TT 6: Superconductivity: Tunnelling and Josephson Junctions I

Time: Monday 9:30–13:00 Location: H 3010

TT 6.1 Mon 9:30 H 3010

Tailoring arbitrary energy-phase relationships using Josephson tunnel junctions — •A. Mert Bozkurt[1,2], Jasper Brookman[1], Valla Fatemi[3], and Anton Akhmerov[1] — [1]Kavli Institute of Nanoscience, Delft University of Technology, P.O. Box 4056, 2600 GA Delft, The Netherlands — [2]QuTech, Delft University of Technology, 2600 GA Delft, The Netherlands — [3]School of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853 USA

Josephson tunnel junctions exhibit a simple current-phase relation, characterized by single harmonics. Conversely, high-transparency Josephson junctions feature multiple harmonics, with the specific harmonics depend on microscopic details of the junction, presenting a challenge for precise control. We find that when two Josephson tunnel junctions are connected in series, their energy-phase relationship is identical to a high-transparency Josephson junction. By connecting multiple arms in parallel and introducing a magnetic flux, we can systematically engineer specific current-phase relationships. As an example, we present a superconducting diode implementation with a high efficiency, a two-terminal device that controls supercurrent flow in one direction differently from the other. The resulting superconducting diode efficiency is robust against the imperfections in the design parameters, making it practical for real-world implementations. Beyond superconducting diodes, we showcase various other energy-phase relationships to demonstrate the versatility of the approach. This technique can be useful for engineering sophisticated energy-phase landscapes for advanced quantum computing systems.

TT 6.2 Mon 9:45 H 3010

Shaping quantized current steps in Josephson junctions using tailored drives — •Fabian Kaap, Christoph Kissling, Victor Gaydamachenko, Asen Georgiev, Lukas Grünhaupt, and Sergey Lotkhov — Physikalisch-Technische Bundesanstalt, Bundesallee 100 38116, Deutschland Braunschweig

Recent experiments have confirmed predictions made nearly four decades ago about the existence of quantized current steps in Josephson junctions and superconducting nanowires - referred to as dual Shapiro steps. These steps, separated by $2ef$, with e the elementary charge and f the frequency, hold potential for a novel current standard. To realize dual Shapiro steps, we embed a $Al/AlO_x/Al$ dc-SQUID in a high-impedance environment made from granular aluminium and oxidized titanium. Demonstration of quantized current steps in the IV-curves is achieved with an external sinusoidal driving signal of frequencies up to 6 GHz, resulting in steps up to $I = n \times 2ef \approx n \times 2\,\mathrm{nA}$. Using a sawtooth shaped driving signal instead, enhances the first dual Shapiro step at positive or negative currents while suppressing the opposite value step, contingent on the slope of the sawtooth signal. We compare the flatness of the enhanced current steps, as compared to the steps generated using the sinusoidal drive, by the peak values of the differential resistance $R_{\mathrm{diff}} = \frac{dU}{dI}$ and find an improvement by a factor of ~ 2.

TT 6.3 Mon 10:00 H 3010

Magnetochiral vortex rachet effect in two-dimensional semiconductor-superconductor Josephson junction arrays — •Simon Reinhardt[1], Johanna Berger[1], Sergei Gronin[2], Geoffrey C. Gardner[2], Tyler Lindemann[2], Michael J. Manfra[2], 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. An out-of-plane magnetic field induces vortices, which form ordered patterns for commensurate values of the frustration parameter. We probe the symmetry of the intrinsic vortex pinning potential using critical current measurements. When applying in-plane magnetic fields we observe non-reciprocal vortex depinning currents, revealing a ratchet-like vortex pinning potential. We discuss how this novel effect can be linked to the anomalous Josephson effect, caused by the combination of Rashba spin-orbit coupling and Zeeman field [1,2,3].

