TT 79: Superconductivity: Superconducting Electronics - Circuit QED

Time: Thursday 9:30–12:45 Location: H 2053

TT 79.1 Thu 9:30 H 2053

Anharmonic quantum oscillator under field drive: probing the AC Stark shift of higher levels — •Martin Weides[1,2], Andre Schneider[1], Patrizia Stehle[1], Jochen Braumueller[1], Hannes Rotzinger[1], Lingzhen Guo[3], Michael Marthaler[3], and Alexey Ustinov[1] — [1]Institute of Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany — [2]Materials Science in Mainz, University Mainz, Germany — [3]Institute for Theoretical Solid State Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

We report on the investigation of a superconducting anharmonic multi-level circuit under the influence of a detuned and strong microwave drive. The AC Stark shift of higher level transition frequencies caused by the applied drive is investigated. We demonstrate that this shift depends on the anharmonicity, the drive amplitude and the detuning between drive and transition frequency. For large detunings we find the shift to be linear to the power of the drive. Experimentally, multi-photon transitions via virtual energy levels of our system up to the third excited state are observed. The measured AC Stark shift of higher order multi-photon transitions under increasing drive amplitude is demonstrated to be in good agreement with the analytic model and numerical simulations. Having a detailed model of the qudit behavior, we can take the qudit as a sensor for high excitation numbers in coupled harmonic systems like microwave resonators or magnonic systems by observing the shift of the qudit levels.

TT 79.2 Thu 9:45 H 2053

Quasiparticle dynamics in microwave resonators from granular aluminum close to the superconductor to insulator transition — •Lukas Grünhaupt[1], Nataliya Maleeva[1], Sebastian T. Skacel[1], Florence Lévy-Bertrand[2], Alexey V. Ustinov[1,3], Hannes Rotzinger[1], Alessandro Monfardini[2], and Ioan M. Pop[1] — [1]Physikalisches Institut, Karlsruhe Institute of Technology, Karlsruhe, Germany — [2]Institut Néel, CNRS and Université Grenoble Alpes, Grenoble, France — [3]Russian Quantum Center, National University of Science and Technology MISIS, Moscow, Russia

Superconducting high kinetic inductance elements constitute a valuable resource for quantum circuit design and millimeter-wave detection. Granular aluminum (GrAl) is a particularly interesting material since it has already shown a kinetic inductance in the range of nH/□ and its deposition is compatible with conventional Al/AlO_x/Al Josephson junction fabrication. We characterize microstrip resonators in the GHz range fabricated from GrAl thin films with resistivity and geometry dependent kinetic inductances between 0.3 and 2.0 nH/□. Our results suggest that non-equilibrium quasiparticles limit their internal qualitiy factors at a level of 10^5. We extract quasiparticle relaxation times on the order of 1 s and we observe quasiparticle producing events approximately every 30 s. The current level of coherence of GrAl resonators makes them attractive for integration in quantum devices, while it also evidences the need to reduce the density of non-equilibrium quasiparticles.

TT 79.3 Thu 10:00 H 2053

Circuit quantum electrodynamics of granular Aluminum resonators — •Nataliya Maleeva[1], Lukas Grünhaupt[1], Florence Levy-Bertrand[2], Martino Calvo[2], Patrick Winkel[1], Wolfgang Wernsdorfer[1], Alexey Ustinov[1,3], Hannes Rotzinger[1], Alessandro Monfardini[2], Mikhail Fistul[3], and Ioan Pop[1] — [1]Physikalisches Institut, KIT, Karlsruhe, Germany — [2]Institut Neel, CNRS, Universite Joseph Fourier Grenoble I, Grenoble, France — [3]RQC, National University of Science and Technology MISIS, Moscow, Russia

Granular Aluminum (GrAl) thin film structures can be used as superinductors in superconducting qubits, or as high kinetic inductance detectors for mm wavelength radiation. Their microstructure consists of pure aluminum grains of 2-5 nm diameter, separated by thin aluminum oxide barriers, forming a self-assembled network of Josephson junctions (JJ). We model microwave resonators made of GrAl as a 1D array of effective Josephson junctions, directly relating their dispersion relation and nonlinearity to GrAl microstructure. Below 20 GHz, we can measure the dispersion relation of GrAl stripline resonators using a circuit QED setup. We observe self-Kerr coefficients in the range of $10^{-1} - 10^4$ Hz/photon, depending on the resonator geometry and the sheet resistance of the film. Using an optical setup designed for mm wave spectroscopy we measure the plasma frequency of the film around 75 GHz. These results are in agreement with values calculated using our effective JJ chain model, and they are encouraging for the design of cQED elements such as qubits or parametric amplifiers using GrAl.

