lütkewitte, Kai-Hong Luo, Michael Stefszky, Laura Padberg, Harald Herrmann, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

Single-photon sources with high purity are a prerequisite for the development of practical photonic quantum computation. Spontaneous parametric down-conversion in periodically poled potassium titanyl phosphate (PPKTP) is a promising approach to generate spectrally pure quantum light by achieving a phase-matching function perpendicular to the pump function. However, the phase-matching function varies with the condition of waveguide fabrication and the quality of periodic poling. Therefore, a precise measurement of the phase matching dependence is crucial for integrated photonic quantum source engineering. In this work, we present a method for measuring the phase-matching function in PPKTP waveguides by exploiting sum-frequency generation. Using the measured phase-matching function, we reconstruct the joint spectral intensity (JSI) for different pump fields to assure the spectral purity of the heralded photon. We observe that the phase matching results in JSI functions with a tilt of around 60°, deviating 15° from a symmetric function required for optimum pure state preparation.

QI 23.26 Wed 16:30 Empore Lichthof

Control of NV centers in nanodiamonds for sensing applications — •Dennis Lönard and Artur Widera — Physics Department and State Research Center OPTIMAS, RPTU Kaiserslautern, Erwin-Schroedinger-Str. 46, 67663 Kaiserslautern, Germany

The nitrogen-vacancy (NV) color center in diamond is an essential platform for magnetic field sensing for technical and biological applications. One major advantage is that the spin state of the NV-center can be read out optically via the fluorescence. Different spin manipulation schemes, like Ramsay or Hahn echo sequences, have been proposed to influence the interaction between the final spin state and the magnetic field that is to be measured. However, the experimentally achieved sensitivities to outer magnetic fields is still far from their theoretical limits, each measurement scheme having its own set of limitations, often due to the dephasing of the spin states of neighboring NV-centers. I will present our work to further improve the limits of sensing, spanning from technical control to the prospect of combining different methods of manipulating and sensing the NV center and exploiting their multi-level structure.

QI 23.27 Wed 16:30 Empore Lichthof

Predicting coupling efficiency of KTP waveguides and fibers by mode measurement — •Florian Lütkewitte, Jan-Lucas Eickmann, Kai Hong Luo, Michael Stefszky, Laura Padberg, Harald Herrmann, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute of Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098, Paderborn, Germany

Reliable generation of photonic quantum states is of high importance for fundamental physics and quantum networks. Due to its unique dispersion properties, spontaneous parametric downconversion (SPDC) in potassium titanyl phosphate (KTP) has gathered extensive research attention as a source of heralded single photons in the telecom range. Fiber-based devices allow for plug-and-play usage omitting time-intensive free-space coupling. Integration of SPDC sources in fiber networks can be achieved with fiber-pigtailed KTP waveguides. However, single-mode waveguides in KTP show imperfect overlap with single-mode fibers due to their asymmetry and a size-mismatch between modes. Thus, optimized mode-adapted fibers are required to obtain a plug-and-play heralded photon source in KTP. In this work, we measured the mode profile of waveguides and several tapered fibers. Comparing the mode overlap, the optimal waveguide-fiber combination has been determined with upper-bound coupling efficiency of $(90\pm1)\%$, based on the mode overlap integral over their measured mode profile.

QI 23.28 Wed 16:30 Empore Lichthof

Integrated optics for scaling up the performace of ion based quantum computers — •Steffen Sauer[1,2], Carl-Frederik Grimpe[3], Anastasiia Sorokina[1,2], Guochun Du[3], Pascal Gehrmann[1,2], Tunahan Gök[6,7], Radhakant Singh[6,7], Pragya Sah[6,7], Babita Negi[7], Maxim Lipkin[6,7], Stephan Suckow[6], Elena Jordan[3], Tanja Mehlstäubler[3,4,5], and Stefanie Kroker[1,2,3] — [1]Institut für Halbleitertechnik, Technische Universität Braunschweig, Braunschweig, Germany — [2]Laboratory for Emerging Nanometrology, Braunschweig, Germany — [3]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [4]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — [5]Laboratorium für Nano- und Quantenengineering, Hannover, Germany — [6]AMO GmbH, Advanced Microelectronic Center Aachen, Aachen, Germany — [7]Chair of Electronic Devices, RWTH Aachen University, Aachen, Germany

Ions trapped on chips are one of the most promising approaches for quantum computers. The approach offers the advantage of high fidelity, long coherence time and scalability. In addition, the ion physics and trap chip technology are well understood. The key component for the scalability of this quantum computers are integrated optical devices, such as waveguides to transport light or grating outcouplers to emit *m beams to the ions. In the joint project ATIQ, this approach is being pursued with the aim of realising a quantum computer with

40 qubits (ions). We present simulations of integrated optical components, their applications on chips and our characterization setups.

QI 23.29 Wed 16:30 Empore Lichthof

Towards a Micro-Integrated Optically Pumped Magnetometer for Biomagnetism in Space — •Kirti Vardhan[1], Sascha Neinert[1,2], Jenichi Felizco[2], Marc Christ[1,2], Kai Gehrke[2], Andreas Thies[2], Olaf Krüger[2], Martin Jutisz[1,2], Mustafa Gündoğan[1,2], Victor Lebedev[3], Stefan Hartwig[3], Simon Nordenström[3], Thomas Middelmann[3], and Markus Krutzik[1,2] — [1]Humboldt-Universität zu Berlin, Berlin, Germany — [2]Ferdinand-Braun-Institut, Berlin, Germany — [3]Physikalisch-Technische Bundesanstalt, Berlin, Germany

Detecting astronauts' neuromuscular degeneration with conventional methods such as surface or needle electromyography is inadequate or too detrimental. Optically pumped magnetometers (OPMs), on the other hand, allow for flexible handling and non-invasive measurements, utilizing the unique properties of alkali atom vapors interacting with external magnetic fields and laser light.

In this poster, we report on our progress towards a miniaturised, ruggedized OPM sensor head based on in-house fabricated MEMS cells for measuring biomagnetic signals in a moderately shielded environment. To this end we compare the performance of first prototypes of a micro-integrated sensor to a functional lab-scale magnetometer setup.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant numbers 50WM2168 and 50WM2169.

QI 23.30 Wed 16:30 Empore Lichthof

Additive manufacturing, micro-integration and semiconductor fabrication for compact cold atom systems — Marc Christ, •Alisa Ukhanova, Simon Kanthak, Thomas Flisgen, Conrad Zimmermann, Jörg Fricke, Olaf Brox, Andrea Knigge, Wolfgang Heinrich, and Markus Krutzik — Ferdinand-Braun-Institut (FBH), Leibniz-Institut für Höchstfrequenztechnik, Berlin

Atom-based quantum sensors allow time- and field-sensing applications with an unrivalled precision compared to their classical counterparts. While lab-based operation of cold atom-based devices is well established, a transition to mobile applications requires miniaturized subsystems with reduced complexity, high stability and low size, weight and power requirements. At FBH, we start to address the miniaturization of the sensor*s physics package towards cm-scale systems, including micro-integrated, vacuum-compatible optical systems for atom trapping and manipulation, compact, 3D-printed vacuum chambers and diffraction grating based atom sources. This poster presents an overview of our efforts towards this goal.

This work is supported by FBH and partially supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant number 50WM1949 and 50WM2070.

QI 23.31 Wed 16:30 Empore Lichthof

Fiber-coupled NV Ensembles in Microdiamond as miniaturized Magnetic Field Probes — •Jonas Homrighausen[1], Jens Pogorzelski[2], Peter Glösekötter[2], and Markus Gregor[1] — [1]Department of Engineering Physics, University of Applied Sciences, Münster, Germany — [2]Department of Electrical Engineering and Computer Science, University of Applied Sciences, Münster, Germany

NV centers in diamond are a very promising candidate for precise measurement of magnetic fields. Especially NV ensembles offer the inherent ability for threedimensional reconstruction of the magnetic field vector while being optically adressable in an optically detected magnetic resonance (ODMR) setup. We utilize these properties by coupling NV ensembles in microdiamond to optical fibers in order to create magnetic probes with high spatial resolution. This however poses challenges, amongst which the efficient delivery of microwave exciation to the fiber tip. In this poster, different methods are discussed for this particular application. We use finite element simulations to compare microwave structures and investigate the according ODMR results. Furthermore, we analyse the effect of crystal orientation with respect to locally homogeneous microwave and magnetic fields.

QI 23.32 Wed 16:30 Empore Lichthof

Towards Optically Integrated Trapped Ion Quantum Computing — •Marco Schmauser[1], Philipp Schindler[1], Thomas Monz[1], Marco Valentini[1], Clemens Rössler[2], Klemens Schüppert[2], Bernhard Lamprecht[3], and Rainer Blatt[1,4] — [1]Universität Innsbruck, Innsbruck, Austria — [2]Infineon Technologies Austria AG, Villach, Austria — [3]Joanneum Research, Weiz, Austria — [4]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften

Trapped ion quantum computers are known to be large and complex experiments. One of the reasons for this is that light guidance between lasers and ions is done mainly by free-beam optics, which means that the overall system requires a lot of space and is susceptible to drifts and vibrations. The only way to make such a system compact and scalable is to increasingly integrate functionality, in this specific case optical elements, from external components directly into the ion trap. To solve this problem, a method has been developed to write single-mode and polarization-maintaining waveguides directly into quartz glass using ultrashort laser pulses. These light guides can be tuned to a specific wavelength, ranging from UV to near infrared. The next step is to realize an ion trap with such integrated waveguides. In this context, the approach of a microstructured trap is pursued, which allows for a scalable trap architecture and is compatible with industrial production. In parallel, an integrated cryogenic quantum computing system is being built to enable fast trap changes and additionally investigate the light delivery to the trap chip.

QI 23.33 Wed 16:30 Empore Lichthof

Quantum memory in noble-gas nuclear spins with alkali metal vapour as optical interface — •Norman Vincenz Ewald[1], Tianhao Liu[2], Luisa Esguerra[1,3], Ilja Gerhardt[4], and Janik Wolters[1,3] — [1]German Aerospace Center (DLR), Institute of Optical Sensor Systems, Berlin — [2]Physikalisch-Technische Bundesanstalt, FB 8.2 Biosignale, Berlin — [3]Technische Universität Berlin, Institut für Optik und Atomare Physik, Berlin — [4]Leibniz University Hannover, Institute of Solid State Physics, Light and Matter Group, Hannover

Quantum memories with storage times well beyond 1 s will spawn manifold applications in quantum communication and information processing, e.g. as quantum token for secure authentication. We present our first steps towards a quantum memory with long storage time in a mixture of the noble gas ^{129}Xe and an alkali metal vapour of ^{133}Cs. A custom glass cell at about room temperature contains both species and is placed inside a table-top magnetic shield. Information will be stored in the collective excitation of nuclear spins of ^{129}Xe, which exhibit hours-long coherence times [1]. ^{133}Cs serves as optical interface for signal photons, which we store in a collective spin excitation using EIT [2]. Coherent information transfer to the noble gas spins is based on spin-exchange collisions and will be controlled by synchronisation of Larmor precession [3].

[1] C. Gemmel et al., *Eur. Phys. J. D* **57**, 303–320 (2010).
[2] L. Esguerra et al., arXiv:2203.06151 (2022).
[3] O. Katz et al., *Phys. Rev. A* **105**, 042606 (2022).

QI 23.34 Wed 16:30 Empore Lichthof

Rack-mounted Laser Systems for Quantum Computing with Be$^+$ and Ca$^+$ Ions — •Gunnar Langfahl-Klabes[1], Niels Kurz[2], Malte Stoepper[1,2], Stephan Hannig[1], and Piet Schmidt[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig — [2]Institute of Quantum Optics, Leibniz University Hannover

Co-locating quantum processing units based on ion traps with classical computers in data centers requires highly integrated, transportable, modularized, turn-key laser systems in an overall form factor that complies with 19-inch rack-mount standards.

The ion trap-based quantum computer of Quantum Valley Lower Saxony (QVLS-Q1) uses Be$^+$ ions as qubits and Ca$^+$ ions for sympathetic cooling. Within three half-height server racks we provide all of the necessary lasers for cooling, repumping, and detection. Our systems feature four monolithic rack drawers that contain customized setups for sum-frequency generation, second-harmonic generation, and frequency shifting. All rack-mounted laser outputs are fiber-coupled. Free-space components for ablation and photoionization are placed close to the vacuum chamber.

The wavelengths used in our setup range from deep-UV to near-IR (235, 313, 375, 397, 422, 470, 515, 626, 854, 866, 1051, 1552 nm). With red light at 626 nm we realize a laser stabilization setup via Doppler-free iodine spectroscopy for the Be$^+$ cooling and detection laser system at 313 nm.

We report on the current status of our laser systems.

QI 23.35 Wed 16:30 Empore Lichthof

Towards coherent single praseodymium ion quantum memories in optical fiber microcavities — •Sören Bieling[1], Nicholas Jobbitt[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 a membrane into optical high-finesse fiber-based Fabry-Pérot microcavities. This allows for efficient addressing and detection of individual ions. We report on the design, commissioning and initial characterization of a next-gen cryogenic scanning microcavity as well as on its experimental integration into and design of a self-built vector magnet. It allows for future coherence prolongation by operating under a zero first-order Zeeman (ZEFOZ) shift magnetic field alongside 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 suitable for deployment in scalable quantum networks.

QI 23.36 Wed 16:30 Empore Lichthof

Towards the implementation of microwave near-field entangling gates in a cryogenic surface-electrode ion trap apparatus — •Niklas Orlowski[1], Chloë Allen Ede[1], Niels Kurz[1], Sebastian Halama[1], Timko Dubielzieg[1], Celeste Torkzaban[1], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany — [2]Physikalisch Technische Bundesanstalt, 38116 Braunschweig, Germany

We discuss ion loading using different lasers for the ablation, ionization, cooling and detection of Beryllium ions and describe measures taken to isolate ions from environmental influences, for example by using vibrational decoupling, electromagnetic shielding, and an XUHV-environment [1]. We demonstrate hyperfine state preparation and manipulation with microwave pulses and discuss requirements on radial mode stability for the implementation of entangling microwave quantum gates [2].

[1] Dubielzig et al. RSI 92.4 (2021): 043201
[2] Zarantonello et al. PRL 123, 260503

QI 23.37 Wed 16:30 Empore Lichthof

Synthesis of depth confined nitrogen vacancy centers in diamond — •Karolina Schüle[1], Christoph Findler[1,2], Johannes Lang[1,2], and Fedor Jelezko[1,3] — [1]Institute for Quantum Optics, Ulm University, Ulm, Germany — [2]Diatope GmbH, Ummendorf, Germany — [3]Center for Integrated Quantum Science and Technology (IQST), Ulm, Germany

The negatively charged nitrogen-vacancy center (NV) is a paramagnetic defect (S=1) in diamond which shows coherence times T2 up to milliseconds even at room temperature. The NV is a promising candidate for quantum applications as its spin state can be initialized, read out optically, and manipulated by a microwave field. One way to fabricate NV centers is ion implantation where nitrogen is added into a single crystal diamond layer followed by an annealing process. The depth of the implanted nitrogen can be adjusted by the implantation energy. Larger kinetic energies are leading to deeper NV centers. At the same time, however, the depth distribution gets also broader limiting the degree of depth confinement. This contradicts the goal of homogeneous properties of the NVs beneficial for e.g. NMR applications. Using the method of indirect overgrowth, where implanted nitrogen is buried below a nanometer-thin capping layer of diamond. The resulting depth of the NV centers is decoupled from the implantation ion energy. Here, we show outstanding depth confinement resulting in single NVs which are located at a depth of around 20 nm confined in a range of approx. 1.4 nm. These NV centers are exhibiting a T2 up to ~100 μs.

QI 23.38 Wed 16:30 Empore Lichthof

Industrially microfabricated ion traps for quantum information processing — •Schey Simon[1,2], Pfeifer Michael Dieter Josef[1,3], Glantschnig Max[1,4], Anmasser Fabian[1,3], Abu Zahra Mohammad[1], Auchter Silke[1,3], Brandl Matthias[1], Schüppert Klemens[1], Colombe Yves[1], and Rössler Clemens[1] — [1]Infineon Technologies Austria AG, Villach, Austria — [2]Stockholm University, Stockholm, Sweden — [3]University of Innsbruck, Austria — [4]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Infineon Technologies is fabricating 2D and 3D ion trap chips in its industrial facilities [1,2]. This poster gives an overview of our work towards large-scale, reliable ion traps.

We are developing multiple fabrication processes on silicon and dielectric substrates for, e.g., multi-metal stacks with low resistance at cryogenic temperatures, and surfaces resilient to UV laser beam exposure, which we characterize using analytical tools (cryogenic probe station, KPFM microscopy). Together with partners, we design and produce ion traps with integrated optical waveguides, and traps for ion shuttling with ~200 electrodes, that will be operated with a custom cryo-compatible electronic chip. We present a second-generation ion trap socket that allows fast exchange of traps, which we use in our ion trapping lab and make available to our partners.

[1] Ph. Holz, S. Auchter et al., Adv. Quantum Technol. 3, 2000031 (2020)
[2] S. Auchter, C. Axline at al., Quantum Sci. Technol. 7, 035015 (2022)

QI 23.39 Wed 16:30 Empore Lichthof

Characterization of single-photon emitters in hexagonal boron nitride at room temperature — •Leonora Meier[1], Pablo Tieben[2], Stefan Kück[1], Andreas Schell[2], and Marco López[1] — [1]PTB, Braunschweig, Deutschland — [2]Leibniz Universität, Hannover, Deutschland

In this work we present a study on point defects of hexagonal boron nitride (hBN) which exhibit high brightness and narrow band single photon properties. So far, several samples containing hBN defects with different concentrations have been fabricated and characterized. The characterization is performed in terms of their spectrum, single-photon purity (g(2)(0)) and stability.

It has been observed that different emitters with hBN defects exhibit different spectra, even though the single-photon purity of g(2)(0) is less than 0.3. The single-photon emission stability remains a challenge. Blinking and bleaching were observed even though the time period of stability differs greatly between different emitters.

To improve the stability of the single-photon emission, different annealing procedures will be applied; for example, heating the sample to 500°C. In addition, the variation of photoluminescence as a function of an in-plane magnetic field will be studied to determine whether hBN point defects can be used as a magnetic sensor.

QI 23.40 Wed 16:30 Empore Lichthof

Near Field Modeling for Quantum Gate Operation — •Axel Hoffmann[1], Florian Ungerechts[2], Rodrigo Munoz[2], Brigitte Kaune[2], Teresa Meiners[2], Christian Ospelkaus[2,3], and Dirk Manteuffel[1] — [1]Institut für Hochfrequenztechnik, Hannover, Leibniz Universität Hannover — [2]Institut für Quantenoptik, Hannover, Leibniz Universität Hannober — [3]PTB Braunschweig, Braunschweig

Surface-electrode ion traps with integrated microwave conductors for near-field quantum control are a promising approach for scaleable quantum computers. The goal of the QVLS-Q1 Project is to realize a scaleable quantum computer based on surface-electrode ion traps. Realizing quantum gate operations with magnetic near-field control comes with high demands on the electromagnetic field design, regarding spatial field distribution and radiation efficiency. Typically the wave length of the gate frequency is much larger than the entire application. Therefore common criteria to design efficient radiating structures can not be applied in a straight forward way. Additionally the spatial distribution, especially the position of the field minimum, is constrained to match specific requirements. These challenges will be discussed in this poster, emphasizing on the possibilities to face the complex goal of minimizing gate errors. A systematic approach will be shown including advanced simulation approaches.

QI 23.41 Wed 16:30 Empore Lichthof

Single Photon Sources at Telecom Wavelengths — •Jonas Grammel[1], Julian Maisch[2], Nam Tran[2], Thomas Herzog[2], Simone Luca Portalupi[2], Peter Michler[2], and David Hunger[1] — [1]Physikalisches Institut, Karlsruher Institut für Technologie — [2]Institut für Halbleiteroptik und Funktionelle Grenzflächen, Universität Stuttgart

Semiconductor single photon sources are fundamental building blocks for quantum information applications. The current limitations of such quantum dot sources are the emitting wavelength and insufficient collection efficiency in fiber-based implementations. In the project *Telecom Single Photon Sources* we aim to realize high brightness, fiber coupled sources of single and indistinguishable photons at the telecom wavelength for the upcoming realization of fiber-based quantum networks. We employ open cavities realized with fiber-based mirrors, in combination with InGaAs quantum dots emitting in the telecom O-band and C-band. To achieve Fourier-limited photons we utilize the lifetime reduction of the emitters via the Purcell effect. We optimize the mode matching between the cavity mode and the guided fiber mode by introducing a fiber-integrated mode-matching optics that can basically reach near-unity collection efficiency.

QI 23.42 Wed 16:30 Empore Lichthof

Packaging and Microfabrication Technology for Scalable Trapped Ion Quantum Computer — •Nila Krishnakumar[1,2,3], Friederike Giebel[1,2,3], Eike Iseke[1,2,3], Konstantin Thronberens[1,2,3], Jacob Stupp[1,2,3], Amado Bautista-Salvador[1,2,3], and Christian Ospelkaus[1,2,3] — [1]PTB, Bundesallee 100, 38116 Braunschweig, Germany — [2]Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany — [3]LNQE, Schneiderberg 39, 30167 Hannover

Ion traps are a leading platform for scalable quantum computing. A physical implementation is based on microfabricated surface-electrode ion traps. A multilayer fabrication method [1] allows geometries which are impossible in single-layer traps. Thick and planarized dielectric-metal layers provide flexibility and better signal routing. The multilayer method requires microfabrication techniques such as UV Photolithography, Reactive Ion Etching(RIE), electroplating and more. Improving the efficiency and yield of the fabrication flow involves testing and updating each technology.

