# TT 26: Superconductivity: Tunnelling and Josephson Junctions

Time: Thursday 9:30–13:00 Location: H10

TT 26.1 Thu 9:30 H10

**Microwave spectroscopy of a long Josephson junction strongly coupled to a resonator** — •Micha Wildermuth[1], Mikhail Fistul[2], Jan Nicolas Voss[1], Andre Schneider[1], Hannes Rotzinger[1,3], and Alexey V. Ustinov[1,3] — [1]Institute of Physics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany — [2]Theoretische Physik III, Ruhr-Universität Bochum, 44801 Bochum Germany — [3]Institute for Quantum Materials and Technology, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

Long Josephson junctions are interesting physical systems due to their strongly nonlinear spatial and temporal dynamics. In the past, most of experiments were performed by coupling long junctions galvanically to measurement lines and recording their DC current-voltage characteristics. Here we explore an alternative approach, where the long junction is attached to a passive microwave resonator and the whole coupled system is measured with an RF technique. This configuration opens up new opportunities of low-dissipative tests and applications, in particular, for Josephson vortex qubits. We present fabrication results, microwave spectroscopy data and numerical simulations of this high-impedance hybrid system.

TT 26.2 Thu 9:45 H10

**Quantum interference in a 1d array of three-terminal Josephson junctions** — •Johanna Berger[1], Christian Baumgartner[1], Lorenz Fuchs[1], Sergei Gronin[2], Geoff Gardner[2], Michael Manfra[2], Nicola Paradiso[1], and Christoph Strunk[1] — [1]Experimental and Applied Physics, University of Regensburg (Germany) — [2]Purdue University, West Lafayette, Indiana (USA)

We present DC transport measurements of an 1d array of three-terminal Josephson junctions based upon an epitaxial Al-InAs heterostructure. Two terminals are connected via a superconducting loop. Under the influence of perpendicular magnetic fields the critical current displays a complex diffraction pattern resembling the superposition of a Fraunhofer pattern-like envelope and SQUID oscillations. In the presence of an additional in-plane magnetic field this pattern develops two asymmetries: The main lobe shows clear supercurrent diode behavior [1], which results in different critical currents depending on the applied current direction. With increasing in-plane magnetic field the diffraction pattern acquires an overall skewness with respect to the perpendicular magnetic field, leading to differently pronounced side lobes. Unlike the diode effect this skewness is not suppressed at higher magnetic fields.

[1] C. Baumgartner *et. al.*, Nat. Nanotechnol. **17**, 39 (2022)

TT 26.3 Thu 10:00 H10

**Highly-packed Nb-C Josephson junction arrays prepared by focused-ion-beam nanoprinting** — •Fabrizio Porrati[1], Felix Jungwirth[1], Sven Barth[1], Gian Carlo Gazzadi[2], Stefano Frabboni[2], Oleksandr V. Dobrovolskiy[3], and Michael Huth[1] — [1]Goethe-University, Institut of Physics, Frankfurt a. M. — [2]Nanoscience Institute-CNR, Modena — [3]University of Vienna, Faculty of Physics, Vienna

Focused ion beam-induced deposition (FIBID) is a direct-write technique for the fabrication of nanostructures of any shape and dimension with high lateral resolution. Here, FIBID is employed to prepare Josephson junction arrays (JJA) consisting of superconducting Nb-C dots coupled through the proximity effect via a thin granular metal layer. The fabrication of the device is straightforward and it takes place in a few seconds. The microstructure and the composition of the JJA are investigated by transmission electron microscopy (TEM) and energy dispersive x-ray spectroscopy (EDS). The superconductor-to-metal transition of the JJA is studied directly by tuning the Josephson junction resistance in 70 nm-spaced Nb-C dots. The observed magnetoresistance oscillations with a period determined by the flux quantum give evidence for the coherent charge transport by paired electrons.

