TT 20: Superconductivity: Tunnelling and Josephson Junctions

Time: Tuesday 9:30–13:00 Location: HSZ 103

TT 20.1 Tue 9:30 HSZ 103

Calorimetry of a phase slip in a Josephson junction — Efe Gümüş[1], Danial Majidi[1], Danilo Nikolic[2], Patrick Raif[2], Bayan Karimi[3], Joonas Peltonen[3], Elke Scheer[2], Jukka Pekola[3], Hervé Courtois[1], Wolfgang Belzig[2], and •Clemens Winkelmann[1] — [1]Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France — [2]Fachbereich Physik, Universität Konstanz, Konstanz, Germany — [3]Centre of Excellence, Department of Applied Physics, Aalto University School of Science, Aalto, Finland

Josephson junctions are a central element in superconducting quantum technology; in these devices, irreversibility arises from abrupt slips of the quantum phase difference across the junction. This phase slip is often visualized as the tunnelling of a flux quantum in the transverse direction to the superconducting weak link, which produces dissipation. Here we detect the instantaneous heat release caused by a phase slip in a Josephson junction, signalled by an abrupt increase in the local electronic temperature in the weak link and subsequent relaxation back to equilibrium. Beyond the advance in experimental quantum thermodynamics of observing heat in an elementary quantum process, our approach could allow experimentally investigating the ubiquity of dissipation in quantum devices, particularly in superconducting quantum sensors and qubits.

TT 20.2 Tue 9:45 HSZ 103

Measurement of two coupled Bloch oscillators based on $Al/AlO_x/Al$-Josephson junctions — •Fabian Kaap and Sergey Lotkhov — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Deutschland Braunschweig

We investigate a system of two coupled Bloch oscillators based on $\sim 50 \times 50\,\mathrm{nm}^2$ Josephson junctions, where one oscillator is a flux tunable SQUID and one is a single junction, respectively. To suppress the quantum oscillations of charge and enable the occurrence of coherent Bloch oscillations, the leads include high ohmic microstrips made from oxidized titanium. Between the resistors and junctions, we design the connection via a capacitively coupled pair of high-kinetic-inductance meanders of granular aluminum. When only the single junction is actively driven by an external bias current I_{B1} the Coulomb blockade of this junction can be tuned by the flux through the passive, non-driven SQUID. If additionally a current I_{B2} is applied through the SQUID we observe synchronisation effects in the IV-curves of both Bloch oscillators when the currents coincide, $I_{\mathrm{B1}} \approx I_{\mathrm{B2}}$. We address experimental issues, such as electron overheating in the leads, the presence of higher harmonics at low bias currents and the onset of Zener tunneling.

TT 20.3 Tue 10:00 HSZ 103

Phase-dependent transport in thermally driven superconducting single-electron transistors — Alexander G. Bauer and •Björn Sothmann — Theoretische Physik, Universität Duisburg-Essen and CENIDE, D-47048 Duisburg, Germany

We investigate thermally driven transport of heat and charge in a superconducting single-electron transistor by means of a real-time diagrammatic transport theory. Our theoretical approach allows us to account for strong Coulomb interactions and arbitrary nonequilibrium conditions while performing a systematic expansion in the tunnel coupling. We find that a temperature bias across the system gives rise to finite heat and charge currents close to the particle-hole symmetric point which depend both on the gate voltage as well as on the phase difference between the superconducting reservoirs. The finite thermoelectric effect arises due to level renormalization from virtual tunneling processes. Furthermore, we find that the phase bias can give rise to finite charge currents even in the presence of an inversion-symmetric temperature bias.

TT 20.4 Tue 10:15 HSZ 103

Josephson nanojunctions fabricated by He focused ion beam irradiation — •Edward Goldobin[1], Max Karrer[1], Christoph Schmid[1], Katja Wurster[1], Ramón Manzorro[2,3], Javier Pablo-Navarro[2,3], Cesar Magen[2,3], Reinhold Kleiner[1], and Dieter Koelle[1] — [1]Physikalisches Institut, Center for Quantum Science (CQ) and LISA$^+$, Universität Tübingen, Germany — [2]Instituto de Nanociencia y Materiales de Aragón (INMA), CSIC-Universidad de Zaragoza, Spain — [3]Laboratorio de Microscopías Avanzadas (LMA), Universidad de Zaragoza, Spain

We use a focused He ion beam (He-FIB) for the nanofabrication of Josephson junctions (JJs) and more complex devices based on $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films [1]. Using an optimum He-FIB irradiation dose, we "write" Josephson barriers across YBCO microbridges. Such JJs have RCSJ-like I–V characteristics, and the dependence of the critical current vs. magnetic field resembles a Fraunhofer pattern. Using higher irradiation doses, we induce insulating regions that can be used for nanopatterning of various circuits, i.e., patterning of SQUID loops, constriction JJs (cJJs), etc.