For scalability and hybrid integration of different control techniques, we discuss the implementation of TSVs (Through substrate vias) and better packaging technologies such as flip-chip bonding. As an alternative to the conventional wire bonding which limits the packaging density, a solder free thermocompression method proposed in [2] using gold stud bumps for flip-chip bonding is studied.

[1] A. Bautista-Salvador et al., New J. Phys. 21, 043011, Patent DE 10 2018 111 220 (2019)

[2] M. Usui et al.,(ICEP-IAAC) pp. 660-665 (2015)

QI 23.43 Wed 16:30 Empore Lichthof

Multi-Output Quantum Pulse Gate: a High-Dimensional Temporal-Mode Decoder — •Laura Serino, Jano Gil-Lopez, Michael Stefszky, Raimund Ricken, Christof Eigner, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

Future quantum technologies will require the implementation of complex quantum communication (QC) networks. Temporal modes (TMs) provide an appealing high-dimensional encoding alphabet based on the time-frequency degree of freedom of photons, leading to important advantages for QC applications. A TM-based QC scheme requires the simultaneous detection of multiple TMs of single photons, which has not yet been achieved.

In this work, we demonstrate high-dimensional single-photon TM decoding with a multi-output quantum pulse gate (mQPG). The mQPG is a device that provides simultaneous projection of multiple TMs onto all the elements of a chosen alphabet (or their superpositions) and maps each result onto a different output frequency. We demonstrate that the mQPG is compatible with single-photon-level input states from a full set of five-dimensional mutually unbiased bases, and we characterize its performance through a detector tomography. We then proceed to demonstrate a proof-of-principle decoder for high-dimensional quantum key distribution based on the mQPG.

QI 23.44 Wed 16:30 Empore Lichthof

Two Stage Quantum Frequency Conversion of SnV-Resonant Photons to the Telecom C-Band — •David Lindler, Tobias Bauer, Marlon Schäfer, and Christoph Becher — Universität des Saarlandes, FR Physik, Campus E2.6, 66123 Saarbrücken

Tin-Vacancy-Centers (SnV) in diamond are a promising candidate for Quantum Nodes in quantum communication networks that store and distribute quantum information [1,2]. 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 photons are converted into the low-loss telecom bands via quantum frequency down-conversion, to avoid the problem of high loss in fibers for SnV-resonant photons at 619 nm.

We here present a two-stage scheme for quantum frequency conversion of SnV-resonant photons to the telecom C-band based on difference frequency generation in PPLN waveguides. The two step process $619\,\mathrm{nm} - 2061\,\mathrm{nm} = 885\,\mathrm{nm}$, $885\,\mathrm{nm} - 2061\,\mathrm{nm} = 1550\,\mathrm{nm}$ drastically reduces noise at the target wavelength compared to the single stage process $619\,\mathrm{nm} - 1030.5\,\mathrm{nm} = 1550\,\mathrm{nm}$, due to pumping in the long wavelength regime. We will present the characterization of key components as well as first results on conversion efficiency and conversion induced noise count rates.

[1] J. Görlitz et al., npj Quant.Inf. 8, 45 (2022).

[2] R. Debroux et al., Phys. Rev. X 11, 041041 (2021).

QI 23.45 Wed 16:30 Empore Lichthof

Entangled Photon Pair Source based on Photonic Chips with Spontaneous Four-Wave-Mixing and Pulsed PDH-Locking — •Maximilian Mengler, Erik Fitzke, Jakob Kaltwasser, and Thomas Walther — TU Darmstadt, Institute for Applied Physics, 64289 Darmstadt

For many applications, such as quantum key distribution (QKD), entangled photon pairs are desirable. We use the process of spontaneous four-wave-mixing to create such pairs in microring resonators on silicon nitride photonic chips. Results in terms of, for example, pair generation rate and coincidental-over-accidental ratio obtained from two distinct chips with different setups, specifications and waveguide geometries will be presented and compared. As the chips are intended as sources for our QKD-System, which is based on time-bins, the PDH-technique used for the locking of the microring resonators to the pump light was adapted to work with pulsed light.

QI 23.46 Wed 16:30 Empore Lichthof

Cavity-enhanced fluorescence of ensemble NV centers — •Kerim Köster[1], Maximilian Pallmann[1], Rainer Stöhr[2], Julia Heupel[3], Cyril Popov[3], and David Hunger[1] — [1]Physikalisches Institut, Karlsruher Institute für Technologie (KIT) — [2]3. Physikalisches Institut, University of Stuttgart — [3]Institute of Nanostructure Technologies and Analytics (INA), Center for Interdisciplinary Nanostructure Science and Technology (CINSaT), University of 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 observe cavity-enhanced fluorescence spectra of an ensemble of shallow-implanted nitrogen vacancy centers in diamond and report a significant 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 superfluorescence.

QI 23.47 Wed 16:30 Empore Lichthof

The Twente-Münster high-speed quantum key distribution link — •Niklas Humberg[1], Alejandro Sánchez-Postigo[1], Daan Stellinga[2], Pepijn Pinkse[2], and Carsten Schuck[1] — [1]Departement for Quantum Technology, Münster, Germany — [2]University of Twente, Enschede, Netherlands

To build a pan-European network for quantum communication, many local nodes are needed to provide every city with access to quantum-secure encryption. One such link between local nodes is being developed between the University of Twente (UT) and the Westfälische Wilhelms-Universität Münster (WWU), to open a secure communication channel between the Netherlands and Germany. High-speed generation of quantum keys over the roughly 85km long dark fiber will be achieved by using wavelength division multiplexing into several frequency channels that operate in parallel. The qubit preparation and detection will be done using silicon nitride-on-insulator photonic integrated circuits. The receiver chip will integrate an interferometer with a 150 ps low-loss delay line in one arm for time bin encoding and an arrayed waveguide grating (AWG) for demultiplexing the wavelength channels. Each AWG output channel will be equipped with an efficient and low-noise superconducting nanowire single-photon detector, which have timing accuracies that are significantly better than the optical delay in the interferometer. We show progress on the chip design and the fabrication of detector devices.

QI 23.48 Wed 16:30 Empore Lichthof

Photon emission from a segmented ion-trap – cavity system: simulation and implementation — •Stephan Kucera, Max Bergerhoff, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

Atom-photon interfaces [1,2] are basic requirements for quantum networks with single trapped ions. The efficiency of such interfaces has been shown to increase significantly by the use of resonators [3]. Following this direction, we are developing a new segmented ion trap for $^{40}Ca^{+}$ ions with an integrated fiber cavity [4,5] envisaging the implementation of a high-rate and high-purity quantum repeater cell (QR-cell) according to [6,7] on the basis of single-photon emission.

[1] C. Kurz et al., Nat. Commun. 5, 5527 (2014)
[2] M. Bock et al., Nat. Commun. 9, 1998 (2018)
[3] M. Meraner et al., Phys. Rev. A 102, 052614 (2020)
[4] H. Takahashi et al., New J. Phys. 15, 053011 (2013)
[5] B. Brandstätter et al., AIP 84, 123104 (2013)
[6] D. Luong et al., Appl. Phys. B 122, 96 (2016)
[7] V. Krutyanskiy et al. arXiv preprint arXiv:2210.05418 (2022)

QI 23.49 Wed 16:30 Empore Lichthof

Polarisation-independent Conversion of single photons from infrared to ultraviolet — •Alireza Aghababaei — Nußallee 12, 53115 Bonn

Wavelength conversion at the single-photon level is required to forge a quantum network from distinct quantum devices. Such devices could include solid-state emitters of single or entangled photons, as well as network nodes based on atoms or ions. We convert single photons emitted from an III-V semiconductor quantum dot at 853nm via sum frequency conversion to the wavelength of the strong transition of Yb ions at 370nm. In this poster, we will present a sagnac setup that allows polarization-independent frequency conversion.

QI 23.50 Wed 16:30 Empore Lichthof

Polarization stabilization of an urban telecom fiber link — •Jonas Meiers, Christian Haen, Stephan Kucera, and Jürgen Eschner — Universität des Saarlandes, Experimentalphysik, 66123 Saarbrücken

Many quantum network designs rely on glass fibers to transmit quantum information encoded into the polarization of photons [1]. Long glass fiber links, especially those deployed outside a laboratory environment are exposed to environmental influences that change the birefringence of the fiber and, as a result, the polarization of transmitted light [2], degrading the polarization-encoded information.

Here, we present the polarization stabilization of a 14 km long urban fiber link running through Saarbrücken, by utilizing lasers as polarization reference and a Gradient-Descent algorithm for error correction. This stabilization provides the necessary transmission process fidelity for quantum communication experiments, which we demonstrate by high-fidelity entanglement distribution with photon pair sources, or by quantum repeater operations.

[1] S. Neumann et al., Nat. Commun. 13, 6134 (2022)
[2] O. Karlsson et al., Journal of Lightwave Technology, 18 (2000)

QI 23.51 Wed 16:30 Empore Lichthof

Observation of quantum Zeno effects for localized spins — •Vitalie Nedelea — Experimentelle Physik 2, Technische Universität Dortmund, 44221 Dortmund, Germany

One of the main dephasing mechanisms for the localized carrier spins in semiconductors is the coupling to the fluctuating nuclear spin environment. Here we present an experimental observation on the effects of the quantum back action under pulsed optical measurements of spin ensemble and demonstrate that the nuclei-induced spin relaxation can be influenced. We show that the fast measurements freeze the spin dynamics and increase the effective spin relaxation time, the so-called quantum Zeno effect. Furthermore, we demonstrate that if the measurement rate is comparable with the spin precession frequency in the effective magnetic field, the spin relaxation rate increases and becomes faster than in the absence of the measurements, an effect known as the quantum antiZeno effect. A theory describing both regimes allows us to extract the system parameters and the strength of the quantum back action.

QI 23.52 Wed 16:30 Empore Lichthof

Quantum Computation and Simulation with Neutral Alkaline-Earth-like Ytterbium Rydberg Atoms in Optical Tweezers — •Nejira Pintul[1], Tobias Petersen[1], Benjamin Abeln[1], Marcel Diem[1], Oscar Murzewitz[1], Koen Sponselee[1], Christoph Becker[1,2], and Klaus Sengstock[1,2] — [1]Zentrum für optische Quantentechnologien, Universität Hamburg, Deutschland — [2]Institut für Laserphysik, Universität Hamburg, Deutschland

Experiments with neutral cold atoms trapped in reconfigurable optical tweezer arrays have recently developed into one of today's leading platforms for quantum simulation and computation, due to the innate scalability, single atom control and Rydberg blockade mechanism for generating two-atom entangling gates. However, to achieve fault-tolerant quantum computing, current atomic life- and coherence times still need improvement to increase fidelities in preparation, gate operation and read-out. Here we present our pathway in constructing an optical tweezer experiment utilizing the alkaline-earth-like atom ^{171}Yb. This isotope offers a multitude of viable advantages for encoding novel high-fidelity qubit and error correction architectures, such as the presence of a highly coherent metastable state, a two valence-electron structure with an optically active ion core and single-photon Rydberg transitions. Main milestones include the characterization of two microscope objectives, the design of magnetic coils along with electric field compensation, the development of homogeneous 2D tweezer holograms and mobile dipole traps for efficient array initialization.

QI 23.53 Wed 16:30 Empore Lichthof

Polarization-preserving quantum frequency conversion for entanglement distribution in trapped-atom based urban area quantum networks — •Tobias Bauer and Christoph Becher — Universität des Saarlandes, FR Physik, Campus E2.6, 66123 Saarbrücken

In quantum communication networks information is stored in internal states of quantum nodes, which can be realized e.g. in trapped ions like 40Ca+ [1]. 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 [2].

We present a high-efficiency, rack-integrated quantum frequency converter for polarization-preserving conversion of 40Ca+-resonant photons to the telecom C-band. This converter is highly suited for real-world application in entanglement distribution experiments in urban area fiber networks, e.g. photonic entanglement [3] or creation of remote entanglement of atomic systems.

[1] C. Kurz et al., Phys. Rev. A. 93, 062348 (2016)
[2] M. Bock, P. Eich et al., Nat. Commun. 9, 1998 (2018)
[3] E. Arenskötter, T. Bauer et al., arXiv:2211.08841

QI 23.54 Wed 16:30 Empore Lichthof

high sensitivity magnetometry with NV centers in diamond at zero field — •Muhib Omar, Arne Wickenbrock, Dmitry Budker, Georgios Chatzidrosos, Till Lenz, Omkar Dungel, and Joseph Rebeirro — Helmholtz Institut Mainz, Deutschland

We investigate a magnetometric protocol for sensing weak ac magnetic fields inside magnetic shieldings using ensembles of Nitrogen-Vacancy (NV) centres in diamond. The aim is to utilise this sensor for zero to ultra low field NMR detection, promising improved Signal-to-Noise ratio by the smaller standoff distance to a NMR sample this type of magnetometer would allow compared to standard optically pumped magnetometers. We present a scheme to enhance photon collection to improve so called shot noise limited sensitivity of magnetic field detection of this sensor type and a scheme that would allow measuring weak ac fields stroboscopically without being limited by effects dominating at very low fields like strain and NV-NV dipolar coupling.

QI 23.55 Wed 16:30 Empore Lichthof

Compact and portable atomic vapor memory for single photon storage — •Alexander Erl[1,2,3], Leon Messner[3,2], Martin Jutisz[3], Luisa Esguerra[2,1], Elizabeth Robertson[2,1], Norman Vinzenz Ewald[2], Elisa Da Ros[3], Mustafa Gündoğan[3], Markus Krutzik[3,4], and Janik Wolters[2,1] — [1]Technische Universität Berlin, Institut für Optik und Atomare Physik, Berlin, Germany — [2]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Optische Sensorsysteme, Berlin, Germany — [3]Humboldt-Universität zu Berlin, Institut für Physik, Berlin, Germany — [4]Ferdinand-Braun-

Institut, Institut für Höchstfrequenztechnik, Berlin, Germany

Quantum memories for single photons are a key component of quantum repeaters for sattelite-based quantum communication over long distances [1,2]. Memories on sattelites for feasible quantum repeater networks must be compact, maintainable and scalable. Reliable storage and retrieval of photons on demand would make a significant contribution to memory assisted quantum key distribution.
We present a compact, rack-mounted, stand-alone warm vapor quantum memory based on electromagnetically induced transparency (EIT) on the Cs D1 line at 895 nm [3]. This mobile setup realizes high fidelity light storage at single photon level with minimal readout noise level.

[1] M. Gündoğan et. al., npj Quantum Information 7, 128 (2021)
[2] N. Sangouard et. al., arXiv:0906.2699 (2009)
[3] L. Esguera, et al., arXiv:2203.06151 (2022)

QI 23.56 Wed 16:30 Empore Lichthof

Quantum network with interacting network qubits — •Emanuele Distante, Severin Daiss, Stefan Langenfeld, Stephan Welte, Philip Thomas, Lukas Hartung, Olivier Morin, and Gerhard Rempe — Max Planck Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

Quantum networks can be realized out of single atoms trapped at the centre of optical resonators which stand at the network nodes and are then connected via optical fibres. In this platform, quantum information is stored into the long-lived ground states of an atom, and the resonator provide an efficient way to entangle the atomic states with flying optical photons. Traveling over the network via the fibres, photons can not only distribute the entanglement over large distance but also provide a means for making two largely separated atoms interact. In this poster we will show how this effective long-distance interaction can be exploited for the realization of different protocols. First, we present a quantum logic gate between distant atoms[1], which denote a rudimental example of distributed quantum computation, then we show the realization of a novel quantum teleportation scheme[2], as well as realization of joint nondestructive measurement on distant qubits leading to entanglement[3].

[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)

QI 23.57 Wed 16:30 Empore Lichthof

Measuring the temporal mode function of photonic states — •Olivier Morin, Stefan Langenfeld, Matthias Körber, Philip Thomas, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Quantum physics, and quantum information in particular, relies on the accurate control of the quantum states. For optical states, while some well-establish techniques exist for the characterization of polarization and spatial degrees of freedom, it remains a non-trivial task to measure the temporal mode function of a photonic quantum state. Here we present an easy-to-implement and accurate solution [1]. Our method is based on homodyne measurements. We show that the proper processing of the auto-correlation function can give access to any complex-valued temporal mode function. Beyond the theoretical principle, we also consider the experimental constraints and provide the key aspects to obtain a trustworthy reconstruction. We have tested our method on an advanced temporal shape and reach a fidelity as high as 99.4%. This technique has also been used to characterize the complex-valued temporal shape of a single photon emitted from a CQED system. Hence, we believe that this method can be applied to many other systems and become a standard routine in quantum optics laboratories.

[1] O. Morin *et al.*, Phys. Rev. A **101**, 013801 (2020)

QI 23.58 Wed 16:30 Empore Lichthof

Characterization of Polarization Drifts on a Deployed Inter-City Fiber Link for Quantum Communication — •Pritom Paul[1,2], Gregor Sauer[2,1], Shreya Gouravaram Navalur[2,1], and Fabian Steinlechner[2,1] — [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, Albert-Einstein-Straße 7, 07745, Germany.

Quantum communication involves the transmission of quantum information between two or more distant nodes in a network by encoding it, for example into the polarization state of photons. Such photons can be transmitted to distant nodes via free space or fiber-based links. In our experiment, we use a fiber link to transmit such photons.

The state of polarization of light changes with propagation along an optical fiber. These changes are irregular over time and occur due to perturbations from the environment such as temperature fluctuations throughout the day as well as the actual movement of the fibers. In the end, one must compensate for these polarization changes in order to effectively readout the quantum correlations in the polarization degree of freedom[1]. In this work, we want to understand the different aspects of these polarization changes on a 150km deployed fiber link between Jena and Erfurt in order to develop and improve our existing polarization compensation techniques. We report on the current status of the project.

[1] C.Z. Peng, et.al, Phys. Rev. Lett. 98, 010505(2007).

QI 23.59 Wed 16:30 Empore Lichthof

Towards optical tweezer arrays for cavity based quantum information processing — •Matthias Seubert, Lukas Hartung, Stephan Welte, Emanuele Distante, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

In recent decades, single neutral atoms in a strongly coupled optical resonator have developed to a powerful tool for quantum information processing and network application [1]. Increasing the number of individually controllable atoms in this platform provides the possibility to increase the efficiency of existing protocols by multiplexing, and additionally opens the way towards novel information processing and network protocols. However, this requires precise control of the atom position within the cavity mode which is a challenging demand.

Here, we show the implementation of a tweezer setup, capable of positioning atoms within an optical cavity, using a 2D acousto-optic deflector. ^{87}Rb atoms are first loaded at the center of the cavity, then transferred into optical tweezers and finally repositioned at subwavelength precision. In this manner, tweezer arrays allow one to load a deterministic number of atoms and to move individual atoms from a strongly coupled to a non-coupled position. In the future, this setup offers the possibility to address individual atoms, detect or rotate their state and generate single atom-photon entanglement.

[1] A. Reiserer and G. Rempe, Rev. Mod. Phys. 87, 1379 (2015)

QI 23.60 Wed 16:30 Empore Lichthof

A quantum frequency converter for the connection of Rb atoms in a cavity over long distances — •Maya Büki, Emanuele Distante, and Gerhard Rempe — Max-Planck-Institute für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching

Rubidium atoms in a cavity are a promising platform for realizing long-distance quantum networks as the atomic ground states can be efficiently entangled with optical photons [1]. However, photons entangled with Rb atoms are typically at a wavelength ($\lambda_{\mathrm{Rb}} = 780\,\mathrm{nm}$) which is unfavourable for long-distance communication due to intrinsic fiber losses in this regime. To efficiently transport the quantum information encoded in optical polarisation qubits over long distances, a wavelength conversion to the telecom regime ($\lambda = 1460 - 1565\,\mathrm{nm}$) is necessary.

Here, we demonstrate such a polarisation conserving quantum frequency converter (QFC) in a Sagnac configuration [2] and investigate the possibilities of increasing the signal-to-noise ratio (SNR) by choosing a suitable final wavelength. Provided a good SNR and high fidelities, the QFC represents one of the many necessary building blocks to establish a long distance quantum network. Furthermore, it can be used to connect diverse platforms operating at different wavelengths, thus forming a hybrid quantum network which takes advantage of the specific capability of each system.

[1] A. Reiserer, G. Rempe, Rev. Mod. Phys. **87**, 1379 (2015).
[2] R. Ikuta *et al.*, Nat. Commun. **9**, 1997 (2018).

QI 23.61 Wed 16:30 Empore Lichthof

Transport waveforms for through-junction ion transport on surface-electrode ion traps for a QCCD architecture — •Rodrigo Munoz[1], Florian Ungerechts[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. These are defined by the spatial division of different operations such as storage, state preparation and readout. A fundamental characteristic of the register-based approach is the translation of ions to reach the different registers of the QCCD architecture. Here, we discuss registers interconnected through a x-junction. We will focus on the necessary through-junction transport.

We will present the different constraints applied to our optimization algorithm in order to obtain trapping potentials for different ion species. Besides, we will also discuss additional conditions that allow a reliable trough-junction transport.