TT 26.4 Thu 10:15 H10

**A particle conserving approach to AC-DC driven interacting quantum dots with superconducting leads** — •Julian Siegl, Jordi Picó-Cortés, and Milena Grifoni — Universität Regensburg, Regensburg, Germany

The combined action of a DC bias and a microwave drive on the transport characteristic of a superconductor-quantum dot-superconductor junction is investigated. To cope with non-equilibrium effects and interactions in the quantum dot, we develop a general formalism for the dynamics of the density operator based on a particle conserving approach to superconductivity. An exact generalized master equation for the reduced dot operator is obtained that treats the interaction inside the dot exactly and showcases the characteristic bichromatic response due to the combination of the AC Josephson effect and an AC voltage. In the weak coupling limit, analytical expressions for the stationary current and the reduced dot operator are provided. In this regime, beside quasiparticle transport, we show that superconducting correlations manifest in anomalous pair tunneling processes involving the tunneling of a Cooper pair. Photon assisted processes allow for subgap transport and rich current-voltage characteristics. For example, we find total current inversion, in which the current flows against the applied DC bias for suitable parameter regimes.

TT 26.5 Thu 10:30 H10

**Model-independent determination of the gap function of nearly localized superconductors** — •Dušan Kavický[1], František Herman[1,2], and Richard Hlubina[1] — [1]Department of Experimental Physics, Comenius University, Mlynská Dolina F2, 842 48 Bratislava, Slovakia — [2]Institute for Theoretical Physics, ETH Zurich, CH-8093, Switzerland

The gap function $\Delta(\omega)$ carries essential information on both, the pairing glue as well as the pair-breaking processes in a superconductor. Unfortunately, in nearly localized superconductors with a non-constant density of states in the normal state, the standard procedure for extraction of $\Delta(\omega)$ cannot be applied. Here, we introduce a model-independent method that makes it possible to extract $\Delta(\omega)$ also in this case. The feasibility of the procedure is demonstrated on the tunneling data for the disordered thin films of TiN. We find an unconventional feature of $\Delta(\omega)$ which suggests that the electrons in TiN are coupled to a very soft pair-breaking mode.

TT 26.6 Thu 10:45 H10

**The DC Josephson effect for a single level weak link: a Green's function formulation within a particle conserving theory of superconductivity** — •Anton Bleibaum and Milena Grifoni — Institute for Theoretical Physics, University of Regensburg, 93053 Regensburg, Germany

In traditional transport set-ups a current only flows when a bias voltage is applied. In the presence of superconducting electrodes a supercurrent can flow through a tunneling barrier even in thermodynamic equilibrium. This phenomenon is called DC-Josephson effect. Most of its features can be captured within mean field BCS-theory, according to which the supercurrent is a function of the phase difference between the two superconductors.

How can this result be reconciled with charge conservation in a physical system? In this work we compute the DC Josephson current in transport set-ups consisting of two superconducting electrodes coupled to a single level non-interacting quantum dot. The computation is based on a particle conserving theory of superconductivity. We first provide a current formula in terms of particle conserving Green's functions. In a second step the infinite hierarchy of equations for the relevant Green's function is solved. The Andreev bound states spectrum naturally follows from the poles of the retarded Green's function, and the DC-current has the form known from BCS theory.

TT 26.7 Thu 11:00 H10

**Engineering the speedup of quantum tunneling in Josephson systems via dissipation** — •Dominik Maile[1], Joachim Ankerhold[1], Sabine Andergassen[2], Wolfgang Belzig[3], and Gianluca Rastelli[4] — [1]Institut für komplexe Quantensysteme, Universität Ulm, Germany — [2]Institut für Theoretische Physik, Universität Tübingen, Germany — [3]Fachbereich Physik, Universität Konstanz, Germany — [4]NO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Povo, Italy

We theoretically investigate the escape rate occurring via quantum tunneling in a system affected by tailored dissipation [1]. Specifically, we study the environmental assisted quantum tunneling of the superconducting phase in a current-biased Josephson junction. We consider Ohmic resistors inducing dissipation both in the phase and in the charge of the quantum circuit. We find that the charge dissipation leads to an enhancement of the quantum escape rate. This effect appears already in the low Ohmic regime and also occurs in the presence of phase dissipation that favors localization. Inserting realistic circuit parameters, we address the question of its experimental observability and discuss suitable parameter spaces for the observation of the enhanced rate.

