Q 31: Poster: Quantum Optics and Photonics II

Time: Tuesday 17:00–19:00 Location: C/Foyer

Q 31.1 Tue 17:00 C/Foyer

Optimized microwave near-field control in a planar ion trap — •Henning Hahn[1], Martina Carsjens[1,2], Amado Bautista[1,2], Sebastian Grondkowski[1], Timko Dubielzig[1], Matthias Kohnen[1,2], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]Physikalisch-Technische Bundesanstalt, Quest Institut, Bundesallee 100, 38116 Braunschweig

Multi-qubit gates with trapped ions require a coupling of the common motional state to the internal spin state of an individual ion. Instead of the more commonly used focused laser beams, recent experiments have shown an alternative approach using magnetic microwave near-field gradients. In an initial demonstration experiment [1], the required field configuration was produced by three near-by microwave conductors integrated in a surface-electrode ion trap.

This poster presents numerical simulations for a second generation trap design [2] based on a single microwave conductor to produce the required field geometry. In particular, we analyse the ratio of sideband Rabi rates to parasitic carrier excitations for the field originating from a single meander-shaped conductor. After analysing the basic geometry, we consider the influence of integrating trap electrodes, fabrication tolerances, and extensions towards a multi-layer design with improved performance.

[1] C. Ospelkaus *et al.*, Nature **476**, 181 (2011)
[2] M. Carsjens *et al.*, Appl. Phys. B **114**, 243 (2014)

Q 31.2 Tue 17:00 C/Foyer

Microwave near-field quantum logic techniques for a cryogenic surface-electrode trap — •Sebastian Grondkowski[1], Martina Wahnschaffe[1,2], Matthias Kohnen[1,2], Timko Dubielzig[1], Henning Hahn[1], and Christian Ospelkaus[1,2] — [1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover — [2]Physikalisch-Technische-Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

We describe the necessary control infrastructure for experiments with integrated microwave near-field surface-electrode ion traps at cryogenic temperatures with applications in quantum simulation and quantum logic. A trap geometry recently developed in our group [1] implements the coupling between the ions' motional and internal state using only a single meander-shaped microwave-conductor. The realization of high-fidelity quantum-logic-operations requires a static bias magnetic field at 22.3 mT to generate a field-independend $^{9}Be^{+}$ hyperfine-qubit, microwave control fields for single-qubit rotations and sideband transitions, dc voltages for trapping fields together with fast DAC-modules to control a pulse-shaping stage and reconfigurable rf trapping potentials. We present the current status of the experiment at room temperature and give an outlook for a future setup at cryogenic temperatures to suppress to effect of anomalous heating due to the small distance between the ions and the trap surface of about 30 μm [2,3].

[1] M. Carsjens et al., Appl. Phys. B 114, 243-250 (2014)
[2] Deslauriers et al., Phys. Rev. Lett. 97, 103007 (2006)
[3] Labaziewicz et al., Phys. Rev. Lett. 100, 013001 (2008)

Q 31.3 Tue 17:00 C/Foyer

Microfabricated Ion Traps for Quantum Logic and Metrology — •Amado Bautista-Salvador[1,2], Martina Wahnschaffe[1,2], Matthias Kohnen[1,2], Teresa Feld[1], Malte Niemann[1], Stefan Ulmer[3], and Christian Ospelkaus[1,2] — [1]Leibniz Universität Hannover, Germany. — [2]Physikalisch-Technische Bundesanstalt, Braunschweig Germany. — [3]RIKEN, Ulmer Iniative Research Unit, Japan.

Here we report on microfabrication techniques for building advanced ion traps for quantum logic and metrology. We first detail an ion trap which includes a single meander-like microwave conductor [1] and metal vias through spin-on-glass (SOG) dielectrics. The conceptual separation between feed lines and gate drive conductors into different layers will decrease residual magnetic fields. The reduction in residual magnetic fields will minimize off-resonant carrier excitations and thus improve gate fidelities [2]. On a second part, we give advances on the fabrication of a micro Penning trap for spin-motional coupling and Coulomb coupling between an (anti-)proton and a $^{9}Be^{+}$ atomic ion. A stack of gold electrodes on thin (200 μm) silicon substrates will produce a double-well potential at a distance of 300 μm from each other with an axial trap frequency of 4 MHz and a motional state exchange time of 3.7 ms. We conclude with a discussion of techniques for loading $^{9}Be^{+}$ and of the optical setup for bringing in the control laser beams.

[1] M. Carsjens et al., Appl. Phys. B, 114, 243-250 (2014).
[2] C. Ospelkaus et al., Nature, 476, 181-184 (2011).

Q 31.4 Tue 17:00 C/Foyer

Ion Surface Trap Heating Rate Measurements, and Progress towards In-Situ Surface Cleaning by Argon Ion Sputtering — •Frederick Hakelberg, Matthias Wittemer, Manuel Mielenz, Henning Kalis, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, Albert-Ludwigs Universität Freiburg

Laser-cooled ions offer a promising system for quantum simulations [1]. Yet scaling to larger systems still proves to be challenging. Surface traps with individually controllable potential wells offer a promising approach by allowing the design of arbitrary patterns of trapped ions [2]. However, the small distances between the ions and the surface of the trap lead to increased motional heating causing motional decoherence on a timescale relevant to simulations. This effect is currently assumed to be caused by monolayers of carbon deposited on the trap surface. In our experiment we use a triangular trap array with individual pseudopotential minima for each ion. Current heating rates of our setup are in the order of 4 quanta per millisecond for $^{25}Mg^{+}$ Ions trapped 40 μm above the surface at $2\pi\times2.5$ MHz trapping frequency, which is comparable to measurements performed by other groups in conventional 1D-surface traps. We follow an approach utilizing a high energy argon ion beam inside the experimental chamber to sputter impurities from the trap surface [3]. We present the progress made towards realization of this in-situ cleaning.

[1] Ch. Schneider *et al.*, Rep. Prog. Phys. **75**, 024401 (2012)
[2] T. Schaetz *et al.*, New J. Phys. **15**, 085009 (2013)
[3] D.A. Hite *et al.*, Phys. Rev. Lett. **109**, 103001 (2012)

Q 31.5 Tue 17:00 C/Foyer

Control of the motional degrees of freedom in an ion surface trap array — •Matthias Wittemer, Manuel Mielenz, Henning Kalis, Frederick Hakelberg, Ulrich Warring, and Tobias Schaetz — Albert-Ludwigs-Universität Freiburg

Laser-cooled ions in (linear) Paul-traps have been proven to be well suited candidates for (1D) quantum simulations. Projecting the Paul-trap's electrode structure onto a plane yields surface traps [1] that might be extended to large scale quantum simulators [2]. Advanced micro-fabrication techniques and geometrical optimization even allow the construction of 2-dimensional trap arrays [3].

We report on experiments within two triangular surface trap arrays, manufactured by Sandia National Labs, that offers 3 distinct trapping wells with a distance of 40 and 80 μm between the trapping centers, respectively. In order to perform adequate quantum simulations manipulation of the ion's motional degrees of freedom is crucial. For individual real-time control of the trapping parameters via 30 control electrodes we therefore recently set up an arbitrary waveform generator based on the work of [4]. We employ analytical calculations as proposed by [5] to control the motional degrees of freedom of laser-cooled Mg+ ions in our trap, which is observed via Raman transitions.

[1] S. Seidelin *et al.*, Phys. Rev. Lett. **96**, 253003 (2006)
[2] Ch. Schneider *et al.*, Rep. Prog. Phys. **75**, 024401 (2012)
[3] T. Schaetz *et al.*, New J. Phys. **15**, 085009 (2013)
[4] R. Bowler *et al.*, Rev. Sci. Instrum. **84**, 033108 (2013)
[5] J. H. Wesenberg, Phys. Rev. A **78**, 063410 (2008)

Q 31.6 Tue 17:00 C/Foyer

Towards quantum simulations in a triangular surface trap — •Manuel Mielenz, Henning Kalis, Frederick Hakelberg, Matthias Wittemer, Ulrich Warring, and Tobias Schaetz — Physikalisches Institut, Albert-Ludwigs Univeritägt Freiburg

In the last decade, surface electrode traps for laser-cooled ions [1] have been established in several laboratories. Such traps constitute a promising tool to extend quantum simulations - already demonstrated for a small number of ions in Paul-traps [2] - to a scalable system. Optimized electrode structures allow trapping ions in an arbitrarily chosen pattern, with each ion in an indiviual potential well [3,4], thus making for instance the simulation of extended lattices of spins or charged particles in a gauge field [5] possible.

Our group, in collaboration with Sandia National Labs, NIST, and R. Schmied, demonstrated trapping ions in a novel kind of surface trap, which exhibits three proximate potential wells arranged in a triangle. Trapping parameters of each ions' well can be individually controlled by making use of 30 control electrodes. Combined with fast, accurate control voltages this will permit to control all degrees of freedom and, thus, the interaction between neighbouring ions.

[1] S. Seidelin *et al.*, Phys. Rev. Lett. **96**, 253003 (2006)
[2] Ch. Schneider *et al.*, Rep. Prog. Phys. **75**, 024401 (2012)
[3] R. Schmied *et al.*, Phys. Rev. Lett. **102**, 233002 (2009)
[4] T. Schaetz *et. al.*, New J. Phys. **15**, 085009 (2013)
[5] A. Bermudez *et al.*, Phys. Rev. Lett. **107**, 150501 (2011)

Q 31.7 Tue 17:00 C/Foyer

Motional state analysis of a linear ion crystal — •Jana Harlos[1], Govinda Clos[1], Diego Porras[2], Ulrich Warring[1], and Tobias Schaetz[1] — [1]Physikalisches Institut, Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Germany — [2]School of Mathematical and Physical Sciences, University of Sussex, Brighton BN1 9RH, UK

Stored atomic ions in a linear Paul trap provide a promising platform for experimental quantum simulations.

A mixed crystal of different Mg isotopes of choice enables the simulation of a single spin in an environment of harmonic oscillators - the spin-boson model. This is realized by coherently coupling the spin system to the vibrational modes of all the ions in the chain with two-photon stimulated Raman transitions [1].

A necessary prerequisite for quantum simulations of this model is the precise knowledge and control of the initial state: To this end, we use sympathetic sideband cooling to prepare the motional ground state, we tailor specific motional state distributions and verify the adjusted simulation parameters by numerical analysis of the recorded state evolutions.

[1] D. Porras, F. Marquardt, J. von Delft, and J. I. Cirac, Phys. Rev. A **78**, 010101 (2008).

Q 31.8 Tue 17:00 C/Foyer

Optimierter Transport kalter Ionen in segmentierten Ionenfallen — •Henning Fürst[1], Michael Goerz[2], Ulrich Poschinger[1], Michael Murphy[3], Simone Montangero[3], Tommaso Calarco[3], Ferdinand Schmidt-Kaler[1], Kilian Singer[1], and Christiane Koch[2] — [1]QUANTUM, Institut für Physik, Universität Mainz, D-55128 Mainz, Germany — [2]Theoretische Physik, Universität Kassel, Heinrich-Plett-Straße 40, D-34132 Kassel, Germany — [3]Institut für Quanteninformationsverarbeitung, Universität Ulm, D-89081 Ulm, Germany

Wir diskutieren die Eignung verschiedener Kontrollverfahren zum präzisen Transport kalter Ionen in modernen, segmentierten Ionenfallen. Die Transportstrecke beträgt hier etwa das 10^4-fache der Breite der Wellenfunktion. Wir verwenden numerische Verfahren zur Optimierung der klassischen und der quantenmechanischen Trajektorie [1], sowie eine analytische, Invarianten-basierte Methode [2]. Wir prüfen deren Anwendbarkeit für realistische Parameter und ebenso für zukünftige, weiter miniaturisierte Ionenfallen. Die entwickelten numerischen Methoden können als Grundlage für weitere Ionenfallenbasierte Optimierungen dienen, zum Beispiel dem Trennen eines Ionen-Kristalls oder der Implantation einzelner Ionen in einen Festkörper, wie es experimentell in unserer Gruppe demonstriert wurde [3,4].