QI 23.62 Wed 16:30 Empore Lichthof

A Quantum Network Node with Crossed Fiber Cavities — •Tobias Frank[1], Gianvito Chiarella[1], Pau Farrera[1], Manuel Brekenfeld[1], Joseph Christesen[1,2], and Gerhard Rempe[1] — [1]MPQ, Hans-Kopfermann-Str. 1, 85748Garching, Germany — [2]NIST, Boulder, Colorado 80305, USA

Recent development in the field of optical cavity QED mainly concern a further reduction of the mode volumes of the resonators, driven by the development of fiber-based Fabry-Perot cavities (FFPCs) [1], and an increase in the number of well-controlled modes the emitters can couple to. We implemented an experiment which combines these two experimental advancements in a single platform consisting of single neutral atoms trapped at the center of two crossed FFPCs. Exploiting the possibilities provided by this platform, we have realized a quantum network node that couples to two spatially and spectrally distinct quantum channels. The node functions as a passive heralded quantum memory [2], achieving a heralded average state fidelity of $94.7 \pm 0.2\,\%$ and neither requires amplitude- or phase-critical control fields [3] nor error-prone feedback loops [4]. Our platform is therefore excellently suited for the realization of future large-scale quantum networks and quantum repeaters.

[1] Hunger et al., New J. Phys. 12, 065038 (2010)
[2] Brekenfeld et al., Nature 591, 570 (2020)
[3] Specht et al., Nature 473, 190 (2011)
[4] Kalb et al., Phys. Rev. Lett. 114, 220501 (2015)

QI 23.63 Wed 16:30 Empore Lichthof

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 (through absorption, diffraction or scattering) 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. We recently implemented such a detector [1] 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.

[1] D. Niemietz et al., Nature 591, 570-574 (2021)

QI 23.64 Wed 16:30 Empore Lichthof

Towards a compact polarization entanglement source based on WGMR — •Sheng-Hsuan Huang[1,2], Thomas Dirmeier[1,2], Golnoush Shafiee[1,2], Alexander Otterpohl[1,2], Florian Sedlmeir[1,2], Dmitry Strekalov[3], 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 — [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91108, USA

Crystalline Whispering Gallery Mode Resonators (WGMR) made from nonlinear materials have been proven to be compact and efficient sources of quantum states, e.g. squeezed states [1] or narrow-band heralded single photons[2,3]. Another feature of WGMR is, that it is possible to couple two pump beams propagating in opposite directions at the same time. As a result, we can treat the WGMR similar to a Sagnac interferometer which is simultaneously a pair of two independent and indistinguishable SPDC sources. Combined, these features make WGMR a potential platform for developing compact and narrow-band entanglement sources.

In our presentation, we discuss the concept and progress of developing a compact polarization entanglement source based on a WGMR that is pumped from two directions.

[1]A. Otterpohl, et.al., Optica 6, 1375-1380 (2019)
[2]J. U. Fürst, et al., Physical review letters 104.15 153901 (2010)
[2]M. Förtsch, et al., Physical Review A 91(2) 023812 (2015)

QI 23.65 Wed 16:30 Empore Lichthof

Apparatus design for scalable cryogenic trapped-ion quantum computing experiments — •Lukas Kilzer, Tobias Pootz, Celeste Torkzaban, Timko Dubielzig, and Christian Ospelkaus — Institute of 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. We describe the design of cryogenic demonstrator machines for this task, focusing on the implementation of surface-electrode ion traps. Trap design and implementation is facilitated through the use of a universal interchangeable socket. The apparatus design is based on a vibration isolated cold head to cool a cryogenic vacuum system to temperatures around 5K. The apparatus features a high density of DC control lines to support transport of qubits through complex processor structures including junctions, dedicated storage, detection and manipulation registers. Multi-qubit quantum gates can be implemented through the use of chip-integrated microwave methods. Two setups are currently under construction, the first being based on $^{9}Be^{+}$ qubits and $^{40}Ca^{+}$ ions for sympathetic cooling; the second setup will be based on $^{43}Ca^{+}$ qubits and $^{88}Sr^{+}$ cooling ions. The first setup will benefit from our experience with the $^{9}Be^{+}$ qubit, whereas the second setup with longer wavelengths for cooling and detection will be amenable for integrated chip-integrated photonics. The system has been designed to accommodate the integration of new components for scaling as the development of the underlying enabling technologies progresses.

QI 24: Integrated Photonics II (joint session Q/QI)

Time: Wednesday 17:00–19:00 Location: A320

QI 24.1 Wed 17:00 A320

Integrated bright broadband PDC source for quantum metrology — •René Pollmann, Franz Roeder, Victor Quiring, Raimund Ricken, Christof Eigner, Benjamin Brecht, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 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. For entangled two photon absorption especially very high brightness combined with high spectro temporal entanglement is crucial to observe a signal. So far these conditions could be met by using high power lasers driving bulk degenerate type 0 spontaneous parametric down conversion (SPDC) sources. This naturally limits the available wavelength ranges and precludes deterministic control over the output state. In this work we show an integrated two colour SPDC source utilising a group-velocity matched lithium niobate waveguide, reaching both high brightness ($> 6.7 \cdot 10^{11}$ pairs/Ws) and large bandwidth ($> 6\,\mathrm{THz}$) while using less than 5 mW of continuous wave pump power. Since the product of the measured correlation time of the photons $\Delta\tau \approx 80\,\mathrm{fs}$ and the pump bandwidth of $\Delta\omega_p \ll 1\,\mathrm{MHz}$ violates the classical Fourier limit, the source shows very strong time frequency entanglement. Furthermore our process can be adapted to a wide range of central wavelengths.

QI 24.2 Wed 17:15 A320

Diced ridge waveguides in titanium indiffused lithium niobate

— •Michelle Kirsch, Christian Kiessler, Christof Eigner, Harald Herrmann, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

Lithium niobate (LN) is a widely used platform for integrated optical devices due to its optical properties, especially the high second order nonlinearity. Well-established titanium indiffused waveguides (Ti:LN) are limited in the ability of creating tightly confined fields due to the low index contrast. Another limitation in Ti:LN waveguide devices is the occurrence of intensity induced photorefractive damage inhibiting applications with high optical intensities in the waveguides. To counteract these challenges we use a ridge waveguide structure to achieve higher confinement in horizontal direction by precision diamond blade dicing in Ti:LN. We analysed the properties of the guided modes in dependence of the waveguide geometry for 1550 nm. Furthermore, we fabricated periodically poled ridge waveguides and characterized the second harmonic generation process by measuring the phase matching function at a pump wavelength of 1550 nm and the efficiency. Here we show an efficiency of $9.44\,\%\mathrm{W}^{-1}\mathrm{cm}^{-2}$. Moreover, we investigated the occurrence of photorefractive damage in the ridge waveguides by measuring the second harmonic power in dependence of the pump power. Here we show a high damage resistance up to a pump power of 500 mW.

QI 24.3 Wed 17:30 A320

Waveguide-Intergrated Superconducting Nanowire Avalanche Single-Photon Detectors — •Connor A. Graham-Scott[1,2,3], Matthias Häussler[1,2,3], Mikhail Yu. Mikhailov[4], and Carsten Schuck[1,2,3] — [1]University of Münster, Physics Institute, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany — [2]CeNTech - Center for NanoTechnology, Heisenbergstr. 11, 48149 Münster, Germany — [3]Center for Soft Nanoscience (SoN), Busso-Peus-Straße 10, 48149 Münster, Germany — [4]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 communication, quantum information and quantum computing. A drawback of SNSPDs, however, is the low signal-to-noise ratio of their electrical output signals, resulting from operating at bias currents below the critical current of the ultra-thin superconducting nanowires.

High signal-to-noise ratio can be achieved by implementing a superconducting nanowire avalanche single photon detector (SNAP) architecture that connects several SNSPD elements in parallel, thus realising operation at high bias current and successive switching of elements upon photon absorption and current redistribution.

Here we show the design, fabrication and measurements of a successive-avalanche architecture SNAP with amorphous molybdenum silicide nanowires integrated with nanophotonic waveguides for on-chip single-photon counting with ultra-high signal-to-noise ratios.

QI 24.4 Wed 17:45 A320

Lithium-niobate microcombs for dual-comb spectroscopy — •Stephan Amann[1], Bingxin Xu[1], Yang He[2], Theodor W. Hänsch[1,3], Qiang Lin[2], Kerry Vahala[4], and Nathalie Picque[1] — [1]Max Planck Institute of Quantum Optics, Garching, Germany — [2]Department of Electrical and Computer Engineering, University of Rochester, Rochester, New York 14627, USA — [3]Faculty of Physics, Ludwig-Maximilian University of Munich, Munich, Germany — [4]T.J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125, USA

On-chip optical microresonators with a high Q-factor can generate soliton microcombs, broad spectra consisting of narrow lines with equal linespacing corresponding to the free spectral range of the resonator. Thin-film lithium niobate is a promising platform due to its large transparency window, strong second- and third-order nonlinearity and electro-optic effect. Here by driving a high-Q thin-film lithium niobate resonator with a picosecond electro-optic comb at 1.5 micron, we report stable soliton generation at a repetition rate locked by the electro-optic comb. Its high peak power grants an oscillation threshold at lower average powers than those necessary with continuous-wave pumping. The microcombs with a line spacing of 100GHz are well suited for spectroscopy in the condensed matter, where the linewidths of absorption features are often of the order of several hundreds of GHz. Dual-comb spectroscopy will leverage the time-domain interference of two microcombs to measure broad spectra within short measurement times.

QI 24.5 Wed 18:00 A320

Design of a satellite-based single photon source for quantum communication — •Najme Ahmadi for the QUICK3-Collaboration — Institute of Applied Physics, Abbe Center of Photonics, Friedrich Schiller University Jena, 07745 Jena, Germany

Technologies of the so-called second quantum revolution have matured such they can now be used in space applications, e.g., long-distance quantum communication. Here we present the design of a compact true single photon source that can enhance the secure data rates in satellite-based quantum key distribution scenarios compared to conventional laser-based light sources. Our quantum light source is based on a fluorescent color center in hexagonal boron nitride. The emitter is off-resonantly excited by a diode laser and coupled to an integrated optics circuit that routes the photons to different experiments. These experiments either characterize the source directly by the second-order correlation function or test extended physical theories beyond the standard model. Our payload is currently being integrated into a 3U CubeSat and scheduled for launch in 2024 into the low Earth orbit. We can therefore evaluate the feasibility of true single photon sources in space and provide a promising route toward a high-speed quantum internet.

QI 24.6 Wed 18:15 A320

Influence of doping on the optical characteristics in lithium niobate — •Laura Bollmers, Laura Padberg, Christof Eigner, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

Lithium niobate (LN) is a well-established material in integrated optics, and it is commonly used in nonlinear photonics. To make LN more versatile, material doping is crucial in improving the device's applicability. Depending on the doping material and concentration, different applications can be realised, e.g. Titanium doping can be used for waveguide fabrication, an essential part of integrated optics. Zinc doping can shift a bandgap to the UV region, enabling the material for UV/VIS application. Erbium doping enables applications for optical amplification, used for integrated laser sources, or quantum optical applications like memories.

Thus, doping LN can lead to a performance boost for optical applications. Especially in thin-film lithium niobate there are completely new application possibilities for doped substrate material. For optimisation, the interplay of experimental analysis and theoretical material modelling is crucial. So, we investigate the absorption spectra influenced by different dopants at different temperatures and show our latest results.

QI 24.7 Wed 18:30 A320

Towards Reconfigurable Lithium-Niobate-on-Insulator integrated non-von Neumann processors — •Julian Rasmus Bankwitz[1,2], Seongmin Jo[2], Francesco Lenzini[1], and Wolfram Pernice[2] — [1]Institute of Physics, University of Münster, Germany — [2]Kirchhoff Institute for Physics, University of Heidelberg, Germany

In recent years Artificial neural networks (ANNs) showed great advantages in a variety of fields like autonomous driving or language recognition. Fast and efficient efficient matrix-vector-multiplications (MVMs) are the building blocks of ANNs, as they represent the mathematical description of the interconnects of the ANN's neurons. With the exponentially increasing amount of data the world is generating every year, classical von-Neumann structured computers are facing their limits in computation speed and energy consumption. Overcoming those boundaries is a crucial task for modern computing, giving rise to alternative platforms like photonic integrated circuits (PICs). Lithium-Niobate-on-Insulator (LNOI) is an emerging material platform due to its broad optical bandwidth, low propagation loss and high second-order nonlinearity, enabling small footprint electro-optically reconfigurable circuits like adjustable ring resonators for non-classical light sources and Mach-Zehnder-Interferometers (MZIs) for electrically tunable optical switches. Here we demonstrate novel approaches of optical ANN matrices utilizing MZIs from LNOI for ultra-fast MVMs. From high precision fabrication engineering and modular PIC design we show high MZI extinction rations above 24 dB combined with GHz range modulation speed.

QI 24.8 Wed 18:45 A320

Light manipulation via integrated focusing grating couplers for quantum computing applications — •Anastasiia Sorokina[1,2], Guochun Du[3], Pascal Gehrmann[1,2], Carl- Frederik Grimpe[3], Steffen Sauer[1,2], Elena Jordan[3], Tanja

Mehlstäubler[3,4,5], and Stefanie Kroker[1,2,3] — [1]Institut für Halbleitertechnik, Technische Universität Braunschweig, Braunschweig, Germany — [2]Laboratory for Emerging Nanometrology, Braunschweig, Germany — [3]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [4]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany — [5]Laboratorium für Nanound Quantenengineering, Leibniz Universität Hannover, Hannover, Germany

Downsizing optical components to control ion species in quantum computation is a vital turning point. Integrating routing and focusing elements into the chip architecture can substantially suppress environmental distortions and boost scalability. We investigated integrated waveguides and grating couplers to produce a linearly polarised Gaussian beam with a predefined emission angle, focus height and the size of the beam at this position. The studies were carried out using Lumerical FDTD simulation software and a subsequent post-processing routine. To address the different wavelengths required for the entire operation of the ion-based QCs, we have evaluated the capabilities and performance of our structures by taking advantage of the two most promising material platforms: Si3N4 and AlN. Our results can help overcome current limitations toward the multi-ion quantum system.

QI 25: Quantum Entanglement II

Time: Thursday 11:00–13:00 Location: B302

QI 25.1 Thu 11:00 B302

Quantifying multiparticle entanglement with randomized measurements — Sophia Ohnemus[1], Heinz-Peter Breuer[1,2], and •Andreas Ketterer[1,2,3] — [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 — [3]Fraunhofer Institut für Angewandte Festkörperphysik IAF, Tullastr. 72, 79108 Freiburg, Germany

Randomized measurements constitute a simple measurement primitive that exploits the information encoded in the outcome statistics of samples of local quantum measurements defined through randomly selected bases. In this work we exploit the potential of randomized measurements in order to probe the amount of entanglement contained in multiparticle quantum systems as quantified by the multiparticle concurrence. We further present a detailed statistical analysis of the underlying measurement resources required for a confident estimation of the introduced quantifiers using analytical tools from the theory of random matrices. The introduced framework is demonstrated by a series of numerical experiments analyzing the concurrence of typical multiparticle entangled states as well as of ensembles of output states produced by random quantum circuits under the influence of noisy gate operations.

QI 25.2 Thu 11:15 B302

Highly entangled graph states — •Zahra Raissi — Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA

Multipartite entanglement is at the very heart of quantum information theory. Among all possible entangled states, k-uniform and absolutely maximally entangled (AME) states, have attracted much attention for a wide range of tasks such as measurement-based quantum computing, quantum networking and quantum error correction. Moreover, many efforts have also focused on showing if the relevant sets of states are also graph states.

The connection between classical codes and k-uniform states has been shown to provide a systematic method of constructing a large set of k-uniform states. In our work, we first show that a much larger class of k-uniform states can be obtained by starting from the graph state representation and asking what is the most general form of the adjacency matrix that is consistent with k-uniformity? With this, we uncover a large class of graph states that are maximally multipartite entangled. At least some of these are inequivalent under stochastic-local-operations and classical communication.

In the second part of our work, we propose and analyze deterministic protocols to generate them. We propose and evaluate deterministic methods to generate multi-photon qudit graph states from multi-level quantum emitters. We present several different explicit protocols that can produce various states either using a single emitter together with time-delayed feedback, or using multiple coupled quantum emitters.

QI 25.3 Thu 11:30 B302

Entanglement from Wehrl Moments using Deep Learning — •Jérôme Denis, François Damanet, and John Martin — University of Liège

In recent years, artificial neural networks (ANNs) have become an increasingly popular tool for studying problems in quantum theory, and in particular entanglement theory. In this work, we analyse to what extent ANNs can provide us with an accurate estimate of the geometric measure of entanglement of pure and mixed symmetric multiqubit states on the basis of a few moments of the Husimi function (Wehrl moments) of the state. We compare the results we obtain by training ANNs with the use of convergence acceleration methods and find that these algorithms do not compete with ANNs when given the same input data. This opens up perspectives for the estimation of SU(2) invariant quantities that should be more easily accessible in experiments than full state tomography.

QI 25.4 Thu 11:45 B302

Constructing generalized SSC witnesses for bound entangled Bell-diagonal states of unequal local dimensions — •Johannes Moerland[1,2], Nikolai Wyderka[1], Hermann Kampermann[1], and Dagmar Bruss[1] — [1]Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, D-40225 Düsseldorf, Germany — [2]Universität Göttingen, Friedrich-Hund-Platz 1, D-37073 Göttingen, Germany

We extend a class of bipartite mixed quantum states, so-called Bell diagonal states, to the case where the dimensions of the subsystems do not match. These states are canonically expressed in a unitary operator basis. To investigate their entanglement properties, we generalize a separability criterion originally derived for hermitian operator bases by Sarbicki, Scala and Chruściński to the case of non-hermitian bases. We then construct entanglement witnesses for arbitrary bipartite quantum states that are equivalent to said separability criterion. While for Bell diagonal states with subsystems of matching dimension our results are equivalent to the CCNR criterion, we show that our witnesses outperform CCNR by constructing appropriate bound entangled states of unequal dimensions.

QI 25.5 Thu 12:00 B302

General class of continuous variable entanglement criteria — Martin Gärttner[1,2,3], •Tobi Haas[4], and Johannes Noll[3] — [1]ITP, Heidelberg, Germany — [2]PI, Heidelberg, Germany — [3]KIP, Heidelberg, Germany — [4]QuIC, Brussels, Belgium

We present a general class of entanglement criteria for continuous variable systems. Our criteria are based on the Husimi Q-distribution and allow for optimization over the set of all concave functions rendering them extremely general and versatile. We show that several entropic criteria and second moment criteria are obtained as special cases. Our criteria reveal entanglement of families of states undetected by any commonly used criteria and provide clear advantages under typical experimental constraints such as finite detector resolution and measurement statistics.

QI 25.6 Thu 12:15 B302

Bipartite entanglement and the arrow of time — •Markus Frembs — Griffith University, Gold Coast, Australia

We provide a new perspective on the close relationship between entanglement and time. Our main focus is on bipartite entanglement, where this connection is foreshadowed both in the positive partial transpose criterion due to Peres [A. Peres, Phys. Rev. Lett., 77, 1413 (1996)] and in the classification of quantum within more general non-signalling bipartite correlations [M. Frembs and A. Döring, arXiv:2204.11471]. Extracting the relevant common features, we identify a necessary and sufficient condition for bipartite entanglement in terms of a compatibility condition with respect to time orientations in local observable algebras, which express the dynamics in the respective subsystems. We discuss the relevance of the latter in the broader context of von

Neumann algebras and the thermodynamical notion of time naturally arising within the latter.

See arXiv:2207.00024 for details.

QI 25.7 Thu 12:30 B302

Average Correlation as an Indicator for Nonclassicality — •Michael Erich Nicolas Tschaffon, Johannes Seiler, and Matthias Freyberger — Institut für Quantenphysik, Universität Ulm, D-89069 Ulm, Germany

Since their introduction, Bell inequalities have been used to verify nonclassicality of bipartite qubit states. While being a popular tool to test and even quantify nonclassicality, Bell inequalities suffer from being complicated to construct experimentally and cumbersome to evaluate and analyse theoretically. We suggest a solution to this trade-off between accurate predictions and simplicity. For this purpose, we introduce another quantity as a new indicator for nonclassicality: average correlation. It has both advantages of indicating whether a state is nonclassical, while still being simple to calculate and measure. We show that based on average correlation we obtain new inequalities that can be used to test nonclassicality. Moreover, we discuss how average correlation can even be used to classify all bipartite qubit states.

QI 25.8 Thu 12:45 B302

Number-phase uncertainty relations and bipartite entanglement detection in spin ensembles — Giuseppe Vitagliano[1,2], Matteo Fadel[3,4], Iagoba Apellaniz[2,5], Matthias Kleinmann[6,2], Bernd Lücke[7], Carsten Klempt[7,8], and •Géza Tóth[2,9,10,11] — [1]Institute for Quantum Optics and Quantum Information, AT-1090 Vienna, Austria — [2]UPV/EHU, ES-48080 Bilbao, Spain — [3]ETH Zürich, CH-8093 Zürich, Switzerland — [4]University of Basel, CH-4056 Basel, Switzerland — [5]Mondragon Unibertsitatea, ES-20500 Mondragón, Spain — [6]Universität Siegen, DE-57068 Siegen, Germany — [7]Leibniz Universität Hannover, DE-30167 Hannover, Germany — [8]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institut für Satellitengeodäsie und Inertialsensorik, DLR-SI, DE-30167 Hannover, Germany — [9]DIPC, ES-20080 San Sebastián, Spain — [10]IKERBASQUE, Basque Foundation for Science, ES-48011 Bilbao, Spain — [11]Wigner RCP, HU-1525 Budapest, Hungary

We present a method to detect bipartite entanglement and EPR steering based on number-phase-like uncertainty relations in split spin ensembles. In particular, we show how to detect bipartite entanglement in an unpolarized Dicke state of many spin-1/2 particles. We demonstrate the utility of the criteria by applying them to a recent experiment given in K. Lange et al. [Science 360, 416 (2018)]. Our methods also work well if split spin-squeezed states are considered. We discuss how to handle experimental imperfections.