TT 79.4 Thu 10:15 H 2053

Echo trains in pulsed electron spin resonance — •Stefan Weichselbaumer[1,2], Petio Natzkin[1,2], Christoph W. Zollitsch[1,2], Martin S. Brandt[2,3], Rudolf Gross[1,2,4], and Hans Huebl[1,2,4] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]Physik-Department, Technische Universität München, Garching, Germany — [3]Walter Schottky Institut, Technische Universität München, Garching, Germany — [4]Nanosystems Initiative Munich, Munich, Germany

Strong coupling between a spin ensemble and a microwave resonator is essential for a coherent exchange of excitation. While today experiments mostly focus on continuous wave experiments, we investigate the dynamics of the coupled spin-resonator system in the strong coupling regime by pulsed ESR measurements. In particular, we use Hahn echos and observe multiple unexpected echo signatures after the first conventional echo. Experimentally, we study an ensemble of phosphorus donor spins in isotopically purified ^{28}Si with ms coherence times. With a static magnetic field, we tune their transition frequency into resonance with a superconducting lumped element microwave resonator. We present experimental data within and outside the strong coupling regime and discuss a model predicting and corroborating the amplitude evolution of the echos based on the echo separation time, the dephasing rate of the spin ensemble, and the linewidth of the microwave resonator.

We acknowledge financial support from the DFG via SPP 1601.

TT 79.5 Thu 10:30 H 2053

Strong coupling between a carbon nanotube based quantum dot circuit and a microwave cavity — •Tino Cubaynes, Laure Bruhat, Jeremie Viennot, Matthieu Dartiailh, Matthieu Desjardins, Audrey Cottet, and Takis Kontos — Laboratoire Pierre Aigrain, ENS, Paris 75005, FRANCE

Circuit quantum electrodynamics allows one to probe, manipulate and couple superconducting quantum bits using cavity photons at an exquisite level. One of its cornerstones is the possibility to achieve the strong coupling which allows one to hybridize coherently light and matter. Mesoscopic-QED inherits the c-QED toolbox and applies it to nano-circuits. I will present cavity transmission and simultaneous transport measurements on a quantum dot circuit -a Cooper pair splitter- embedded in a microwave cavity. By using a new cavity-DQD coupling scheme, the strong coupling of a photonic system to a hybrid circuit has been reached [1]. Our findings open the path to ultra-long distance entanglement of quantum dot based qubits. They could be adapted to many other circuit designs, shedding new light on the roadmap for scalability of quantum dot setups. I will also present current development on a nanofabrication technique allowing integration of prisitine carbon nanotube in mesoscopic-QED devices. From this perspective we can envision carbon nanotube based circuit with high tunability and very low decoherence.

[1] L. E. Bruhat , T. Cubaynes, et al. arXiv:1612.05214 (2016)

TT 79.6 Thu 10:45 H 2053

Non-degenerate Parametric Resonance in Superconducting Cavity — Waltraut Wustmann[1] and •Vitaly Shumeiko[2] — [1]Laboratory for Physical Sciences, College Park, Maryland 20740, USA — [2]Chalmers University of Technology, S-41296 Göteborg, Sweden

We present a theory for non-degenerate parametric resonance in a tunable superconducting cavity. We consider both regimes of down- and up- conversion. In the first, parametric amplification regime we focus a nonlinear gain close to the parametric instability threshold. Here the quantum noise undergoes four-mode squeezing and less efficient amplification than the coherent signal. This results in enhancement of output signal-to-noise ratio compared to the input.

Above the instability threshold, the system enters the parametric oscillation regime with two correlated beams having uncertain phase difference. Continuous degeneracy of the oscillator state is in drastic contrast to the two-fold degeneracy of the degenerate parametric oscillator. This property leads to a broadening of the output radiation spectrum, and divergence of the linear response at the oscillation frequencies. Application of a small on-resonance input lifts the degeneracy and locks the radiation phases.