[1] D. Reich et al., J. Chem. Phys 136(10), 104103 (2012).
[2] E. Torrentegui et al., Phys. Rev. A 83, 013415 (2011).
[3] T. Ruster et al., Phys. Rev. A 90, 033410 (2014).
[4] G. Jacob et al., arXiv:1405.6480 (2014).

Q 31.9 Tue 17:00 C/Foyer

Scaling down cryogenic surface ion traps based on silicon — •Kirill Lakhmanskiy[1], Michael Niedermayr[1], Philip Holz[1], Muir Kumph[1], Alexander Erhard[1], Stefan Partel[2], Johannes Edlinger[2], Yves Colombe[1], Michael Brownnutt[1], and Rainer Blatt[1,3] — [1]Universität Innsbruck, Austria — [2]FH Vorarlberg, Austria — [3]IQOQI, Innsbruck, Austria

We report on our recent experimental results using surface ion traps based on intrinsic silicon in cryogenic environment. Silicon is a broadly used material in the semiconductor industry. Unfortunately, silicon has high RF losses, and cannot be used as-is to make RF ion traps. Until now, there have been two approaches around this issue. One consists in adding an electrode that shields the substrate from the RF; another one uses highly doped silicon as a conductive electrode material. Here we take another approach and use silicon as a substrate for the trap electrodes [1]: below T = 25 K, the charge carriers in intrinsic silicon freeze out, leaving the substrate as a good insulator with low RF losses. Our traps were fabricated using a deep reactive ion etching process followed by silicon oxidation and metal deposition. With such traps, we were able to show very low ion heating rates at a 230 um ion-electrode separation, with a good repeatability in a sample of 6 traps [1]. Our current goal is to scale down our traps while keeping the heating rate sufficiently low to perform high fidelity quantum manipulation.

[1] M. Niedermayr et al., New J. Phys. 16, 113068, 2014

Q 31.10 Tue 17:00 C/Foyer

2D arrays of ion traps for quantum simulations — •Philip Holz[1], Muir Kumph[1], Martin Meraner[1], Alexander Erhard[1], Kirill Lakhmanskiy[1], Michael Niedermayr[1], Stefan Patel[2], Stephan Kasemann[2], Johannes Edlinger[2], Yves Colombe[1], Michael Brownnutt[1], and Rainer Blatt[1,3] — [1]Uni Innsbruck, Austria — [2]FH Vorarlberg, Austria — [3]IQOQI Innsbruck, Austria

Ion traps are a promising tool for quantum simulations [1]. The possibility of producing superposition states as well as entanglement between qubits allows, in principle, to efficiently run simulations that are not tractable for classical computers.

Currently, simulations are typically implemented using strings of ions. However, certain problems such as the 2D Ising model [2] would be simulated more naturally in a 2D architecture, e.g. in an array of individual ion traps. Furthermore, such arrays are a possible way of implementing a scalable quantum computer [3].

We have proposed a 2D architecture consisting of individual surface traps in which interactions between nearest-neighbour ions can be deterministically switched on and off [4]. Recently we have shown trapping and shuttling of ions in a relatively large array [5]. I will report on our efforts to miniaturize the array in order to increase the coupling between adjacent qubits and realize coherent operations.

[1] R. Blatt, C.F. Roos, Nature Phys. 8, 277284 (2012), [2] J.W. Britton et al., Nature 84, 489 (2012), [3] J.I. Cirac and P. Zoller, Nature 404, 579 (2000), [4] M. Kumph et al., New J. Phys. 13, 073043 (2011), [5] M. Kumph et al., arXiv:1402.0791

Q 31.11 Tue 17:00 C/Foyer

Collective coupling between two ions and a cavity for an enhanced quantum interface — •Konstantin Friebe[1], Bernardo Casabone[1], Birgit Brandstätter[1], Klemens Schüppert[1], Rainer Blatt[1,2], and Tracy Northup[1] — [1]Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25/4, 6020 Innsbruck, Austria — [2]Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria

In this proof-of-principle experiment, we demonstrate that collective effects improve the performance of a quantum interface between atomic qubits and single photons. Two trapped ions are coupled to the mode of an optical cavity and prepared in a maximally entangled state. By changing the phase of this state, we can control its coupling to the cavity. Thus, the coupling strength of the ion–cavity system can be tuned from sub- to superradiance. The superradiant coupling is then used to enhance the transfer of quantum information from a logical qubit encoded in the two-ion state onto a single photon [1]. In the context of quantum networks, this result provides a possible way for the implementation of distributed quantum computing with several small-scale quantum computers in optical cavities.

[1] B. Casabone et al., arXiv:1408.6266 (2014)

Q 31.12 Tue 17:00 C/Foyer

Kalte Ionen für Cavity-QED Experimente: Ein faserbasierter Resonator in einer segmentierten Paulfalle — •Andreas Pfister, Marcel Salz, Max Hettrich und Ferdinand Schmidt-Kaler — Johannes Gutenberg Universität Mainz, Germany

Die Übertragung von Verschränkung zwischen entfernten Quantensystemen, eine Grundvoraussetzung der Quantenkommunikation, benötigt eine effiziente Schnittstelle zwischen Photonen und stationären Qubits. Obwohl immer mehr Cavity-QED-Experimente mit atomaren Ionen interessante Ergebnisse erzielen, ist das Regime der starken Kopplung von Licht mit Ionen noch unerreicht (siehe z.B. [1,2]).

Wir haben ein System in Betrieb genommen, welches die starke Kopplung zwischen den Photonen und $^{40}Ca^{+}$-Ionen durch eine mikrostrukturierte, segmentierte Paulfalle ermöglichen soll, in die ein faserbasiertes Resonatormodul mit geringem Modenvolumen und hoher Finesse eingebaut ist. Darin ist der Transport von einzelnen Ionen entlang der Fallenachse in den Resonatorbereich und heraus möglich, bei typischen Fallenfrequenzen von 1.3 – 1.8MHz. Die Faserenden wurden mit einem Focused Ion Beam (FIB) bearbeitet, so dass die Resonatoren eine Finesse von 15000 bei einem Spiegelabstand von $230\mu m$ erreichen.

Unsere Arbeit zeigt, dass die Bearbeitung mit einem FIB bei hoher Finesse Krümmungsradien, ermöglicht, die bisher unzugänglich waren. Wir stellen außerdem mit unserem integrierten Falle-Resonator-System einen weiteren Schritt in Richtung Quantenrepeater vor.

[1] M. Steiner et al., Phys. Rev. Lett. **110**, 043003 (2013)
[2] B. Brandstätter et al., Rev. Sci. Instrum. **84**, 123104 (2013)

Q 31.13 Tue 17:00 C/Foyer

Coupling, controlling, and processing non-transversal photons with a single atom — •Elisa Will, Michael Scheucher, Jürgen Volz, and Arno Rauschenbeutel — Vienna Center for Quantum Science and Technology, TU Wien, Atominstitut, Stadionallee 2, A-1020 Wien, Austria

In our experiment we investigate the strong interaction between single ^{85}Rb atoms and light confined in a bottle microresonator, a novel type of whispering-gallery-mode (WGM) microresonator. These resonators offer the advantage of very long photon lifetimes in conjunction with near lossless in- and out-coupling of light via tapered fiber couplers. In addition, we recently showed that the longitudinal polarization component of their evanescent field results in an inherent link between the local polarization of the light and its propagation direction. This fundamentally alters the physics of light-matter interaction leading to a new class of optical microresonators based on chiral interaction of light and matter [1].

Building on these properties, we recently realized a fiber-integrated optical Kerr-nonlinearity. There, the presence of the atom results in a strong nonlinear response of the resonator to the number of incident photons. As a consequence, we observe a nonlinear phase shift close to the maximum value of π between the cases where one or two photons pass the resonator [2]. Furthermore, we show that this results in entanglement between the two previously independent photons.

[1] C. Junge et al., Phys. Rev. Lett. **110**, 213604 (2013)
[2] J. Volz et al., Nature Photon. **8**, 965 (2014)

Q 31.14 Tue 17:00 C/Foyer

Excitons in MoS2 coupled to a Microcavity — •Michael Förg[1], Hanno Kaupp[1,2], Thomas Hümmer[1,2], Hisato Yamaguchi[3], Theodor W. Hänsch[1,2], Alexander Högele[1], and David Hunger[1,2] — [1]Ludwig-Maximilians Universität München Faculty of Physics, Schellingstr. 4/III, D-80799 München, Germany — [2]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany — [3]Center for Integrated Nanotechnologies, Materials Physics and Applications Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Two-dimensional atomic crystals of transition metals dichalcogenides have come to be a recent field of interest due to their attractive optoelectronic properties. In the scope of this work we investigate the excitons in monolayer molybdenum disulphide (MoS2) coupled to a microcavity. Due to high exciton binding energies and a strong oscillator strength it is possible to observe collective strong coupling of excitons and photons at room temperature[1]. In our experiment we use a tunable open-access cavity with one curved mirror and one planar mirror on top of which MoS2 is placed. This type of setup allows to control the spatial separation of both cavity mirrors and thus to see effects of the confinement on the polariton state. Furthermore we have a defined, microscopic cavity mode, which can form a potential for the exciton polaritons and thus lead to interaction effects. We report on the current state of the experiment.

[1] Liu, Xiaoze, et al. "Strong light-matter coupling in two-dimensional atomic crystals." arXiv preprint arXiv:1406.4826 (2014).

Q 31.15 Tue 17:00 C/Foyer

Single-Mode Photon Blockade in Single-Atom Cavity QED — •Christoph Hamsen, Haytham Chibani, Tatjana Wilk, and Gerhard Rempe — Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching

Large light-matter couplings are a prerequisite for quantum information and can be used to mediate interactions of otherwise non-interacting photons. A paradigm is the strongly-coupled atom-cavity system where the coupling rate between a single atom and a single mode of light exceeds all decay rates. Such a system exhibits large optical nonlinearities resulting from the anharmonic dressed-state ladder of the Jaynes-Cummings model, a direct consequence of its quantum nature. This anharmonicity can either be resolved spectrally by probing the higher excitation states or via photon statistics of the emitted light. In the latter case, driving the system resonant to an eigenstate of the first manifold, excitation by a first photon blocks the transmission of a second. This so-called photon blockade was previously observed for a multi-state atom coupling to two polarization modes, where the mode excited via the external driving field was blocked by a polarizer and only photons channeled into the other mode were evaluated [1]. Here, we investigate the pristine Jaynes-Cummings system consisting of a two-level atom strongly coupled to a single mode of light. We demonstrate that a Poissonian driving field is converted into a sub-Poissonian stream of photons. The time-dependent two-photon correlation function grants insight into the system's internal dynamics.

