TT 10: Focus Session: New Bright Sources of Quantum Microwaves

Quantum microwaves are an important building block of future quantum technologies. The Focus Session brings together groups that are currently pioneering the use of conventional quantum microwave sources to demonstrate the first proof of principle experiments in quantum communication and sensing, with groups that have recently realized new bright sources of quantum microwaves operating based on completely novel and simple schemes. The goal is to provide a bridge of shared expertise between two parts of the community aiming from different angles at novel quantum technologies using microwaves.

Organized by: Joachim Ankerhold, Björn Kubala, Ciprian Padurariu (Ulm University)

Time: Monday 15:00–18:45 Location: H2

Invited Talk TT 10.1 Mon 15:00 H2

Quantum dynamics of a microwave resonator strongly coupled to a tunnel junction — •Jérôme Esteve — Laboratoire de Physique des Solides, CNRS, Université Paris-Sud, Université Paris-Saclay, Orsay, France

The coupling of a quantum system, such as an atom or a resonator, to a bath can be modeled under certain hypotheses by a quantum master equation in the Lindblad form. In this description, two effects arise from the coupling to the bath: the first is a shift of the energy levels, called Lamb shift, and the second is an irreversible energy exchange with the bath in the form of quantum jumps.

A tunnel junction galvanically coupled to a resonator realizes a bath for the resonator mode. In the strong coupling regime, where the characteristic impedance Z_c of the resonator is on the order of the quantum of resistance $R_K = h/e^2$, we will show that both the Lamb shift and the jump operators strongly depend on the resonator state. Different Fock states experience different Lamb shifts, which introduces a nonlinearity, and quantum jumps from a specific Fock state to another can be forbidden by tuning the coupling parameter $\sqrt{\pi Z_c/R_K}$ to specific values.

We will discuss the dynamics of the resonator mode resulting from this engineered bath and consider possible applications including quantum Zeno dynamics and the realization of a qubit without Josephson effect.

Invited Talk TT 10.2 Mon 15:30 H2

Quantum optics with artificial atoms in an open space — •Oleg Astafiev — Royal Holloway University of London, Egham, UK

Superconducting quantum systems in open space allow one to reproduce textbook phenomena of quantum optics on a new basis of fully controllable artificial quantum systems (artificial atoms). Such systems, differently from natural atoms, can be easily coupled to their environment and other circuit elements and therefore new quantum-optical phenomena can be demonstrated with the single quantum systems. Particularly, a regime of strong coupling to an open 1D transmission line, when the atom relaxes with high probability of the photon emission into the line, has been experimentally achieved. With the strong coupling we were able to experimentally realise a series of effects, useful for applications and also interesting from the fundamental point of view, using the artificial atom as a quantum source and a sensor of specific properties of electromagnetic waves. The following phenomena have been demonstrated: a tuneable on-demand single-photon source, an absolute power sensor, a quantum wave mixer, etc. All these effects are difficult to demonstrate with natural atoms.

Invited Talk TT 10.3 Mon 16:00 H2

Quantum microwaves with a DC-biased Josephson junction — •Fabien Portier[1], Ambroise Peugeot[1], Chloé Rolland[1], Marc Westig[1], Gerbold Ménard[1], Yuri Mukharsky[1], Hélène le Sueur[1], Patrice Roche[1], Philippe Joyez[1], Carles Altimiras[1], Patrice Bertet[1], Daniel Esteve[1], Denis Vion[1], Max Hofheinz[1], Pérola Milman[2], Bjoern Kubala[3], Simon Dambach[3], and Joachim Ankerhold[3] — [1]SPEC (UMR 3680 CEA-CNRS), CEA Paris-Saclay, 91191 Gif-sur-Yvette, France — [2]LMPQ, Université Paris Diderot, CNRS UMR 7162, 75013, Paris, France — [3]ICQS and IQST, University of Ulm, 89069 Ulm, Germany