[1] D. Maile, J. Ankerhold, S. Andergassen, W. Belzig, G. Rastelli, arXiv:2203.08075 (2022)

**15 min. break**

TT 26.8 Thu 11:30 H10

**Nonreciprocity in current-biased Josephson junctions in the presence of Yu-Shiba-Rusinov bound states** — •Martina Trahms[1], Bharti Mahendru[1], Idan Tamir[1], Larissa Melischek[1], Jacob F. Steiner[1], Nils Bogdanoff[1], Olof Peters[1], Gaël Reecht[1], Clemes B. Winkelmann[2], Felix von Oppen[1], and Katharina J. Franke[1] — [1]Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany — [2]Univ. Grenoble Alpes, Institute Néel, 38042 Grenoble, France

Magnetic impurities on superconducting surfaces are known to locally disturb Cooper pairs and form Yu-Shiba-Rusinov (YSR) states. We employ current-biased Josephson spectroscopy in a scanning tunnelling microscope to study the phase dynamics of Josephson junctions in the presence of YSR states. For that purpose Mn and Cr adatoms are evaporated on a superconducting Pb(111) surface and investigated with a superconducting Pb tip. We observe switching currents that are significantly larger than the retrapping currents, identifying the junction as underdamped. In the presence of magnetic atoms, a local reduction of switching currents is observed. Additionally, we find a nonreciprocal behavior of the retrapping currents with respect to the current-sweep direction, i.e., the absolute value of the retrapping current depends on whether the current sweep starts at positive or negative bias values. In our experiment both species of magnetic atoms lead to a nonreciprocal retrapping-current behavior, albeit with a different directionality. We suggest a correlation between the damping of the Josephson junction and the electron-hole asymmetry of the YSR states.

TT 26.9 Thu 11:45 H10

**Josephson effect through two superconducting magnetic impurity states** — •Fabian Ziesel[1], Ciprian Padurariu[1], Björn Kubala[1,2], and Joachim Ankerhold[1] — [1]ICQ and IQST, Ulm University, Germany — [2]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany

A mK-STM functionalized with a magnetic impurity at the tip can probe a sample with a second impurity, thus realizing tunneling between Yu-Shiba-Rusinov (YSR) states [1]. We study the Josephson effect in such a system as a sensitive probe of the magnetic orientation of the impurities. Using Keldysh Green's functions, we show that the subgap bound states are spin-polarized and give rise to a spin polarized Josephson current. At low transmission, the YSR states of the impurities hybridize weakly, whereas at large transmission, the bound states are strongly phase-dependent, resembling spin split Andreev bound states [2]. The spin structure of the current becomes strongly phase-dependent. For aligned or anti-aligned magnetic impurities, we show that an unusual quantum phase transition emerges. While such a Josephson current can be used as a sensitive spin probe, we find that it is accompanied by significant feedback in the form of a Josephson spin torque acting to align/anti-align the impurities.

[1] H. Huang *et al.*, Nat. Phys. **16**, 1227 (2020)
[2] B. Bujnowski *et al.*, EPL **115**, 67001 (2016)

TT 26.10 Thu 12:00 H10

**Spin-orbit coupling assisted transport phenomena in superconducting magnetic tunnel junctions** — •Andreas Costa and Jaroslav Fabian — University of Regensburg, Germany

Superconducting magnetic junctions exhibit fascinating physical phenomena, making them essential building blocks for modern technologies like quantum computing. Particularly attractive are multicomponent junctions in which the broken space-inversion symmetry additionally rises strong spin-orbit coupling (SOC). Pairing the interplay of these two most important spin interactions—exchange and SOC—with superconducting coherence has already been demonstrated to lead to unique signatures in spectroscopy and transport, and is furthermore expected to induce topological superconductivity hosting Majorana states. In this theory talk, we will focus on the most intriguing transport ramifications of SOC in superconducting magnetic junctions, covering giant transport magnetoanisotropies in the junctions' conductance and Josephson-current flow [1], the possibility to generate sizable transverse anomalous (Josephson) Hall effects [2,3], as well as nonreciprocal transport and supercurrent-diode characteristics in proximitized 2DEG Josephson junctions [4] that were experimentally classified through robust Josephson-inductance measurements.

