Q 17: Quantum Effects

Time: Thursday 16:30–18:30 Location: P

Q 17.1 Thu 16:30 P

Inverse design of artificial two-level systems with Mössbauer nuclei in thin-film cavities — •Oliver Diekmann, Dominik Lentrodt, and Jörg Evers — Max-Planck-Institut für Kernphysik, Heidelberg, Germany

We theoretically investigate the platform of Mössbauer nuclei in thin-film cavities for applications in x-ray quantum optics. Thin-film cavities are stacks of layers of different materials. One or several of the layers consist of a Mössbauer isotope (typically Fe57), i.e. the nuclei within this layer have a spectrally very narrow nuclear transition. At low probing intensities, the nuclei-cavity system is equivalent to a quantum few-level scheme, e.g. a single, thin layer of Mössbauer nuclei in the cavity forms an artificial two-level system (TLS) whose transition frequency and decay constant we can tune by e.g. modifying the surrounding cavity. The capabilities of the platform have already been hinted in a number of experiments.

While it is possible to ab initio calculate the quantum optical system simulated by a cavity structure, the inverse problem of finding the cavity structure to realize a desired level scheme is an open problem. Using a quantum optical framework based on the electromagnetic Green function, we could recently solve this problem for the TLS case, and determined its full tuning capabilities while taking into account practical considerations. The approach will also allow for extensions to multi-level schemes, otherwise inaccessible at hard x-ray energies, and, thus, promises to further the field of x-ray quantum optics towards applications in spectroscopy and x-ray based quantum technologies.

Q 17.2 Thu 16:30 P

Open Quantum Systems Approach to Photonic Bose-Einstein Condensation — •Andris Erglis[1] and Stefan Yoshi Buhmann[2] — [1]University of Freiburg, Germany — [2]University of Kassel, Germany

The photonic Bose-Einstein condensate is a recently observed collective ground state of a coupled light-matter system. We describe this novel quantum state on the basis of macroscopic quantum electrodynamics in dispersing and absorbing environments. To describe the coupled photon-dye dynamics dynamics, we derive a master equation using Nested Open Quantum Systems approach with all the necessary parameters to describe the condensation process. This approach allows us to describe the photon condensate in arbitrary geometries because all the decay constants can be expressed in terms of Green's tensor.

In the first step we derive constants responsible for spontaneous and cavity decay and laser pumping by tracing out the respective photon field baths. In the second step we trace out the rovibrational modes of the molecules as an effective bath which are influenced by dissipation constants derived in the first step. From that we derive the cavity mode absorption and emission rates of the dye molecules.

Q 17.3 Thu 16:30 P

Photon-number entanglement generated by sequential excitation of a two-level atom — Stephen C Wein[1], Juan Carlos Loredo[2], Maria Maffei[3], Paul Hilaire[2], Abdelmounaim Harouri[2], Niccolo Somaschi[4], Aristide Lemaitre[2], Isabel Sagnes[2], Loic Lanco[2,5], Olivier Krebs[2], Alexia Auffeves[3], Christoph Simon[1], Pascale Senellart[2], and •Carlos Anton-Solanas[2,6] — [1]University of Calgary, Canada — [2]C2N-CNRS, France — [3]Institut Néel-CNRS France — [4]Quandela SAS, France — [5]Univ. Paris Diderot, France — [6]Carl von Ossietzky Univ., Germany

During the spontaneous emission of light from an excited two-level atom, the atom briefly becomes entangled with the photonic field, producing the entangled state $\alpha|e,0\rangle + \beta|g,1\rangle$, where g and e are the ground and excited states of the atom, and 0 and 1 are the vacuum and single photon states. We experimentally show that the spontaneous emission can be used to deliver on demand photon-number entanglement encoded in time. By exciting a charged quantum dot (an artificial two-level atom) with two sequential π pulses, we generate a photon-number Bell state $\alpha|00\rangle + \beta|11\rangle$. We characterize the quantum properties of this state using time-resolved photon correlation measurements. We theoretically show that applying longer sequences of π pulses to a two-level atom can produce multipartite time-entangled states with properties linked to the Fibonacci sequence. Our results show that spontaneous emission is a powerful entanglement resource and it can be further exploited to generate new quantum photonic states (multipartite and also high-dimensional entangled states.

