TT 66: Superconductivity: Tunneling, Josephson Junctions, SQUIDs

Time: Wednesday 15:00–19:15 Location: H 2053

TT 66.1 Wed 15:00 H 2053

Coherent terahertz emission from $Bi_2Sr_2CaCu_2O_8$ intrinsic Josephson junction stacks — •Fabian Rudau[1], Boris Gross[1], Raphael Wieland[1], Nickolay Kinev[2], Manabu Tsujimoto[3], Min Ji[4,5], Ya Huang[4,5], Xianjing Zhou[4,5], Deyue An[4,5], Thomas Judd[1], Peiheng Wu[5], Takeshi Hatano[4], Huabing Wang[4,5], Valery Koshelets[2], Dieter Koelle[1], and Reinhold Kleiner[1] — [1]Physikalisches Institut and Center for Collective Quantum Phenomena in LISA+, Universität Tübingen, Tübingen, Germany — [2]Kotel'nikov Institute of Radio Engineering and Electronics, Moscow, Russia — [3]Kyoto University, Kyoto, Japan — [4]National Institute for Materials Science, Tsukuba, Japan — [5]Research Institute of Superconductor Electronics, Nanjing University, Nanjing, China

Stacks of intrinsic Josephson junctions, made of the high temperature superconductor $Bi_2Sr_2CaCu_2O_8$, are promising candidates to be used as generators of electromagnetic waves in the terahertz regime, in principle allowing frequencies up to $\sim$10 THz. Ranging from 0.4 to 1 THz, coherent emission was detected from large, rectangular stacks, producing several tens of microwatt in power. Despite of several years of research, the mechanism of synchronizing all the junctions in the stack is still not fully understood. We investigated the heat distribution and electromagnetic standing waves in such stacks, as well as the generation of terahertz radiation, using a combination of electric transport measurements, direct radiation detection and low temperature scanning laser microscopy. Recent experimental results from our collaboration will be presented and compared to numerical simulations.

TT 66.2 Wed 15:15 H 2053

Multi-photon dressing of an anharmonic superconducting many-level quantum circuit — •Jochen Braumüller[1], Joel Cramer[1], Steffen Schlör[1], Hannes Rotzinger[1], Lucas Radtke[1], Alexander Lukashenko[1], Ping Yang[1], Sebastian Skacel[1], Sebastian Probst[1], Michael Marthaler[2], Lingzhen Guo[2], Alexey V. Ustinov[1,3], and Martin Weides[1] — [1]Karlsruhe Institute of Technology (KIT), Physikalisches Institut, 76131 Karlsruhe, Germany — [2]Karlsruhe Institute of Technology (KIT), Institut für Theoretische Festkörperphysik, 76131 Karlsruhe, Germany — [3]National University of Science and Technology MISIS, Moscow 119049, Russia

We report on the investigation of a superconducting anharmonic multi-level circuit that is coupled to a harmonic readout resonator. We observe multi-photon transitions via virtual energy levels of our system up to the fifth excited state. The back-action of these higher-order excitations on our readout device is analyzed quantitatively and demonstrated to be in accordance with theoretical expectation. By applying a strong microwave drive we achieve multi-photon dressing of our system which is dynamically coupled by a weak probe tone. The emerging higher-order Rabi sidebands and associated Autler-Townes splittings involving up to five levels of the investigated anharmonic circuit are observed. Experimental results are in good agreement with master equation simulations.

TT 66.3 Wed 15:30 H 2053

Non-linear classical dynamics in a superconducting circuit containing a cavity and a Josephson junction — •Selina Meister, Björn Kubala, Vera Gramich, Michael Mecklenburg, Jürgen T. Stockburger, and Joachim Ankerhold — Institute for Complex Quantum Systems, Ulm University, Albert-Einstein-Allee 11, 89069 Ulm, Germany

Motivated by recent experiments [1] a superconducting hybrid circuit consisting of a voltage biased Josephson junction in series with a resonator is studied. For strong driving the dynamics of the system can be very complex, even in the classical regime. Studying the dissipative dynamics within a Langevin-type description, we obtain well-defined dynamical steady states.

In contrast to the well-known case of anharmonic potentials, like the Duffing or parametric oscillator, in our case the non-linearity stems from the peculiar way the external drive couples to the system [2]. We investigate the resonance behaviour of this non-linear hybrid system, in particular when driving at higher- or subharmonics. The resulting down- and up-conversions can be observed both, as resonances in the I-V curve, and in the emitted microwave radiation, which yields additional spectral information.

[1] M. Hofheinz et al., PRL 106, 217005 (2011).
[2] V. Gramich et al., PRL 111, 247002 (2013).