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[1] PRB 95, 024514 (2017)
[2] PRB 100, 060507(R) (2019)
[3] PRB 101, 104508 (2020)
[4] Nat. Nanotechnol. (2021)

TT 26.11 Thu 12:15 H10

**Non-equilibrium transport in Josephson junctions through interacting nanostructures** — •Jordi Picó Cortés[1,2], Gloria Platero[2], and Milena Grifoni[1] — [1]Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany — [2]Instituto de Ciencia de Materiales de Madrid (CSIC) E-28049, Spain

Studying transport through interacting nanostructures is challenging due to the interplay between strong interactions and the coupling to large thermalized leads. In the case of superconducting leads, this is further complicated by a number of features particular to Josephson junctions, chiefly the effect of Cooper pairs and the resulting anomalous transport. In this work, we develop a diagrammatic approach to transport through weakly coupled Josephson junctions [1,2,3] which treats the interaction inside the dot exactly and employ it to describe the conventional and Josephson currents. The dynamics of Cooper pairs out of equilibrium are described in a particle-conserving formalism, which avoids issues arising from the usual BCS treatment, allowing us to extend the description of electron pairing inside the dot and the $0-\pi$ transition beyond the usual equilibrium treatment.

[1] M. Governale, M.G. Pala, J. König, Phys. Rev. B 77, 134513 (2008)
[2] B. Hiltscher, M. Governale, J. König, Physical Review B 86, 235427 (2012)
[3] J. Siegl, J. Picó-Cortés, M. Grifoni, arXiv:2205.13936 (2022)

TT 26.12 Thu 12:30 H10

**Interplay of Cooper pair and quasiparticle tunneling in the dynamics of an Anderson pseudospin** — •Christoph Rohrmeier, Jordi Picó-Cortés, Andrea Donarini, and Milena Grifoni — Institute of Theoretical Physics, University of Regensburg, Germany

In an interacting quantum dot coupled to superconducting reservoirs, the state of the system can be described in terms of a pseudospin [1] where "up" represents a fully occupied and "down" means an empty dot [2]. We investigate the dynamics of this Anderson pseudospin with the help of a generalized master equation based on a particle-conserving approach to superconductivity [3]. Superconducting correlations involved in Cooper pair and quasiparticle tunneling manifest in the pseudospin dynamics. The pseudospin precession is governed by an effective magnetic field [4] of which we give an analytical expression including finite gap, bias as well as interaction.

[1] P. Anderson, Phys. Rev. 112, 1900 (1958)
[2] M. Governale, M. Pala, Jürgen König, Phys. Rev. B 77, 134513 (2008)
[3] J. Siegl, J. Picó-Cortés, M. Grifoni, arXiv:2205.13936 (2022)
[4] C. Rohrmeier and A. Donarini, Phys. Rev. B 105, 205418 (2022)

TT 26.13 Thu 12:45 H10

**Evolution of Andreev bands in half-filled superconducting periodic Anderson model** — •Vladislav Pokorny[1] and Panch Ram[2] — [1]Institute of Physics, Czech Academy of Sciences, Na Slovance 2, CZ-18221 Praha 8, Czech Republic — [2]Faculty of Mathematics and Physics, Charles University, Ke Karlovu 5, CZ-12116 Praha 2, Czech Republic

Two-dimensional systems where the surface of a superconductor is coated with a molecular layer draw recently a lot of attention as they represent ideal setups for studying the competition between magnetism and superconductivity. The physics of such system can be studied using the superconducting periodic Anderson model which describes a conduction band with superconducting pairing hybridized with a nondispersive band of correlated electrons. We use the dynamical mean-field theory to solve this problem by mapping the lattice model to the superconducting impurity Anderson model with a self-consistent bath. This method neglects spatial correlations between lattice sites while local quantum fluctuations are fully taken into account. We show the behavior of the in-gap Andreev bands and how the singlet-doublet (zero-pi) quantum phase transition in the impurity model is reflected in the induced pairing in the correlated band.