Q 17.4 Thu 16:30 P

Superradiant emission of an atomic beam into an optical cavity — •Simon B. Jäger, Haonan Liu, John Cooper, and Murray J. Holland — JILA, National Institute of Standards and Technology, and University of Colorado, Boulder, Colorado 80309-0440, USA

We investigate the different emission regimes of a pre-excited and collimated atomic beam traversing an optical cavity. In the regime where the cavity degrees of freedom can be adiabatically eliminated, we find that the atoms undergo superradiant emission when the collective linewidth exceeds transit-time, homogeneous, and inhomogeneous broadening mechanisms. In this regime we find a superradiant phase where the atomic beam undergoes continuous monochromatic light emission. We analyze the stability of the emission frequency with respect to homogeneous and inhomogeneous frequency shifts and predict the emergence of dynamical superradiant phases where the emission spectrum shows several frequency components.

Q 17.5 Thu 16:30 P

Classifying and harnessing multi-mode light-matter interaction in lossy resonators — •Dominik Lentrodt[1], Oliver Diekmann[1], Christoph H. Keitel[1], Stefan Rotter[2], and Jörg Evers[1] — [1]Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg — [2]Institute for Theoretical Physics, Vienna University of Technology (TU Wien), 1040 Vienna, Austria

In this contribution, we present a practical framework to characterize multi-mode effects on quantum systems coupled to lossy resonators. By relating recently developed quantum optical few-mode models [1, 2] to the Mittag-Leffler pole expansion [3] of the cavity's classical Green's function, we identify three distinct classes of multi-mode effects in the loss-dominated regime. We show that these effects are crucial for understanding spectroscopic signatures in leaky and absorptive resonators, and that they further provide a tuning knob to design artificial quantum systems through such environments. Both aspects are illustrated with applications in x-ray cavity QED with Mössbauer nuclei [4, 5].

[1] D. Lentrodt and J. Evers, *PRX* **10**, 011008 (2020)
[2] I. Medina et al. *PRL* **126**, 093601 (2021)
[3] P. Lalanne et al. *Laser & Photonics Reviews* **12**, 1700113 (2018)
[4] R. Röhlsberger and J. Evers, *Quantum optical phenomena in nuclear resonant scattering*, in "Modern Mössbauer Spectroscopy", edited by Y. Yoshida and G. Langouche (2021)
[5] D. Lentrodt, K. P. Heeg, C. H. Keitel, and J. Evers, *PRResearch* **2**, 023396 (2020)

Q 17.6 Thu 16:30 P

Spatio-temporal control of correlations with non-local dissipation — Kushal Seetharam[4], Alessio Lerose[3], Rosario Fazio[2], and •Jamir Marino[1] — [1]jamirmarino@gmail.com — [2]fazio@ictp.it — [3]alerose@sissa.it — [4]kis@mit.edu

[I am applying for a contributed talk]

Controlling the spread of correlations in quantum many-body systems is a key challenge at the heart of quantum science and technology. Correlations are usually destroyed by dissipation arising from coupling between a system and its environment. Here, we show that dissipation can instead be used to engineer a wide variety of spatio-temporal correlation profiles in an easily tunable manner. We describe how dissipation with any translationally-invariant spatial profile can be realized in cold atoms trapped in an optical cavity. A uniform external field and the choice of spatial profile can be used to design when and how dissipation creates or destroys correlations. We demonstrate this control by preferentially generating entanglement at a desired wavevector. We thus establish non-local dissipation as a new route towards engineering the far-from-equilibrium dynamics of quantum information, with potential applications in quantum metrology, state preparation, and transport.

Q 17.7 Thu 16:30 P

Towards a coherent spin photon interface for quantum repeaters using NV centers in diamond — •Maximilian

Pallmann[1], Jeremias Resch[1], Jonathan Körber[3], Julia Heupel[2], Cyril Popov[2], Rainer Stöhr[3], and David Hunger[1] — [1]Karlsruher Institut für Technologie — [2]Universität Kassel — [3]Universität Stuttgart

Building a long distance quantum network is one of the big challenges in the field of quantum communication, which requires the development of a quantum repeater. A crucial component of this is an efficient, coherent spin photon interface, and coupling single color centers in diamond to a microcavity is a promising approach therefor. In our experiment, we integrate a diamond membrane to an open access fiber-based Fabry-Perot microcavity to attain emission enhancement into a single well-collectable mode as well as spectral filtering. Simulations predict the feasibility of a strong enhancement of the ZPL emission efficiency, reaching values of up to 80%. We present a spatially resolved characterization of a coupled cavity-membrane device and present a cryogenic cavity platform featuring sub pm mechanical noise during quiet periods.