[1] W. Mayer *et al.*, Nat. Commun. **11** (2020) 212
[2] C. Baumgartner *et al.*, Nat. Nanotechnol. **17** (2021) 39
[3] S. Reinhardt *et al.*, arXiv:2308.01061 (2023)

TT 6.4 Mon 10:15 H 3010

Experimental and simulated realization of magnetization-controlled critical current in a ferromagnetically constricted Josephson junction — •Lukas Kammermeier and Elke Scheer — Universität Konstanz

We present an experimental realization of a magnetization (M) controlled Josephson junction in a superconductor-ferromagnet S-S'-S (S'=S/F) hybrid structure, which allows for a post-manufacturing manipulation of the critical current I_c. We observe multiple and non-monotonic discrete jumps of $I_c(M)$ up to full supression depending on the magnetic history. In addition we reproduce the observed effects in micromagnetic simulations with MuMax3 [1] and a simple model of stray-field-mediated suppression of I_c. Resulting in a semi quantitaive microscopic explanation for the jumps in the $I_c(M)$ measurements.

[1] A. Vansteenkiste, AIP Advances 4 (2014) 107133

TT 6.5 Mon 10:30 H 3010

Equal-spin Cooper pairs across S/M interfaces with strongly polarized magnets — •Danilo Nikolic and Matthias Eschrig — Institut für Physik, Universität Greifswald, Felix-Hausdorff-Str. 6, 17489 Greifswald, Germany

Motivated by recent experiments on the proximity effect in the superconductor (S) - helimagnet (M) systems [1], we present a systematic theoretical study of such an effect in SM systems with strongly polarized M featuring different textures of magnetization. The theory is done in the framework of the quasiclassical Usadel Green's formalism. However, due to the large splitting between the spin bands, the standard Usadel approach [2] cannot be applied directly but a somewhat modified description is required [3]. Applying this approach, we account for equal-spin triplet correlations and investigate their influence on observables, e.g., the critical temperature of S. Moreover, due to the strong spin polarization of M, Josephson junctions involving it represent a promising platform for studying the novel superconducting diode effect. This effect can be explained through the coupling between the superconducting phase and the gauge field induced by the inhomogeneous magnetization in M [4].

[1] A. Spuri *et al.*, arXiv:2305.02216 (2023)
[2] A. I. Buzdin, Rev. Mod. Phys. **77** (2005) 935
[3] R. Grein *et al.*, Phys. Rev. Lett. **102** (2009) 227005
[4] A. B. Vorontsov *et al.*, Phys. Rev. Lett. **101** (2008) 127003; I. V. Bobkova *et al.*, Phys. Rev. B **96** (2017) 094506

TT 6.6 Mon 10:45 H 3010

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

In this talk, we study a Josephson junction formed between two magnetic impurities. Such a junction was recently realized using a scanning tunneling microscope tip functionalized with a magnetic impurity that probes a second impurity on the sample [1]. We suggest that the Josephson effect can determine and also influence the relative magnetic orientation of the impurities due to a Josephson-induced exchange interaction that arises, similarly to Josephson junctions with two magnetic layers [2].

Our theoretical approach treats the Josephson and spin dynamics equally. We identify a key experimental signature of spin dynamics: a small d.c. bias results in excess d.c. current due to the coupling between spins and the Josephson phase. We also discuss spin control, exemplified by inducing a spin-flip of an impurity using an adiabatic voltage pulse, and provide a protocol for calculating the appropriate temporal area of the pulse.