TT 66.4 Wed 15:45 H 2053

Displacement of microwave squeezed states with Josephson parametric amplifiers — •Ling Zhong[1,2,3], Kirill Fedorov[1], Martin Betzenbichler[1,2], Stefan Pogorzalek[1,2], Alexander Baust[1,2,3], Edwar Xie[1,2,3], Max Haeberlein[1,2], Manuel Schwarz[1,2,3], Peter Eder[1,2], Jan Goetz[1,2], Karl Friedrich Wulschner[1,2], Edwin Menzel[1], Hans Hübl[1,2], Frank Deppe[1,2], Achim Marx[1], 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), Schellingstraße 4, 80799 München, Germany

Propagating quantum microwaves are promising building blocks for quantum communication. Interestingly, such itinerant quantum microwaves can be generated in the form of squeezed photon states by Josephson parametric amplifiers (JPA). We employ a specific "dual-path" setup for both state reconstruction and JPA characterization. Displacement operations are performed by using a directional coupler after the squeezing. We compare our results with theory predictions. In particular, we discuss our experiments in the context of remote state preparation and quantum teleportation with propagating microwaves.

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TT 66.5 Wed 16:00 H 2053

The parity effect in a Jospehson junction array — Jared Cole[1], Andreas Heimes[2], and •Michael Marthaler[2] — [1]Chemical and Quantum Physics, School of Applied Sciences, RMIT University, Melbourne, Victoria 3001, Australia — [2]Institut für Theoretische Festkörperphysik, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany

We study transport in a Josephson junction array for small Josephson energies. For very small Josephson energy the transport is dominated by single quasiparticle tunneling. We consider a regime where there is enough energy to inject quasiparticles by breaking a cooper-pair, but transport inside of the array is dominated by the parity effect. This means that the current is caried by a small number of quasiparticles above the gap. We observer the crossover temperature T^*, which is also known from parity experiments in superconducting single electron transistors.

TT 66.6 Wed 16:15 H 2053

Even-odd flux quanta effect in the Fraunhofer oscillations of an edge-channel Josephson junction — •Benjamin Baxevanis, Viacheslav Ostroukh, and Carlo Beenakker — Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands

We calculate the beating of $h/2e$ and h/e periodic oscillations of the flux-dependent critical supercurrent through a quantum spin-Hall insulator between two superconducting electrodes [1]. A conducting pathway along the superconductor connects the helical edge channels via a non-helical channel, allowing an electron incident on the superconductor along one edge to be Andreev reflected along the opposite edge. We find the appearance of Fraunhofer oscillations with an even-odd effect: Large peaks in the critical current at even multiples of $h/2e$ alternate with smaller peaks at odd multiples. This even-odd effect has been recently observed in one series of experiments by Pribiag et al. [2].

[1] B. Baxevanis et al. arXiv:1411.6638
[2] V.S. Pribiag et al. arXiv:1408.1701

TT 66.7 Wed 16:30 H 2053

Experiments on phase retrapping in φ Josephson junctions — •Edward Goldobin[1], Rosina Menditto[1], Martin Weides[2], Dieter Koelle[1], and Reinhold Kleiner[1] — [1]University of Tübingen, Tübingen, Germany — [2]KIT, Karlsruhe, Germany

We experimentally study retrapping of the phase in φ Josephson junctions (JJs) based on superconductor-insulator-ferromagnetsuperconductor (SIFS) 0-π heterostructures[1,2]. Such φ JJs have a doubly degenerate ground state (two potential energy wells) with the phases $\pm\varphi$ ($0 < \varphi < \pi$). We study in which of these two wells the phase is trapped upon return of the JJ to the zero voltage state. We find that for $T > T^* \approx 2.4\,\mathrm{K}$ (large damping) the phase is always trapped in the $+\varphi$ state. However, for lower T (small damping) the trapping result is a statistical mixture of the $+\varphi$ and the $-\varphi$ states due to the presence of noise in the system. The probability for retrapping to the $-\varphi$ state increases and oscillates as T is decreasing below T^*, reaching a saturation value of $\sim 30\%$ for $T \lesssim 1.2\,\mathrm{K}$. These results are compared with theory[3], which predicts the butterfly effect in the limit of low damping.

[1] E. Goldobin et al. Phys. Rev. Lett. **107**, 227001 (2011).
[2] H. Sickinger et al. Phys. Rev. Lett. **109**, 107002 (2012).
[3] E. Goldobin et al. Phys. Rev. Lett. **111**, 057004 (2013).