Investigations of the irradiated regions by scanning transmission electron microscopy (STEM) provide information on the modification of the crystalline structure of YBCO on the atomic scale. STEM analysis reveals the amorphization thresholds for irradiation of 1D and 2D patterns (depending on the beam size), and provides insights into the current resolution limits for the fabricaton of YBCO cJJs.

[1] B. Müller et al., Phys. Rev. Applied **11**, 044082 (2019)

TT 20.5 Tue 10:30 HSZ 103

Theory of scanned Josephson tunneling spectroscopy in cuprates — •Peayush Choubey[1] and Peter Hirschfeld[2] — [1]Department of Physics, Indian Institute of Technology Roorkee, Roorkee 247667, India — [2]Department of Physics, University of Florida, Gainesville, Florida 32611, USA

The scanned Josephson tunneling spectroscopy (SJTS) is a direct local probe of superconducting gap order parameter. To the best of our knowledge, SJTS studies have been limited to the cases where superconducting sample and superconducting tip, both, have the same gap symmetry- either s-wave or d-wave. One might assume that in an s-to-d SJTS study of cuprates the critical current would vanish everywhere, as naively expected for planar junctions. We show here that this is not the case. Employing first-principles Wannier functions for $Bi_2Sr_2CaCu_2O_8$, we develop a scheme to compute Josephson critical current and quasiparticle tunneling current measured by SJTS with sub-angstrom resolution. We demonstrate that the critical current due to tunneling between an s-wave tip and a superconducting cuprate sample has largest magnitude above O sites and it vanishes above Cu sites as a direct consequence of the d-wave gap symmetry in cuprates. Moreover, we predict various signatures of pair density waves in underdoped cuprates that can be tested in future SJTS studies.

TT 20.6 Tue 10:45 HSZ 103

Critical temperature of superconductor-ferromagnetic bilayers with helimagnetic metals — •Danilo Nikolic, Subrata Chakraborty, Alfredo Spuri, Elke Scheer, Angelo Di Bernardo, and Wolfgang Belzig — Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany

Motivated by recent experiments on the proximity effect in superconductor-ferromagnet structures with the helimagnetic ordering of magnetization in the latter, we present a systematic theoretical study of the critical temperature of such systems. By employing the quasiclassical Usadel approach [1], we account for two different configurations of magnetization in the ferromagnet and investigate their impact on the critical temperature (T_c) of the superconductor. Besides recovering the known results for the case of uniform magnetization [2], we find a nontrivial behavior of T_c in the case of spiral magnetization. Our theory suggests that this can be attributed to the emergence of long-range spin-triplet correlations generated in the ferromagnet [3]. Finally, our model predicts that the presence of spiral magnetization can reduce the critical temperature in the experimentally relevant range of parameters. This effect is the subject of ongoing experiments.

[1] A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005)
[2] Z. Radović *et al.*, Phys. Rev. B **44**, 759 (1991);
Ya. V. Fominov *et al.*, Phys. Rev B **66**, 014507 (2002)
[3] A. F. Volkov *et al.*, Phys. Rev. B **73**, 104412 (2006)

TT 20.7 Tue 11:00 HSZ 103

Equal-spin Cooper pair injection in superconducting spintronics devices — •Matthias Eschrig[1] and Xavier Montiel[2] — [1]Institute of Physics, University of Greifswald, Germany — [2]Department of Materials Science & Metallurgy, University of Cam-

bridge, UK

In a number of recent experiments unusual behavior was observed in ferromagnet/ferromagnet/superconductor devices when a precession of the magnetization was induced by ferromagnetic resonance. By using a non-equilibrium Usadel Green function formalism, we solve for spin-resolved distribution functions and demonstrate that the spin injection process in superconductors is governed by the inverse proximity effect in the superconducting layer. We find that equal-spin Cooper pairs, which are produced by the two misaligned ferromagnetic layers, transport spin inside the S layer. This then results in an increase of the injected spin current below the superconducting critical temperature. Our calculations provide the first evidence of the essential role of equal-spin Cooper pairs on spin-transport properties of S/F devices and pave new avenues for the design of superconducting spintronics devices.

15 min. break

TT 20.8 Tue 11:30 HSZ 103

Vortex phase transitions in frustrated two-dimensional semiconductor-superconductor Josephson junction arrays — •Simon Reinhardt[1], Christian Baumgartner[1], Sergei Gronin[2], Geoffrey C. Gardner[2], Tyler Lindemann[2], Michael J. Manfra[2], Tatyana I. Baturina[1], Nicola Paradiso[1], and Christoph Strunk[1] — [1]Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany — [2]Purdue University, West Lafayette, Indiana 47907, USA

We study two-dimensional Josephson junction arrays in hybrid aluminum/InGaAs/InAs semiconductor-superconductor heterostructures. Using a cold resonator technique, we measure both the inductive response as well as the DC transport properties of the array. A perpendicular magnetic field induces highly ordered vortex configurations for integer and fractional values of the frustration parameter. In the vicinity of the matching fields we observe pronounced dip-to-peak transitions of the differential resistance as a function of current bias, which have previously been interpreted as signatures of a non-equilibrium vortex Mott transition [1]. The scaling behaviour of the differential conductance in our array of ballistic SNS junctions is compared with previous results on diffusive Josephson junction arrays.