[1] K. M. Birnbaum et al., Nature 436, 87-90 (2005)

Q 31.16 Tue 17:00 C/Foyer

Passively Stable Optical Fiber Cavities — •Seyed Khalil Alavi, Wolfgang Alt, Jose C. Gallego Fernández, Sutapa Ghosh, Miguel Martinez-Dorantes, Dieter Meschede, and Lothar Ratschbacher — Institut für Angewandte Physik, Wegelerstr. 8, D-53115, Bonn, Germany

Optical Fabry-Pérot cavities formed by two fiber end facets with laser machined cavity mirrors offer many advantages for Cavity Quantum Electro-Dynamics (CQED) experiments. Their small mode volume gives rise to large light-matter coupling strengths, and their intrinsic fiber coupling facilitates experimental integration. Such cavities are usually actively locked using piezo-mechanical feedback. Here, we investigate passively stable optical Fabry-Pérot fiber cavities. Two laser-machined optical fibers with coated end-facets are placed inside a ferrule to form a rigid fiber cavity. The tight fit of the ferrule and the fibers transversely align the cavity, which is glued to a fixed longitudinal separation to match resonances at the desired atomic transitions. We show that this mechanically rigid unit is vibrationally stable and that its temperature sensitivity can be used to fine-tune the cavity resonance frequency. Furthermore, we demonstrate self-locking of a cavity with a finesse of approximately 20,000 to a reference laser and analyze its frequency stability.

Q 31.17 Tue 17:00 C/Foyer

Atom-cavity physics with a Bose-Einstein condensate in an ultra-narrow band resonator — •Jens Klinder, Hans Kessler, Matthias Wolke, and Andreas Hemmerich — Institut für Laserphysik, Universität Hamburg

A Bose-Einstein condensate (BEC) is prepared inside an optical resonator with an ultra-narrow band width on the order of the single photon recoil energy. For transverse pumping with a traveling wave, matter wave superradiance is observed [1]: above a critical intensity superradiant light pulses are emitted into the cavity and the atoms are collectively scattered into coherent superpositions of discrete momentum states, which can be precisely controlled by adjusting the effective cavity-pump detuning δ_{eff}. For transverse pumping with a standing wave the physics encountered depends on the sign of δ_{eff}: at positive $\delta_{\text{eff}} > 0$, matter wave superradiance is found, similarly as for traveling wave pumping. At negative $\delta_{\text{eff}} < 0$, the Hepp-Lieb-Dicke phase transition is observed: a stationary intra-cavity field emerges, which confines the BEC in a self-organized lattice potential. Due to the narrow cavity bandwidth we operate in a regime where a sweep across the phase boundary on a ms time scale leads to significant hysteresis with an enclosed loop area showing power law scaling with respect to the transition time [2].

[1]H. Keßler et al., Phys. Rev. Lett. 113, 070404 (2014)
[2]J. Klinder et al., arXiv:1409.1945v2

Q 31.18 Tue 17:00 C/Foyer

Dyadic Green Function of Spatially Dispersive Bodies: Towards Quantum Optics at Nanometre Separation — •Robin Schmidt and Stefan Scheel — Institut für Physik, Universität Rostock, Universitätsplatz 3, 18055 Rostock, Germany

With the advances in modern nanophotonics and nanooptics, ever smaller metallic and dielectric structures become feasible. The strongly confined evanescent fields are associated with enormous field enhancements, thus creating a platform for single-excitation quantum optics at nanometre separation. Quantum effects such as decay rates and dis-

persion forces depend on the local density of states (LDOS). Recently, the LDOS has been measured on nanoscales with high accuracy [1]. Both the LDOS and the Casimir forces can mathematically be described in terms of dyadic Green functions, which primarily depend on the geometrical settings and dielectric properties of media under consideration. At small separation nonlocal effects have to be taken into account, as the electromagnetic stress and energy density formally diverge at the surface [2].
Here we present the LDOS in the vicinity of a spatially dispersive dielectric sphere. The results have been obtained by making use of the Huygens principle and the extinction theorem. This approach does not require additional boundary conditions.

References:
[1] A. W. Schell, P. Engel, J.F.M. Werra, C. Wolff, K. Busch, and O.Benson, Nano Lett., 14 (5), 2623, (2014)
[2] S.A.R. Horsley and T.G. Philbin, New J. Phys. 16, 013030, (2014)

Q 31.19 Tue 17:00 C/Foyer

The Schmidt decomposition and entanglement in the context of waveguide quantum electrodynamics — •Christoph Martens[1] and Kurt Busch[1,2] — [1]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2A, 12489 Berlin, Germany — [2]Humboldt-Universität zu Berlin, Institut für Physik, AG Theoretische Optik & Photonik, Newtonstr. 15, 12489 Berlin, Germany

The combination of low-dimensional waveguiding structures with embedded single emitters emerges as a promising candidate to form a concept of basic building blocks for quantum-information processing networks [1]. On this account, studies of the light-matter interaction in waveguides with embedded emitters on the quantum level are sine quibus non to forge ahead with the realization of quantum-information processing networks. The discipline of physics engaged in these studies is *waveguide quantum electrodynamics (WQED)*.

In this contribution, we show how to link up WQED with the *Schmidt decomposition* [2] in order to attain a quantitative description of entanglement between single emitters and quantized light in a waveguide. Furthermore, we apply this description to a waveguide with a single, embedded Λ-system and quantify the generation of entanglement between this emitter and a single-photon pulse by scattering processes.

[1] H.J. Kimble, "The quantum internet", Nature **453,** 1023 (2008)
[2] C.C. Gerry and P.L. Knight, "Introductory Quantum Optics" (Cambridge University Press, Cambridge, 2005)

Q 31.20 Tue 17:00 C/Foyer

Quantization of the power divider and applications in circuit QED — •Marius Schöndorf[1], Luke Govia[1], Bruno Taketani[1], Emily Pritchett[2], and Frank Wilhelm-Mauch[1] — [1]Universität des Saarlandes, Saarbrücken — [2]HRL Laboratories, Malibu, CA

Superconducting qubits are a promising candidate architecture for quantum computing and quantum information.They work in the microwave regime and therefore microwave devices are required for control and manipulation. In this work one such microwave device, the power divider, is described quantum mechanically using scattering matrix formalism. Application of the scattering matrix to specific input states leads us to an effect similar to the Hong-Ou-Mandel effect, one of the most characteristic effects in quantum optics. Furthermore we address the open question of the strong enhancement in the second order correlation function at low input power, seen in the experiment of Chen et al. [Phys. Rev. Lett. 107, 217401 (2012)]. Our results show, that the enhancement is basically caused by dark counts of the Josephson photomultiplier [Phys. Rev. Lett. 107, 217401 (2012)] used in the experiment. Finally, we present setups for microwave photon counters that combine several Josephson photomultipliers and circulators with power dividers.

Q 31.21 Tue 17:00 C/Foyer

Quantum Walks in Circuit QED — •Peter Schuhmacher, Luke Govia, Bruno Taketani, and Frank Wilhelm-Mauch — Theoretical Physics, Saarland University, 66041 Saarbruecken, Germany

The study of quantum algorithms in quantum information theory has shown that it is linked to the theory of quantum walks. Implementation of quantum algorithms on a quantum computer is equivalent to implementing quantum walks on arbitrary graphs. Our goal is to find an efficient architecture in circuit QED realizing this in small directed graph structures. In particular, we discuss the challenges of reservoir engineering suitable for directed walks as they are, e.g., proposed for accelerated artificial intelligence applications.

Q 31.22 Tue 17:00 C/Foyer

General three-photon interference in a 2D 3×3 waveguide — •Simon Mährlein[1,2], Joachim von Zanthier[1,2], and Girish S. Agarwal[3,2] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany — [2]Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen, Germany — [3]Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078-3072, USA

In analogy to the original two-photon Hong-Ou-Mandel experiment [1] we investigate three-photon interference in a two dimensional 3×3 waveguide (three input modes and three output modes). We consider the case of three single photons being inserted into the three separate input ports. For certain parameters of the waveguide we can find a suppression of the coincidence event, so that the three photons never leave the waveguide in three different output modes. This corresponds to the Hong-Ou-Mandel effect extended to the case of three interfering photons. Similar to the Hong-Ou-Mandel experiment the output states display entanglement in their photon number, where the exact form of the states depends on the parameters of the waveguide.

[1] C. K. Hong, Z. Y. Ou & L. Mandel (1987). Measurement of subpicosecond time intervals between two photons by interference. Physical Review Letters, 59(18), 2044-2046.

Q 31.23 Tue 17:00 C/Foyer

A versatile setup for the measurement of temporal photon-correlations for sources with coherence times similar to detector dead-times — •Johannes Hölzl[1,2], Alexandra Popp[1], Thomas Mehringer[1,2], Henning Weier[3], and Joachim von Zanthier[1,2] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen — [2]2 Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen — [3]qutools GmbH, 81371 München

We present a Hanbury-Brown Twiss Setup to measure temporal photon-correlations of light sources with coherence times down to hundreds of picoseconds. Effects occuring due to the peculiarities of the single-photon-detectors like dead-time and afterpulsing and their influence on the results of the measurement are discussed.

Q 31.24 Tue 17:00 C/Foyer

Remote Quantum Imaging with Thermal Light Sources — Anton Classen[1], •Raimund Schneider[1,2], Thomas Mehringer[1,2], and Joachim von Zanthier[1,2] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen — [2]Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen

It has been shown that imaging techniques involving higher order spatial correlation functions can be used to beat the classical resolution limit [1]. In case of an array of regularly arranged thermal light sources, applying specific detector positions results in a suppression of all but the highest spatial frequency component of the correlation functions. The more general case of irregularly arranged sources allows also to extract particular spatial frequency components of the correlation functions, dependent on the emitter geometry and the detector arrangement. Based on this insight we introduce the concept of remote imaging. Hereby the distance between two remote sources can be measured by use of two independent reference sources, located at a large distance with respect to the remote sources. By varying the distance between the two pairs of emitters as well as between the reference sources, the spacing between the two remote sources can be determined via analysis of the higher order spatial correlation functions.

[1] S. Oppel, T. Büttner, P. Kok, J. von Zanthier, Superresolving Multiphoton Interferences with Independent Light Sources, Phys. Rev. Lett. 109, 233603 (2012)

Q 31.25 Tue 17:00 C/Foyer

Experimental Quantum Imaging of an irregular array of Thermal Light Sources — •Thomas Mehringer[1,2], Anton Classen[1], Raimund Schneider[1,2], and Joachim von Zanthier[1,2] — [1]Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen — [2]Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen

Measuring multiphoton interferences is a common technique in the field of quantum imaging. Recently we demonstrated that with a setup of N equidistant independent thermal light sources a spatial resolution below the classical Abbe limit can be reached by measuring spatial photon correlations of order m = N [1]. By choosing particular detector positions, the highest spatial frequency of the correlation signal can be isolated producing a reduced fringe spacing which leads to the increased resolution. Here we show that for an arbitrary array of irregular arranged sources any desired spatial frequency can be isolated by measuring spatial photon correlations of order m ≥ 3. We discuss how this technique can be used for imaging with a resolution beyond the classical limit. The experiment is realised with optical fibers, each serving as an independent pseudothermal source, which brings the advantage of being versatile with respect to the source geometry.