[1] G. Vitagliano et al., arXiv:22104.05663.

QI 26: Quantum Control (joint session QI/Q)

Time: Thursday 11:00–13:00 Location: B305

Invited Talk QI 26.1 Thu 11:00 B305

Quantum firmware: optimal control for quantum simulators — •Tommaso Calarco — Forschungszentrum Jülich, 52428 Jülich, Deutschland — Universität zu Köln, 50937 Köln, Deutschland

Quantum optimal control has been shown to improve the performance of quantum technology devices up to their limits in terms e.g. of system size and speed of operation. This talk will review our recent results with a variety of quantum technology platforms, focusing in particular on ultracold atoms, and introduce our newly developed software for automatic calibration of quantum operations - the fundamental building block of next-generation quantum firmware.

QI 26.2 Thu 11:30 B305

Optimal Control in the Chopped Random Basis — •Matthias Müller — Forschungszentrum Jülich GmbH

We are at the verge of the second quantum revolution where quantum technology leaves the lab and enters industrial products. Fragile quantum systems with their unique features like superposition and entanglement can offer new perspectives in computation, communication and sensing/metrology. However, they need sophisticated mechanisms of control to perform the desired tasks. Quantum Optimal Control has proven to be a powerful tool to accomplish this task. I will report on the optimization in the dressed chopped random basis (dCRAB) [1], a versatile and robust approach to Quantum Optimal Control, that allows both closed-loop and open-loop optimization with limited pulse bandwidth and guaranteed convergence in a broad range of typical applications. The interplay of constraints, control resources and noise [2,3] is crucial for the overall performance of the controlled operation which obeys fundamental bounds that can be found also in full quantum control [4].

[1] M.M. Müller et al., Rep. Prog. Phys. 85 076001 (2022) [2] S. Lloyd et al., PRL 113, 010502 (2014) [3] M.M. Müller et al., arxiv:2006.16113 (2020) [4] S. Gherardini et al., Phys. Rev. Research 4 (2), 023027 (2022)

QI 26.3 Thu 11:45 B305

Graph test for controllability of qubit arrays — •Fernando Gago-Encinas, Monika Leibscher, and Christiane P. Koch — Freie Universität Berlin, Arnimallee 14, 14195 Berlin

Universal quantum computing requires evolution-operator controllability of the system used as quantum processing unit. Given a specific architecture characterized by the two-qubit couplings and local controls it uses, we seek to determine whether it is controllable or not. The standard test constructing the dynamical Lie algebra becomes demanding and even unfeasible already for a relatively small number of qubits. We present a controllability test for arrays of coupled qubits based on graph theory that significantly broadens the number of cases that can be analyzed. We showcase the algorithm for different examples, including some systems based on IBM's devices.

QI 26.4 Thu 12:00 B305

Optimal Control of Bipartite Entanglement with Local Unitary Control — •Emanuel Malvetti — Department of Chemistry, Technische Universität München, Lichtenbergstr. 4, 85737 Garching, Germany — Munich Centre for Quantum Science and Technology & Munich Quantum Valley, Schellingstr. 4, 80799 München, Germany

A pure quantum state on a bipartite system can always be transformed into a diagonal form using local unitary transformations. This is the well-known Schmidt decomposition. Here we consider a closed bipartite system with local unitary control. The Schmidt decomposition allows us to define a reduced control system on the Schmidt values, which is equivalent to the original control system. We will explicitly describe this reduced control system and study its properties. In particular, we will treat the case of rank one drift Hamiltonians and some low dimensional cases in detail.

QI 26.5 Thu 12:15 B305

Taking Markovian Quantum Dynamics to Thermal Limits: Principles, Practice, and Perspectives — •Thomas Schulte-Herbrüggen[1,2], Frederik vom Ende[1,2], Emanuel Malvetti[1,2], and Gunther Dirr[3] — [1]Technical University of Munich (TUM) — [2]Munich Centre for Quantum Science and Technology (MCQST) and Munich Quantum Valley (MQV) — [3]Institute of Mathematics, Universität Würzburg

To begin with, consider the following engineering problem: Which quantum states can be reached by coherently controlling n-level quantum systems coupled to a thermal bath in a switchable Markovian way? We address this question by giving (inclusions for) reachable sets of coherently controllable open quantum systems with switchable coupling to a thermal bath of temperature T as an additional resource.

A core problem reduces to the dynamics of the eigenvalues of the density operator. It translates into a toy model of studying points in the standard simplex allowing for two types of controls: (i) permutations within the simplex, (ii) contractions by a dissipative semigroup. We show how toy-model solutions pertain to the reachable set of the original controlled Markovian quantum system. Beyond the case $T = 0$ (amplitude damping) we present results for $0 < T < \infty$ by using recent methods of extreme points of the d-majorisation polytope.

We give illustrating examples, experimental applications, and perspectives at the intersection of control theory with resource theory.

Refs.: Proc. MTNS (2022), 1069 and 1073

QI 26.6 Thu 12:30 B305

Tailoring feedback control loops to work best where it matters the most — •Robin Oswald — ETH Zürich

Experiments in AMO physics rely on many feedback control loops stabilizing quantities such as temperatures, magnetic fields and laser phase, frequency and intensity. In most cases, PID controllers are used for these tasks, but they only allow for coarse adjustment of the relevant trade-offs. Here, I will present methods to augment and tailor control loops to be particularly effective in one or several narrow frequency bands, i.e. where there are particularly strong disturbances or where the apparatus is especially vulnerable to them, or both. Using examples from our trapped-ion laboratory I will illustrate how we can leverage these techniques to improve the performance of the feedback loops, and ultimately our experiments.

QI 26.7 Thu 12:45 B305

Unitary Interpolation — •Michael Schilling, Matthias Müller, and Felix Motzoi — Forschungszentrum Jülich, Jülich, Deutschland

The generation of matrix exponentials and associated differentials, required to determine the time evolution of quantum systems, is frequently the primary source of running time in quantum control problems. We introduce two ideas for the time efficient approximation of matrix exponentials of linear parametric Hamiltonians. We modify the Trotter and Suzuki-Trotter product formulas from approximation to interpolation schemes to improve their accuracy. To achieve our target fidelities within a single interpolation step and avoid the need of exponentiation, we furthermore define the interpolation on a grid of interpolation intervals. We demonstrate a speed up of at least an order of magnitude when compared with eigenvalue decomposition, Runge-Kutta and Suzuki-Trotter based approaches. This holds true independent of system dimension, for problems with few time dependent controls.

QI 27: Precision Measurements with Optical Clocks (joint session Q/QI)

Time: Thursday 11:00–13:00 Location: E001

Invited Talk QI 27.1 Thu 11:00 E001

Quantum metrology with non-classical states of light — •Michèle Heurs — Institute for Gravitational Physics, Leibniz Universität Hannover, Callinstraße 38, 30167 Hannover, Germany

Nowadays, non-classical (fixed-quadrature “squeezed”) light is routinely used in second-generation interferometric gravitational wave detectors such as aLIGO and AdVirgo to increase their detection sensitivity, leading to some of the most exciting astrophysical discoveries of the past years. Beyond this well-known application example, squeezing is a quantum technique that can benefit precision metrology in many other areas. It can be useful whenever the signal-to-noise ratio of the measurement is fundamentally limited by the quantum noise of the employed and technically already ultra-stabilised laser light.

This talk will highlight exemplary applications of squeezed light, ranging from interferometric gravitational wave detection to sub-shot-noise limited spectroscopy. The latter example makes use of high-frequency squeezed light sources, so-called *squeezing combs*, which will be introduced in this talk. These squeezing combs exhibit entanglement between the individual upper and lower squeezing sidebands which occur at the free spectral ranges of the squeezing cavity. This feature makes squeezing combs a promising resource for applications in quantum information.

QI 27.2 Thu 11:30 E001

A strontium optical clock based on Ramsey-Bordé spectroscopy — •Amir Mahdian[1], Oliver Fartmann[1], Ingmari C Tietje[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, Leibniz-Institut für Höchstfrequenztechnik, Berlin

We are developing an optical frequency reference based on Ramsey-Bordé interferometry using a thermal atomic beam. The $5s^2\ ^1S_0 \rightarrow 5s5p\ ^3P_1$ intercombination line in strontium is chosen as our clock transition, which should allow for an Allan deviation as low as 2×10^{-15} between 100 s and 1000 s.

After an overview of the current state of our atom interferometer, the latest developments in our laser systems and frequency stabilization will be presented. Moreover, I outline two methods for reading the population of the associated quantum states in the clock transition, along with the progress on spectroscopy on the $5s5p\ ^3P_1 \rightarrow 5p^2\ ^3P_0$ line at 483 nm.

This work is supported by the German Space Agency (DLR), with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) 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.

QI 27.3 Thu 11:45 E001

Instability investigation for a dual-wavelength coating frequency stabilization cavity — •Fabian Dawel[1,2], Alexander Wilzewski[1,2], Johannes Kramer[1,2], Lennart Pelzer[1,2], Marek Hild[1,2], Kai Dietze[1,2], Gayatri Sasidharan[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

Optical resonators are a key tool for stabilizing lasers. For many experiments space is limited, so it is advantageous to lock multiple lasers to the same resonator. But so far, the correlation in noise contributions for two or more lasers on the same mirror pair has not been investigated. In this talk we present the stabilization of two lasers operating at 729 nm and 1069 nm on one mirror pair. We measure the effect of photo-thermal noise (PTN) and residual-amplitude modulation (RAM) on laser frequency instability. We find correlations between optical power and frequency. The wavelength coating stack next to the substrate shows PTN noise which is suppressed by coherent cancelation to a level of $3 \times 10^{-8}\ \frac{\mathrm{Hz}}{\mathrm{W}}$. The stack on top of this shows a PTN of $7 \times 10^{-7}\ \frac{\mathrm{Hz}}{\mathrm{W}}$. As expected, there is no significant cross-correlation between the lasers for noise induced by RAM. We measured relative frequency instabilities of less than 10^{-14} for both lasers, where the instability of one laser is limited by RAM. This work shows that dual-wavelength coatings can be used for highly stable laser applications, which makes it a viable tool for precision spectroscopy experiments.

QI 27.4 Thu 12:00 E001

The COMPASSO mission and its iodine clock — •Frederik Kuschewski[1], Thilo Schuldt[1], Martin Gohlke[2], Markus Oswald[1], Jonas Bischof[1], Jan Wüst[1,3], Alex Boac[1], Andre Bussmeier[1], Klaus Abich[1], Tasmim Alam[1], Tim Blomberg[1], and Claus Braxmeier[1,3] — [1]DLR Institute of Quantum Technologies — [2]DLR Institute of Space Systems — [3]Ulm University

High-precision clock technologies have a variety of applications both in lab environments and in space, such as research of geodesy, test of relativity theory and also navigation with the GNSS (global navigation satellite system) network. However, the established clock technologies in space (rubidium standards and masers) lack in precision and long-term stability, limiting the accuracy of space research and navigation. Optical clocks have the potential to improve the performance by orders of magnitude, hence offering unprecedented accuracy in numerous fields of research and high-precision navigation [1]. The DLR COMPASSO mission will demonstrate the first optical clock technology in orbit and its payload will be installed on the Bartolomeo platform of the ISS with a scheduled launch in 2025. In this contribution, we will present the mission architecture and highlight the features of the ruggedized clock technology [2], which utilizes modulation transfer spectroscopy in molecular iodine yielding a long-term fractional stability of up to 10^{-15}. [1] Schuldt, T. et al. GPS Solut. **25**, 83 (2021). [2] Schuldt, T. et al. Appl. Opt. **56**, 4, (2017).

QI 27.5 Thu 12:15 E001

Vibration isolation and frequency feedforward techniques in ultra-stable laser systems. — •Sofia Herbers[1], Jialiang Yu[1], Jan Kawohl[1], Mattias Misera[1], Thomas Legero[1],

Uwe Sterr[1], Anders Wallin[2], Kalle Hanhijärvi[2], Thomas Lindvall[2], and Thomas Fordell[2] — [1]Physikalisch-Technische Bundesanstalt (PTB), Germany — [2]VTT Technical Research Center of Finland Ldt., Finland

To improve the performance of metrology and precision measurements with optical clocks, ultra-stable lasers with extremely low frequency instability are required. Amongst others, accelerations acting on the laser systems' ultra-stable resonators limit the frequency stability even though the resonators' acceleration sensitivity is reduced by novel mounting designs and the best commercially available vibration isolation systems are used to reduce vibrations.

To overcome this limitation, we investigate adding additional feedback corrections to a commercial vibration isolation platform as well as applying feedforward corrections to the laser frequency. Additional seismometers and a tiltmeter are placed on the vibration isolation platform to detect its movement. The sensor outputs are used to generate correction signals that are either sent back to the actuators of the vibration isolation platform or sent forward to the laser frequency.

We acknowledge support by the Project 20FUN08 NEXTLASERS, which has received funding from the EMPIR programme cofinanced by the Participating States and from the European Union*s Horizon 2020 Research and Innovation Programme.

QI 27.6 Thu 12:30 E001

E2-M1 polarisability of the strontium clock transition at the 813 nm lattice magic wavelength — •Joshua Klose, Sören Dörscher, and Christian Lisdat — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

To accurately determine the frequency shift of the clock transition caused by the optical lattice with fractional uncertainty of 10^{-17} or below, one must account for electric-quadrupole (E2) and magnetic-dipole (M1) interactions in a strontium lattice clock. However, the values of the E2-M1 polarisability difference of the clock states, $(5s^2)\,{}^1S_0$ and $(5s5p)\,{}^3P_0$, found in recent publications [1, 2] exhibit large discrepancies. We report on an independent experimental determination of the differential E2-M1 polarisability, $\Delta\alpha_{\mathrm{qm}}$, by measuring the differential light lattice shift between samples with different motional state distributions, leveraging the different dependence of the light shift terms on the atomic motional state. We find a value of $\Delta\alpha_{\mathrm{qm}} = -987^{+174}_{-223}\,\mu$Hz, which is in agreement with the value reported in Ref. [1] as well as the result of another recent investigation [3].

This project has been supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2123 QuantumFrontiers – Project-ID 390837967, SFB 1464 TerraQ – Project-ID 434617780 – within project A04, and SFB 1227 DQ-*mat* – Project-ID 274200144 – within project B02.

[1] I. Ushijima *et al.*, Phys. Rev. Lett. **121**, 263202 (2018)
[2] S. G. Porsev *et al.*, Phys. Rev. Lett. **120**, 063204 (2018)
[3] K. Kim *et al.*, arXiv:2210.16374 (2022)

QI 27.7 Thu 12:45 E001

An indium ion clock with a systematic uncertainty on the 10^{-18}-level — •Hartmut Nimrod Hausser[1], Tabea Nordmann[1], Jan Kiethe[1], Nishant Bhatt[1], Moritz von Boehn[1], Ingrid Maria Dippel[1], Jonas Keller[1], and Tanja E. Mehlstäubler[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Leibniz Universität Hannover, Hannover, Germany

Frequency is the most accurate physical property that can be measured by man-made machines. Nowadays, the best atomic clocks are based on optical transitions and reach systematic uncertainties around 1×10^{-18} surpassing the clocks that currently define the SI unit of time by a factor of 100 and more. Because of its intrinsically low sensitivities, $^{115}\mathrm{In}^+$ is a candidate for a clock with a systematic uncertainty on the 10^{-19}-level, not only for a single but also multiple indium ions. This so-called "multi-ion clock" allows for shorter averaging times to reach a given statistical uncertainty level [1,2].

In this talk, we will demonstrate clock operation with an $^{115}\mathrm{In}^+$ ion sympathetically cooled by three $^{172}\mathrm{Yb}^+$ ions in a segmented linear Paul trap. The systematic uncertainty is evaluated on the 10^{-18}-level. The setup is optimized for clock operation with multiple $^{115}\mathrm{In}^+$ ions allowing for a similar systematic uncertainty as a single-ion clock [1]. First clock operation with multiple indium ions featuring individual state readout on an EMCCD camera is shown and discussed.

[1] N. Herschbach et al., *Appl. Phys. B* **107**, 891-906 (2012)
[2] J. Keller et al., *Phys. Rev. A* **99**, 013405 (2019)

QI 28: Spin Qubits

Time: Thursday 11:00–13:00 Location: F428

Invited Talk QI 28.1 Thu 11:00 F428

Conveyor-mode single-electron shuttling in Si/SiGe for a scalable quantum computing architecture — •Inga Seidler[1], Tom Struck[1], Ran Xue[1], Stefan Trellenkamp[2], Hendrik Bluhm[1], and Lars R. Schreiber[1] — [1]JARA-FIT Institute for Quantum Information, Forschungszentrum Jülich GmbH and RWTH Aachen University, Aachen, Germany — [2]Helmholtz Nano Facility (HNF), Forschungszentrum Jülich, Jülich, Germany

Small spin-qubit registers defined by single electrons confined in Si/SiGe quantum dots operate successfully and connecting these could permit scalable quantum computation. Shuttling the electron qubit between registers is a natural choice for high-fidelity coherent links. We demonstrate proof-of-principle of shuttling of a single electron by a gate induced propagating wave-potential in Si/SiGe. Independent from its length only four sinusoidal control signals and low tuning effort are required. We transfer a single electron over a distance of 420 nm and observe a high single-electron shuttling fidelity of 99.42+-0.02 % including a reversal of direction [1]. Theoretical considerations of dephasing mechanisms promise coherent transport over 10 um [2]. Measuring the sensor response while transferring the electron enables us to detect the electron motion. Our shuttle can be readily embedded in industrial fabrication of Si/SiGe qubit chips and paves the way to solving the signal-fanout problem for a fully scalable semiconductor quantum-computing architecture.

[1] I.Seidler et al., npj Quant. Inf. 8, 100 (2022). [2] V. Langrock et al., arXiv:2202.11793.

QI 28.2 Thu 11:30 F428

Driven non-local gates in double quantum dot spin qubits — •Stephen McMillan and Guido Burkard — Universität Konstanz, Konstanz, Deutschland

A critical element towards the realization of quantum networks is non-local coupling between nodes. Scaling connectivity beyond nearest-neighbor interactions requires the implementation of a mediating interaction often termed a "quantum bus". Cavity photons have long been used as a bus by the superconducting qubit community, but it has only recently been demonstrated that spin-based qubits in double quantum dot architectures can reach the strong coupling regime [1,2] and exhibit spin-spin interactions via real or virtual photons [3,4]. Two-qubit gate operations are predicted in the dispersive regime where cavity loss plays a less prominent role [5]. Here we explore the potential for driving entanglement, in the context of a CNOT operation, between two non-local single-spin qubits dispersively coupled to a common mode of a superconducting resonator. [1] X. Mi et al., Nature 555, 599 (2018) [2] N. Samkharadze et al., Science 359, 1123 (2018) [3] F. Borjans et al. Nature 577, 195 (2020) [4] P. Harvey-Collard et al. arXiv:2108.01206 (2021) [5] M. Benito et al. Phys. Rev. B 100, 081412(R) (2019)

QI 28.3 Thu 11:45 F428

Cavity QED with hybrid quantum-dot donor systems — •Jonas Mielke[1], Jason R. Petta[2], and Guido Burkard[1] — [1]University of Konstanz, Konstanz, Germany — [2]University of California, Los Angeles, USA

Nuclear spins show exceptionally long coherence times but the underlying good isolation from their environment is a challenge when it comes to controlling nuclear spin qubits.

A hybrid system in which an electron is shared between a quantum dot (QD) and ^{31}P donor atom implementing a e^--spin-nuclear spin flip-flop qubit has been realized. Employing ac-magnetic fields, this system can be harnessed to couple the nuclear spin to microwave cavity photons [1,2]. A related system with an electron confined in a double QD and subject to a B-field gradient constitutes a flopping mode e^--spin qubit that couples to cavity photons by electrical means

[3,4].

We envision an architecture combining the key ideas of the two aforementioned systems and theoretically investigate the interaction between a nuclear spin with a microwave cavity by electrical means. We demonstrate nuclear spin readout [5] and a cavity mediated nuclear spin $\sqrt{i\text{SWAP}}$-gate with a gate fidelity approaching 95% [6].

[1] Tosi et al., PRB 98, 075131 (2018)
[2] Tosi et al., Nat. Comm. 8, 450 (2017)
[3] Benito et al., PRB 96, 235434 (2017)
[4] Mi et al., Nature 555, 7698 (2018)
[5] Mielke et al., PRX Quantum 2, 020347 (2021)
[6] Mielke et al., arXiv:2209.10026 (2022)

QI 28.4 Thu 12:00 F428

Perspectives for a solid-state-based quantum register based on NV centers aligned along linear crystal defects in diamond — •Reyhaneh Ghassemizadeh, Wolfgang Körner, Daniel F. Urban, and Christian Elsässer — Fraunhofer Institute for Mechanics of Materials IWM, Wöhlerstr. 11, 79108 Freiburg, Germany

Due to its outstanding coherence properties, the negatively charged nitrogen-vacancy defect (NV center) in diamond has an excellent potential for implementing qubits in future solid-state-based quantum computing hardware. However, the structuring of point defects on the atomic scale remains an experimental challenge. We present a theoretical study using density functional theory (DFT) on the interaction between one dimensional crystal defects (dislocations) and NV centers [1]. We evaluate to which extent dislocation lines that are naturally present in diamond may be used for structuring NV centers. We model the most common types of dislocations in diamond and evaluate their influence on the defect formation energy, structural geometry, electronic defect levels and zero-field splitting (ZFS) parameters of NV centers in close proximity. Our simulations reveal that dislocations potentially trap NV defects with an energy release of up to 3 eV. In general, the properties of NV centers at dislocations show strong deviations with respect to their bulk values. However, the lowest energy configuration of a NV center at the core of a 30° partial glide dislocation shows very bulk-like properties. This opens the perspective to align multiple functional NV centers in a linear-chain arrangement.