[1] N. Poccia et al., Science **349**, 1202 (2015)

TT 20.9 Tue 11:45 HSZ 103

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 — [2]Institut für Theoretische Physik and Center for Quantum Science, Universität Tübingen — [3]Fachbereich Physik, Universität Konstanz — [4]INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento

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 *et al.*, PRB 106, 045408 (2022)

TT 20.10 Tue 12:00 HSZ 103

Complete magnetic control over the superconducting thermoelectric effect — •Jabir Ali Ouassou[1], César González-Ruano[2], Diego Caso[2], Farkhad G. Aliev[2], and Jacob Linder[1] — [1]Center for Quantum Spintronics, Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway — [2]Departamento Física de la Materia Condensada C-III, INC and IFIMAC, Universidad Autónoma de Madrid, Madrid 28049, Spain

Giant thermoelectric effects are known to arise at the interface between a superconductor and strongly polarized ferromagnet, and this enables the construction of efficient thermoelectric generators. We predict that the thermopower of such generators can be completely controlled by a magnetic input signal: not only can the thermopower be toggled on and off by rotating a magnet, but even the sign of the thermopower can be reversed. This *in situ* control diverges from conventional thermoelectrics, where the thermopower is usually fixed by the device design.

TT 20.11 Tue 12:15 HSZ 103

Quantum phases in a frustrated sawtooth chain of Josephson junctions — •Benedikt J.P. Pernack, Mikhail V. Fistul, and Ilya M. Eremin — Ruhr-Universität Bochum, Bochum Germany

We present a theoretical study of quantum phases occurring in a frustrated sawtooth chain of small Josephson junctions. In the model the frustration f arises due to the Josephson couplings having alternating signs (0 and π Josephson junctions) in a single lattice cell. At the critical value of $f = 3/4$ such a system displays a phase transition from the ordered state into the frustrated one with a highly degenerate ground state characterized by penetration of topological (anti)vortices [1]. Introducing additional capacitances to the ground, we derive an effective Ising quantum spins model with a long-range interaction between well separated vortices/antivortices, and obtain various collective quantum phases and quantum phase transitions between them.

[1] A. Andreanov and M. V. Fistul, J. Phys. A: Math. Theor. 52, 105101 (2019)

TT 20.12 Tue 12:30 HSZ 103

Low-energy model for superconducting quantum dot systems — •Vladislav Pokorný[1] and Martin Žonda[2] — [1]FZU - Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 182 21 Prague, Czech Republic — [2]Faculty of Mathematics and Physics, Charles University, Ke Karlovu 5, 121 16 Prague, Czech Republic

We present a method to extract the Andreev bound state energies of a single-level quantum dot connected to superconducting leads from the imaginary-time results of quantum Monte-Carlo method without the use of analytic continuation techniques like maximum entropy method. We describe the system using the superconducting impurity Anderson model and show that for low energies it maps on an atomic-like model. The parameters of this model can be extracted from the self-energy calculated in imaginary-frequency domain using the hybridization-expansion quantum Monte Carlo method. We compare the results to zero-temperature numerical renormalization group data to show the limits of usability of the low-energy model.

TT 20.13 Tue 12:45 HSZ 103

Tracking current path in multi-terminal graphene Josephson junctions — •Devang Parmar — Institute for Quantum Materials and Technologies (IQMT), Karlsruhe institute of Technology, 76021 Karlsruhe, Germany.

Multiterminal Josephson junctions have been predicted to be platforms to observe various exotic phenomena such as new topological phases of matter [1], correlated states [2-5] or the so-called Andreev molecules [6,7]. In order to control the electronic properties of these complex devices, it is important to comprehend and track the supercurrent flow with respect to their geometries and superconducting lead peculiarities.

Here, we investigated the supercurrent in multi-terminal superconductor-graphene-superconductor (SGS) junctions. Together with magnetic interferometry experiments in these multiterminal graphene devices, we clearly observe that the contact transparencies can be very different from one lead to the other which mainly drives the entire transport properties in SGS. Our work provides insights of the supercurrent flow in multiterminal Josephson junctions and paves the way for further investigations in more complex multiterminal devices.

[1] R. P. Riwar et al., Nat Commun 7, 11167 (2016)
[2] A. Freyn et al., Phys. Rev. Lett. 106, 257005 (2011)
[3] A. H. Pfeffer et al., Phys. Rev. B 90, 075401 (2014)
[4] R. Mélin et al., Phys. Rev. B 100, 035450 (2019)
[5] K.-F. Huang et al., arXiv preprint arXiv:2008.03419 (2020)
[6] Z. Su et al., Nat. Commun. 8, 585 (2017)
[7] J.-D. Pillet et al., Nano Lett. 19, 7138 (2019)