[1] H. Huang *et al.*, Phys. Rev. Research **3** (2021) L032008
[2] X. Waintal *et al.*, Phys. Rev. B **65** (2002) 054407

TT 6.7 Mon 11:00 H 3010

Spectral and transport properties of spin-filter Josephson junctions — •Niklas L. Schulz, Anna-Izabella Levbarg, Danilo Nikolic, and Matthias Eschrig — Institut für Physik, Universität Greifswald, D-17489 Greifswald, Germany

Recent experiments [1] showed that the supercurrent in spin-filter Josephson junctions [2], which incorporate a ferromagnetic insulating barrier (FI), strongly varies with the barrier's width and results in a temperature-induced incomplete $0-\pi$ transition. Motivated by this, we provide a full theoretical study of an S-FI-S junction within the quasi-classical Usadel theory [3] and investigate spectral and transport properties. We model the FI interface using a scattering matrix approach that effectively enters the quasi-classical theory as boundary conditions allowing to account for various effects arising from the interface [4]. We found temperature-induced $0-\pi$ transitions in S-FI-S junctions which depend on the barrier width. Moreover, self-consistent calculations show incomplete $0-\pi$ transitions. Finally, such systems represent an intermediate step towards S-FI-F-FI-S junctions, which are expected to exhibit the superconducting diode effect [5] and are subject of ongoing research.

[1] R. Caruso *et al*, Phys. Rev. Lett. **122**, 047002 (2019)
[2] K. Senapati *et al*, Nat. Mater. **10**, 849-852 (2011)
[3] K. D. Usadel, Phys. Rev. Lett. **25**, 507 (1970)
[4] M. Eschrig *et al*, New J. Phys. **17**, 083037 (2015)
[5] R. Grein *et al*, Phys. Rev. Lett. **102**, 227005 (2009)

15 min. break

Invited Talk TT 6.8 Mon 11:30 H 3010

Theory of supercurrent diode effect and other spin-orbit-driven phenomena in superconducting magnetic junctions — •Andreas Costa — University of Regensburg, Germany

Their extraordinary physical properties to tailor spin-polarized triplet supercurrents—exploiting, e.g., spin-orbit coupling (SOC)—make superconducting magnetic junctions a promising platform to implement quantum-computing concepts or explore topological effects.

The first part of this talk will give a more general overview of such junctions' SOC-driven transport anomalies, covering giant transport magnetoanisotropies that result from the triplet-current-inducing unconventional (spin-flip) Andreev-reflection process [1,2] and sizable transverse Hall supercurrents that originate from SOC-induced skew scattering of charge carriers [3].

In the second part of the talk, we will focus on our theoretical model developed to understand the supercurrent diode effect (SDE) in Al/InAs-based Josephson-junction arrays [4–6]. The competition between SOC and an appropriately aligned magnetic field imprints a strong polarity dependence on the critical Josephson currents with characteristic features, such as 0–π-like transitions and a possible reversal of the SDE, that we could further characterize with our model.

This work has been supported by DFG Grants 454646522 and 314695032 (SFB 1277), and by ENB IDK Topological Insulators.

1] Phys. Rev. Lett. **115** (2015) 116601
[2] Phys. Rev. B **95** (2017) 024514
[3] Phys. Rev. B **100** (2020) 060507(R)
[4] Nat. Nanotechnol. **17**(2022)39
[5] Nat. Nanotechnol. **18** (2023) 1266
[6] Phys. Rev. B **108** (2023) 054522

TT 6.9 Mon 12:00 H 3010

A diode effect in an Ising-superconductor Josephson junction — •Sourabh Patil[1], Gaomin Tang[2,3], and Wolfgang Belzig[1] — [1]Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany — [2]Graduate School of China Academy of Engineering Physics, 100193 Beijing, China — [3]Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

Two Ising superconductors proximitized by ferromagnetic layers can be used to build a Josephson junction. This setup allows for tunable spin-triplet pairing correlations, letting us control charge and spin supercurrents through the in-plane magnetic exchange fields [1]. Recently, there has been significant interest in the study of the superconducting diode effect. A Josephson diode allows a greater dissipationless supercurrent to flow in one direction compared to the other [2].