[1] R. Ghassemizadeh, et al., Phys. Rev. B 106, 174111 (2022)

QI 28.5 Thu 12:15 F428

Controlling nuclear spin qubits in silicon carbide — •Pierre Kuna[1], Erik Hesselmeier[1], Di Liu[1], Vadim Vorobyov[1], Florian Kaiser[2], and Jörg Wrachtrup[1] — [1]3. Physikalisches Institut, Universität Stuttgart — [2]LIST, Luxembourg

The V2 color center in silicon carbide (SiC) emerged as promising CMOS compatible optically interfaced spin systems in solid state materials. V2 centers combine excellent spin and optical properties, i.e., ms spin coherence times and transform limited optical linewidth, even after nanophotonic integration[1]. Additionally, the di-atomic lattice of SiC provides an elegant pathway to further expand on existing quantum computing approaches demonstrated in the diamond counterpart.

Here, we present theoretical considerations and experimental results towards high-fidelity nuclear spin control in SiC. Using the V2 center as the control (electron) spin, and the surrounding nuclear spins as computational qubits, our first goal is to implement single shot readout (SSR). With this enabling technique, we plan to implement quantum computational algorithms on multiple nuclear spins.

We strive to demonstrate significantly increased fidelities and coherence times based the half-integer control spin, which results in a frozen core that prevents nuclear spin flip-flops. Additionally, the different gyromagnetic ratios of 29-silicon and 13-carbon nuclear spins should allow us to dynamically couple and decouple nuclear spins using an external magnetic field, which can increase the complexity of attainable quantum computing circuits.

[1] C. Babin et al., Nat. Mater. 21, 67 (2022)

QI 28.6 Thu 12:30 F428

Control and coherence of tin-vacancy qubits in diamonds — •C. Waas, H. Beukers, M. Pasini, N. Codreanu, J. Brevoord, L. De Santis, Z. Ademi, S. Niese, F. Gu, V. Dobrovitski, J. Borregaard, and R. Hanson — QuTech and Kavli Institute of Nanoscience, Delft University of Technology, 2628CJ Delft, The Netherlands

Color centers in diamonds are promising building blocks for realizing quantum network nodes, thanks to their good optical and spin properties as well as the naturally occurring ^{13}C-memory qubits in the diamond. Using NV centers, a multi-node network and teleportation of qubit states between non-neighboring nodes have been demonstrated (1). However, the optical properties of the NV currently hinder on-chip integration and scaling-up of quantum networks.

The tin-vacancy (SnV) center emerged as a resourceful alternative platform thanks to its improved optical properties, the second-long relaxation times expected around 1K, and compatibility with nanophotonic integrated devices, thanks to the first-order insensitivity to electric field fluctuations arising from its symmetry properties. Together with the recent developments in diamond nanofabrication techniques and hybrid integrated photonics, this makes the SnV interesting for realizing scalable platforms and on-chip devices. Here we report on the fabrication of single SnV centers in diamond and the investigation of their optical and spin coherence properties. Furthermore, we present our work towards spin-state control of the SnV qubit state at 1K.

(1) Hermans S. et al. Qubit teleportation between non-neighbouring nodes in a quantum network. Nature 605, 663-668 (2022).

QI 28.7 Thu 12:45 F428

Manipulating electron spin entanglement with a scanning tunnelling microscope — •Carsten Henkel[1] and Baruch Horovitz[2] — [1]Universität Potsdam, Institut für Physik und Astronomie — [2]Ben Gurion University of the Negev, Department of Physics, Beer Sheva, Israel

The tunnel current of a scanning microscope contains, in its fluctuations, information about localised spin sites in the contact region. In a magnetic field, this provides an alternative take on electron spin resonance spectroscopy. We showed previously that the features of the current spectrum can be explained by two localised spins that provide interfering tunnelling pathways [1]. The two spins experience effective exchange and Dzyaloshinskii-Moriya couplings and decay channels when the electronic contacts are integrated out [2]. Observed spin spectra can be fitted to the results of a master equation [3]. We report on voltage quenches and current measurements that manipulate the two-spin state and analyse its entanglement [2].

[1] B. Horovitz and A. Golub, Phys. Rev. B 99 (2019) 241407(R)
[2] B. Horovitz and C. Henkel, Phys. Rev. B (Lett.) 104 (2021) L081405
[3] Y. Manassen, M. Jbara, M. Averbukh, Z. Hazan, C. Henkel, and B. Horovitz, Phys. Rev. B 105 (2022) 235438

QI 29: Quantum Thermodynamics and Open Quantum Systems II

Time: Thursday 14:30–16:30 Location: B302

QI 29.1 Thu 14:30 B302

The role of generalized entropies in thermodynamics — •Bilal Cantürk — Institute of Physics, University of Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany

Generalized entropies have direct consequences on the foundations of thermodynamics, statistical mechanics, information theory, and quantum thermodynamics [1]. Based on formal group theory, a generalized entropy so-called universal group entropy was proposed in [2] which covers some other generalized entropies as its special cases. In our studies [3,4] we investigated whether universal group entropy and its special cases satisfy some fundamental physically accessible conditions such as stability of the average value of the physical observables and the third law of thermodynamics. I will present our findings, their possible implications, and their compatibility with some recent studies [5]. References [1] Lostaglio, M. Rep. Prog. Phys. 82, 114001 (2019). [2] Tempesta, P. Ann.Phys. (N Y) 365, 180 (2016). [3] Canturk, B., et. al. Ann Phys (N Y) 377, 62 (2017). [4] Canturk, B., et. al. Int. J. Mod. Phys. B 32, 1850274 (2018). [5] Oikonomou, T., et. al. Phys. A: Stat. Mech. Appl. 578, 126126 (2021).

QI 29.2 Thu 14:45 B302

Correlations facilitate ergotropy transmission — •Rick Simon, Janet Anders, and Karen Hovhannisyan — University of Pots-

dam, Institut für Physik und Astronomie, 14476 Potsdam, Germany

Ergotropy quantifies the amount of unitarily extractable work stored in a system, and it is routinely used to measure the “charge level” of quantum batteries. A fundamental primitive in any (future) quantum power grid will be transmitting ergotropy from one system to another. Here we study energy-preserving unitary transmission channels for the case where both systems are qubits. More specifically, we take two noninteracting qubits and apply a joint unitary that commutes with the total Hamiltonian. When the initial state is factorized, we find that part of the transmitted ergotropy will necessarily be lost. However, the transmission can be lossless when the initial state is correlated. Moreover, despite the fact that no energy is injected into the total system during the transmission, the receiver may gain more ergotropy than is lost by the emitter. This extra gain is achieved at the expense of the correlations between the systems, which affects the reusability of the transmission channel. The degradability problem of the transmission-facilitating correlations is mitigated by the fact that these correlations need not be finely tuned. Indeed, by analyzing large sets of randomly sampled initial states, we found that, for a fixed (high enough) value of mutual information, most initial states incur no losses during ergotropy transmission.

QI 29.3 Thu 15:00 B302

Nonequilibrium quantum thermodynamics in open systems: the influence of initial correlations — •Alessandra Colla[1], Niklas Neubrand[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

Finding a consistent formulation of quantum thermodynamics for general nonequilibrium processes is a fundamental and relevant question of recent research that has prompted the development of several proposals for the definition of basic thermodynamics quantities such as work, heat and entropy production. We have recently put forth one such approach (Phys. Rev. A 105, 052216) which relies on techniques of open quantum systems to determine an effective Hamiltonian as the operator for internal energy. The original formulation of the approach assumes factorizing initial conditions between the system of interest and the bath. We show here that the theory may be extended to any initial system-bath correlations with the important result that the effective Hamiltonian is unaffected by the presence of the initial correlations.

QI 29.4 Thu 15:15 B302

Long-time equilibration can determine transient thermality — •Karen Hovhannisyan[1], Somayyeh Nemati[1], Carsten Henkel[1], and Janet Anders[1,2] — [1]Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam, Germany — [2]Department of Physics and Astronomy, University of Exeter, Stocker Road, Exeter EX4 4QL, UK

When two initially thermal many-body systems start interacting strongly, their transient states quickly become non-Gibbsian, even if the systems eventually equilibrate. To see beyond this apparent lack of structure during the transient regime, we use a refined notion of thermality, which we call g-local. A system is g-locally thermal if the states of all its small subsystems are marginals of global thermal states. We numerically demonstrate for two harmonic lattices that whenever the total system equilibrates in the long run, each lattice remains g-locally thermal at all times, including the transient regime. This is true even when the lattices have long-range interactions within them. We compare our findings with the well-known two-temperature model. While its standard form is not valid beyond weak coupling, we show that at strong coupling it can be partially salvaged by adopting the concept of a g-local temperature.

QI 29.5 Thu 15:30 B302

power output, efficiency and role of the thermodynamic limit in nonequilibrium open quantum opto-mechanical engines — •Paulo José Paulino de Souza[1], Igor Lesanovsky[1,2], and Federico Carollo[1] — [1]Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany — [2]School of Physics and Astronomy and Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems,The University of Nottingham, Nottingham, NG7 2RD, United Kingdom

Cavity systems constitute a paradigmatic setting for optomechanical energy conversion. Experiments with atoms coupled to cavity modes are typically realized in nonequilibrium conditions, described by phenomenological models which cannot be derived via a weak system-bath coupling. This makes their interpretation as quantum engines challenging. Here, we present an effective, yet fully consistent, thermodynamic description for cavity-atom optomechanical systems, which exploits their nonequilibrium nature to achieve an energetic balance in terms of the persistent heat currents. To investigate the impact of collective behavior on their performance, we derive two thermodynamic limits, related to a weak and a strong optomechanical coupling, respectively. We illustrate our ideas focussing on a time-crystal quantum engine and discuss mechanical power generation, energy-conversion efficiency, and the emergence of metastable behavior in both limits.

QI 29.6 Thu 15:45 B302

A Rydberg ion quantum engine — •Wilson Martins[1], Igor Lesanovsky[1,2], and Federico Carollo[1] — [1]Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076Tübingen, Germany — [2]School of Physics and Astronomy and Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems, The University of Nottingham, Nottingham,NG7 2RD, United Kingdom

We present and analyse a protocol for operating a quantum engine. Our engine is based on trapped laser-driven Rydberg ions, which constitute a quantum simulation platform where internal and external degrees of freedom can be controlled precisely. Our engine operates under out-of-equilibrium conditions in a setting where external laser-driving competes with dissipation and coherent interaction. We show that for a system of two trapped ions extractable work can be stored in the relative external motion of the trapped ions. We explore a driving protocol and quantify the stored work via the so-called ergotropy: the maximum amount of work that can be obtained from a quantum system.

QI 29.7 Thu 16:00 B302

Measurement feedback models of friction beyond the diffusive limit — •Michael Gaida and Stefan Nimmrichter — Universität Siegen, Deutschland

A typical approach to open quantum systems of motional degrees of freedom is often described in the limit of Brownian motion, which naturally arises from either weak coupling to thermal environments or from weak continuous monitoring.

Here we go beyond the diffusive description and provide a general Markovian measurement feedback model for friction: It involves randomly occur- ring POVM measurements of momentum combined with unitary feedback operations. This enables us to describe arbitrary linear or nonlinear friction forces for quantum particles and quantum optomechanical systems.

For linear friction, we find that our model is equivalent to a random position measurement feedback process involving squeezing. Moreover, we highlight the connection to dissipative spontaneous collapse models.

QI 29.8 Thu 16:15 B302

Initial Correlations in Open Quantum Systems: Constructing Linear Dynamical Maps and Master Equations — •Niklas Neubrand[1], 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

We investigate the dynamics of open quantum systems which are initially correlated with their environment. Our strategy [1, 2] is to analyze how given, fixed initial correlations modify the evolution of the open system with respect to the corresponding uncorrelated dynamical behavior with the same fixed initial environmental state, described by a completely positive dynamical map. We show that, for any predetermined initial correlations, one can introduce a linear dynamical map on the space of operators of the open system which acts exactly like the proper dynamical map on the set of physical states and represents its unique linear extension. Furthermore, we demonstrate that this construction leads to a linear, time-local master equation with generalized Lindblad structure involving time-dependent, possibly negative transition rates. Finally, we illustrate the formalism with the Jaynes-Cummings model and consider the reduced dynamics of a two-level atom which is initially correlated with a single-mode radiation field.

[1] A. Colla, N. Neubrand, and H.-P. Breuer, New J. Phys., 2022
[2] N. Neubrand, Master Thesis, Uni Freiburg, 2022,
DOI 10.6094/UNIFR/231431

QI 30: Quantum Algorithms

Time: Thursday 14:30–16:30 Location: B305

Invited Talk QI 30.1 Thu 14:30 B305

Adaptive constant-depth circuits for manipulating non-abelian anyons — Sergey Bravyi[1], Isaac Kim[2], Alexander Kliesch[3], and •Robert König[3] — [1]IBM T.J. Watson Research — [2]University of California, Davies — [3]Technische Universität München

We consider Kitaev's quantum double model based on a finite group G and describe quantum circuits for (a) preparation of the ground state, (b) creation of anyon pairs separated by an arbitrary distance, and (c) non-destructive topological charge measurement. We show that for any solvable group G all above tasks can be realized by constant-depth adaptive circuits with geometrically local unitary gates and mid-circuit measurements. Each gate may be chosen adaptively depending on previous measurement outcomes. Constant-depth circuits are well suited for implementation on a noisy hardware since it may be possible to execute the entire circuit within the qubit coherence time. Thus our results could facilitate an experimental study of exotic phases of matter with a non-abelian particle statistics. We also show that adaptiveness is essential for our circuit construction. Namely, task (b) cannot be realized by non-adaptive constant-depth local circuits for any non-abelian group G. This is in a sharp contrast with abelian anyons which can be created and moved over an arbitrary distance by a depth-1 circuit composed of generalized Pauli gates.

Preprint available at arXiv:2205.01933.

QI 30.2 Thu 15:00 B305

Performance of Portfolio Optimization with QAOA — •Vanessa Dehn and Thomas Wellens — Fraunhofer Institut für Angewandte Festkörperphysik IAF, Freiburg, Deutschland

The quantum approximate optimization algorithm (QAOA) is a promising candidate to solve the portfolio optimization problem more efficiently than classical computers in case of a large number of assets. For a given list of assets, the problem is formulated as a quadratic binary optimization problem and studied using different versions of QAOA (different mixers). To solve the problem with good performance, we discuss technical aspects such as providing a good choice of the penalty factor in case of the standard version of QAOA and deducing suitable initial circuit parameters as starting point for the classical optimizer [1]. Furthermore, we investigate the warm-start version of QAOA and evaluate to what extent the improved performance of WS-QAOA is due to quantum effects.

[1] S. Brandhofer, D. Braun, V. Dehn, G. Hellstern, M. Hüls, Y. Ji, I. Polian, A. Singh Bhatia and T. Wellens, arXiv:2207.10555

QI 30.3 Thu 15:15 B305

Excitations of Quantum Many-Body Systems via Purified Ensembles: A Unitary-Coupled-Cluster-based Approach — Carlos L. Benavides-Riveros[1,2], Lipeng Chen[2], Christian Schilling[3,4], •Sebastián Mantilla[2], and Stefano Pittalis[5] — [1]Pitaevskii BEC Center, CNR-INO and Dipartimento di Fisica, Università di Trento, Trento, Italy. — [2]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), München, Germany — [4]Ludwig-Maximilians-Universität München, München, Germany — [5]CNR-Istituto Nanoscienze, Modena, Italy

State-average calculations based on mixture of states are increasingly being exploited across chemistry and physics as versatile procedures for addressing excitations of quantum many-body systems. If not too many states should need to be addressed, calculations performed on individual states are also a common option. Here we show how the two approaches can be merged into one method, dealing with a generalized yet single pure state. Implications in electronic structure calculations are discussed and for quantum computations are pointed out.

The talk is based on: Phys. Rev. Lett. 129, 066401 (2022).

QI 30.4 Thu 15:30 B305

Purified-Ensembles Variational Quantum Algorithm for Excited States — •Cheng-Lin Hong[1], Lexin Ding[1], Carlos L. Benavides-Riveros[2,3], Luis Colmenarez[2], and Christian Schilling[1] — [1]LMU Munich, Munich, Germany — [2]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [3]INO-CNR BEC Center,Trento, Italy

Variational quantum algorithms (VQA) can obtain an approximation ground state of the target Hamiltonian. Methods based on VQA for calculating excited states currently involve high-depth unitary implementation or specific previously-found ground states. To directly extend the VQA framework to excited states, we propose an algorithm based on the purification of weighted ensemble states. This algorithm uses the Gross-Oliveira-Kohn (GOK) variational principle and chooses the appropriate set of weights to construct a BCS-like state; the exponential form of the BCS-like state allows efficient implementation on near-term quantum devices. Combined with variational quantum circuits, we can obtain all excited states we want.

QI 30.5 Thu 15:45 B305

Guaranteed efficient energy estimation of quantum many-body Hamiltonians using ShadowGrouping — •Alexander Gresch[1] and Martin Kliesch[1,2] — [1]Institute for Theoretical Physics, Heinrich Heine University Düsseldorf — [2]Institute for Quantum-Inspired and Quantum Optimization, Hamburg University of Technology

Energy estimation in quantum many-body Hamiltonians is a paradigmatic task in various research fields. In particular, an efficient estimation procedure may be crucial in achieving a quantum advantage for a practically relevant problem. Variational quantum algorithms (VQAs) are among the leading approaches for achieving this goal. However, the measurement effort due to the high required accuracy constitutes a crucial bottleneck.

In this work, we aim to find an optimal energy estimation strategy for single-qubit measurements with rigorous performance guarantees. Given any empirical estimator $\hat{E}$ of the energy E relying on different Pauli basis measurements, we derive a tail bound for the estimator $\hat{E}$. Finding the optimal Pauli bases, we show to be NP-hard. Therefore, we develop a heuristic yet efficient estimation strategy based on our tail bound. It combines shadow estimation methods with grouping strategies for Pauli strings. Therefore, we call it *ShadowGrouping*. Numerically, we demonstrate that ShadowGrouping outperforms state-of-the-art methods in estimating the electronic ground-state energies of various small molecules. Hence, this work provides a promising way, e.g., to tackle the measurement bottleneck of VQAs.

QI 30.6 Thu 16:00 B305

Programmable adiabatic demagnetization for systems with trivial and topological excitations — •Anne Matthies[1,2], Achim Rosch[1], Mark Rudner[3], and Erez Berg[2] — [1]University of Cologne, Cologne, Germany — [2]Weizmann Institute of Science, Rehovot, Israel — [3]University of Washington, Seattle, USA

Preparing the ground state of a many-body Hamiltonian on a quantum device is of central importance, both for quantum simulations of molecules and materials, and for a variety of quantum information task. We propose a simple, robust protocol to prepare a low-energy state of an arbitrary Hamiltonian on a quantum computer. The protocol is inspired by the *adiabatic demagnetization* technique, used to cool solid state systems to extremely low temperatures. The adiabatic cooling protocol is demonstrated via an application to the transverse field Ising model. We use half of the qubits to model the system and the other half as a bath. Each bath spin is coupled to a system spin. In a strong magnetic field, the bath spins are prepared in the polarized ground state. By an adiabatic downward sweep of the magnetic field, we change the energy of the bath spins and allow for resonant processes that transfer entropy from the system to the bath qubits. After each cycle, the bath is reset to the ground state.

We find that the performance of the algorithm in the presence of a finite error rate depends on the nature of the excitations of the system; systems with non-local (topological) excitations are more difficult to cool. Finally, we explore ways to partially mitigate this problem.

[arXiv:2210.17256]

QI 30.7 Thu 16:15 B305

Variational quantum amplitude estimation on noisy quantum processors — •Tobias Nauck, Thomas Wellens, and Andreas Ketterer — Fraunhofer Institut für Angewandte Festkörperphysik

The quantum amplitude estimation algorithm provides a quadratic speedup over classical Monte Carlo methods in the task of approximately evaluating integrals. This maximum speedup can, however, only be achieved with quantum circuits of exponentially growing depths which is unfeasible on noisy intermediate-scale quantum processors. In order to tackle the problem of impractically large circuit depths, we develop a hybrid algorithm that approximates circuits with depths exceeding a predefined threshold using a classical variational approximation. To do so, we maximize the fidelty between the invovled circuits and an appropriate variational circuit of low depth on neighboring qubits. In terms of numerical simulations, we show how the introduced variational algorithm depends on the choice of the aforementioned threshold depth and discuss its vulnerability to noise in terms of quantum gate errors.