Tunneling of a Cooper pair through a dc-biased Josephson junction is possible only if collective excitations (photons) are produced in the rest of the circuit to conserve the energy. The probability of tunneling and photon creation, well described by the theory of dynamical Coulomb blockade, increases with the coupling strength between the tunneling charge and the circuit mode, which scales as the mode impedance. Using very simple circuits with only one or two high impedance series resonators, we first show the equality between Cooper pair tunneling rate and photon production rate. Then we demonstrate a blockade regime for which the presence of a single photon blocks the next tunneling event and the creation of a second photon. Finally, using two resonator with different frequencies, we demonstrate photon pair production, two-mode squeezing, and entanglement between the two modes leaking out of the resonators.

15 min. break.

Invited Talk TT 10.4 Mon 16:45 H2

Photodetectors and metamaterials for on-chip microwave photonics — •Frank K. Wilhelm-Mauch — Theoretical Physics, Saarland University, Campus E2.6, 66123 Saarbrücken, Germany

Superconducting quantum nanodevices are a unique platform for on-chip microwave photonics. They allow engineered sources, strong quantum nonlinearities, and excellent amplification. In this presentation, I will describe two additional toolsets for this platform: For one, the Josephson-Photomultiplier (JPM) allows photodetection of microwaves that is insensitive to the phase. This. on the one hand, can be used to taylor measurement backaction to, e.g., selectively detect only the parity of a quantum register but to not resolve fixed-parity states, and to use create nonclassical microwave states by measurement and displacement only. On the other hand, the JPM is an attractive platform for qubit measurement due to its low technological overhead. I will present new results on the possibility of generalizing this concept to reaching number resolution. On the other hand, superconducting metamaterials can be used to taylor the spectrum of propagating photons. Left-handed transmission lines create a large density of states that can be enhanced even further by using left-handed superlattices. This allows to study a wealth of unconventional dissipative phase-transitions with long-range order.

Invited Talk TT 10.5 Mon 17:15 H2

Correlated Cooper pair transport and microwave photon emission in the Coulomb blockade — •Juha Leppäkangas[1,2], Michael Marthaler[1], Mikael Fogelström[2], and Göran Johansson[2] — [1]Institut für Theoretische Festkörperphysik, Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Microtechnology and Nanoscience, MC2, Chalmers University of Technology, Göteborg, Sweden

We study theoretically electromagnetic radiation emitted by inelastic Cooper-pair tunneling. We consider a dc-voltage-biased superconducting transmission line terminated by a Josephson junction. The leading-order expansion in the tunneling coupling, similar to the "P(E)-theory", can be used to investigate the photon emission statistics in the limit of sequential (independent) Cooper-pair tunneling. By explicitly evaluating the system characteristics up to the fourth-order in the tunneling coupling, we account for dynamics between consecutively tunneling Cooper pairs. Within this approach we investigate how temporal correlations in the charge transport can be seen in the second-order coherence of the emitted microwave radiation. In particular, we find that a Coulomb blockade provided by a high zero-frequency impedance can be used to create antibunched microwave photons at a very high rate.

TT 10.6 Mon 17:45 H2

Nonlinear quantum dynamics and hidden cats states in a cavity conductor hybrid — •Andrew Armour[1], Bjoern Kubala[2], and Joachim Ankerhold[2] — [1]School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK — [2]Institute

for Complex Quantum Systems and IQST, Ulm University, Albert Einstein-Allee 11, 89069 Ulm, Germany

Coupling a mesoscopic conductor to a microwave cavity can lead to fascinating feedback effects which generate strong correlations between the dynamics of photons and charges. We explore the connection between cavity dynamics and charge transport in a model system consisting of a voltage-biased Josephson junction embedded in a high-Q cavity. We find that strong nonlinearities which occur in the cavity dynamics are associated with the emergence of novel regimes of charge and photonic transport. We also show that when the state of the cavity is conditioned on measurements of the number of photons emitted one can reveal fragile features, such as cat states, which are lost within the usual unconditioned dynamics.