Q 17.8 Thu 16:30 P

Phonon pair creation by tearing apart quantum vacuum fluctuations — •Florian Hasse[1], Robin Thomm[1], Deviprasath Palani[1], Matthias Wittemer[1], Ulrich Warring[1], Tobias Schaetz[1], Christian Fey[2], and Ralf Schützhold[3] — [1]Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Hermann-Herder-Strasse 3, 79104 Freiburg — [2]Universität Hamburg, Fachbereich Physik, Luruper Chaussee 149, 22761 Hamburg — [3]Institut für Theoretische Physik, Technische Universität Dresden, 01062 Dresden

We switch the trapping field of two ions sufficiently fast to tear apart quantum vacuum fluctuations and, thereby, create squeezed states of motion [1]. This process can be interpreted as an experimental analog to the particle pair creation during a cosmic inflation in the early universe [2] and is accompanied by the formation of entanglement in the ions' motional degree of freedom [3]. Hence, our platform allows studying the causal connections of squeezing, pair creation, and entanglement and might permit to cross-fertilise between concepts in cosmology and applications of quantum information processing.

[1] Wittemer, M. et al. Phys. Rev. Lett. 123, 180502 (2019)
[2] Schuetzhold, R. et al., Phys. Rev. Lett. 99, 201301 (2007)
[3] Fey, C. et al., Phys. Rev. A 98, 033407 (2018)

Q 17.9 Thu 16:30 P

Fully fiber coupled devices for efficient cryogenic spectroscopy of single and small ensembles of rare earth ions — Jannis Hessenauer[1], •Evgenij Vasilenko[1], Xiaoyu Cheng[1,2], Tobias Krom[1,3], Christina Ioannou[1], Christopher Hins[1], Senthil Kuppusamy[1], Mario Ruben[1], Philippe Goldner[4], and David Hunger[1] — [1]Karlsruher Institut für Technologie, Karlsruhe, Germany — [2]Universität Stuttgart, Stuttgart,Germany — [3]Universität Heidelberg, Heidelberg,Germany — [4]Institut de Recherche de Chimie Paris IRCP, Paris, France

Rare earth ions in solid state hosts are a prime candidate for optically addressable spin qubits, owing to their excellent optical and spin coherence times. In order to achieve an efficient spin-photon interface, we try to couple single ions to a fiber-based Fabry-Pérot cavity. However, operation of these cavities at cryogenic temperatures has proven difficult, due to high demands on the mechanical stability. To tackle these challenges, we report on the development of two different, monolithic cavity assemblies, both sacrificing some lateral scanning ability in order to significantly increase the passive stability.

Characterizing the optical and spin properties of rare earth doped materials requires spectroscopic measurements of ensembles, such as spectral hole burning and photon echo spectroscopy. We report on the development of a miniaturized, fiber-coupled scheme to perform these experiments, requiring only microscopic amounts of sample and comparatively low laser power in order to see well resolved spectral hole signatures.

Q 17.10 Thu 16:30 P

Steady-state diagonalization of a dielectric medium with dispersion and dissipation — •Sascha Lang[1,2], Ralf Schützhold[1,3,2], and William G. Unruh[4] — [1]Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany — [2]Fakultät für Physik, Universität Duisburg-Essen, 47057 Duisburg, Germany — [3]Institut für Theoretische Physik, Technische Universität Dresden, 01062 Dresden, Germany — [4]Department of Physics and Astronomy, University of British Columbia, Vancouver V6T 1Z1, Canada

The established Hopfield model for non-dissipative dielectrics incorporates dispersion by coupling the electric field inside a medium to a continuous set of harmonic oscillators. We further add dissipation by coupling each of these *matter oscillators* to a scalar environment field [1]. After canonical quantization, the Heisenberg equations of motions can be solved in terms of steady-state solutions which diagonalize the system Hamiltonian. Therefore, our model has a well-defined ground state, which is essential for describing quantum vacuum phenomena such as quantum radiation (e.g. photon creation from vacuum).

[1] S. Lang, R. Schützhold, W. G. Unruh, "Quantum radiation in dielectric media with dispersion and dissipation", Phys. Rev. D 102, 125020 (2020)

Q 17.11 Thu 16:30 P

Optical Signatures of Quantum Vacuum Nonlinearities in the Strong Field Regime — •Leonhard Klar[1,2], Holger Gies[1,2], and Felix Karbstein[1,2] — [1]Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, 07743 Jena, Germany — [2]Helmholtz-Institut Jena, 07743 Jena, Germany

Quantum electrodynamics (QED) is the most precisely tested quantum field theory. Nevertheless, particularly in the high-intensity regime it predicts various phenomena, that so far have not been directly accessible in experiments, such as light-by-light scattering phenomena induced by quantum vacuum fluctuations.