[1] S. Oppel, T. Büttner, P. Kok, J. von Zanthier, Superresolving Multiphoton Interferences with Independent Light Sources, Phys. Rev. Lett. 109, 233603 (2012)

Q 31.26 Tue 17:00 C/Foyer

Analysis of Multimode Thermal Photon Statistics — •Christian R. Müller[1,2], Michael Förtsch[1,2], Thomas Gerrits[3], Sae Woo Nam[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, University of Erlangen-Nuremberg (FAU), Germany — [3]National Institute of Standards and Technology, Boulder, CO, USA

The evaluation of temporally resolved photon statistics [1] plays a crucial role in a wide variety of quantum optical applications. Examples range from the discrimination of coherent states in quantum receivers [2] to the characterization of entangled states and single photon sources [3]. An important figure characterizing the quality of a single photon source is the the effective number of modes. We evaluate the single photon statistics in light generated by PDC inside a whispering gallery mode resonator and measured with a transition edge sensor [4] with respect to the effective mode number. In doing so, we compare two different approaches analyzing either the second-order intensity correlation function or a maximum likelihood estimation based on multimode photon statistics.

[1] L. Mandel, Proc. Phys. Soc. 74,3 (1959)
[2] C. R. Müller et al., CLEO:QELS, FM3A.6 (2014)
[3] M. Förtsch et al., Nat. Comm. 4, 1818 (2013)
[4] A. E. Lita et al., Opt. Express 16, 5 (2008)

Q 31.27 Tue 17:00 C/Foyer

Towards continuous-variable quantum key distribution at GHz rates — Imran Khan[1,2], •Birgit Stiller[1,2], Kevin Jaksch[1,2], Nitin Jain[1,2], Tobias Röthlingshöfer[1,2], Christian Peuntinger[1,2], Christoph Marquardt[1,2], and Gerd Leuchs[1,2] — [1]Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1/Bldg. 24, D-91058 Erlangen, Germany — [2]Institute for Optics, Information and Photonics, University of Erlangen-Nuernberg, Staudtstraße 7/B2, 91058 Erlangen, Germany

The ability to securely distribute keys at high rates is of crucial importance for the future of practical quantum key distribution (QKD). In state-of-the-art continuous-variable (CV) implementations, these rates are limited by the bandwidth of the detectors. With recent publications showing shot-noise limited homodyne detectors in the GHz regime, CV-QKD with GHz rates may soon be a reality. In our work, we analyze how this high speed regime might impact current experimental setups in fiber and free space and discuss possible improvements.

Q 31.28 Tue 17:00 C/Foyer

Experimental Investigation of Quantum Discord and Entanglement in Bi-partite Systems — •Christian Peuntinger[1,2], Vanessa Chille[1,2], Niall Quinn[3], Callum Croal[3], Ladislav Mišta[4], Christoph Marquardt[1,2], Gerd Leuchs[1,2], and Natalia Korolkova[3] — [1]Max Planck Institute for the Science of Light, Günther-Scharowsky-Str. 1/Bldg. 24, Erlangen, Germany — [2]Institute of Optics, Information and Photonics, University of Erlangen-Nürnberg, Staudtstr. 7/B2, Erlangen, Germany — [3]School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, UK — [4]Department of Optics, Palacký University, 17. listopadu 12, 771 46 Olomouc, Czech Republic

We experimentally investigate quantum features in a bi-partite Gaussian state. The state is generated by modulating an initially squeezed state and mixing it with the vacuum on a symmetric beamsplitter. Due to the modulation, the squeezing is destroyed and the output state is separable, but it possesses Gaussian quantum discord. The quantum nature of the state is experimentally revealed by acting locally on one part of the discordant state. By attenuating one of the output modes we explore discord dynamics in an open system and measure the counterintuitive discord increase. To further highlight the quantumness of the separable bi-partite state we demonstrate the recovery of entanglement. By considering an "environmental system" purifying the state we are able to unveil the flow of correlations in the global system and link the effects above to entanglement with the environment.

Vanessa Chille et al., ArXiv:1411.6922

Q 31.29 Tue 17:00 C/Foyer

Integration of a high-speed continuous-variable quantum random number generator — •Imran Khan[1,2], Christoph Pacher[3], Momtchil Peev[3], Bernhard Schrenk[3], Christoph Varga[3], Philipp Grabenweger[3], Bettina Heim[1,2], Christoph Marquardt[1,2], and Gerd Leuchs[1,2] — [1]Max Planck Institute for the Science of Light, Guenther-Scharowsky-Str. 1/Bldg. 24, 91058 Erlangen, Germany — [2]Institute for Optics, Information and Photonics, University of Erlangen-Nuernberg, Staudtstraße 7/B2, 91058 Erlangen, Germany — [3]Optical Quantum Technology, Department of Safety & Security, AIT Austrian Institute of Technology, Donau-City-Straße 1, 1220 Vienna, Austria

Many cryptographic applications, such as quantum key distribution, rely on the output of random number generators (RNGs). The measurement of a pure quantum state can guarantee true random numbers uncorrelated to any other measured series of numbers, as opposed to classical physical or algorithmic RNGs. The quantum mechanical vacuum state is such a pure state. It has been demonstrated that it can be used as a source of random numbers using homodyne detection. In our work, we discuss the photonic and electronic integration of such a continuous-variable-based quantum RNG and the associated challenges to achieve rates in the GHz regime.

Q 31.30 Tue 17:00 C/Foyer

Towards randomness expansion in the measurement-device-independent setup — •Felix Bischof, Hermann Kampermann, and Dagmar Bruss — Institut fuer Theoretische Physik 3, Heinrich-Heine-Universität Düsseldorf

Randomness expansion schemes are essential ingredients of random number generators. They transform a string of initially private random numbers into a longer private random string. Here we investigate whether and how a measurement-device-independent setup can be used for randomness expansion. The setup consists of sending devices and measurement devices under the assumption that the sending devices have controlled output, whereas the measurement devices are uncharacterized.

Q 31.31 Tue 17:00 C/Foyer

Experimental apparatus for quantum simulation with two-dimensional ^{9}Be$^+$ Coulomb crystals — •Karsten Pyka, Harrison Ball, Terry McRae, Claire Edmunds, Michael W. Lee, Samuel Henderson, and Michael J. Biercuk — The University of Sydney, Sydney, Australia

We report on the development of a new experimental setup designed for Quantum Simulation studies at a computationally relevant scale using laser-cooled ^{9}Be$^+$ ion-crystals in a Penning trap. The trap geometry is optimized using numerical calculations for trapping large ion crystals with enhanced optical access and reduced anharmonic perturbations. Separate loading and spectroscopy zones prevent long term drifts of the trapping parameters due to contamination of the trap electrodes with Be deposits. Our customized superconducting magnet provides a homogenous ($dB/B < 10^{-6}$) magnetic field at 3T required for ion trapping. Laser frequencies required for cooling/detection and spin-motion entanglement are generated from telecom wavelength fiber laser systems in the IR via nonlinear conversion. Our new approach employs high-efficiency telecom modulators and mode-selecting cavities to generate multiple beamlines from a single Sum-Frequency-Generation step. Ultimately, this newly developed setup will allow for studies of many-body spin systems with tuneable interaction strength from infinite-range to nearest-neighbour type interaction.

Q 31.32 Tue 17:00 C/Foyer

Time-resolved boson sampling for arbitrary distinguishabilities — •Simon Laibacher and Vincenzo Tamma — Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ[ST]), Universität Ulm, D-89069 Ulm, Germany

Recently, the boson sampling problem (BSP) has drawn a lot of interest. It is formulated as the task to sample from the probability distribution of finding N single input bosons at the output of a linear interferometer. We present a description of the boson sampling setup in terms of correlation measurements. For this purpose, we consider single photons with an arbitrary spectral distribution and describe the full time-dependence of the output probabilities for correlated detections of N photons [1]. By integrating over all possible detection times, we obtain the detection probabilities for the original formulation of the BSP generalized to the case of arbitrary distinguishability between the photons. This allows us to describe the transition of the output probability distribution from the ideal case of completely indistinguishable particles to the classical case of complete distinguishability.

We further demonstrate how a similar formalism can be applied to describe Hanbury-Brown-Twiss correlation experiments of arbitrary order with thermal input states [2].

[1] V. Tamma and S. Laibacher, (2014), arXiv:1410.8121.
[2] V. Tamma and S. Laibacher, (2014), arXiv:1409.7426.

Q 31.33 Tue 17:00 C/Foyer

Practical quantum repeater using cavity-QED and optical coherent light — •Denis Gonta and Peter van Loock — Institut für Physik, Johannes Gutenberg-Universität Mainz, Staudingerweg 7, 55128 Mainz

In the framework of cavity QED, we propose a practical quantum repeater scheme that uses coherent light and chains of atoms coupled to optical cavities. In contrast to conventional schemes, we avoid the usage of two-qubit quantum logical gates by exploiting solely the cavity QED evolution. In our previous paper [1], we already proposed a dynamical quantum repeater scheme in which the entanglement between the two neighbouring repeater nodes was distributed using the controlled displacements of input coherent light, while the generated low-fidelity entangled pairs were purified using ancillary (four-partite) entangled states. In this work, the entanglement distribution is realized using the controlled phase shifts of input coherent light, while the entanglement purification avoids the usage of ancillary entangled resources. Our repeater scheme exhibits reasonable fidelities and repeater rates providing an attractive platform for long-distance quantum communication.

[1] D. Gonta and P. van Loock, Phys. Rev. A 88, 052308 (2013).

Q 31.34 Tue 17:00 C/Foyer

Ultrafast long-distance quantum communication with linear optics — •Fabian Ewert, Marcel Bergmann, and Peter van Loock — Institut für Physik, Johannes Gutenberg-Universität, Staudingerweg 7, D-55128 Mainz

We present an all-optical, ultrafast scheme for long-distance quantum communication based on quantum parity encoded qubits and linear optics. Provided individual qubits, as well as two-qubit entangled Bell states, can be prepared for this encoding, scalable quantum communication is possible (with rates independent of the total distance), while all the remaining operations after state preparation can be performed with experimentally feasible, static linear optics.

Q 31.35 Tue 17:00 C/Foyer

Protecting an optical qudit against photon loss — •Marcel Bergmann and Peter van Loock — Institut für Physik, Johannes Gutenberg-Universität, Staudingerweg 7, D-55128 Mainz

We present a new class of quantum error correcting codes for the amplitude damping channel. First, using sources of so-called NOON states and linear optics, a systematic way to obtain quantum codes for the loss-tolerant encoding of an arbitrary qubit into multimode bosonic systems is introduced. We compare our codes to existing loss codes with regards to their scaling and their resource consumption (total number of photons and modes). Our method is then shown to be easily extendible to the case of an arbitrary qudit. Finally, we explicitly propose a scheme for the experimental generation of a four-photon qubit code entirely based on linear optics, with the two-photon NOON-state resources corresponding to the well-known Hong-Ou-Mandel states, which are easily obtainable from pairs of single photons combined at a beam splitter.

