TT 13: Focussed Session: Superconducting Quantum Circuits

Time: Tuesday 9:30–12:30 Location: HSZ 03

Invited Talk TT 13.1 Tue 9:30 HSZ 03

Photons, Qubits and Computers - A Quantum Mechanics Lab on a Chip — •Andreas Wallraff — Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland

In our lab we experimentally investigate the interaction of matter and light on the level of single quanta. Our approach, known as circuit quantum electrodynamics [1], combines ideas of atomic physics, quantum optics and solid state physics to perform state of the art quantum mechanics experiments on a single chip. This is achieved by coupling single photons stored in high quality microwave frequency resonators to fully controllable superconducting two-level systems (qubits) realized in macroscopic electronic circuits. In particular, we have recently observed the formation of qubit/light molecules involving one, two or three photons [2], where we probe the quantum nonlinearity of the qubit/field interaction. This experiment unambiguously demonstrates that the radiation field in the on-chip cavity is quantized. We have also performed quantum optics experiments with no photons at all. In this situation, i.e. in pure vacuum, we have been able to resolve the nonresonant interaction of a qubit with the cavity vacuum fluctuations [3]. This interaction leads to a renormalization in the qubit transition frequency, known as the Lamb shift. The high degree of control achievable over a collection of two-level systems and their interactions also renders the circuit QED architecture attractive for quantum information processing.

[1] A. Wallraff et al., Nature (London) 431, 162 (2004).
[2] J. Fink et al., Nature (London) 454, 315 (2008).
[3] A. Fragner et al., Science 322, 1357 (2008).

Topical Talk TT 13.2 Tue 10:00 HSZ 03

Two-photon probe of the Jaynes-Cummings model and controlled symmetry breaking in circuit QED — Frank Deppe[1], Matteo Mariantoni[1], Edwin P. Menzel[1], •Achim Marx[1], Rudolf Gross[1], S. Saito[2], K. Kakuyanagi[2], H. Tanaka[2], K. Semba[2], T Meno[3], H. Takayanagi[4], and E. Solano[5] — [1]Walther-Meissner-Institut and TU München, Germany — [2]NTT Basic Research Laboratories, NTT Corp., Japan — [3]NTT Advanced Technology, NTT Corp., Japan — [4]Tokyo University of Science and International Center for Materials Nanoarchitectronics, Japan — [5]Universidad del País Vasco - Euskal Herriko Unibertsitatea, Spain

Superconducting qubits behave as artificial two-level atoms. Coupling them to on-chip microwave resonators has given rise to the field of circuit quantum electrodynamics. In this work, we report on the observation of key signatures of a two-photon driven Jaynes-Cummings model, which unveils the upconversion dynamics of a superconducting flux qubit coupled to an on-chip resonator. Our experiment and theoretical analysis show clear evidence for the coexistence of one- and two-photon driven level anticrossings of the qubit-resonator system. This results from the controlled symmetry breaking of the system Hamiltonian, causing parity to become a not well-defined property. Our study provides deep insight into the interplay of multiphoton processes and symmetries in a qubit-resonator system. We ackowledge support from SFB 631, NIM, CREST-JST, JSPS-KAKENHI(18201018) and MEXT-KAKENHI(18001002), EuroSQIP, and the Ikerbasque Foundation.

Topical Talk TT 13.3 Tue 10:30 HSZ 03

Landau-Zener Transitions in Qubit-Oscillator Settings — •Sigmund Kohler — Institut für Physik, Universität Augsburg, 86135 Augsburg

The coupling between a qubit and a mode of a transmission line induces Landau-Zener transitions of the qubit upon switching the gate voltage or the magnetic flux that penetrates the superconducting loop. The adiabatic energies of this system are characterized by multiple exact and avoided level crossings for which the usual two-level Landau-Zener formula is no longer applicable. We derive selection rules for the multi-level transitions and present an exact expression for the corresponding transition probabilities [1,2]. Applications include quantum state preparation like single-photon generation and the controllable creation of qubit-oscillator entanglement. If the circuit is driven by a rf signal, the phase of the reflected signal depends on the state of the qubit. We discuss the possibility of monitoring Landau-Zener transitions in that way. A natural generalization addresses the coupling of the qubit to a bath of harmonic oscillator. This defines the dissipative Landau-Zener problem which recently gained interest in the context of adiabatic quantum computation. We derived an exact solution of this problem in the zero-temperature limit [3].