TT 10.7 Mon 18:00 H2

Generating Pairs of Entangled Microwave Photons by Josephson-Photonics Devices — •Simon Dambach[1], Ambroise Peugeot[2], Juha Leppäkangas[3], Björn Kubala[1], Marc Westig[2], Yuri Mukharsky[2], Carles Altimiras[2], Denis Vion[2], Daniel Esteve[2], Fabien Portier[2], and Joachim Ankerhold[1] — [1]Institut für komplexe Quantensysteme, Universität Ulm, Germany — [2]SPEC (UMR 3680 CEA-CNRS), CEA Paris-Saclay, France — [3]Physikalisches Institut, Karlsruher Institut für Technologie, Germany

The realization of bright and efficient sources for entangled microwave photons is considered of paramount importance for many future applications of quantum technology. Josephson-photonics devices are very promising candidates for this task since they allow one to create a broad range of different entangled states in a surprisingly simple way [1]. In these devices, Cooper-pair tunneling across a dc-voltage–biased Josephson junction simultaneously creates photons in several series-connected microwave cavities. Steady states with multifaceted entanglement properties are reached naturally due to the interplay of these multiphoton creation processes and subsequent individual photon leakage from the cavities. Sophisticated pulse shaping as required in conventional circuit-QED architectures is thus not necessary here. In this talk, we present a theoretical study of the bipartite entanglement in both the cavity modes and the output transmission lines. Analytical results for weak driving, complemented by numerical calculations for the full nonlinear case, show good agreement with experimental data.
[1] S. Dambach et al., New J. Phys. **19**, 023027 (2017).

TT 10.8 Mon 18:15 H2

Full photon counting statistics at non-degenerate Josephson parametric resonance — •Lisa Arndt and Fabian Hassler — JARA-Institute for Quantum Information, RWTH Aachen University, D-52056 Aachen, Germany

Due to parametric down conversion, a dc-biased Josephson junction coupled to two microwave resonators emits photon pairs when the Josephson frequency matches the sum of the two resonance frequencies. Recent experiments have shown that such a setup permits analyzing the correlation of the radiation [1]. Motivated by these results, we study theoretically the full counting statistics (FCS) of a non-degenerate parametric oscillator below the instability threshold. We focus on the limit of long measurement times and derive the FCS for arbitrary detuning between the driving frequency and the sum of the resonance frequencies. Additionally, we study the impact of asymmetry in the linewidth of the modes—a distinctive property of the non-degenerate resonance effect. In particular, we find that the frequency of the photons emitted by the mode with the larger linewidth is shifted by the total detuning, while the other mode emits photons at the resonance frequency.
[1] M. Westig, B. Kubala, O. Parlavecchio, Y. Mukharsky, C. Altimiras, P. Joyez, D. Vion, P. Roche, D. Esteve, M. Hofheinz, M. Trif, P. Simon, J. Ankerhold, and F. Portier, Phys. Rev. Lett. **119**, 137001 (2017)

TT 10.9 Mon 18:30 H2

Steady-state generation of Wigner-negative states in 1D resonance fluorescence — •Fernando Quijandria, Ingrid Strandberg, and Göran Johansson — Microtechnology and Nanoscience, MC2, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

In this work, we generate nonclassical states of the electromagnetic field by utilizing the strong coupling between an artificial two-level atom and a one-dimensional waveguide. We use the negativity of the Wigner function as an indicator of nonclassicality. States characterized by a negative Wigner function are a necessary element for protocols promising to overcome classical computational power. We study the steady-state emission from a continuously driven atom using the method of quantum trajectories. We simulate the conditioned evolution of an atom being subjected to quadrature meassurement. In turn, from the measurement statistics we are able to reconstruct the state of the emitted field. We show that using this setup it is possible to generate coherent superpositions of Fock states beyond vacuum and single-photons.
[1] F. Quijandría, I. Strandberg and G. Johansson. arXiv:1806.01355 (2018), accepted in Phys. Rev. Lett. (in press).