For the frequency conversion regime we evaluate a nonlinear conversion coefficient, and identify an optimum pump strength at which a full inter-mode conversion can be achieved.

[1] W. Wustmann, V. Shumeiko, Phys. Rev. Appl. 8 (2017) 024018.

15 min. break.

TT 79.7 Thu 11:15 H 2053

Time-Translation Symmetry Breaking and Reentrant First Order Transition in Periodically Driven Quantum Oscillators — •Jennifer Gosner[1], Yaxing Zhang[2], Mark Dykman[3], and Joachim Ankerhold[1] — [1]Institute for Complex Quantum Systems and IQST, Ulm University, Germany — [2]Department of Physics, Yale University, USA — [3]Department of Physics and Astronomy, Michigan State University, USA

Breaking of discrete time-translation symmetry is a well-known phenomenon in dissipative periodically driven systems. Such systems reveal generic properties, which apply to all multiple-period transitions, but do not occur in period doubling. Here, we investigate a nonlinear oscillator, that is driven at three times the eigenfrequency [1]. Multiple crossings of eigenstates occur with varying parameters of the driving field. Physically, they result from interference of the Floquet wave functions in the classically inaccessible region. We discuss time-translational symmetry breaking, and develop a detailed analysis of the phase-space structure and its symmetries.

In the presence of dissipation, a quantum oscillator can support three states of period-three vibrations that co-exist with the state of no vibrations. With varying detuning a reentrant first-order transition appears, where the populations of these states change exponentially strongly. We study tunneling as well as switching via quantum activation. The results allow revealing "time crystals" in simple quantum systems, including the systems studied in circuit QED.

[1] Y.Zhang et al., PRA **96**, 052124 (2017)

TT 79.8 Thu 11:30 H 2053

Enhancing photon squeezing one Leviton at a time — •Flavio Ronetti[1,2], Dario Ferraro[3], Jérôme Rech[2], Thibaut Jonckheere[2], Thierry Martin[2], and Maura Sassetti[1] — [1]Università di Genova and CNR-SPIN, Via Dodecaneso 33, 16146, Genova, Italy — [2]Aix Marseille Univ, Université de Toulon, CNRS, CPT, Marseille, France — [3]Istituto Italiano di Tecnologia, Graphene Labs, Via Morego 30, I-16163 Genova, Italy

A mesoscopic device in the simple tunnel junction or quantum point contact geometry emits microwaves with remarkable quantum properties, when subjected to a sinusoidal drive in the GHz range. In particular, single and two-photons squeezing as well as entanglement in the frequency domain have been recently reported [1]. By revising the photo-assisted noise analysis developed in the framework of electron quantum optics [2], we present a detailed comparison between the cosine drive case and other experimentally relevent periodic voltages like rectangular and Lorentzian pulses [3]. We show that the latter drive is the best candidate in order to enhance quantumness and purity of the outgoing single and two-photons states in view of quantum information perspectives.

[1] G. Gasse, et al., Phys. Rev. Lett. 111, 136601 (2013).
[2] J. Dubois, et al., Nature 502, 659 (2013).
[3] D. Ferraro, et al., in preparation (2017)

TT 79.9 Thu 11:45 H 2053

Remote state preparation with propagating quantum microwaves — •Stefan Pogorzalek[1,2], Kirill G. Fedorov[1,2], Behdad Ghaffari[1,2], Minxing Xu[1,2], Peter Eder[1,2,3], Michael Fischer[1,2,3], Edwar Xie[1,2,3], Achim Marx[1], Frank Deppe[1,2,3], and Rudolf Gross[1,2,3] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]Physik-Department, TU München, 85748 Garching, Germany — [3]Nanosystems Initiative Munich (NIM), 80799 München, Germany

Propagating two-mode squeezed (TMS) microwave states enable applications of quantum communication and sensing with superconducting quantum circuits [1]. In our work, we perform experimental studies of TMS microwave states, which are generated by the means of flux-driven Josephson parametric amplifiers and linear circuit elements [2, 3]. We use the TMS states for the demonstration of a basic quantum communication protocol, namely, remote state preparation (RSP) in which the sender has knowledge of a to-be-teleported quantum state. In particular, we experimentally demonstrate the feasibility of the continuous variable RSP protocol with analog feed-forward by remotely preparing single-mode squeezed states.