[1] K. Saito *et al.*. Europhys. Lett. **76**, 22 (2006).
[2] D. Zueco, P. Hänggi, and S. Kohler, New. J. Phys. **10**, 115012 (2008).
[3] M. Wubs *et al.*, Phys. Rev. Lett. **97**, 200404 (2006).

15 min. break

Topical Talk TT 13.4 Tue 11:15 HSZ 03

Experiments on the quantum of heat conductance — •Jukka Pekola[1], Matthias Meschke[1], Andrey Timofeev[1], Wiebke Guichard[2], Meri Helle[1], and Mikko Möttönen[1,3] — [1]Low Temperature Laboratory, Helsinki University of Technology, Finland — [2]Institut Neel, C.N.R.S., Grenoble, France — [3]Department of Applied Physics, Helsinki University of Technology, Finland

The fundamental limit to transmit heat via a single channel is governed by the quantum of thermal conductance. This has been demonstrated in experiments on both phonons [1,2] and electrons [3]: here we present two experiments [4,5] on this phenomenon based on electromagnetic coupling (photons). In the first experiment tunable electric impedance is used to modulate the radiated heat between two resistors at different temperatures in a superconducting micro-circuit. In the second experiment we demonstrate electronic refrigeration at the quantum limit using superconductor-normal metal tunnel junctions. We discuss the limits of classical and quantum heat exchange in an electrical circuit.

[1] K. Schwab, E. A. Henriksen, J. M. Worlock, M. L. Roukes, Nature 404, 974 (2000).
[2] C. S. Yung, D. R. Schmidt, A. N. Cleland, Appl. Phys. Lett. 81, 31 (2002).
[3] O. Chiatti, J. T. Nicholls, Y. Y. Proskuryakov, N. Lumpkin, I. Farrer, D. A. Ritchie, Phys. Rev. Lett. 97, 056601 (2006).
[4] M. Meschke, W. Guichard, J. P. Pekola, Nature 444, 187 (2006).
[5] A.V. Timofeev, M. Helle, M. Meschke, M. Möttönen, J.P. Pekola, submitted (2008).

Topical Talk TT 13.5 Tue 11:45 HSZ 03

Preparation of arbitrary quantum states in a microwave resonator — •Max Hofheinz, Haohua Wang, Markus Ansmann, Radoslaw Bialczak, Erik Lucero, Matthew Neeley, Aaron O'Connell, Daniel Sank, James Wenner, John Martinis, and Andrew Cleland — University of California, Santa Barbara, USA

Two-level systems, or qubits, can be prepared in arbitrary quantum states with exquisite control, just using classical electrical signals. Achieving the same degree of control over harmonic resonators has remained elusive, due to their infinite number of equally spaced energy levels. Here we exploit the good control over a superconducting phase qubit by using it to pump photons into a high-Q coplanar wave guide resonator and, subsequently, to read out the resonator state. This scheme has previously allowed us to prepare and detect photon number states (Fock states) in the resonator [1]. Using a generalization of this scheme [2] we can now create arbitrary quantum states of the photon field with up to approximately 10 photons. We analyze the prepared states by mapping out the corresponding Wigner function, which is the phase-space equivalent to the density matrix and provides a complete description of the quantum state.

[1] MH *et al.* Nature **454**, 310 (2008)
[2] Law, Eberly. Phys. Rev. Lett **76**, 1055 (1996)

TT 13.6 Tue 12:15 HSZ 03

Phase diffusion in single-qubit lasers — •Stephan André[1,2], Valentina Brosco[1,2], Alexander Shnirman[2,3], and Gerd Schön[1,2] — [1]Institut für Theoretische Festkörperphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany — [2]DFG Center for Functional Nanostructures (CFN), Universität Karlsruhe, 76128 Karlsruhe, Germany — [3]Institut für Theorie der Kondensierten Materie, Universität Karlsruhe, 76128 Karlsruhe, Germany

Recent experiments explored the dynamics of superconducting qubits, playing the role of artificial atoms, coupled to quantum electrical resonators. Single-qubit lasers were realized by creating a population inversion in the qubit [1]. In contrast to conventional lasers, single-qubit lasers are characterized by a strong qubit-oscillator coupling and a richer noise spectrum for the qubit.

We theoretically investigate the spectral properties of single-qubit lasers, focussing on the effects of the strong coupling and of 1/f-noise [2]. Specifically, we show that low-frequency charge fluctuations can explain the inhomogeneous broadening of the spectrum observed in the experiment.

[1] O. Astafiev *et al.*, Nature **449**, 588 (2007)
[2] S. André *et al.*, arXiv:0807.4607 (2008)