QI 31: Single Quantum Emitters (joint session Q/QI)

Time: Thursday 14:30–16:30 Location: E214

Invited Talk QI 31.1 Thu 14:30 E214
Quantum information with atomic quantum metasurfaces and integrated nanophotonics — •Rivka Bekenstein for the SHIPTRAP-Collaboration — Hebrew University, Jerusalem, Israel

Quantum information processing with photonic qubits requires on-demand single photon sources, linear components, along with more advanced components such as quantum memories and deterministic nonlinearity to implement logic gates between photonic qubits. I will discuss two promising systems for generating and controlling photonic qubits. I will first present our fiber-coupled single-photon-source based on silicon-vacancy centers in nanophotonic cavity diamond. This source features high efficiency, purity, temporal control, and integrability. We have been able to demonstrate arbitrarily temporally shaped single photon pulses with high purity ($g2(0) = 0.0168$) and detection efficiency of 14.9. This achievement combined with previously demonstrated spin-photon gates and long-lived memory, enables on-demand generation of streams of correlated photons useful for one-way quantum computation. I will then present our quantum-metasurfaces-based quantum protocols for large-scale entanglement generation and quantum holography. These work build upon our recent analysis of quantum metasurfaces: two-dimensional atomic arrays which control light coherently by scattering.

QI 31.2 Thu 15:00 E214
Efficient High-Fidelity Flying Qubit Shaping — •Benedikt Tissot and Guido Burkard — Universität Konstanz

Single photon emission is the cornerstone of numerous quantum technologies, such as distributed quantum computing as well as several quantum internet and networking protocols. We find the upper limit for the photonic pulse emission efficiency for imperfect emitters and show a path forward to optimize the fidelity. The outlined theory for stimulated Raman emission is applicable to a wide range of physical systems including quantum dots, solid state defects, and trapped ions, as well as various parameter regimes in particular for any pulse duration. Furthermore, the mathematical idea to use input-output theory for pulses to absorb the dominant emission process into the coherent dynamics, followed by a quantum trajectory approach has great potential to study other physical systems.

QI 31.3 Thu 15:15 E214
Localized creation of yellow single photon emitting carbon complexes in hexagonal boron nitride — •Anand Kumar[1], Chanaprom Cholsuk[1], Askhan Zand[1], Mohammad Nasimuzzaman Mishuk[1], Tjorben Matthes[1], Falk Eilenberger[1], Sujin Suwanna[2], and Tobias Vogl[1] — [1]Abbe Center of Photonics, Institute of Applied Physics, Friedrich Schiller University Jena, 07745 Jena, Germany — [2]Mahidol University, Bangkok 10400, Thailand

Single-photon emitters in solid-state systems have received a lot of attention as building blocks for numerous quantum technology applications. Defect-based single-photon emitters in hexagonal boron nitride (hBN) stand out due to their optical and physical properties, such as room temperature operation and high single photon luminosity. However, the localized fabrication of these emitters in the crystal lattice is still not very well understood and thus the integration with optical and electronic platforms remains challenging. In the present work, we demonstrate the localized fabrication of emitters by electron beam irradiation using a scanning electron microscope with sub-micron lateral precision. Density functional theory calculations, coupled with experimentally observed emission lines at 575 nm show that the emitters are related to the presence of carbon-based defects, which are activated by the electron beam interaction. We also present results on correlating crystal structure properties and polarization dynamics. Our results indicate that these emitters have a high fabrication yield of identical emitters, which is a crucial advantage for the realization of quantum integrated devices.

QI 31.4 Thu 15:30 E214
Fingerprinting color centers in hexagonal boron nitride — •Chanaprom Cholsuk[1], Sujin Suwanna[2], and Tobias Vogl[1] — [1]Abbe Center of Photonics, 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

Optical quantum technologies promise to revolutionize today's information processing and sensing. Crucial to many quantum applications are efficient sources of pure single photons. For a quantum emitter to be used in such application, or for coupling between different quantum systems, the optical emission wavelength of the quantum emitter needs to be tailored. Here, we use density functional theory (DFT) to calculate and manipulate the transition energy of fluorescent defects in the two-dimensional hexagonal boron nitride.

Our calculations feature the HSE06 functional which accurately predicts the electronic band structures of 267 different defects. Moreover, using strain-tuning we can tailor the optical transition energies of suitable quantum emitters to precisely match those of quantum technology applications. The complete photophysical properties of the emitters including spectrum profile, Huang-Rhys factor, radiative and non-radiative lifetime, quantum efficiency, and excitation and emission dipoles are also revealed. We thereby not only have a promising pathway for tailoring quantum emitters that can couple to other solid-state qubit systems but also get access to the complete fingerprint of the emitters for identifying the defect structure of the emitters.

QI 31.5 Thu 15:45 E214
Will a single two-level atom simultaneously scatter two photons? — •Luke Masters, Xinxin Hu, Martin Cordier, Gabriele Maron, Lucas Pache, Arno Rauschenbeutel, Max Schemmer, and Jürgen Volz — Department of Physics, Humboldt Universität zu Berlin, 10099 Berlin, Germany

The interaction of light with a single two-level emitter is the most fundamental process in quantum optics, and is key to many quantum applications. As a distinctive feature, two photons are never detected simultaneously in the light scattered by the emitter. This is commonly interpreted by saying that a single two-level quantum emitter can only absorb and emit single photons. However, it has been theoretically proposed that the photon anti-correlations can be thought to arise from quantum interference between two possible two-photon scattering amplitudes, which one refers to as coherent and incoherent. This picture is in stark contrast to the aforementioned one, in that it assumes that the atom even has two different mechanisms at its disposal to scatter two photons at the same time. Here, we validate the interference picture by experimentally verifying the 40-year-old conjecture that, by spectrally rejecting only the coherent component of the fluorescence light of a single two-level atom, the remaining light consists of photon pairs that have been simultaneously scattered by the atom. Our results offer fundamental insights into the quantum-mechanical interaction between light and matter and open up novel approaches for the generation of highly non-classical light fields.

QI 31.6 Thu 16:00 E214
Multi-channel waveguide-integrated single photon sources — •Chaiyasit Nenbangkaeo, Alexander Eich, Tobias Spiekermann, and Carsten Schuck — Institute of Physics, University of Münster, Germany

Integrated quantum photonic technology requires large numbers of single quantum emitters. While single-emitter systems have successfully been embedded into nanophotonic waveguides [1], the integration of larger numbers of single-photon sources into complex photonic circuits has remained a challenge. Here we show a novel approach that allows for simultaneously coupling single-photons from several independent colloidal quantum dots into tantalum pentoxide waveguides (Ta2O5). We employ a lithographic technique that probabilistically inserts quantum dots into a waveguide array and then deterministically remove multi-emitter systems until only a single-emitter per waveguide channel remains, thus achieving high-yield integration of single-photon sources across multiple nanophotonic channels. We demonstrate the feasibility of our method with autocorrelation measurements, showing anti-bunching of quantum dot photoluminescence for each individual channel. Our work paves the way for deterministically equipping photonic integrated circuits with large numbers of single-photon sources benefitting a wide range of applications in quantum technology.

[1] Eich, Alexander, et al., ACS Photonics 2022 9 (2), 551-558

QI 31.7 Thu 16:15 E214

Photoluminescence Excitation Characteristics of Color Centers in hBN at Room Temperature — •Pablo Tieben[1,2], Hiren Dobariya[2], Nora Bahrami[1,2], and Andreas W. Schell[1,2] — [1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany — [2]Gottfried Wilhelm Leibniz Universität, Hannover, Germany

In the rapidly developing field of quantum technologies single photons play an important role for a number of applications. Optically active color centers in hexagonal boron nitride (hBN) are of particular interest as they exhibit bright single photon emission over a broad range as well as narrow linewidths at and even well above room temperature. Furthermore, as a solid-state single photon source, these emitters can be reliably integrated into photonic circuits and thus offer a large advantage in terms of scalability. A dependency of the fluorescence emission of single emitters on the excitation wavelength has been observed recently, implying a more complex level structure. Systematic measurements of this dependency could reveal more information about the underlying energy levels and thus atomic structure of these defects. Particularly interesting are patterns in the separation between excited states for a classification of different types of emitters. We perform spectroscopic measurements while varying the excitation wavelength over a large range to gain further insight into their characteristic properties and energy level schemes. By analysis of the excitation spectrum of individual defects, we are extracting information on the distribution of energetic transitions across a large number of emitters.

QI 32: Quantum Optics and Quantum Information with Rigid Rotors (joint session MO/Q/QI)

Time: Thursday 14:30–16:30 Location: F102

QI 32.1 Thu 14:30 F102

Cooling and control of the translational and rotational motion of a nano rotor — •Peter Barker[1], Antonio Pontin[1], Marko Toros[2], Hayden Fu[1], Tania Monteiro[1], Jonathan Gosling[1], and Markus Rademacher[1] — [1]University College London, UK — [2]University of Glasgow, Glasgow, UK

There has been significant interest in controlling the motional degrees of isolated, single nanoparticles, trapped within optical fields in high vacuum. They are seen as ideal candidates for exploring the limits of quantum mechanics in a new mass regime while they are also massive enough to be considered for future laboratory tests of the quantum nature of gravity. In this talk I will report on the control and cooling of all translational and rotational degrees of freedom of a nanoparticle trapped in an optical tweezer using cooling via coherent elliptic scattering where translational temperatures in the 100 μK range were reached, while temperatures as low as 5\,mK were attained in the librational degrees of freedom. I will also outline nanoparticle characterisation techniques based on the control and measurement of the librational and translational motion. This work opens up future applications in quantum science and the characterisation of single isolated nanoparticles free of interference from a substrate.

QI 32.2 Thu 14:45 F102

Polarization control of optically levitated nanoparticles — •Yanhui Hu, James Sabin, Mudassar Rashid, and James Millen — Department of Physics, King's College London, Strand, London

The optical control of anisotropic particles opens up applications in torque sensing and the study of rotational quantum mechanics. The angular modes of a levitated particle are markedly different from the linear modes, and new tools are required to achieve full control. In the Levitated Nanophysics Group at King's College London we work with nanofabricated silicon nanorods, which allow enhanced control over all degrees-of-freedom. We control the rotation of the nanorods through a recently discovered method for generating transverse optical vortices, which can be used to exert a large torque on an array of levitated nanoparticles. We also present a method to simultaneously cool all of the linear and angular modes of levitated, anisotropic particles, without the necessity for a delicate optical cavity.

QI 32.3 Thu 15:00 F102

Surface-induced decoherence and heating of charged rigid rotors — •Lukas Martinetz, Klaus Hornberger, and Benjamin A. Stickler — University of Duisburg-Essen

Levitating charged particles in ultrahigh vacuum provides a preeminent platform for quantum information processing, for quantum-enhanced force and torque sensing, for probing physics beyond the standard model, and for high-mass tests of the quantum superposition principle. Existing setups, ranging from single atomic ions to ion chains and crystals to charged molecules and nanoparticles, are crucially impacted by fluctuating electric fields emanating from nearby electrodes used to control the motion. In this article, we provide a theoretical toolbox for describing the rotational and translational quantum dynamics of charged nano- to microscale objects near metallic and dielectric surfaces, as characterized by macroscopic dielectric response functions. The resulting quantum master equations describe the coherent surface-particle interaction due to image charges and Casimir-Polder potentials as well as surface-induced decoherence and heating with the experimentally observed frequency and distance scaling. We explicitly evaluate the master equations for relevant setups, thereby providing the framework for describing and mitigating surface-induced decoherence as required in future quantum technological applications.

QI 32.4 Thu 15:15 F102

Decoherence-Free Rotational Degrees of Freedom for Quantum Applications — •Julen S. Pedernales, Francesco Cosco, and Martin B. Plenio — Institut für Theoretische Physik und IQST, Albert-Einstein-Allee 11, Universität Ulm, D-89081 Ulm, Germany

I will describe the use of spherical t-designs for the systematic construction of solids whose rotational degrees of freedom can be made robust to decoherence due to external fluctuating fields while simultaneously retaining their sensitivity to signals of interest. Specifically, the ratio of the signal phase accumulation rate from a nearby source to the decoherence rate caused by fluctuating fields from more distant sources can be incremented to any desired level by using increasingly complex shapes. This allows for the generation of long-lived macroscopic quantum superpositions of rotational degrees of freedom and the robust generation of entanglement between two or more such solids with applications in robust quantum sensing and precision metrology as well as quantum registers.

[1] J. S. Pedernales, F. Cosco, and M. B. Plenio, Phys. Rev. Lett. 125, 090501 (2020).

QI 32.5 Thu 15:30 F102

Group report: Precision spectroscopy and quantum information with trapped molecules — •Brandon Furey, Stefan Walser, Zhenlin Wu, Guanqun Mu, Rene Nardi, and Philipp Schindler — Institut für Experimentalphysik, Universität Innsbruck, Österreich

The quantum molecules group at the University of Innsbruck utilizes a range of innovative advances in molecular spectroscopy and quantum logic spectroscopy (QLS) to study molecular rovibrational structure and explore quantum information processing with trapped molecules. The efforts of our group are divided into three projects. The first is pump-probe recoil spectroscopy, where we measure the rovibrational population dynamics excited by a pump pulse by mapping them to the electronic state of an atomic ion via QLS. The second project investigates state-dependent force spectroscopy, where an optical tweezer generates a state-dependent force on a trapped molecule. Our third project is demonstrating superpositions of rotational states in a diatomic molecular ion built using stimulated Raman transitions driven by two beams from an optical frequency comb. This could pave the way for using quantum error correction to realize the use of trapped molecules for quantum information or memory. We are interested in creating the rotational superposition states that form the codewords of a truncated $Z_3 \subset Z_6$ linear rotor code. In order to demonstrate ultrafast light-matter interaction in our system, we have measured the photodissociation spectrum of $CaOH^+$ using an optical parametric amplifier.

QI 32.6 Thu 15:45 F102

From the rotation of a planar rigid rotor in electric fields to the semifinite-gap structure of an optical superlattice — •Marjan Mirahmadi[1], Bretislav Friedrich[1], Burkhard Schmidt[2], and Jesús Pérez-Ríos[1,3,4] — [1]Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany — [2]Weierstraß-Institut, Berlin, Germany — [3]Department of Physics, Stony Brook University, NY , USA — [4]Institute for Advanced Computational Science, Stony Brook University, NY, USA

We show that two seemingly unrelated problems – the trapping of an atom in a one-dimensional optical superlattice (OSL) formed by the interference of optical lattices whose spatial periods differ by a factor of two, and the libration of a polar polarizable planar rotor (PR) in combined electric and optical fields – have isomorphic Hamiltonians. It is possible to establish a map between the translations of atoms in the former system and the rotations of the rotor due to the coupling of its permanent and induced electric dipole moments to the external fields. The latter system belongs to the class of conditionally quasi-exactly solvable problems in quantum mechanics and exhibits intriguing spectral properties. We make use of our findings to explain the *semifinite-gap* band structure of the OSL. This band structure follows from the eigenenergies obtained as solutions of the Whittaker-Hill equation and their genuine and avoided crossings. Furthermore, the mapping makes it possible to establish correspondence between concepts, such as localization on the one hand and orientation/alignment on the other.

QI 32.7 Thu 16:00 F102

Experimental advances in the quest for perfect enantiomer-specific state control of cold molecules — •Juhyeon Lee[1], Johannes Bischoff[1], Alicia. O. Hernandez-Castillo[2], Boris Sartakov[1], Gerard Meijer[1], and Sandra Eibenberger-Arias[1] — [1]Fritz Haber Institute of the Max Planck Society, Berlin, Germany — [2]Harvey Mudd College, Claremont, Callifornia, USA

Enantiomer-specific state transfer (ESST) was recently developed using tailored microwave fields [1]. This technique enables the population or depopulation of a rotational state of a chosen enantiomer, providing a way of quantum-controlled chiral separation. Recently, we have explored spectroscopic schemes to overcome previous limitations in the transfer efficiency of ESST: thermal population of the rotational levels and M_J degeneracy [2]. We improved the transfer efficiency up to 50%, and quantitatively studied ESST for the first time [3]. The experimental ESST efficiency was $\sim$ 20% lower than theoretically expected. We attribute this partially to imperfections in the microwave polarizations and their respective orthogonality. We show a method to experimentally determine the polarization of microwave fields in-situ by quantitative analysis of molecular Rabi oscillations.

[1] S. Eibenberger, et al., Phys. Rev. Lett. 118, 123002 (2017)
[2] M. Leibscher, et al., Commun. Phys. 5, 1 (2022).
[3] J. H. Lee, et al., Phys. Rev. Lett. 128, 173001 (2022)

QI 32.8 Thu 16:15 F102

Photoelectron circular dichroism in rotationally excited mixtures — •Alexander Blech[1], Loren Greenman[2], Reinhard Dörner[3], and Christiane P. Koch[1] — [1]Fachbereich Physik, Freie Universität Berlin, Berlin, Germany — [2]Department of Physics, Kansas State University, Manhattan, KS, USA — [3]Institut für Kernphysik, Goethe-Universität, Frankfurt am Main, Germany

Gas phase experiments with chiral molecules may be carried out with randomly oriented molecules because there exist enantiomer-sensitive observables that survive orientational averaging. The strength of these observables is directly related to the enantiomeric excess and vanishes in the limit of a racemic mixture. Here we turn the perspective around and investigate whether it is possible to detect chiral signatures from racemic, but rotationally excited mixtures. We focus on photoelectron circular dichroism (PECD), which is the forward-backward asymmetry in the photoelectron angular distributions of chiral molecules upon ionization with circularly polarized light. Based on an analysis of the electric dipole response in rotationally excited molecular ensembles, we show that PECD can be observed in racemic mixtures by breaking the isotropy of the orientational distribution.

QI 33: Quantum Networks II (joint session QI/Q)

Time: Thursday 14:30–16:30 Location: F428

QI 33.1 Thu 14:30 F428

A quantum interface between NV center matter qubits and Thulium rare-earth ion quantum memory compatible light — •M.C. Roehsner[1], M. Iuliano[1], A.J. Stolk[1], M. Sholkina[1], N. Alfasi[1], T. Chakraborty[1], W. Tittel[1,2], and R. Hanson[1] — [1]QuTech & Kavli Institute of Nanoscience, Delft University of Technology — [2]Department of Applied Physics, University of Geneva & Schaffhausen Institute of Technology, Geneva

Quantum networks promise to enable applications ranging from secure communication to fundamentally new kinds of computation. However, the individual components of quantum networks may be realized with different kinds of physical systems, requiring specialized interfaces. Here we present our work towards interfacing a diamond Nitrogen Vacancy (NV) center, well suited as a local quantum processing network node [1], with light compatible with Tm-based rare-earth ion quantum memories, well suited for long-range quantum repeaters [2]. We demonstrate two-photon quantum interference between photons emitted from an NV center with weak coherent light resonant with a Tm-based memory, probing the indistinguishability of the photons created by these disparate sources, using a low noise two-step quantum frequency conversion process. Furthermore, we present latest results towards teleporting a memory-compatible time-bin qubits into the NV center. With this quantum interface between different physical systems, we aim to bridge the gap between two key network components.
[1] Hermans, S.L.N. et al. Nature 605 (2022) [2] Davidson J.H. et al. Phys. Rev. A 101 (2020)

QI 33.2 Thu 14:45 F428

Space-borne quantum memories for global quantum networking — •Mustafa Gündoğan[1], Jasminder Sidhu[2], Daniel Oi[1], and Markus Krutzik[1] — [1]Humboldt-Universität zu Berlin, Berlin, Germany — [2]University of Strathclyde

Exponential losses in optical fibres limit the transmission of quantum information to around few hundred kilometres. Quantum repeaters based on the heralded storage of entangled photon pairs were proposed to increase this direct transmission limit. Nevertheless, these architectures are still limited to around few thousand kilometres.

In this talk I will present our proposal for placing quantum memories on board orbiting satellites to enable quantum networking at a truly global scale. The first idea relies on building a network of satellites equipped with QM with storage times of <1s. One can then create a quantum repeater in space to cover global distances [1]. The second idea is to use a single orbiting satellite equipped with two QMs: one with long ($\sim$h) and the other short ($\sim$ms) storage times. Quantum information is then shuttled across the globe in a time-delayed quantum repeater fashion. This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant number 50WM2055.

[1] M. Gündoğan *et. al.*, npj Quantum Information **7**, 128 (2021)

QI 33.3 Thu 15:00 F428

Towards remote entanglement of single erbium dopants — •Alexander Ulanowski[1], Fabian Salamon[1], Benjamin Merkel[1], and Andreas Reiserer[1,2] — [1]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany — [2]TU München and Munich Center for Quantum Science and Technology, 85748 Garching, Germany

In a future quantum internet, coherent emitters will exchange quantum states over global distances, preferably using optical fibers to establish entanglement between remote spins. To this end, erbium dopants are a promising platform due to the optical transition in the telecom band enabling low-loss distribution of photons. To realize an efficient spin-photon interface for single dopants, we embed a thin erbium doped crystal into a tuneable high-finesse Fabry-Perot resonator. In our experiment we achieve up to 110-fold Purcell enhancement while the coherence is preserved up to the lifetime limit by avoiding proximal interfaces [1]. Using spectral multiplexing gives us access to hundreds of individual dopants which exhibit a low spectral diffusion (< 0.2 MHz) currently limited by the nuclear spin bath [2]. To further improve the spectral stability and enable entanglement generation via photon interference, we thus investigate spin-free ^{29}Si crystals as a possible host material [3]. Furthermore, we expect considerable stability improvement by applying real-time feedback on the emitter frequency. This opens perspectives for long-distance entanglement at kilohertz rates.

[1] B. Merkel et al., Phys. Rev. X 10, 041025 (2020).
[2] A. Ulanowski et al., Sci. Adv. 8, eabo4538 (2022).
[3] Y. Liu et al., Journ. Cryst. Growth, 126733 (2022).