Q 31.36 Tue 17:00 C/Foyer

Efficient State Analysis and Entanglement Detection — •Christian Schwemmer[1,2], Lukas Knips[1,2], Geza Toth[3,4,5], Tobias Moroder[6], Matthias Kleinmann[3], David Gross[7], Otfried Gühne[6], and Harald Weinfurter[1,2] — [1]Department für Physik, LMU, D-80797 München — [2]MPI für Quantenoptik, D-85748 Garching — [3]Department of Theoretical Physics, University of the Basque Country UPV/EHU, E-48080 Bilbao — [4]IKERBASQUE, Basque Foundation for Science, E-48011 Bilbao — [5]Wigner Research Centre for Physics, Hungarian Academy of Sciences, H-1525 Budapest — [6]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, D-57068 Siegen — [7]Physikalisches Institut, Universität Freiburg, D-79104 Freiburg

Multipartite entanglement lies at the very heart of quantum mechanics and offers many fascinating applications like, e.g., quantum computing or quantum metrology. Hence, experimentally friendly tools for fast entanglement detection and characterization with better than exponential scaling are needed. Here, we implement such an efficient scheme, tomography in the permutationally invariant subspace, and compare its performance against compressed sensing tomography and standard tomography for a six-photon symmetric Dicke state. For data processing, we developed a scalable fitting algorithm based on convex optimization. By means of this algorithm, we were also able to study systematic deviations of the maximum likelihood estimation for fidelity and negativity, which for finite statistics get (strongly) biased for constrained optimization.

Q 31.37 Tue 17:00 C/Foyer

Status of a loophole-free Bell test with entangled atoms — •Kai Redeker[1], Daniel Burchardt[1], Norbert Ortegel[1], Robert Garthoff[1], Wenjamin Rosenfeld[1,2], and Harald Weinfurter[1,2] — [1]Ludwig-Maximilians-Universität, München — [2]Max-Planck-Institut für Quantenoptik, Garching

Bell's inequality allows to test the validity of local hidden variable theories. To perform a conclusive Bell test on a pair of entangled particles, one has to fulfill two major requirements: the state measurements need to be highly efficient and space-like separated.

We present the status of our experiment which aims at fulfilling both requirements. We employ entanglement between single trapped ^{87}Rb-atoms and single photons to create heralded entanglement between separated atoms[1]. To provide sufficient time for the measurement of atomic states, the distance between the atom traps has been extended to 400m. Our ionization-based state detection scheme reads the atomic state within less than 1μs (including random setting of the measurement basis) with a fidelity of 95%. Together with the heralded entanglement this will enable to close both loopholes in one experiment.

Q 31.38 Tue 17:00 C/Foyer

Higher-order separability conditions — •Evgeny Shchukin — Johannes-Gutenberg University of Mainz, Institute of Physics, Mainz, Deutschland

We derive a set of higher-order conditions for bipartite entanglement. We start with a minimization problem for the single-partite case and, using the results obtained, establish some inequalities for higher-order moments satisfied by all bipartite separable states. We also demonstrate that our fourth-order condition cannot be violated by Gaussian states. Violations of all our conditions are provided, so they can be used as entanglement tests.

Q 31.39 Tue 17:00 C/Foyer

One qubit and three qutrits can be entangled in 11 different ways — •Christina Ritz[1], Matthias Kleinmann[2], and Otfried Gühne[1] — [1]Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Germany — [2]Department of Theoretical Physics, University of the Basque Country UPV/EHU, P.O. Box 644, E-48080 Bilbao, Spain

The classification of tripartite entanglement regarding the invariance under invertible SLOCC-transformations has been studied thoroughly for the case of qubits. However when dealing with higher dimensions only the case of 2x2xN has been studied in detail [1]. We present the full classification for a qubit-qutrit-qutrit system, based on a method introduced by Lamata [2], resulting in 11 classes of genuine multipartite entanglement that are not convertible under invertible SLOCC. Additionally we study the hierachy of entanglement within 2x3x3 systems, leading to 5 classes, from which all other classes can be obtained by non-invertible local operations. Finally we discuss the generalization to the case of 2xMxN and identify the maximal M,N for which a finite number of entanglement classes can be found.

[1] A.Miyake and F.Verstraete, Phys. Rev. A 69, 012101 (2004)

[2] L.Lamata et al., Phys. Rev. A 75, 022318 (2007)

Q 31.40 Tue 17:00 C/Foyer

Evaluation of the quantumness of spin systems — •Fabian Bohnet-Waldraff[1], Olivier Giraud[2], and Daniel Braun[1] — [1]Institut für theoretische Physik, Universität Tübingen, 72076 Tübingen, Germany — [2]LPTMS, CNRS and Université Paris-Sud, UMR 8626, Bât. 100, 91405 Orsay, France

The quantumness of a single spin j state can be defined as the distance to the convex hull of classical, i.e. SU(2) coherent, spin states [1]. This renders quantumness for a pure, symmetric tensor product of spin-1/2 states essentially equivalent to geometric entanglement, which is based on the overlap with separable states. Recently, a tensor representation of spin systems was introduced that generalizes the Bloch sphere picture to larger spins [2].

We investigate the connection between the properties of these tensors and the quantumness of the underlying spin state, employing new tools from the spectral theory of symmetric tensors.

[1] O. Giraud, P. Braun, and D. Braun, New Journal of Physics **12**, 063005 (2010).

[2] O. Giraud, D. Braun, D. Baguette, T. Bastin, and J. Martin, arXiv:1409.1106 (2014).

Q 31.41 Tue 17:00 C/Foyer

Scalable architecture for quantum simulation and quantum computation with more than 100 individually addressable qubits — •Malte Schlosser, Sascha Tichelmann, Daniel Ohl de Mello, Felix Stopp, Kathrin Luksch, and Gerhard Birkl — Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt, Germany

Efficient quantum simulation and quantum information processing requires scalable architectures that guarantee the allocation of large-scale qubit resources. In our work, we focus on the implementation of multi-site geometries based on microfabricated optical elements. This approach allows us to develop flexible, integrable and scalable configurations of multi-site focused beam traps for the storage and manipulation of single-atom qubits and their interactions [1].

We give an overview on the investigation of ^{85}Rb atoms in two-dimensional arrays of well over 100 individually addressable dipole traps featuring trap sizes and a tunable site-separation in the single micrometer regime. Furthermore, we experimentally demonstrate single-atom quantum registers with more than 100 occupied sites, single-site resolved addressing of single atom quantum states in a reconfigurable fashion and discuss progress in introducing Rydberg based interactions in our setup.

[1] For an overview see: M. Schlosser, S. Tichelmann, J. Kruse, and G. Birkl, Quant. Inf. Proc. **10**, 907 (2011).

Q 31.42 Tue 17:00 C/Foyer

Multi-Mode Tavis-Cummings Model with Time-Delayed Feedback Control — •Wassilij Kopylov[1], Tobias Brandes[1], Milan Radonjić[2], Antun Balaž[3], and Axel Pelster[4] — [1]Institute for Theoretical Physics, Technische Univesität Berlin, Germany — [2]Photonics Center, Institute of Physics Belgrade, University of Belgrade, Serbia — [3]Scientific Computing Laboratory, Institute of Physics Belgrade, University of Belgrade, Serbia — [4]Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

We study a multi-mode Tavis-Cummings model [1] which reveals a complex phase diagram with multiple stable stationary states at mean-field level. Adding a time-delayed Pyragas feedback control term [2,3] in the equations of motion allows to tune the stability of the stationary states and, thus, modifies the underlying phase diagram. In addition, we analyze in detail how an external heat bath for the atoms changes the system dynamics both without and with time-delayed feedback control.

[1] M. Tavis and F.W. Cummings, Phys. Rev. **170**, 379 (1968)

[2] K. Pyragas, Phys. Lett. A **170**, 421 (1992)

[3] W. Just, A. Pelster, M. Schanz, and E. Schöll, Phil. Trans. Roy. Soc. A **368**, 303 (2010)

Q 31.43 Tue 17:00 C/Foyer

Interference and diagnosis of imperfect bosons — •Malte C. Tichy[1], Young-Sik Ra[2], Hyang-Tag Lim[2], Clemens Gneiting[3], Yoon-Ho Kim[2], and Klaus Mølmer[1] — [1]Department of Physics and Astronomy, University of Aarhus, Denmark — [2]Department of Physics, Pohang University of Science and Technology, Pohang, Korea — [3]Physikalisches Institut der Albert-Ludwigs-Universität, Freiburg, Germany

We study the many-body interference of imperfect (partially distinguishable, dephased or mixed) bosons in multi-mode networks using double-sided Feynman diagrams. The many-particle event probability becomes a multi-dimensional tensor-permanent [1], which interpolates between distinguishable particles and ideal identical bosons. The strength of interference is quantified by the permanent of the distinguishability matrix, which is composed of all mutual scalar products of the single-particle mode-functions. Based on this method, we develop a protocol for the differential diagnosis of decoherence processes in interferometers and for the precise characterization of few-photon states [2]. Double-Fock-superpositions of the form $(|N,M\rangle+|M,N\rangle)/\sqrt{2}$ are shown to provide versatile and powerful tools that combine the phase-super-sensitivity of N00N-state with bosonic bunching, which allows detailed insight into decoherence processes in a single experiment.

[1] M.C. Tichy, arXiv:1410.7687

[2] M.C. Tichy, Y.-S. Ra, H.-T. Lim, C. Gneiting, Y.-H. Kim, K. Mølmer, arXiv:1410.1299

Q 31.44 Tue 17:00 C/Foyer

Atomic Bell-state projection assisted by multiphoton coherent states — •Juan Mauricio Torres, József Zsolt Bernád, and Gernot Alber — Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany

We present a postselective Bell-state projection which is capable of projecting two material qubits onto a Bell state with the help of ancillary coherent multiphoton states and postselection by balanced homodyne photodetection [1]. This photon-assisted Bell projection is generated by coupling almost resonantly the two material qubits to single modes of the radiation field in two separate cavities in a Ramsey-type interaction sequence and by measuring the emerged field states in a balanced homodyne detection scenario. We include in our analysis the case of different coupling strengths of the two material qubits to the radiation field and how this affects the performance of our protocol. Provided this photonic postselection is successful we explore the theoretical possibilities of realizing unit fidelity quantum teleportation and entanglement swapping with 25% success probability.

[1] J.M. Torres, J.Z. Bernád and G. Alber, Phys. Rev. A 90, 012304 (2014)

Q 31.45 Tue 17:00 C/Foyer

Implementing controlled NOT operations with ancillary multiphoton states — •Ludwig Kunz, József Zsolt Bernád, Mauricio Torres, and Gernot Alber — Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Germany

We investigate the possibility of implementing a CNOT-gate with the help of two material qubits and ancillary coherent multiphoton states. The material qubits, usually implemeted by two-level atoms or ions, are assumed to cross a high-finesse cavity and to interact resonantly with a single-mode of the radiation field. The two qubits are sent through the cavity one after the other. They interact with the radiation field in such a way that the CNOT-gate can be implemented by appropriate postselection of the resulting quantum state of the radiation field. The gate operation which we obtain has imperfections and we control these errors through the flight times. We also investigate the role played by these imperfections in an entanglement purification scheme.

Q 31.46 Tue 17:00 C/Foyer

Koenig-Digraph Interaction (KDI) Model of Decoherence, Dissipation and Quantum Darwinism (QD) based on Random Unitary Operations (RUO) — •Nenad Balaneskovic[1], Gernot Alber[1], and Jaroslav Novotny[1,2] — [1]Institut für Angewandte Physik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany — [2]Department of Physics, FNSPE, Czech Technical University in Prague, 115 19 Praha 1 - Stare Mesto, Czech Republic

We discuss characteristic properties of QD when pure decoherence is disturbed by dissipation. Based on digraph interaction models of open qubit systems interacting with their respective environment by iterated and randomly applied (controlled-NOT-type) unitary operations

(RUO), we introduce a unitary two-qubit dissipation operator into our RUO-digraph interaction model of pure decoherence. We investigate the QD-appearance of Classicality from the analytically determined asymptotic dynamics of the resulting quantum Markov chain.