Here, we study a new kind of Josephson diode that uses supercurrent interference. It is created through a Josephson junction, incorporating a small non-magnetic barrier with perfect transmission combined with a fully polarized ferromagnetic barrier in the tunneling limit. The superposition of the current-phase relations from these two barriers results in the diode effect in the junction. This unique design attains diode efficiencies of up to 20

[1] G. Tang et al., Phys. Rev. B 104 (2021) L241413
[2] R. Souto et al., Phys. Rev. Lett. 129 (2022) 267702

TT 6.10 Mon 12:15 H 3010

Performance study of gate-controlled superconducting currents in Nb devices — •Leon Ruf, Jennifer Koch, Elke Scheer, and Angelo Di Bernardo — University of Konstanz, Universitätsstraße 10, 78457 Konstanz, Germany

Gate controlled superconductivity (GCS) has recently attracted great attention. It was reported [1] that the superconducting state can be suppressed in gated nanoconstrictions by a gate voltage. The authors attribute their observation to an electric field induced perturbation of the superconducting state, giving the next milestone for future superconducting and CMOS compatible transistors. However, the mechanism for the GCS effect is strongly under debate. Other works report about different mechanism caused by a leakage current: high-energy quasiparticle injection [2], low-energy mediated phonon excitation [3] or hot-spot generation [4]. Here we are studying the performance of Nb Dayem bridges made by electron beam lithography and lift off. Our observations show the GCS effect also for relatively large bridges increasing the critical current. We observe a linear anticorrelation between the critical current and the amplitude of the gate leakage current. We discuss our findings in the light of the suggested mechanism [1-4].

[1] G. De Simoni et al., Nat. Nanotechnol. 13 (2018) 802
[2] L.D. Alegria et al., Nat. Nanotechnol. 16 (2021) 404
[3] M.F. Ritter et al. Nat. Electron. 5 (2022) 71
[4] J. Basset, et al. Phys. Rev. Research 3 (2021) 043169

TT 6.11 Mon 12:30 H 3010

Non-Hermitian phase-biased Josephson junctions — •Jorge Cayao[1] and Masatoshi Sato[2] — [1]Department of Physics and Astronomy, Uppsala University, Box 516, S-751 20 Uppsala, Sweden — [2]Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

We study non-Hermitian Josephson junctions formed by conventional superconductors with a finite phase difference under non-Hermiticity naturally appearing due to coupling to normal reservoirs. Depending on the structure of non-Hermiticity, the low-energy spectrum hosts topologically stable exceptional points either at zero or finite real energies as a function of the superconducting phase difference. Interestingly, we find that the corresponding phase-biased supercurrents acquire divergent profiles at such exceptional points, an instance that turns out to be a natural and unique non-Hermitian effect signalling a possible way to enhance the sensitivity of Josephson junctions.

TT 6.12 Mon 12:45 H 3010

Quantum size effects on Andreev transport in Josephson junctions — Gábor Csire[1], •Balázs Ujfalussy[2], and Nóra Kucska[2] — [1]Materials Center Leoben Forschung GmbH, Roseggerstraße 12, 8700 Leoben, Austria — [2]HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

Measurements of the critical current density, superconducting coherence length, and superconducting transition temperature in single-domain, epitaxially-grown Nb(110)/Au(111)/Nb(110) junctions show an oscillatory behavior as a function of the thickness of the Au layers. We apply the first principles-based microscopic theory of inhomogeneous relativistic superconductivity to understand both the fundamentals and the specifics of the underlying physical mechanism of this behavior. We study the effects of spin-orbit coupling, and the effect of confinement and show that they induce a complex structure of Andreev states in the superconducting state which in turn modifies the quasi-particle spectrum and the Josephson supercurrent. Our study reveals the coexistence of two superconducting phases in the gold layers, the usual intraband s-wave phase and an additional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase stemming from interband pairing (without magnetic field). The results indicate the rich interplay between quantum size and proximity effects which suggests the possibility of modifying superconducting transport properties by exploiting thickness-dependent quantum size effects.