QI 33.4 Thu 15:15 F428

Hong-Ou-Mandel Interference in LNOI — •Silia Babel, Laura Bollmers, Marcello Massaro, Kai Hong Luo, Michael Stefszky, Federico Pegoraro, Philip Held, Harald Herrmann, Christof Eigner, Benjamin Brecht, Laura Padberg, and Christine Silberhorn — Paderborn University, Integrated Quantum Optics, Institute for Photonic Quantum Systems (PhoQS), Warburger Str. 100, 33098 Paderborn, Germany

A quantum computer can be built solely using single photons sources, linear optics and single photon detectors. For the realisation of a photonic quantum computer, a particular interest has been devoted to the study of integrated networks since these offer many advantages such as stability, the possibility of compact devices and high efficiency, and thus provide scalability. The foundation of these integrated networks are directional couplers and interference between single photons.

A interesting platform for this purpose is Lithium Niobate on Insulator (LNOI) since it combines the advantages of conventional lithium niobate, such as a wide transparency window and high nonlinear coefficients, with a high integration density. To show that this material is suited for the realisation of integrated quantum networks, we demonstrate Hong-Ou-Mandel interference (HOMI) of telecom photons on a balanced directional coupler. We designed and fabricated the coupler in-house and achieve a raw HOMI visibility of (93.5±0.7)%. Our work demonstrates a crucial building block for integrated quantum networks based on LNOI.

QI 33.5 Thu 15:30 F428

Portable warm vapor memory — •Martin Jutisz[1], Elisa Da Ros[1], Alexander Erl[2,3], Leon Messner[1,3], Luisa Esguerra[3,2], Janik Wolters[3,2], Mustafa Gündoğan[1], and Markus Krutzik[1,4] — [1]Humboldt-Universität zu Berlin, Berlin, Germany — [2]Technische Universität Berlin, Berlin, Germany — [3]Deutsches Zentrum für Luft- und Raumfahrt, Berlin, Germany — [4]Ferdinand-Braun-Institut (FBH), 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 status of integration and test of a portable rack-mounted system. The implementation of the optical memory is based on electromagnetically induced transparency on the Cesium D1 line at 894 nm. Three lasers are frequency stabilized to provide pump, signal and control pulses. Automated locking is realized via a FPGA-based tool for laser frequency stabilization. The storage platform is provided by a heated Cesium vapour cell in a three-layer magnetic shield. Possibilities of micro integration are also being investigated.

This work is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry of Economics and Technology (BMWK) under grant number 50RP2090.

[1] M. Gündoğan et. al., npj Quantum Information 7, 128 (2021)

QI 33.6 Thu 15:45 F428

Single erbium dopants in nanophotonic resonators — •Jakob Pforr[1,2], Andreas Gritsch[1,2], Alexander Ulanowski[1,2], and Andreas Reiserer[1,2] — [1]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany — [2]TU München and Munich Center for Quantum Science and Technology, 85748 Garching, Germany

Single erbium dopants in nanophotonic resonators are promising for the realization of quantum networks owing to their outstanding optical and spin coherence properties [1] and their large spectral multiplexing potential [2]. Previous experiments used yttrium-based host crystals, in which erbium is integrated in well-defined sites. However, these crystals are not compatible with established nanofabrication techniques, which hinders scalable integration into on-chip photonic circuits. To address this challenge, we have spectroscopically studied ensembles of erbium dopants in silicon nanostructures. After optimizing the erbium implantation procedure, we have observed two well-defined lattice sites with narrow inhomogeneous broadening (< 1 GHz), narrow homogeneous linewidths (< 0.01 MHz) and optical lifetimes of 0.2 ms [3]. In one-dimensional photonic crystal resonators ($Q > 10^4$, $V \sim \lambda^3$), we observe single dopants with a 60-fold Purcell-enhanced emission. We will present studies of the optical coherence, spectral diffusion, spin properties and spectral multiplexing capability of these devices.

References:
[1] Merkel et. al. 2020. PRX 10(4): 041025.
[2] Ulanowski et. al. 2021. SciAdv 8(43): eabo4538.
[3] Gritsch et. al. 2021. PRX 12(4): 041009.

QI 33.7 Thu 16:00 F428

High fidelity single-shot readout of telecom emitters in a Fabry-Perot resonator — •Fabian Salamon[1,2], Alexander Ulanowski[1,2], Johannes Früh[1,2], and Andreas Reiserer[1,2] — [1]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany — [2]TU München and Munich Center for Quantum Science and Technology, 85748 Garching, Germany

Erbium dopants are prime candidates for the realisation of extended quantum networks, as they combine second-long ground state coherence with a coherent optical transition in the telecommunication window, where loss in optical fibers is minimal [1].

To implement quantum information processing in this novel platform, we perform single-shot readout of the spin state by resonantly driving the optical transition and detecting the subsequently emitted photons. We overcome the challenge that erbium lacks a cycling transition [2] by using a Fabry-Perot resonator with a narrow linewidth (50 MHz) [3] in order to selectively enhance the readout transition.

Combined with our recent advances in spectral multiplexing [4], the successful implementation of high-fidelity single-shot readout is a key step towards high-rate entanglement of distant erbium dopants.

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[2] M. Raha et al., Nat. Commun. 11, 1605 (2020).
[3] B. Merkel, A. Ulanowski & A. Reiserer, Phys. Rev. X 10, 041025 (2020).
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QI 33.8 Thu 16:15 F428

Electromagnetically Induced Transparency in hollow-core light-cages: Simulation tool and experimental preparation — •Dominik Ritter[1], Esteban Gómez-López[1], Jisoo Kim[2], Markus Schmidt[2,4], Harald Kübler[3], and Oliver Benson[1] — [1]Humboldt-Universität zu Berlin, 12489 Berlin, Germany — [2]Leibniz Institute of Photonic Technology, 07702 Jena, Germany — [3]University of Stuttgart, 70569 Stuttgart, Germany — [4]Otto Schott Institute of Material Research, 07743 Jena, Germany

Quantum repeaters and memories are needed to overcome efficiently the losses of long-distance quantum networks [1]. A promising system to host a quantum memory is atomic vapours, which can be enhanced with guiding photonic structures [2].

We will present a simulation program and experimental measurements for enhanced light matter interaction in hollow-core light-cages (LC) inside a warm cesium vapor cell. The program calculates the absorption spectra of alkali vapors under Electromagnetically Induced Transparency (EIT). Propagation of light pulses through the bare atomic vapor and the LC are simulated, where a linear loss model is assumed. This use of the LC would lead towards controllable time delay of photons in an easy to use and easy to implement device and eventually a reliable platform for a quantum memory for single photons using the EIT-storage scheme [3].

[1] P. v. Loock et al., Adv. Quantum Technol. 3, 1900141 (2020). [2] K. F. Reim et al., Phys. Rev. Lett. 107, 053603 (2011). [3] J. Wolters et al., Phys. Rev. Lett. 119, 060502 (2017).

QI 34: Concepts and Methods III

Time: Friday 11:00–13:00 Location: B302

QI 34.1 Fri 11:00 B302

Quantum Bell Inequalities from Information Causality — •Prabhav Jain[1], Mariami Gachechiladze[1], and Nikolai Miklin[2] — [1]TU Darmstadt, Germany — [2]Heinrich-Heine-Universität Düsseldorf, Germany

Characterizing the set of quantum correlations in the space of all possible non-signalling theories is a hard but important problem. For a given Bell scenario, quantum bell inequalities which bound the set of possible observed correlation are relevant not only as a theoretical interest but for several applications such as QKD etc. A fundamental goal is to 'derive' this quantum set from physical/empirical principles without assuming any of the formalism.

In this work, we propose to use information causality as one such physical principle. We derive new quantum Bell inequalities for arbitrary measurement settings and outcomes in a bipartite scenario while improving on some previous known results by obtaining the tightest bounds so far for such scenarios. We also investigate how our new polynomial inequalities in the observed probability distributions relate to other well known principles such as macroscopic locality and almost quantum correlations.

QI 34.2 Fri 11:15 B302

Solution of the convex single-body quantum marginal problem and its physical relevance — •Julia Liebert[1], Federico Castillo[2], Jean-Philippe Labbé[3], Arnau Padrol[4], Eva Philippe[4], Rolando Reiner[1], and Christian Schilling[1] — [1]University of Munich (LMU), Munich, Germany — [2]Pontificia Universidad Catolica de Chile, Macul, Chile — [3]École de Technologie Supérieure, Montréal, Canada — [4]Sorbonne Université, Paris, France

The single-body quantum marginal problem asks whether given single-body reduced density matrices are compatible to some multipartite quantum state. In a recent breakthrough, A. Klyachko has solved this general problem on an abstract mathematical level. Urged by the limited scope of that solution to artificially small quantum systems, we explain why the convex-relaxed variant of that compatibility problem is the more relevant one for practical purposes. By using tools from convex analysis, we then provide a comprehensive solution to the latter problem for any multipartite quantum state with a fixed spectrum, leading to a complete hierarchy of necessary and sufficient spectral constraints which are valid for systems of arbitrary size. In the context of fermions and bosons, these novel conditions lead to a physical relevant generalization of Pauli's famous exclusion principle.

QI 34.3 Fri 11:30 B302

Compensating for non-linear distortions in controlled quantum systems — •Juhi Singh[1,2], Robert Zeier[1], Tommaso Calarco[1,2], and Felix Motzoi[1] — [1]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, 50937 Köln, Germany

Predictive design and optimization methods for controlled quantum systems depend on the accuracy of the system model. Any distortion of the input fields in an experimental platform alters the model accuracy and eventually disturbs the predicted dynamics. These distortions can be non-linear with a strong frequency dependence so that the field interacting with the microscopic quantum system has limited resemblance to the input signal. We present an effective method for estimating these distortions which is suitable for non-linear transfer functions of arbitrary lengths and magnitudes provided the available training data has enough spectral components. Using a quadratic estimation, we have successfully tested our approach for a numerical example of a single Rydberg atom system. The transfer function estimated from the presented method is incorporated into an open-loop control optimization algorithm allowing for high-fidelity operations in quantum experiments.

QI 34.4 Fri 11:45 B302

Entanglement Batteries — •Ye-Chao Liu, Otfried Gühne, and Stefan Nimmrichter — Universität Siegen, Siegen, Germany

Quantum entanglement is an essential resource for many kinds of applications like quantum communication over a quantum network, eventually realizing the quantum internet. The unavoidable noise and losses between the links call for additional hardware that can gradually build up and store entanglement for later use – an entanglement battery.

In this contribution, we introduce the concept of entanglement batteries charged by repeated interactions with a provided stream of Bell pairs. We show that, although perfect SWAP and iSWAP gates can both fully charge entanglement batteries using Bell states, their behaviors differ significantly if the charging interaction strength is restricted to a partial swap or even fluctuates. We compare two exemplary charging protocols: one that repeatedly uses a single Bell state for charging, and another one that uses a fresh Bell state for each charging step. We further assess the performance of entanglement charging under losses.

QI 34.5 Fri 12:00 B302

Device-independent randomness extraction from almost separable multipartite states — •Giacomo Carrara, Federico Grasselli, Hermann Kampermann, Dagmar Bruss, and Gláucia Murta — Heinrich-Heine-Universität Düsseldorf

Bell inequalities represent a fundamental tool for many quantum information tasks that exploit nonlocality. In particular they can be used for device-independent (DI) protocols, where the parties do not need to trust or characterize the underlying systems and measurement devices. Specifically, the violation of a Bell inequality allows to certify the randomness of the parties' outcomes with respect to a potential eavesdropper. Even though entanglement is necessary for the violation of a Bell inequality, the relation between nonlocality and entanglement is more intricate than one might expect. In [*Phys. Rev. Lett.*, **108**, 100402 (2012)] the authors show that maximal DI randomness can be obtained, in the bipartite scenario, from almost separable states. In this work, we extend this result to the multipartite scenario. In particular, we analyze the amount of randomness that can be extracted from a state arbitrarily close to a fully separable state using a suitably chosen multipartite Bell inequality. In order to achieve this result, we employ both standard numerical convex optimization and analytical methods.

QI 34.6 Fri 12:15 B302

Symmetry restoration of mean-field approaches: Rationalization through quantum information theory — •Javier Faba[1,2], Vicente Martín[1], Luis Robledo[2], Lexin Ding[3], and Christian Schilling[3] — [1]Center for Computational Simulation, Universidad Politécnica de Madrid, Campus Montegancedo, 28660 Boadilla del Monte, Madrid, Spain — [2]Departamento de Física Teórica and CIAFF, Universidad Autónoma de Madrid, 28049 Madrid, Spain — [3]Faculty of Physics, Arnold Sommerfeld Centre for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstr. 37, 80333 München, Germany

The quantum many-body problem is of central importance in various subfields of the quantum sciences, particularly in quantum chemistry, solid state and nuclear physics. A promising solution strategy — developed and primarily used so far only in nuclear physics — is based on the following wisdom: Starting from a mean-field solution one systematically improves the variational energy by introducing different levels of quantum correlation through a restoration of the symmetries broken by the former.

In this talk, we will rationalize this general wisdom by providing a concise definition of quantum correlation in this context. To be more specific, we will explain how quantum information concepts can help us in order to describe the correlation structure of mean field and symmetry restored ground states of relevant models that exhibit spontaneous symmetry breaking of both abelian and non abelian symmetries.

QI 34.7 Fri 12:30 B302

Rescaling decoder for 2D topological quantum color codes on 4.8.8 lattices — Pedro Parrado Rodriguez[1], •Manuel Rispler[2,3], and Markus Müller[2,3] — [1]Department of Physics, College of Science, Swansea University, — [2]Institute for Quantum Information, RWTH Aachen University, D-52056 Aachen, Germany — [3]Peter Grünberg Institute, Theoretical Nanoelectronics, Forschungszentrum Jülich, D-52425 Jülich, Germany

Fault-tolerant quantum computation relies on scaling up quantum error correcting codes in order to suppress the error rate on the encoded quantum states. Topological codes, such as the surface code or color codes, are leading candidates for practical scalable quantum error correction and require efficient and scalable decoders. In this work, we propose and study the efficiency of a decoder for two-dimensional topological color codes on the 4.8.8 lattice (also known as the square-octagon code), by building on the work of Sarvepalli and Raussendorf [Phys. Rev. A 85, 022317 (2012)], for color codes on hexagonal lattices. The decoder is based on a rescaling approach, in which syndrome information on a part of the qubit lattice is processed locally, and then the lattice is rescaled iteratively to smaller sizes. We find a threshold of 6.0% for code capacity noise.

QI 34.8 Fri 12:45 B302

Exploiting Graph Symmetries for Quantum Dynamics Algorithmically — •Armin Johannes Römer[1,2], Robert Zeier[3], and Thomas Schulte-Herbrüggen[1,4,5] — [1]Technische Universität München (TUM) — [2]Forschungszentrum Jülich GmbH, IEK-9 — [3]Forschungszentrum Jülich GmbH, PGI-8 (Quantum Control) — [4]Munich Center for Quantum Science and Technology (MCQST) — [5]Munich Quantum Valley e.V. (MQV)

Coupled n-level systems (spins) can classically be represented as coloured graphs, where vertices relate to local spins and differently coloured edges stand for pairwise couplings of different type.

We present an efficient algorithm to exploit graph symmetries for arriving at symmetry-adapted bases. Its core scales classically with the number of spins as vertices of the graph: *its input is merely the graph's adjacency matrix*, it avoids calculating the underlying graph automorphism group, *and its output is a transformation matrix into a symmetry adapted basis.* It connects the Weisfeiler-Leman algorithm, known from graph isomorphism problems, with cutting-edge versions of calculating central idempotents in MAGMA.

We demonstrate how classical graph symmetry carries over to quantum Hilbert space. Worked examples illustrate principles and practice in a manner applicable to, e.g., quantum simulation, quantum dynamics, and quantum information.

QI 35: Quantum Computers: Algorithms and Benchmarking

Time: Friday 11:00–13:00 Location: B305

QI 35.1 Fri 11:00 B305

Advantages of Measurement-based Variational Quantum Eigensolvers — •Anna Schroeder[1,2], Matthias Heller[3], and Mariami Gachechiladze[2] — [1]Merck KGaA, Frankfurter Str. 250, Darmstadt, Germany — [2]Quantum Computing Group, TU Darmstadt, Mornewegstr. 30, Darmstadt, Germany — [3]Fraunhofer IGD, Darmstadt, Germany

The variational quantum eigensolver (VQEs) is a hybrid algorithm to compute the lowest eigenvalue and its corresponding eigenvector for a given operator. The idea is to optimize classically over a parametrized quantum circuit, the ansatz, to generate a quantum state that minimizes the cost function, typically the expectation value of the Hamiltonian. Recently, a different approach to VQE has been considered. Ferguson et al., PRL 2021 discussed unifying the VQE framework with measurement-based quantum computing (MB-VQE). Here instead of parametrizing gates, one starts with highly entangled resource states (e.g., graph states) and optimizes over local measurements. This scheme has already demonstrated an advantage over the gate-based model for small perturbations of Toric code Hamiltonians, as it allows for more compact construction of certain ansaetze while enjoying shallower circuit depths - an imperative property for implementation on NISQ hardware. In our work, we deepen the investigation of MB-VQE advantage by considering more general resource states and larger classes of Hamiltonians, which helps us develop a more rigorous understanding of the advantageous ansaetze in MB-VQE for given problem classes.

QI 35.2 Fri 11:15 B305

Molecular Quantum Circuit Design — •Jakob Kottmann — Institut for Computer Science, University of Augsburg

An integral part of science is the formulation of simple concepts capable to capture the essential aspects of complex processes. A prominent examples is the reduction of molecules to simple graphs with the atomic nuclei as vertices connected by edges representing so - called chemical bonds.

Design principles for the construction of quantum circuits are in high demand and are currently being researched heavily - current methodologies however often lack simplicity and interpretability.

Here, an interpretable design concept for quantum circuits based on chemical graphs is presented. It provides physical insight and interpretaility for each individual circuit element and leads to heuristics for the construction, optimisation, and interpretation of quantum circuits suitable for ground state preparation.

QI 35.3 Fri 11:30 B305

Perspectives of running DMFT calculations on NISQ hardware — •Jannis Ehrlich, Daniel F. Urban, and Christian Elsässer — Fraunhofer-Institut für Werkstoffmechanik IWM, Freiburg, Germany

Quantum computers promise to enhance numerical calculations of correlated electron systems. While the simulation of full electronic systems is far out of reach due to the large number of states that need to be considered, effective model systems can already be implemented on currently available NISQ devices. The Dynamical Mean Field Theory (DMFT) is such an embedding approach, in which the Greens function of a correlated orbital has to match both, the orbitals description as site of a regular lattice and as impurity in an Anderson impurity model (AIM). Both models are solved in an iterative self-consistency loop, where the solution of the AIM is the limiting part of DMFT calculations on conventional computers today. Here, we introduce a possible way of solving the AIP on a quantum computer using hybrid approaches like the variational quantum eigensolver (VQE). We present results of experiments on IBMQ hardware for the two-site DMFT model. Moreover, we show how state-of-the-art error mitigation strategies improve the results. A post-correction scheme is presented to ensure physical symmetries in the final self-consistent Greens function and self-energy and we derive and discuss the requirements on the quantum hardware needed for a successful implementation of the algorithm.

QI 35.4 Fri 11:45 B305

QRydDemo - Quantum Computing with Rydberg Atoms — •Sebastian Weber[1], Philipp Ilzhöfer[2], Govind Unnikrishnan[2], Ratnesh Kumar Gupta[2], Jiachen Zhao[2], Jennifer Krauter[2], Achim Scholz[2], Moritz Wilke[2], Alice Pagano[3], Daniel Jaschke[3], Nicolai Lang[1], Nastasia Makki[1], Hans Peter Büchler[1], Simone Montangero[3], Jürgen Stuhler[4], Tilman Pfau[2], and Florian Meinert[2] — [1]Institute for Theoretical Physics III and IQST, University of Stuttgart, Germany — [2]5th Institute of Physics and IQST, University of Stuttgart, Germany — [3]Institute for Complex Quantum Systems, Ulm University, Germany — [4]Toptica Photonics AG, Gräfelfing, Germany

The QRydDemo Consortium aims to realize a quantum computer demonstrator with up to 500 atomic qubits trapped in arrays of optical tweezers. Exciting the atoms with lasers to Rydberg states, allows for rapidly switching interactions between the atoms on and off, enabling the implementation of fast and high-fidelity gate operations. Our quantum processor based on the optical tweezer architecture promises many exciting new possibilities. One novel aspect we aim to explore is the potential to change the qubit connectivity during a quantum computation. I will provide an overview of the QRydDemo project and demonstrate our online emulator that allows future users of our hardware to get familiar with QRydDemo's native gate operations.

QI 35.5 Fri 12:00 B305

Proposed method to produce large multipartite nonlocality and benchmark quantum computers — •Jan Lennart Bönsel[1], Otfried Gühne[1], and Adán Cabello[2] — [1]Universität Siegen, Germany — [2]Universidad de Sevilla, Spain

Nonlocality is a characteristic of quantum mechanics that does not occur in a local realistic model. Thus, nonlocality is an interesting property to exclude local realistic models, which can be tested by Bell inequalities. Mermin- and Ardehali-Bell inequalities can be formulated for a large number of qubits N. For these inequalities, the ratio of the quantum violation to the classical bound increases exponentially in N. In practice, the amount of nonlocality that can be produced is limited by noise and restrictions on the possible qubit interactions. In addition, to certify nonlocality, a number of terms that grows exponentially with the number of qubits have to be measured, which becomes infeasible for systems with many qubits.