In addition, we concentrate on KDIs which comprise environmental qubits that do not interact among themselves by unitary quantum operations and are thus suitable to physically describe objective quantum measurements performed on an open system by autonomous observers (environmental qubits). In particular, we 1) investigate whether it is possible to achieve the most efficient storage of classical information about a system into its environment by altering the strength parameter of the dissipation operator and 2) discuss the structure of the corresponding dissipative attractor space of our extended RUO qubit-model of QD.

Q 31.47 Tue 17:00 C/Foyer

Dissipative preparation of entangled states — •Joachim Fischbach and Matthias Freyberger — Institut für Quantenphysik, Universität Ulm, D-89069 Ulm, Germany

Usually a quantum system is prepared by starting from a well defined initial state. After applying several unitary operations, the final state is reached. Dissipative state preparation schemes, in contrast, start from an arbitrary initial state and, without exerting any external control operations, end up in the final steady state. In our contribution we focus on the dissipative preparation of entangled states. We try to transfer methods from unitary state preparation, like projective measurements, to enhance the fidelity of our preparation scheme. This seemingly counterintuitive approach combines the excellent control available in contemporary experiments with the apparent advantages of a dissipative state preparation, where environmental effects are in-cooperated into the scheme.

Q 31.48 Tue 17:00 C/Foyer

Engineering adiabaticity with optimal control — •Lukas S. Theis[1], Tobias Chasseur[1], Daniel J. Egger[1], and Frank K. Wilhelm[1,2] — [1]Universität des Saarlandes, Saarbrücken, Germany — [2]IQC and Dept. of Physics and Astronomy, University of Waterloo, Canada

In this work the time evolution of a system modelled by Landau-Zener (LZ) physics is studied using numerical optimal control methods. Within the framework of superconducting qubits one makes use of avoided crossings, governed by LZ physics, to realize entangling gates that are crucial for quantum computation. In particular adiabatic time evolution, i.e. staying in the same energy branch all the time, is the basis of many proposals for quantum computing schemes.

This work addresses one of many possible examples for such a time evolution: adiabatic population transfer between two bare states, such as a qubit and a resonator. The numerical results reveal the possibility to preserve adiabaticity at limiting time, finding a non-uniform quantum speed limit. Additionally, an analytical approach using the Magnus expansion is presented, which explains the observed pulse shapes.

Q 31.49 Tue 17:00 C/Foyer

Detours to Diabaticity — •Tobias Chasseur[1], Lukas Theis[1], Yuval Sanders[2], Daniel Egger[1], and Frank Wilhelm[1,2] — [1]Universität des Saarlandes, Saarbrücken, Germany — [2]IQC and Dept. of Physics and Astronomy, University of Waterloo, 200 University Ave. W, Waterloo, ON, N2L 3G1, Canada

For a finite-velocity linear sweep through an avoided crossing, Landau-Zener theory predicts a not vanishing transition probability between the basis states. However due to spurious couplings in frequency tuned quantum bits one would like to suppress such transitions.

This poster presents a way to keep a Landau-Zener(LZ) crossing fully diabatic at finite crossing velocity based on an ansatz of an oscillation augmented sweep. Several pulse shapes will be explained by a model of separated photon-assisted linear LZ-transitions as well as through numerical methods of optimal control. Furthermore there is a discussion of their mutual advantages and an examination of robustness.

Q 31.50 Tue 17:00 C/Foyer

Efficient single photon absorption by a recoiling atom — •Nils Trautmann and Gernot Alber — Institut für Angewandte Physik, Technische Universität Darmstadt,D- 64289, Germany

We investigate the impact of the center of mass motion on the attempt to efficiently excite a single two-level atom trapped close to the focal point of a parabolic mirror. We derive analytical expressions for the probability of exciting the atom and observables related to the momentum and position of the center of mass motion. By using these expressions, we are able to investigate the dynamics of the system far beyond the Lamb-Dicke regime. Furthermore, we propose a technique to overcome the limitations caused by the center of mass motion by using a time dependent trapping potential.

Q 31.51 Tue 17:00 C/Foyer

Cherenkov friction on a neutral particle moving parallel to a dielectric — Gregor Pieplow and •Carsten Henkel — University of Potsdam, Germany

Based on a fully relativistic framework and the assumption of local equilibrium, we describe a simple mechanism of quantum friction for a particle moving parallel to a dielectric [1]. The Cherenkov effect explains how the bare ground state becomes globally unstable and how fluctuations of the electromagnetic field and the particle's dipole are converted into pairs of excitations. Modelling the particle as a silver nano-sphere, we investigate the spectrum of the force and its velocity dependence. We find that the damping of the plasmon resonance in the silver particle has a relatively strong impact near the Cherenkov threshold velocity.

[1] G. Pieplow and C. Henkel, arXiv:1402.4518, to be published in J. Phys. Cond. Matt. (2015), special issue 'Casimir physics'.

Q 31.52 Tue 17:00 C/Foyer

Quantum Reflection and Interference of Matter Waves from Periodically Doped Surfaces — •Benjamin A. Stickler and Klaus Hornberger — Faculty of Physics, University of Duisburg-Essen, Lotharstrasse 1, Duisburg, Germany

We show that periodically doped but flat surfaces can act as quantum reflection gratings for atomic and molecular matter waves [1]. Quantum reflection, i.e. the occurrence of a finite reflectivity in the absence of a classical turning point [2], is typically observed by scattering polarizable particles off flat surfaces [3]. Diffraction elements for matter waves can be realized by exploiting that quantum reflection is locally supressed by charged dopants. We present a full quantum scattering theory for reflection from attractive periodic surface potentials and investigate the requirements for the observation of multiple diffraction peaks.

[1] B.A. Stickler, U. Even, K. Hornberger: Quantum reflection and interference of matter waves from periodically doped surfaces, arXiv:1410.7243 [quant-ph]. [2] H. Friedrich, J. Trost: Working with WKB waves far from the semi-classical limit, Phys. Rep. 397, 6 (2004). [3] B.S. Zhao et al.: Quantum reflection of Helium atom beams from a micro-structured grating, Phys. Rev. A 78, 010902 (2008).

Q 31.53 Tue 17:00 C/Foyer

Towards quantum frequency down-conversion of indistinguishable single photons — •Benjamin Kambs, Andreas Lenhard, Matthias Bock, Richard Nelz, and Christoph Becher — Universität des Saarlandes, FR 7.2 Experimentalphysik, 66123 Saarbrücken, Germany

Establishing quantum communication networks over long distances requires photons within one of the low-loss telecom bands of optical fibers, most commonly around 1310 nm (telecom O-band) or 1550 nm (telecom C-band). However, single-photon sources typically emit at wavelengths of electronic transitions in the visible or near infrared range. One approach to overcome this gap is to employ nonlinearities of solid state systems in order to convert the frequency of the photons. Whilst the conversion of single photons conserving their non-classical anti-bunching behavior has been shown already, the impact of conversion on indistinguishabilty has to be investigated, yet.

Here we propose a frequency down-conversion setup, converting single photons emitted at 905 nm by InAs/GaAs quantum dots to the telecom C-band and show first experimental results regarding its performance. The setup will be used to test the indistinguishability of subsequently converted photons via HOM-interference measurements. Furthermore wavelength differences between two photons emitted by spatially separated quantum dots are to be compensated via frequency conversion in order to create indistinguishability.

Q 31.54 Tue 17:00 C/Foyer

Realization of an optical parametric oscillator for the down-conversion of single photons to the telecom O-band — •Richard Nelz, Benjamin Kambs, and Christoph Becher — Universität des Saarlandes, FR 7.2 Experimentalphysik, Campus E2.6, 66123 Saarbrücken

Recently, much progress has been achieved in the fabrication of single photon emitters based on color centers in diamond, e.g., SiV-centers emitting at 738 nm [1]. However, efficient single photon transmission in future quantum networks requires wavelengths within one of the low-loss bands of optical fibers. We here propose an experimental scheme for frequency downconversion of single photons at 738 nm into the telecom O-band around 1310 nm. In order to achieve the required difference frequency generation process, a strong cw signal at 1690 nm from an optical parametric oscillator (OPO) is mixed with the single photons in a periodically poled lithium niobate (PPLN) waveguide crystal. Here, we present a performance study of a home-built singly resonant OPO delivering the necessary high-power output at 1690 nm and its tunability over a wide spectral range. Finally, we analyze the feasibility of the proposed scheme for realistic experimental parameters.

[1] E. Neu et al., New J. Phys. **13** 025012 (2011)

Q 31.55 Tue 17:00 C/Foyer

Parametric down-conversion sources for applications in quantum information — •Sabine Euler[1,2], Stephanie Lehmann[1], and Thomas Walther[1,2] — [1]TU Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt — [2]CASED, Mornewegstraße 32, 64293 Darmstadt

We present two different applications for a type-II parametric down-conversion (PDC) process in PPKTP waveguide-chips pumped by a cw diode laser around 404nm. In a first experiment the twin-photons are prepared according to the BB84 protocol for quantum key distribution. Based only on passive optical components our approach offers a possibility to authenticate the quantum channel of the communication using two-photon interference effects. The second experiment aims at implementing a source of two identical photons by a stimulated process. One of the PDC photons is fed back into the chip where in a difference frequency generation (DFG) process between a pump photon @404nm and the single PDC photon @808nm two additional red photons are generated. We will discuss the current state of the experiments.

Q 31.56 Tue 17:00 C/Foyer

Spectrum of the light scattered by unharmonically trapped cavity-cooled atoms — •Ralf Betzholz, Marc Bienert, and Giovanna Morigi — Theoretische Physik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

Cavity quantum electrodynamics with single atoms opens the possibility of realizing well controlled quantum interfaces. In addition the spectrum of light emitted by the resonator allows to monitor the dynamics of the atomic internal and external degrees of freedom. When the atom, trapped in an unharmonic potential, is cooled by the cavity field the spectral sidebands of the emitted light allows the readout of the full thermal distribution. We evaluate the cavity output spectrum and the spectrum of resonance fluorescence for the parameters of the experiment in Ref. [1]. This technique opens the perspective to perform feedback on the atomic motion.

[1] T. Kampschulte *et al.*, *Phys. Rev. A* **89**, 033404 (2014)

Q 31.57 Tue 17:00 C/Foyer

Lasing Without Inversion in neutralem Quecksilber bei 253,7 nm — •Benjamin Rein und Thomas Walther — TU Darmstadt, Institut für Angewandte Physik, AG Laser und Quantenoptik, Schlossgartenstr. 7, D-64289 Darmstadt

Die Entwicklung von kontinuierlich strahlenden Lasern mit Wellenlängen im UV- und VUV-Bereich ist ein herausforderndes und aktuelles Forschungsfeld, da sich viele Anwendungen in Bereichen wie z.B. der Biomedizin oder der Laserlithographie ergeben. Eine Standardmethode zur Erzeugung entsprechender Wellenlängen ist die Frequenzverdopplung bzw. -vervierfachung, welche durch die Auswahl an nicht-linearen Medien stark beschränkt ist. Lasing Without Inversion (LWI) basiert auf einer kohärenten Anregung atomarer Übergänge um die Absorption auf dem Laserübergang zu unterdrücken und stellt einen alternativen Ansatz zur Erzeugung kurzer Wellenlängen dar.