TT 66.8 Wed 16:45 H 2053

Signatures of singlet-triplet pairing in Josephson transport between a conventional and a noncentrosymmetric superconductor — Björn Sothmann[1] and •Rakesh Tiwari[2] — [1]Département de Physique Théorique, Université de Genève , CH-1211 Genève 4, Switzerland — [2]Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

We investigate Josephson response of a junction consisting of a noncentrosymmetric superconductor tunnel coupled to a conventional s-wave superconductor via a double quantum dot. In the presence of an inhomogenous magnetic field acting on the two quantum dots forming the double quantum dot, the current phase relationship becomes highly asymmetric. The asymmetry in the critical current can be used to quantify the triplet-singlet pairing ratio in the noncentrosymmetric superconductor.

15 min. break.

Invited Talk TT 66.9 Wed 17:15 H 2053

Probing Andreev Bound States in One-Atom Superconducting Contacts — •Hugues Pothier, Camille Janvier, Leandro Tosi, Çağlar Girit, Marcelo Goffman, Daniel Esteve, and Cristiàn Urbina — Quantronics Group, SPEC, CEA-Saclay, France

Superconductors are characterized by a dissipationless current. Since the work of Josephson 50 years ago, it is known that a supercurrent can even flow through tunnel junctions between superconductors. This Josephson effect also occurs through any type of "weak links" between superconductors: non-superconducting materials, constrictions, ... A unified understanding of the Josephson effect has emerged from a mesoscopic description of weak links. It relies on the existence of doublets of localized states that have energies below the superconducting gap: the Andreev bound states. I will present experiments performed on the simplest conductor possible, a single-atom contact between superconductors, that illustrate these concepts. The most recent work demonstrates time-domain manipulation of quantum superpositions of Andreev bound states.

TT 66.10 Wed 17:45 H 2053

Superconducting phase transition in STM tips — •Matthias Eltschka[1], Berthold Jäck[1], Maximilian Assig[1], Markus Etzkorn[1], Christian R. Ast[1], and Klaus Kern[1,2] — [1]Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany — [2]Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

The superconducting properties of systems with dimensions comparable to the London penetration depth considerably differ from macroscopic systems. We have studied the superconducting phase transition of vanadium STM tips in external magnetic fields. Employing Maki's theory we extract the superconducting parameters such as the gap or the Zeeman splitting from differential conductance spectra. While the Zeeman splitting follows the theoretical description of a system with $s = 1/2$ and $g = 2$, the superconducting gaps as well as the critical fields depend on the specific tip. For a better understanding of the experimental results, we solve a one dimensional Usadel equation modeling the superconducting tip as a cone with the opening angle α in an external magnetic field. We find that only a small region at the apex of the tip is superconducting in high magnetic fields and that the order of the phase transition is directly determined by α. Further, the spectral broadening increases with α indicating an intrinsic broadening mechanism due to the conical shape of the tip. Comparing these calculations to our experimental results reveals the order of the superconducting phase transition of the STM tips.

TT 66.11 Wed 18:00 H 2053

Dynamics of a nanoscale Josephson junction probed by scanning tunneling microscopy — •Christian R. Ast[1], Berthold Jäck[1], Matthias Eltschka[1], Markus Etzkorn[1], and Klaus Kern[1,2] — [1]Max-Planck-Institut für Festkörperforschung, Stuttgart — [2]Institut de Physique de la Matière Condensée, EPFL, Lausanne

The Josephson effect is an intriguing phenomenon as it presents an interplay of different energy scales, such as the Josephson energy ϵ_J (critical current), charging energy ϵ_C, and temperature T. Using a scanning tunneling microscope (STM) operating at a base temperature of 15 mK, we create a nanoscale superconductor-vacuum-superconductor tunnel junction in an extremely underdamped regime (Q≫10). We observe extremely small retrapping currents also owing to strongly reduced ohmic losses in the well-developed superconducting gaps. While formally operating in the zero temperature limit, i. e. the temperature T is smaller than the Josephson plasma frequency ω_J ($k_B T \ll \hbar\omega_J = \sqrt{8\epsilon_J\epsilon_C}$), experimentally other phenomena, such as stray photons, may perturb the Josephson junction, leading to an effectively higher temperature. The dynamics of the Josephson junction can be addressed experimentally by looking at characteristic parameters, such as the switching current and the retrapping current. We discuss the dynamics of the Josephson junction in the context of reaching the zero temperature limit.