In this work, we address this problem. On the one hand, we consider the Ardehali-Bell operator for the linear cluster state, which can be prepared by nearest neighbour interactions only. On the other hand, we investigate how the violation of the Bell inequality can be estimated by measuring the terms of the Bell operator at random. For this purpose, we study the confidence level for an observed violation given the number of measured observables. As the linear cluster state is important for quantum computations and can be readily prepared on many quantum computing platforms, the violation of the Bell inequality could serve as a benchmark for quantum computers.

QI 35.6 Fri 12:15 B305

Principles of Quantum Functional Testing — Nadia Milazzo[1,2,3], Olivier Giraud[2], •Giovanni Gramegna[1], and Daniel Braun[1] — [1]Institut für theoretische Physik, Universität Tübingen, 72076 Tübingen, Germany — [2]Université Paris Saclay, CNRS, LPTMS, Orsay 91405, Franc — [3]ColibrITD, 91, rue du Faubourg Saint-Honoré 75008 Paris

Testing the functionality of quantum devices will be needed as their availability increases. In this context, a complete characterization of the quantum channel implemented by the device is unfeasible except for the simplest and smallest quantum chips. Rather, quantum functional testing aims at determining as fast as possible whether the device can be accepted or rejected according to the producer pecifications on the key characterizing parameters. In particular, it is desirable to waste as little time as possible on devices that do not function properly. We investigate the possibility to speed up the testing process by using repetition of the channel: on one hand this would increase the impact of coherent errors enhancing their detectability, on the other hand the amplification of incoherent errors might have the opposite effect. This also motivates the introduction of non-greedy adaptive experimental design, where the decision on whether to repeat the channel or more generally which sequence of measurement to perform is established based on the information already gathered from previous measurements. Finally, we investigate the impact of different decision criteria on the efficiency of the testing procedure

QI 35.7 Fri 12:30 B305

Characterizing crosstalk of superconducting transmon processors — •Andreas Ketterer and Thomas Wellens — Fraunhofer Institut für Angewandte Festkörperphysik IAF, Tullastr. 72, 79108 Freiburg, Germany

Currently available quantum computing hardware based on superconducting transmon architectures realizes networks of hundreds of qubits with the possibility of controlled nearest-neighbor interactions. However, the inherent noise and decoherence effects of such quantum chips considerably alter basic gate operations and lead to imperfect outputs of the targeted quantum computation. In this talk we focus on the characterization of crosstalk effects which manifest themselves in correlations between simultaneously executed quantum gates on neighboring qubits. After a short explanation of the origin of such correlations we show how to efficiently and systematically characterize the magnitude of such crosstalk effects on an entire quantum chip using the randomized benchmarking protocol. In particular, we demonstrate the introduced protocol by running it on real quantum hardware provided by IBM. Lastly, we use the gained information in order to propose novel and more accurate means to simulate noisy quantum hardware by devising an appropriate crosstalk-aware noise model.

QI 35.8 Fri 12:45 B305

Noise mitigating adaptive quantum tomography — •Adrian Aasen and Martin Gärttner — Kirchhoff-Institut für Physik, Universität Heidelberg, Heidelberg, Germany

Quantum tomography is the process of reconstructing density matrices, or quantum states, and is the golden standard for state discrimination. It is quite an active field partially due to the recent development and benchmarking requirements of quantum computers and hardware. Common for all near term quantum devices is that they are noisy. Knowing how readout errors affect the tomographic estimate and how to mitigate the effect of noise is of significant interest. We leverage two strategies to reduce the overall experimental cost and improve control over noise in experimental setups. Firstly, we limit the use of noisy measurements to fit within a "noise budget". Subsequently we give a theoretical prescription for how to derive an optimal set of measurements within these restrictions, given some noise model. Secondly, we use adaptive strategies, suitable for both maximal likelihood estimation and Bayesian inference, to maximize information extraction per measurement. Combining these two strategies provide an optimal protocol to reach a desired reconstruction accuracy in a noisy environment.

QI 36: Quantum Metrology (joint session QI/Q)

Time: Friday 11:00–13:00 Location: F428

QI 36.1 Fri 11:00 F428

Super-Resolution Imaging with Multiparameter Quantum Metrology in Passive Remote Sensing — •Emre Köse and Daniel Braun — Institut für Theoretische Physik, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany

We study super-resolution imaging theoretically using a distant n-mode interferometer in the microwave regime for passive remote sensing, used e.g., for satellites like the "soil moisture and ocean salinity (SMOS)" mission to observe the surface of the Earth. We give a complete quantum mechanical analysis of multiparameter estimation of the temperatures on the source plane. We find the optimal detection modes by combining incoming modes with an optimized unitary that enables the most informative measurement based on photon counting in the detection modes and saturates the quantum Cramér-Rao bound from the symmetric logarithmic derivative for the parameter set of temperatures. In our numerical analysis, we achieved a quantum-enhanced super-resolution by reconstructing an image using the maximum likelihood estimator with a pixel size of 3 (km), which is ten times smaller than the spatial resolution of SMOS with comparable parameters. Further, we find the optimized unitary for uniform temperature distribution on the source plane, with the temperatures corresponding to the average temperatures of the image. Even though the corresponding unitary was not optimized for the specific image, it still gives a super-resolution compared to local measurement scenarios for the theoretically possible maximum number of measurements.

QI 36.2 Fri 11:15 F428

Activation of metrologically useful genuine multipartite entanglement — •Róbert Trényi[1,2,3], Árpád Lukács[1,4,3], Paweł Horodecki[5,6], Ryszard Horodecki[5], Tamás Vértesi[7], and Géza Tóth[1,2,8,3] — [1]Dept. of Theoretical Physics, U. of the Basque Country UPV/EHU, Bilbao, Spain — [2]DIPC, San Sebastián, Spain — [3]Wigner Research Centre for Physics, Budapest, Hungary — [4]Dept. of Mathematical Sciences, Durham University, United Kingdom — [5]International Centre for Theory of Quantum Technologies, University of Gdansk, Gdansk, Poland — [6]Faculty of Applied Physics and Mathematics, National Quantum Information Centre, Gdansk University of Technology, Gdansk, Poland — [7]Institute for Nuclear Research, Debrecen, Hungary — [8]IKERBASQUE, Bilbao, Spain

In quantum metrology, the usefulness of a quantum state is determined by how much it outperforms separable states. For the maximal metrological usefulness genuine multipartite entanglement (GME) is required. In order to improve the usefulness of a quantum state we consider a scheme of having several of its copies. With this scheme, it is possible to find a large class of practically important entangled states that can achieve maximal metrological performance in the limit of many copies, whereas in the single copy case these states can even be non-useful. Thus, we essentially activate quantum metrologically useful GME. Moreover, this maximal usefulness is attained exponentially fast with the number of copies and it can be achieved by measurements of simple correlation observables. We also give examples of improving the usefulness outside of the above mentioned class.

QI 36.3 Fri 11:30 F428

Quantum metrology with ultracold chemical reactions —
Seong-Ho Shinn[1], Uwe R. Fischer[1], and •Daniel Braun[2] — [1]Seoul National University — [2]Eberhard Karls University Tübingen

Classical chemical reactions are routinely used for extremely sensitive detection schemes in chemical, biological, and medical analysis, and have even been employed in the search for dark matter. Now we show that coherent, ultracold chemical reactions harbor great potential for quantum metrology [1]: In an atom-molecule Bose-Einstein condensate (BEC), a weak external perturbation can generate elementary excitations, "reactons", of a reaction field. In an appropriate atom-dominant parameter regime this translates to the coherent creation of molecules which can be selectively detected with modern spectroscopic techniques. This promises to improve the viability of previously proposed BEC-based sensors for gravitational waves and other physical quantities, for which so far no practical read-out scheme could be demonstrated.

[1] Seong-Ho Shinn, Uwe R. Fischer, and Daniel Braun, arXiv:2208.06380

QI 36.4 Fri 11:45 F428

Quantum metrology from randomized measurements —
•Satoya Imai[1], Otfried Gühne[1], and Géza Tóth[2,3,4,5] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Str. 3, 57068 Siegen, Germany — [2]Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain — [3]Donostia International Physics Center (DIPC), ES-20080 San Sebastian, Spain — [4]IKERBASQUE, Basque Foundation for Science, E-48013 Bilbao, Spain — [5]Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary

A central task in quantum metrology is to consider a parameter encoding on a quantum system and to improve schemes to reach optimal precision. To reach higher precision, precise control of state preparation and favorable measurements may be necessary. In practice, however, unavoidable noise effects, such as magnetic field fluctuations, may affect the estimation accuracy. A key idea to address this situation is to perform a random measurement on the quantum system and access local unitary invariants. This procedure motivates the study of quantum metrology without a common reference frame between several parties. In this talk, we present a systematic method to investigate the estimation sensitivity in the dynamics based on nonlinear interaction Hamiltonians. We show that the well-known Heisenberg scaling is achievable and even better scaling is attainable.

QI 36.5 Fri 12:00 F428

Closed-loop Quantum Optimal Control for Electronic Spins —
•Thomas Reisser[1,2], Marco Rossignolo[3,4], Matthias M. Müller[1], Felix Motzoi[1], Fedor Jelezko[3], Simone Montangero[4,5], and Tommaso Calarco[1,2] — [1]Forschungszentrum Jülich GmbH — [2]University of Cologne — [3]Ulm University — [4]Università degli Studi di Padova — [5]INFN, Sezione di Padova

To unlock the full potential of many quantum technologies, quantum optimal control (QOC) algorithms and strategies are used to enhance and enable operations on a quantum system. While some methods depend on simulations and good models of the system, it can be helpful to close the loop with an experiment in order to tweak the given controls for a specific setup. The Quantum Optimal Control Suite (QuOCS) is designed to perform black-box optimization in connection with an arbitrary experiment or simulation. Due to its interface with the experiment control software Qudi [1] is has been used successfully for the optimization of pulses for color centers in diamond and also two-qubit gates with Rydberg Atoms [2]. We show the main features of the QuOCS software package and report on recent developments and applications of QOC on electron spins in crystals with a focus on quantum sensing.

References:

[1] J. M. Binder et al., Qudi: A modular python suite for experiment control and data processing, SoftwareX (2017)

[2] A. Pagano et al., Error budgeting for a controlled-phase gate with strontium-88 rydberg atoms, PRR (2022)

QI 36.6 Fri 12:15 F428

Quantum Wasserstein distance based on an optimization over separable states —
•Géza Tóth[1,2,3,4] and József Pitrik[4,5,6] — [1]Theoretical Physics and EHU Quantum Center, University of the Basque Country UPV/EHU, ES-48080 Bilbao, Spain — [2]Donostia International Physics Center (DIPC), ES-20080 San Sebastián, Spain — [3]IKERBASQUE, Basque Foundation for Science, ES-48011 Bilbao, Spain — [4]Wigner Research Centre for Physics, HU-1525 Budapest, Hungary — [5]Alfréd Rényi Institute of Mathematics, HU-1053 Budapest, Hungary — [6]Department of Analysis, Institute of Mathematics, Budapest University of Technology and Economics, HU-1111 Budapest, Hungary

We define the quantum Wasserstein distance such that the optimization is carried out over bipartite separable states rather than bipartite quantum states in general, and examine its properties. Surprisingly, we find that its self-distance is related to the quantum Fisher information. We discuss how the quantum Wasserstein distance introduced is connected to criteria detecting quantum entanglement. We define variance-like quantities that can be obtained from the quantum Wasserstein distance by replacing the minimization over quantum states by a maximization. We extend our results to a family of generalized quantum Fisher information.

[1] G. Tóth and J. Pitrik, arXiv:2209.09925.

QI 36.7 Fri 12:30 F428

Infrared laser absorption magnetometry with Ensembles of Nitrogen-Vacancy centres —
•Felipe Perona[1,2], Julian Bopp[2], Jonas Wollenberg[2], and Tim Schröder[1,2] — [1]Ferdinand-Braun-Institut (FBH), Berlin, Germany — [2]Humboldt-Universität zu Berlin, Department of Physics, Berlin, Germany

Magnetometers based on ensembles of Nitrogen-Vacancy (NV) centres have shown sub-nanotesla sensitivities [1]. The applied measurement concept relies on the detection and analysis of the intensity of the NV's red fluorescence, which, under the proper conditions, encodes the value of a magnetic field at the defect location. A less explored approach is using the infrared absorption of the NV centre at 1042 nm as a medium to read its local magnetic environment [2]. This strategy avoids the necessity of implementing high photon collection efficiencies, improves the read-out contrast, and simplifies the sensing setup, allowing a higher degree of integration. In this work, we implement infrared laser absorption magnetometry and demonstrate that such magnetometer can reach high sensitivities. To maximize this sensitivity, we engineer the NV density of our diamonds and optimize it for this task. We integrate the concept into a compact device towards enabling miniaturized, portable magnetometers.

[1] H. Clevenson et al., "Broadband magnetometry and temperature sensing with a light-trapping diamond waveguide", Nat. Phys., 11:5, 2015 [2] V. Acosta et al., "Broadband magnetometry by infrared-absorption detection of nitrogen-vacancy ensembles in diamond", Appl. Phys. Lett., 97:17, 2010

QI 36.8 Fri 12:45 F428

Gradient Magnetometry with Atomic Ensembles —
•Iagoba Apellaniz[1], Iñigo Urizar-Lanz[1], Zoltán Zimborás[1,2,3], Philipp Hyllus[1], and Géza Tóth[1,3,4] — [1]Department of Physics, University of the Basque Country UPV/EHU, P. O. Box 644, E-48080 Bilbao, Spain — [2]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany — [3]Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary — [4]IKERBASQUE, Basque Foundation for Science, E-48013 Bilbao, Spain

We calculate precision bounds for estimating the gradient of the magnetic field based on the quantum Fisher information for various types of ensembles, such as for example, a single atomic ensemble with an arbitrary density profile, where the atoms cannot be addressed individually and which is a very relevant case for experiments.

We present a method to find spin states for gradient magnetometry with two spatially separated atomic ensembles based on states for sensing a global phase shift, such as the GHZ state or the Dicke state.

[1] I. Apellaniz et al., Phys. Rev. A, 97 053603 (2018)

[2] G. Vitagliano et al., arXiv:2104.05663 (2021)

QI 37: Quantum Many Body Systems

Time: Friday 14:30–16:15 Location: F428

QI 37.1 Fri 14:30 F428

Metastable discrete time-crystal resonances in a dissipative central spin system — •Albert Cabot[1], Federico Carollo[1], and Igor Lesanovsky[1,2] — [1]Institut für Theoretische Physik, Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany — [2]School of Physics and Astronomy and Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems, The University of Nottingham, Nottingham, NG7 2RD, United Kingdom

We consider [1] the non-equilibrium behavior of a central spin system where the central spin is periodically reset to its ground state. The quantum mechanical evolution under this effectively dissipative dynamics is described by a discrete-time quantum map. Despite its simplicity this problem shows surprisingly complex dynamical features. In particular, we identify several metastable time-crystal resonances. Here the system does not relax rapidly to a stationary state but undergoes long-lived oscillations with a period that is an integer multiple of the reset period. At these resonances the evolution becomes restricted to a low-dimensional state space within which the system undergoes a periodic motion. Generalizing the theory of metastability in open quantum systems, we develop an effective description for the evolution within this long-lived metastable subspace and show that in the long-time limit a non-equilibrium stationary state is approached. Our study links to timely questions concerning emergent collective behavior in the "prethermal" stage of a dissipative quantum many-body evolution as well as to the phenomenon of quantum synchronization. [1] A. Cabot et al., Phys. Rev. B 106, 134311 (2022)

QI 37.2 Fri 14:45 F428

Haldane phase in one-dimensional systems of Rydberg atoms — •Johannes Mögerle and Hans Peter Büchler — Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, 70550 Stuttgart, Germany

Quantum many body physics features a wide range of interesting phenomena. This includes new, so-called topological quantum phases, which appear due to entanglement. One of the earliest proposed such phase is the Haldane phase in a one-dimensional Spin 1 chain, which later was found to be a symmetry protected topological phase. A promising platform to realize all kinds of topological phases are Rydberg atoms with their strong and tunable interactions.

This work focuses on numerically simulating the Haldane phase in a parameter regime which is accessible in Rydberg systems. Moreover, we are proposing a concrete example of experimental parameters using a three level system in Rubidium atoms to realize a groundstate close to the famous AKLT state.

QI 37.3 Fri 15:00 F428

Series expansions with multiple quasi-particle types for the dual Dicke-Ising model — •Andreas Schellenberger, Lea Lenke, and Kai Phillip Schmidt — FAU Erlangen-Nürnberg, Erlangen, Deutschland

The established approach of perturbative continuous unitary transformations (pCUT) constructs effective quantum many-body Hamiltonians in a perturbative series that conserve the number of one quasi-particle type. We extend the pCUT method to similarity transformations – dubbed pcst^{++} – allowing for multiple quasi-particle-types with complex-valued energies. This enlarges the field of application to closed and open quantum many-body systems with unperturbed operators corresponding to arbitrary superimposed ladder spectra. To illustrate the new possibility of the pcst^{++} method to specifically tackle interacting light-matter systems, we discuss the dual Dicke-Ising model. We determine low-energy spectral properties and investigate potential conversion processes between different quasi-particle types.

QI 37.4 Fri 15:15 F428

Reviving product states in the disordered Heisenberg chain — •Henrik Wilming[1], Tobias J. Osborne[1], Kevin S.C. Decker[2], and Christoph Karrasch[2] — [1]Leibniz Universität Hannover, Appelstraße 2, 30167 Hannover, Germany — [2]Technische Universität Braunschweig, Institut für Mathematische Physik, Mendelssohnstraße 3, 38106

When a generic quantum system is prepared in a simple initial condition, it typically equilibrates toward a state that can be described by a thermal ensemble. A known exception are localized systems which are non-ergodic and do not thermalize, however local observables are still believed to become stationary. Here we demonstrate that this general picture is incomplete by constructing product states which feature periodic high-fidelity revivals of the full wavefunction and local observables that oscillate indefinitely. The system neither equilibrates nor thermalizes. This is analogous to the phenomenon of weak ergodicity breaking due to many-body scars and challenges aspects of the current MBL phenomenology, such as the logarithmic growth of the entanglement entropy. To support our claim, we combine analytic arguments with large-scale tensor network numerics for the disordered Heisenberg chain. Our results hold for arbitrarily long times in chains of 160 sites up to machine precision.

QI 37.5 Fri 15:30 F428

Linked-cluster expansions of perturbed topological phases — •Viktor Kott, Matthias Mühlhauser, and Kai Phillip Schmidt — FAU, Erlangen-Nürnberg, Deutschland

We investigate the robustness of Kitaev's toric code in a uniform magnetic field on the square and honeycomb lattice by perturbative linked cluster expansions using a full graph decomposition. In particular, the full graph decomposition allows to correctly take into account the non-trivial mutual exchange statistics of the elementary anyonic excitations. This allows us to calculate the ground-state energy and excitation energies of the topological phase which are then used to study the quantum phase transitions out of the topologically ordered phase as a function of the field direction.

QI 37.6 Fri 15:45 F428

Systematic Analysis of Diagonal Ordering Patterns in Bosonic Lattice Models with Algebraically Decaying Density-Density Interactions — •Jan Alexander Koziol[1], Antonia Duft[1], Giovanna Morigi[2], and Kai Phillip Schmidt[1] — [1]Department of Physics, Staudtstraße 7, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany — [2]Theoretical Physics, Saarland University, Campus E2.6, D-66123 Saarbrücken, Germany

We propose a general approach to analyse diagonal ordering patterns in bosonic lattice models with algebraically decaying density-density interactions on arbitrary lattices. The key idea is a systematic search for the energetically best order on all unit cells of the lattice up to a given extent. Using resummed couplings we evaluate the energy of the ordering pattern in the thermodynamic limit using finite unit cells. We apply the proposed approach to the atomic limit of the extended Bose-Hubbard on a triangular lattice at fillings $f = 1/2$ and $f = 1$. We investigate the ground-state properties of the antiferromagnetic long-range Ising model on the triangular lattice and determine a six-fold degenerate plain-stripe phase to be the ground state for finite decay exponents. We also probe the classical limit of the Hamiltonian describing Rydberg atom arrangements on the sites and links of the Kagome lattice.

QI 37.7 Fri 16:00 F428

Series expansions in open and non-Hermitian quantum many-body systems with multiple quasi-particle types — •Lea Lenke, Andreas Schellenberger, and Kai Phillip Schmidt — FAU Erlangen-Nürnberg

The established approach of perturbative continuous unitary transformations (pCUT) constructs effective quantum many-body Hamiltonians in a perturbative series that conserve the number of one quasi-particle type. We extend the pCUT method to similarity transformations – dubbed pcut^{++} – allowing for multiple quasi-particle-types with complex-valued energies. This enlarges the field of application to closed and open quantum many-body systems with unperturbed operators corresponding to arbitrary superimposed ladder spectra. To this end a generalized counting operator is combined with the quasi-particle generator for open quantum systems recently introduced by Schmiedinghoff and Uhrig [1]. The pcut^{++} then yields model-independent quasi-particle conserving effective Hamiltonians and Lindbladians allowing a linked-cluster expansion similar to the conventional pCUT method. We illustrate the application of the pcut^{++} method by discussing representative open and non-Hermitian quantum systems.

[1] G. Schmiedinghoff and G. S. Uhrig, "Efficient flow equations for dissipative systems", (2022), arXiv:2203.15532 [cond-mat.quant-ph].