Quecksilber bietet eine Niveaustruktur mit der sich LWI bei 253,7 nm und 185 nm realisieren lässt. Für LWI bei 253,7 nm sind Laser mit einer Wellenlänge von 435,8 nm und 546,1 nm für die kohärente Anregung notwendig, an die hohe Anforderungen bezüglich der spektralen Eigenschaften gestellt werden. Eine detaillierte theoretische Betrachtung zeigt, dass LWI in Quecksilber in einem experimentell zugänglichen Parameterraum realisiert werden kann.

Die experimentelle Umsetzung ist soweit fortgeschritten, dass erste Amplification Without Inversion (AWI) Messungen mit einem vorhandenen 253,7 nm Lasersystem, basierend auf Frequenzvervierfachung, durchgeführt werden können.

Q 31.58 Tue 17:00 C/Foyer

indirect control of spin precession by electric field via spin-orbit coupling — •liping yang[1,3] and changpu sun[2,3] — [1]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics and University of the Chinese Academy of Sciences, Beijing 100190, People's Republic of China — [2]Beijing Computational Science Research Center, Beijing 100084, China — [3]Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

The spin-orbit coupling (SOC) can mediate electric-dipole spin resonance (EDSR) within an a.c. electric field. By applying a quantum linear coordinate transformation, we find that the essence of EDSR could be understood as a spin precession under an effective a.c. magnetic field induced by the SOC in the reference frame, which is exactly following the classical trajectory of this spin. Based on this observation, we find an upper limit for the spin-flipping speed in the EDSR-based control of spin. For two-dimensional case, the azimuthal dependence of the effective magnetic field can be used to measure the ratio of the Rashba and Dresselhaus SOC strengths.

Q 31.59 Tue 17:00 C/Foyer

Nonlinear single Compton scattering by a superposition of Volkov waves — •Alessandro Angioi and Antonino Di Piazza — Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg

An electron interacting with a laser field can emit radiation; this process is known as Compton scattering. In the presence of a sufficiently strong laser field, the electron can absorb a large average number of laser photons before emitting a high-energy one [1]. Thus, one needs to employ laser-dressed states, called Volkov states, in order to treat correctly the large number of interactions. Nonlinear Compton scattering for a head-on collision between an intense short laser pulse and an electron of definite momentum has been thoroughly investigated in [2]. Here, we study the process of nonlinear Compton scattering with the incoming electron not having a definite momentum, i.e., when it is described by a superposition of Volkov states [3]. In particular, the influence of the electron momentum spread in the emission spectrum is investigated.

[1] A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel, Extremely high-intensity laser interactions with fundamental quantum systems, *Rev. Mod. Phys.* **84**, 1177 (2012).
[2] F. Mackenroth and A. Di Piazza, Nonlinear Compton scattering in ultrashort laser pulses, *Phys. Rev. A* **83**, 032106 (2011).
[3] A. Angioi, F. Mackenroth, and A. Di Piazza, *in preparation.*

Q 31.60 Tue 17:00 C/Foyer

Multi-mode Theory of a Quantum FEL — •Rainer Endrich[1], Enno Giese[1], Peter Kling[1,2], Wolfgang P. Schleich[1], and Roland Sauerbrey[2] — [1]Institut für Quantenphysik, Universität Ulm, 89069 Ulm, Germany — [2]Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany

Free-Electron Lasers (FELs) provide coherent and widely tunable radiation of high brilliance. Most theoretical descriptions of these devices are based on classical physics in agreement with experimental results. However, due to the experimental progress in recent years an FEL in the so-called quantum regime (Quantum FEL), which possesses more favorable radiation properties than its classical counterpart and which can only be described by quantum mechanics, seems to be feasible. We have developed a new approach in this regime based on the two-level behavior of the electrons interacting with a one-dimensional single-mode within the framework of a single-particle model. We now extend this model to three spatial dimensions and include spontaneous emission similar to that of a two-level atom. In particular, we investigate this radiation mechanism, derive the corresponding decay constant and discuss the fundamental differences in comparison to atom optics.

Q 31.61 Tue 17:00 C/Foyer

Many-electron theory of the Quantum FEL — •Peter Kling[1,2], Roland Sauerbrey[1], Rainer Endrich[2], Enno Giese[2], and Wolfgang P. Schleich[2] — [1]Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden — [2]Universität Ulm, D-89069 Ulm

A free-electron laser (FEL) distinguishes itself from other light sources mainly by its wide tunability – FELs are even operating in the X-ray regime of the spectrum. However, the radiation of such an X-ray FEL has inferior properties. To improve these properties Bonifacio *et al.* [1] proposed to enter to a domain where quantum effects become important. In a single-electron model we have identified this "Quantum FEL" as an effective two-level system for the momentum states of the electron and have made a connection to the Jaynes-Cummings model.

We now generalize our previous results to a situation where many electrons interact simultaneously with the laser field. After developing a technique based on collective projection operators for the electrons we obtain a similar two-level behaviour as in the single-particle case. However, in the many-particle case the correct analogy to quantum optics is not the Jaynes-Cummings model but the Dicke model, where a collection of two-level atoms is interacting with a quantized radiation field. We find exponential gain of the laser field in a single pass of the electrons and start-up from vacuum. Furthermore, we calculate the first order corrections to the deep quantum regime and find the connection to the results of Bonifacio *et al.* [1].

[1] R. Bonifacio, N. Piovella, G. R. M. Robb and A. Schiavi, Phys. Rev. ST Accel. Beams **9**, 090701 (2006).

Q 31.62 Tue 17:00 C/Foyer

Microwave guiding of free electrons and interaction-free measurements — •Sebastian Thomas, Jakob Hammer, Philipp Weber, and Peter Hommelhoff — Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstraße 1, 91058 Erlangen

We discuss the guiding of free electrons on a chip using microwave fields and applications of this technique [1]. In particular, we intend to use it for studying an electron-based "interaction-free measurement", an interferometric scheme that makes it possible to detect the presence of an object with minimal disturbance of the object. Realizing this scheme with electrons may enable a large reduction of radiation damage in electron microscopy [2]. As basic building blocks of electron interference experiments, we show the design of an electron beam splitter [3] and an electron mirror based on the microwave guide. Additionally, we discuss the performance of interaction-free measurements in the determination of transparency and phase shifts [4].

[1] J. Hoffrogge, R. Fröhlich, M. Kasevich, P. Hommelhoff, Phys. Rev. Lett. 106, 193001 (2011)
[2] W. Putnam, M. Yanik, Phys. Rev. A 80, 040902 (2009)
[3] J. Hammer, S. Thomas, P. Weber, P. Hommelhoff, arXiv: 1408.2658 (2014)
[4] S. Thomas, C. Kohstall, P. Kruit, P. Hommelhoff, Phys. Rev. A 90, 053840 (2014)

Q 31.63 Tue 17:00 C/Foyer

One-directional Quantum Synchronization of Atomic Ensembles — •Alexander Roth and Klemens Hammerer — Institute for Theoretical Physics, Leibniz University Hannover

In the classical regime, as first demonstrated by Huygens, can coupled oscillators undergo phase-synchronization and it has been shown that two detuned ensembles of atoms coupled by a cavity show a similar synchronization, but in the quantum regime [1]. We are investigating if and how this effect emerges if the coupling of the two ensembles is one-directional. This coupling can be realized with the atom clouds in two separate, cascaded cavities creating a one-directional coupling between the cavities.

[1] PRL 113.15 (Oct. 6, 2014) M. Xu, D. Tieri, E. Fine, J. K. Thompson, and M. Holland. "Synchronization of Two Ensembles of Atoms".

Q 31.64 Tue 17:00 C/Foyer

Entanglement in the x-ray regime using nuclear transitions — •Fabian Lauble[1], Wen-Te Liao[1,2,3], and Adriana Pálffy[1] — [1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany — [2]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [3]Center for Free Electron Laser Science, Hamburg, Germany

Compared to optical photons, x-rays are less plagued by the diffraction limit and can be much better focused. The future potential of x-ray qubits however relies crucially on the possibility to control the quantum behavior of single x-ray photons, for which atomic nuclei rise as natural candidates. Here we show theoretically that using the technique of nuclear forward scattering, single x-ray photons can be controlled and we present several alternatives of x-ray entanglement generation. In particular, a setup for generating the special superposition of a simultaneously forward- and backward-propagating collective excitation in a nuclear sample [1] is addressed. Our setup relies on actively manipulating the scattering channels of single x-ray quanta with the help of a normal incidence x-ray mirror to create a nuclear polariton which propagates in two opposite directions. The two counter-propagating polariton branches are entangled by a single x-ray photon, while their phase relation can be controlled by the hyperfine magnetic field in the sample for instance by coherent storage [2].

[1] W.-T. Liao and A. Pálffy, Phys. Rev. Lett. 112, 057401 (2014).
[2] W.-T. Liao, A. Pálffy and C. H. Keitel, Phys. Rev. Lett 109, 197403 (2012).

Q 31.65 Tue 17:00 C/Foyer

Strong coupling and vacuum Rabi splitting in the x-ray regime — •Xiangjin Kong and Adriana Pálffy — Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany

The strong coupling regime of cavity quantum electrodynamics has been successfully reached for atoms in optical and microwave cavities and brings light-matter interaction to the single-photon level [1]. An extension towards higher frequencies is hindered by the fact that at present x-ray cavities with both high quality (Q) factor and small mode volume (V) required to demonstrate strong-coupling effects are not yet available. Here, we theoretically show that strong coupling in x-ray regime can be reached already with available technology in thin film cavities [2] using Mössbauer nuclear transitions to control single x-ray photons. In particular, our system demonstrates vacuum Rabi splitting, which is an important signature of strong coupling [3].

[1] Raimond J. M., Brune M. and Haroche S., Rev. Mod. Phys. 73, 565 (2001).
[2] R. Röhlsberer et al., Nature 482, 199 (2012).
[3] Bishop L. S. et al., Nature Phys. 5, 1059 (2008).

Q 31.66 Tue 17:00 C/Foyer

Ultra-narrow-linewidth semiconductor laser with optical feedback from Fabry-Perot resonator — •Wojciech Lewoczko-Adamczyk[1,2], Christoph Pyrlik[1], Andreas Wicht[1], Achim Peters[1,2], Götz Erbert[1], and Günther Tränkle[1] — [1]Ferdinand-Braun Institut, Leibniz Institut für Höchstfrequenztechnik, Berlin, Germany — [2]Institut für Physik, Humboldt-Universität zu Berlin, Germany

Narrow-linewidth lasers attract growing interest of opto-electronic industry and both, applied and fundamental scientific community. The application spectrum includes coherent optical communication protocols, high precision spectroscopy, metrology (atomic clocks, light- and matter-wave interferometers), and coherent manipulation of atoms and molecules. We present an ultra-narrow-linewidth semiconductor laser consisting of a DFB-diode optically self-locked to a mode of an external Fabry-Perot resonator. This unique combination enables for reduction of the emission linewidth of the laser by a few orders of magnitude as compared to standard grating-based extended-cavity lasers (ECDLs). Our preliminary measurements, carried out with a macroscopic test setup, have already demonstrated that the frequency noise of our laser is at least a factor 1000 lower than that of ECDL for all Fourier frequencies above 1 kHz. We succeeded in reaching the intrinsic linewidth of the order of a few Hz. This work is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50WM1141.