The authors acknowledge support from DFG through FE 1564/1-1.

[1] R. Di Candia *et al.*, EPJ Quantum Technol. **2**, 25 (2015).
[2] K. G. Fedorov *et al.*, Phys. Rev. Lett. **117**, 020502 (2016).
[3] K. G. Fedorov *et al.*, arXiv:1703.05138 (2017).

TT 79.10 Thu 12:00 H 2053

New Spectroscopic Methods in Quantum Microwave Photonics: Accessing Correlated Noise, and Multiphoton Processes — •Tomás Ramos and Juan José García-Ripoll — Instituto de Física Fundamental IFF CSIC, Calle Serrano 113b, Madrid 28006, Spain

In this talk, we present new methods for characterizing correlated noise and multiphoton scattering processes in experiments with propagating photons in superconducting circuits.

First, we study how correlated dephasing noise is manifested in single-photon scattering experiments. We introduce a general noise model that describes correlated gaussian and non-gaussian noise, 1/f noise, white noise, telegraph noise, etc, and we study how the transmission lineshapes are modified on each case. Only for white noise, the dephasing can be characterized by a constant 'dephasing rate', but a general dephasing response depends on the photon's detuning. In addition, we demonstrate a general relation between these spectroscopic measurements and standard time-resolved Ramsey measurements, allowing one to infer the effect of correlated noise in one experiment from the knowledge of the other.

Second, we provide a spectroscopic protocol to characterize photon-photon interactions mediated by a qubit in a transmission line. The experimental method requires coherent state inputs and homodyne detection at the qubit's output, and it can be generalized to determine the multiphoton scattering matrix of any quantum object [1].

[1] T. Ramos, J.J. García-Ripoll, PRL 119, 153601 (2017).

TT 79.11 Thu 12:15 H 2053

Probing the strongly driven spin-boson model in a superconducting quantum circuit — L. Magazzù[1], P. Forn-Diaz[2], Ron Belyansky[2], J.-L. Orgiazzi[2], M.A. Yurtalan[2], M.R. Otto[2], A. Lupascu[2], C. Wilson[2], and •M. Grifoni[3] — [1]Institute of Physics, University of Augsburg, Universitätsstrasse 1, D-86135 Augsburg, Germany — [2]Institute for Quantum Computing, University of Waterloo, Waterloo N2L 3G1, Canada — [3]Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany

Quantum two-level systems interacting with the surroundings are ubiquitous in nature. The interaction suppresses quantum coherence and forces the system towards a steady state. Such dissipative processes are captured by the paradigmatic spin-boson model, describing a two-state particle, the "spin", interacting with an environment formed by harmonic oscillators. A fundamental question to date is to what extent intense coherent driving impacts a strongly dissipative system. Here we investigate experimentally and theoretically a superconducting qubit strongly coupled to an electromagnetic environment and subjected to a coherent drive. This setup realizes the driven Ohmic spin-boson model. We show that the drive reinforces environmental suppression of quantum coherence, and that a coherent-to-incoherent transition can be achieved by tuning the drive amplitude. An out-of-equilibrium detailed balance relation is demonstrated. These results advance fundamental understanding of open quantum systems in the case of strong light-matter interaction.

[1] arXiv:1709.01157

TT 79.12 Thu 12:30 H 2053

Quasiparticle dynamics in Andreev quantum dots — •Leandro Tosi, Marcelo Goffman, Cristian Urbina, and Hugues Pothier — Quantronics group, SPEC, CEA Saclay, France

In contrast with a bulk superconductor, a single-channel phase-biased superconducting weak link hosts a discrete subgap quasiparticle state, called "Andreev state". It can be seen as a sort of quantum dot in which zero, one or two quasiparticles can be trapped, not due to electrostatic barriers, but to the phase drop. This "Andreev quantum dot" constitutes a very simple playground to explore the foundations of mesoscopic superconductivity.

I will present experiments on Andreev quantum dots obtained at one-atom contacts between aluminum electrodes, in which we probe the dynamics of quasiparticles trapping and un-trapping using circuit-QED like techniques [1]. I will focus in particular on the effect of the cavity on this dynamics.

[1] C. Janvier et al., Science 349, 1199 (2015)