TT 66.12 Wed 18:15 H 2053

Supersymmetry in a Cooper-pair box shunted by a Josephson rhombus — •Jascha Ulrich, Daniel Otten, and Fabian Hassler — JARA-Institute for Quantum Information, RWTH Aachen University

Recently, a new kind of quantum-mechanical supersymmetry has been proposed providing a generalization of supersymmetry of the free particle to the presence of a periodic potential. Here, we propose a physical realization in a Cooper-pair box shunted by an effectively pi-periodic Josephson junction rhombus. For a characteristic ratio between the strength of the 2pi- and the pi-periodic junction, this yields a degeneracy of the energy levels all the way from the weak junction/charge qubit limit to the strong junction/transmon regime. We give explicit results for the required rhombus parameters as a function of the conventional junction strength and show that tuning in and out of the supersymmetric point is easily achieved by varying the junction strength or an external gate voltage. We furthermore discuss a microwave experiment for level spectroscopy and conclude that the supersymmetry could indeed be realized with currently existing Josephson junction technology.

TT 66.13 Wed 18:30 H 2053

Dynamical phase squeezing in layered superconductors (limit of two coupled junctions) — •Beilei Zhu[1], Robert Höppner[1], Tobias Rexin[1], Andrea Cavalleri[1,2,3], and Ludwig Mathey[1,4] — [1]ZOQ & ILP, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany — [2]MPI for Structure and Dynamics of Matter, 22761 Hamburg, Germany — [3]Clarendon Laboratory,Department of Physics, Oxford University, Parks Road, Oxford OX1 3PU,UK — [4]The Hamburg Center for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany

We study the dynamics of a layered superconductor with alternating inter-layered coupling, driven by an external potential that models a light pulse coupling to an optical phonon mode, inspired by [1,2]. We study a minimal model consisting of one strong junction and one weak junction, coupled to a heat bath. We describe this toy model using a Langevin formalism and treat it numerically. The strong junction plays as an amplifier of the external driving on the weak junction. We find that the phase fluctuations of the weak junction are squeezed under near-resonant driving of strong junction. The power spectrum demonstrates that the squeezing occurs in the low frequency regime. We also consider a quantum version for a driven single Josephson Junction.

[1] Fausti et al., Science, 331, 6014 189-191 (2011)
[2] Kaiser et al., arXiv:1205.4661

TT 66.14 Wed 18:45 H 2053

Redistribution of phase fluctuations in a periodically driven cuprate superconductor — •Robert Höppner[1], Beilei Zhu[1], Tobias Rexin[1], Ludwig Mathey[1,4], and Andrea Cavalleri[2,3] — [1]Zentrum für Optische Quantentechnologien und Institut für Laserphysik, Hamburg, Germany — [2]Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany — [3]Department of Physics, Oxford University, Clarendon Laboratory, Parks Road, Oxford, UK — [4]The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany

We study the thermally fluctuating state of a bi-layer cuprate superconductor under the periodic action of a staggered field oscillating at optical frequencies. This analysis distills essential elements of the recently discovered phenomenon of light enhanced coherence in YBCO, which was achieved by periodically driving infrared active apical oxygen distortions. The effect of a staggered periodic perturbation is studied using a Langevin description of driven, coupled Josephson junctions, which represent two neighboring pairs of layers and their two plasmons. We demonstrate that the external driving leads to a suppression of phase fluctuations of the low-energy plasmon, an effect which is amplified via the resonance of the high energy plasmon, with a striking suppression of the low-energy fluctuations, as visible in the power spectrum. We also find that this effect acts onto the in-plane fluctuations, which are reduced on long length scales and we discuss the behavior of vortices in the ab-planes and across the weakly coupled junctions.

TT 66.15 Wed 19:00 H 2053

Dynamics of a driven Josephson junction at high temperature

— •Tobias Rexin[1,2,3], Beilei Zhu[1,2,3], Robert Hoeppner[1,2,3], and Ludwig Mathey[1,2,3,4] — [1]Uni Hamburg — [2]Institut für Laserphysik Hamburg — [3]Zentrum für optische Quantentechnologien — [4]Center for Ultrafast Imaging

The present work investigates the dynamics of a single driven Josephson junction coupled to a thermal bath. Applying an extended version of the Fokker-Planck equation, namely the Kramers equation, we analytically treat the dynamics of both degrees of freedom the phase and the charge density. Interestingly, instead of heating the junction, the driving can suppress the phase fluctuations [1]. This is motivated by recent pump-probe experiments of high T_c superconductors reported in [2,3]. In ref [1], we have developed a description of the dynamics in these materials by modeling them as an array of Josephson junctions. The single junction model is a simplification of the Josephson junction array, which already exhibits qualitative aspects of the driven array.

[1] R.Höppner et al. *preprint* arXiv:1406.3609v2
[2] W. Hu, et al., *Nature Materials* **13**, 705 (2014).
[3] S. Kaiser, et al. *Phys. Rev. B* **89**, 184516 (2014).