Q 31.67 Tue 17:00 C/Foyer

Technology platform for micro-integrated semiconductor laser modules for quantum optical sensor applications in space — •Christian Kürbis[1], Ahmad Bawamia[1], Wojciech Lewoczko-Adamczyk[1,2], Martin Heyne[1], Mandy Krüger[1], Andreas Wicht[1,2], Götz Erbert[1], Achim Peters[2], and Günther Tränkle[1] — [1]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Str. 4, 12489 Berlin, Germany — [2]Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, 12489 Berlin, Germany

We present the design and implementation of semiconductor laser modules that are suitable for quantum optical experiments in space. We report on the integration of two arbitrary laser chips, micro-optics, DC and HF electronics including fiber-coupling into a single-mode, polarization maintaining fiber on a structured AlN-substrate with a footprint of 80 x 30 mm^2. Moreover, we present the packaging of the AlN-substrate into a hermetically sealed housing with custom-made feedthroughs for all DC, HF and optical signals. Results of mechanical vibration and shock tests, as well as thermal cycling tests on subassemblies of the laser modules are shown. We present the electro-optical performance of a Master Oscillator Power Amplifier (MOPA) module with a distributed feedback laser (DFB) as master oscillator operating on the above-named technology platform.

This work is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50WM1141.

Q 31.68 Tue 17:00 C/Foyer

Gain and excited state absorption in Tb^{3+}:$LiLuF_4$ — •Ahmad Majid[1], Philip Werner Metz[1], Daniel-Timo Marzahl[1], Christian Kränkel[1,2], and Günter Huber[1,2] — [1]Institut für Laser-Physik, Universität Hamburg, Deutschland — [2]The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Deutschland

Because of their numerous potential applications, for example, optical data storage, biochemical spectroscopy, and laser material processing, many efforts have been made regarding the development of visible solid state lasers. Due to the $^5D_4 \rightarrow ^7F_5$ laser transition, located within the green spectral region, the trivalent terbium ion is an excellent candidate for visible solid state lasers. The first terbium laser was demonstrated in 1967. In this case pulsed laser operation in the 544 nm band was achieved under flash-lamp pumping. Due to the long excited state life-time of 5 ms of Tb^{3+}:$LiLuF_4$, it seems to be well suited for Q-switched laser operation in the visible spectral range. The emission spectroscopy shows that other laser transitions at 586 nm and 620 nm could be possible. However excited state absorption spectroscopy (ESA) proves that gain in the green and yellow region can be achieved while it is impossible to achieve laser emission at 620 nm.

Q 31.69 Tue 17:00 C/Foyer

Spectroscopic Properties of Sm^{3+}-doped and Tb^{3+}-doped $SrAl_{12}O_{19}$ — •Daniel-Timo Marzahl[1], Philip Werner Metz[1], Benedikt Stumpf[1], Fabian Reichert[2], Christian Kränkel[1,3], and Günter Huber[1,3] — [1]Institut für Laser-Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]Center for Free-Electron Laser Science, Luruper Chaussee 149, 22761 Hamburg, Germany — [3]The Hamburg Center for Ultrafast Imaging, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

The hexaaluminate $SrAl_{12}O_{19}$ (SRA) offers excellent thermo-mechanical properties, low phonon energies, a large band gap, and a high thermal conductivity. These properties make rare-earth doped SRA interesting as a gain material for visible lasers. Such lasers may find application in medicine, biophotonics, and spectroscopy.

SRA exhibits a low crystal field depression. Hence the energetic position of the 5d bands remains high. Energetically lower lying 5d bands could cause excited state absorption, which may prevent laser operation.

In our laboratory Sm^{3+}-doped and Tb^{3+}-doped SRA crystals were grown by the Czochralski technique. In this contribution we report on their spectroscopic properties and discuss the potential as active gain media for visible solid state lasers. The spin forbidden transitions of Sm^{3+} and Tb^{3+} exhibit the highest cross sections in the visible spectral range at 593 nm and 542 nm, respectively, with values in the order of 10^{-21} cm^2.

Q 31.70 Tue 17:00 C/Foyer

Vollständig Festkörperbasierter Ar^+-Laserersatz — •Tobias Beck, Jochen Baaz und Thomas Walther — TU Darmstadt, Institut für Angewandte Physik, Schlossgartenstr. 7, 64289 Darmstadt

Es wird eine Laserquelle vorgestellt, die zur Kühlung relativistischer Schwerionen am Experimentierspeicherring ESR der GSI eingesetzt wird. Sie basiert auf einem Yb-Faserverstärker bei 1030 nm mit einer Ausgangsleistung von bis zu 16 W. Die erzeugte Strahlung wird frequenzvervierfacht zu 257 nm und ist 16 GHz modensprungfrei abstimmbar. Bei der Zielwellenlänge stehen etwa 100 mW Ausgangsleistung für Experimente zur Verfügung. Durch einen Frequenz-Offsetlock wird das System auf eine externe Referenz stabilisiert. Eine Weiterentwicklung betrifft ein gepulstes System mit Pulsdauern zwischen 80 ps und 50 ns.

Q 31.71 Tue 17:00 C/Foyer

Auswirkung von SHG in einem Überhöhungsresonator auf die spektrale Linienbreite und das Rauschspektrum — Benjamin Rein, •Thorsten Führer und Thomas Walther — TU Darmstadt, Institut für Angewandte Physik, AG Laser und Quantenoptik, Schlossgartenstr. 7, D-64289 Darmstadt

Viele Bereiche, wie beispielsweise die Präzisionsspektroskopie oder die Anwendung von Effekten basierend auf atomarer Kohärenz [1] erfordern schmale spektrale Linienbreiten. Laserdioden mit externem Resonator (ECDL) weisen sehr geringe Linienbreiten auf. Oft stehen allerdings die benötigten Wellenlängen nicht direkt zur Verfügung, sondern werden mittels nichtlinearer Optik erzeugt. In diesem Beitrag werden die Auswirkungen von SHG auf die spektrale Linienbreite untersucht. Ein aktives ECDL Stabilisierungsverfahren [2] ermöglicht es, die Linienbreite des ECDL während des Abstimmens sowie im Betrieb bei einer fixen Wellenlänge konstant zu halten. Insbesondere lässt sich die Linienbreite innerhalb gewisser Schranken beliebig einstellen. Basierend auf der Technik der selbst-heterodynen Detektion werden Messungen präsentiert, die eine Fragmentierung der Linienbreite in verschiedene Rauschtypen ermöglichen. Es zeigt sich, dass die Frequenzverdopplung einen größeren Einfluss auf die Linienbreite hat als erwartet. Die Ursachen für diesen Effekt werden präsentiert.

[1] M. Sturm, B. Rein, T. Walther, and R. Walser, „Feasibility of UV lasing without inversion in mercury vapor,“ arXiv:1404.4242 (2014).
[2] T. Führer and T. Walther, „Control and active stabilization of the linewidth of an ECDL,“ Applied Physics B 108, 249-253 (2012).

Q 31.72 Tue 17:00 C/Foyer

Ein regenerativer Ti:Saphir Verstärker zur Erzeugung synchroner Pulse bei 940nm und 960nm — •Lukas Mader[1], Vincenzo Talluto[1], Thomas Walther[1] und Thomas Blochowicz[2] — [1]Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstr. 7, 64289 Darmstadt — [2]Institut für Festkörperphysik, Technische Universität Darmstadt, Hochschulstr. 8, 64289 Darmstadt

Die Erzeugung synchroner Laserpulse bei verschiedenen Wellenlängen ist von großem Interesse für Spektroskopie und Messtechnik. Die Synchronisation mehrerer Lasersysteme ist jedoch aufwändig und teuer. Unser Ansatz ist ein regenerativer Ti:Sa-Verstärker. Dieser wird gleichzeitig von zwei schmalbandigen cw-Diodenlasern geseedet und erzeugt so synchrone Pulse mit fourierlimitierter Bandbreite bei den Seedwellenlängen. Die benötigten Wellenlängen von 940nm und 960nm liegen dabei weit vom Verstärkungsmaximum von Ti:Saphir entfernt. Das Verhältnis der Pulsenergien bei beiden Wellenlängen lässt sich beliebig über die Seedleistungen variieren. Die erreichte Pulsenergie beträgt bis zu 4mJ. Über eine effiziente Frequenzverdreifachung können bis zu 1mJ bei 320nm erzeugt werden. Der regenerative Verstärker wird in einem Experiment zur Triplett-Solvatationsdynamik eingesetzt. Wir präsentieren das Lasersystem und den aktuellen Stand des Experiments.

Q 31.73 Tue 17:00 C/Foyer

Relative intensity noise reduction of a quantum dot laser subject to optical feedback — Mariangela Gioannini[2], •Robert Pawlus[1], Lukas Drzewietzki[1], Sébastien Hartmann[1], Wolfgang Elsässer[1], and Stefan Breuer[1] — [1]Institute of Applied Physics, Technische Universität Darmstadt, Germany — [2]Dipartimento di Elettronica, Politecnico di Torino, Italy

We study the improvement of relative intensity noise (RIN) of an InAs/InGaAs quantum dot (QD) laser by optical feedback (OFB). The laser emits simultaneously at the ground-state (GS) and the excited-state (ES) wavelengths. Recently, switching between GS and ES wavelengths by OFB has been investigated both experimentally and by numerical modeling (M. Virte et al. Appl. Phys. Lett. 105, 121109, 2014). An improvement in RIN by OFB has also recently been reported for a quantum cascade laser (C. Juretzka et al., Electron. Lett. 49, 1548, 2013). Here, we study the influence of GS- and ES-selective OFB on the RIN and emission-state transitions of a QD laser both experimentally and by simulations. Experiments yield a significant RIN reduction when spectrally-selective GS or ES OFB is applied as well as for GS+ES OFB. The observed RIN improvement and emission-state transitions are discussed by means of numerical modeling.

Q 31.74 Tue 17:00 C/Foyer

Amplitude stability of a continuous-wave emitting two-state InAs/InGaAs quantum-dot laser: experiment and simulation — •Robert Pawlus[1], Mariangela Gioannini[2], Lukas Drzewietzki[1], Sébastien Hartmann[1], Wolfgang Elsässer[1], and Stefan Breuer[1] — [1]Institute of Applied Physics, Technische Universität Darmstadt, Germany — [2]Dipartimento di Elettronica, Politecnico di Torino, Italy

We experimentally and numerically study the amplitude stability of an InAs/InGaAs quantum dot (QD) laser emitting at a ground-state (GS) and an excited-state (ES) wavelength of 1250 nm and 1180 nm. Two-state QD lasers form an attractive model system to study the particular carrier dynamics in semiconductor lasers. In [1] for example, GS and ES output power fluctuations versus time have experimentally been observed. Recently, coupled steady-state power emitted by a two-state QD laser was reported where the carrier coupling between GS and ES could be identified as its origin [2]. In this work, we extend these initial investigations towards a comprehensive study of the spectrally-resolved amplitude stability of GS and ES in dependence on laser biasing conditions. We find a improvement in stability up to a factor of 20 dB when GS and ES emit simultaneously. In addition, we investigate and explain the specific trends of stability in dependence on the laser biasing conditions and related advantages based on the coupling of GS and ES. [1] E. A. Viktorov et al. Opt. Lett. 31, 2302 (2006). [2] M. Gioannini et al., Opt. Express 22, 23402 (2014).