Our focus is on all-optical signatures of quantum vacuum effects which can be probed in high-intensity laser experiments with state-of-the-art technology. More specifically, we aim at identifying experimentally viable scenarios where the signal photons encoding the signature of QED vacuum nonlinearity can be distinguished from the large background of the driving laser photons.

As an example, we study the collision of up to four optical laser pulses and pay attention to sum and difference frequency generation. We demonstrate how this information can be used to enhance the signal photon yield in laser pulse collisions for a given total laser energy.

Q 17.12 Thu 16:30 P

X-ray vacuum diffraction at finite spatio-temporal offset — •Ricardo Oude Weernink[1,2,3] and Felix Karbstein[1,2,3] — [1]Helmholtz-Institut Jena, Jena, Germany — [2]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany — [3]Theoretisch-Physikalisches Institut, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Jena, Germany

Quantum electrodynamics predicts effective non-linear interactions mediated by the quantum vacuum between applied strong electromagnetic fields. One prominent signature of these non-linear interactions is photon-photon scattering. Measuring this process experimentally using macroscopic fields is a difficult endeavour and has yet to be achieved. In such high-intensity laser experiments separating the signal from the relatively large background poses a major challenge. Our research focuses on finding the optimal combination of beam positioning, laser modes and parameters.

In this poster we study the nonlinear QED signature of x-ray vacuum diffraction in the head-on collision of optical high-intensity and x-ray free-electron laser pulses at finite spatio-temporal offsets between the laser foci. To this end, we model both the pump and probe fields as pulsed paraxial Gaussian beams and analyze this effect from first principles. We focus on vacuum diffraction both as an individual signature of quantum vacuum nonlinearity and as a potential means to improve the signal-to-background-separation in vacuum birefringence experiments. Our work is relevant for ongoing and projected experiments at SACLA (Japan) and the European XFEL (Germany).

Q 17.13 Thu 16:30 P

Strong interaction between free electrons and high-Q whispering gallery modes — •Jan-Wilke Henke[1,2], Arslan S. Raja[3], Armin Feist[1,2], Guanhao Huang[3], Germaine Arend[1,2], Yujia Yang[3], F. Jasmin Kappert[1,2], Rui Ning Wang[3], Marcel Möller[1,2], Jiahe Pan[3], Junqiu Liu[3], Ofer Kfir[1,2], Tobias J. Kippenberg[3], and Claus Ropers[1,2] — [1]Max Planck Institute for Biophysical Chemistry, Göttingen, Germany — [2]4th Physical Institute, University of Göttingen, Göttingen, Germany — [3]Swiss Federal Institute of Technology Lausanne, Lausanne, Switzerland

Achieving strong coupling of electron beams with single photons promises advancements in quantum optics with free electrons and will enable observation of effects like cavity photon-mediated electron-electron entanglement.

Here, we demonstrate the interaction of a free-electron beam with a single, continuous wave-pumped optical mode of a chip-based silicon nitride microresonator [1]. Employing resonant enhancement, which allows for achieving unity electron-photon scattering efficiency at unprecedentedly low optical pump powers, we observe electron-light phase matching of the interaction. Finally, we discuss the prospect of electron-mediated photon generation and entanglement.

This combination of integrated photonics with electron microscopy enables tailoring of the electron-light interaction, which paves the way to experiments in the strong-coupling regime.

[1] J.-W. Henke, A. S. Raja, et al., preprint, arXiv:2105.03729 (2021)

Q 17.14 Thu 16:30 P

Nonlinear optics at the single photon level with an organic molecule — •André Pscherer[1], Manuel Meierhofer[1], Daqing Wang[1], Hrishikesh Kelkar[1], Diego Martín-Cano[1], Tobias Utikal[1], Stephan Götzinger[2,1,3], and Vahid Sandghdar[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen, Germany — [2]Department of Physics, Friedrich-Alexander University Erlangen-Nürnberg (FAU), Erlangen, Germany — [3]Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander University Erlangen-Nürnberg, Erlangen, Germany

Nonlinear light-matter interactions usually involve macroscopic materials and high intensities, often involving pulsed lasers. Here, we show that a single organic molecule embedded in a solid matrix can strongly couple to a high-finesse Fabry-Pérot cavity to mediate nonlinear interactions at the level of single photons. We demonstrate vacuum Rabi oscillations, single-photon switching, photon number sorting and four-wave mixing [1].

[1] A. Pscherer, *et al.*, arXiv:2105.02560 (2021)