TT 25: Superconductivity: Supercurrent Diode Effect

Time: Wednesday 9:30–12:30 Location: H32

TT 25.1 Wed 9:30 H32

Gate Tunable Anomalous Josephson and Supercurrent Diode Effect — •Johanna Berger[1], Simon Reinhardt[1], Christian Baumgartner[1], Lorenz Fuchs[1], Tim Ascherl[1], Andreas Costa[2], Sergei Gronin[3], Geoff Gardner[3], Tyler Lindemann[3], Michael Manfra[3], Jaroslav Fabian[2], Denis Kochan[2,4], Christoph Strunk[1], and Nicola Paradiso[1] — [1]Institut für Experimentelle und Angewandte Physik, University of Regensburg, 93040 Regensburg, Germany — [2]Institut für Theoretische Physik, University of Regensburg, 93040 Regensburg, Germany — [3]Purdue University, West Lafayette, Indiana 47907 USA — [4]Institute of Physics, Slovak Academy of Sciences, 84511 Bratislava, Slovakia

The discovery of the supercurrent diode effect by Ando et al. [1] and its observation in a rich variety of systems caused an increasing interest in the physics of non-reciprocal superconductivity.
Here, we study Josephson junctions in hybrid Al/InGaAs/InAs structures, which harbor strong Rashba spin-orbit interaction. In combination with a Zeeman field, this gives rise to an anomalous phase shift φ_0 in the current-phase relation (CPR). The presence of high harmonics in the CPR gives rise, in addition, to the supercurrent diode effect [2,3,4]. Using an asymmetric superconducting quantum interferometer we simultaneously measure the φ_0-shift and supercurrent diode effect on a single junction [5]. By electrostatic gating of the junction, we reveal the link between the φ_0-shift and supercurrent diode effect.

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Unconventional Josephson Supercurrent Diode Effect Induced by Chiral Spin-Orbit Coupling — •Andreas Costa[1], Osamu Kanehira[2], Hiroaki Matsueda[2], and Jaroslav Fabian[1] — [1]University of Regensburg, Germany — [2]Tohoku University, Japan

First-principles calculations have recently predicted that chiral materials lacking mirror symmetries—such as twisted van-der-Waals homobilayers—can feature unconventional radial Rashba coupling with spins aligned fully parallel (instead of tangentially) to momentum.

In this talk, we will address Josephson transport through vertical superconductor/ferromagnet/superconductor junctions hosting crossed (radial and tangential) Rashba fields at the interfaces and demonstrate that their interplay with ferromagnetic exchange can lead to supercurrent rectification even when the magnetization is collinear with the current. This so-called unconventional supercurrent diode effect (SDE) originates from spin precessions inside the ferromagnet, which imprint polarity-dependent transmission probabilities on the Cooper pairs being well-distinct from the conventional SDE, and provides a sensitive probe of chiral spin textures.

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TT 25.3 Wed 10:00 H32

Tunable Field-Free Unidirectional Diode Effect in Single-Crystal Superconducting Device — •Tobias Faeth[1], Damien Berube[2], Killian Rigaux[2], Yuqiang Fang[3], Anyuan Gao[2], Thao Dinh[2], Yufei Liu[2], Jianxiang Qiu[2], Houchen Li[2], Charles Reichhardt[4], Cynthia Reichhardt[4], Fuqiang Huang[3], and Suyang Xu[2] — [1]Max Plack Instiute for Microstructure Physics, Halle (Saale), Germany — [2]Harvard University, Cambridge, USA — [3]Bejing University, Beijing, China — [4]Los Alamos National Laboratory, Los Alamos, USA

Superconducting diodes could become critical components of multiple technologies, from energy-efficient superconducting computing to large scale effective quantum computing, memories and switches. In this talk, we report a device made out of a 2D superconductor, that exhibits field-free, tunable, and perfectly rectifying diode effect. Starting from finite field differential conductance experiments, we demonstrate diode efficiencies up to 30% at 100mT. Measuring nonlinear resistances, we characterize magnetochiral anisotropy (MCA) and calculate a MCA coefficient of $\gamma = 6.0 \times 10^8$ $\mathrm{T^{-1}A^{-1}}$, the highest ever reported. Setting the field back to 0, we investigate a novel geometry, while carrying out differential conductance measurements. In the new geometry, we find $I_c^+ = 0$ while $I_c^- = 2\mu A$, a 100% diode efficiency. We hypothesize this effect is attributed to uneven vortex flow under opposite biases. We substantiate this model with computations that confirm increased diode efficiency under the novel geometry.

TT 25.4 Wed 10:15 H32

Tunable Diode effect in a Superconducting Tunnel Junction with Biharmonic Drive — •David Scheer[1], Rubén Seoane Souto[2], Fabian Hassler[1], and Jeroen Danon[3] — [1]Institute for Quantum Information, RWTH Aachen University, 52056 Aachen, Germany — [2]Instituto de Ciencia de Materiales de Madrid, Consejo Superiorde Investigaciones Científicas (ICMM-CSIC), 28049, Madrid, Spain — [3]Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

A Josephson diode is a superconducting circuit element that enables non-reciprocal transport, allowing a dissipationless supercurrent to preferentially flow in a single direction. Existing methods for achieving the required symmetry breaking mostly rely on specifically-designed materials or carefully-engineered circuits composed of multiple Josephson junctions. In this talk, we demonstrate that applying a biharmonic drive to a conventional superconducting tunnel-junction induces a diode effect through harmonic mixing processes that shift the supercurrent region. We show that, in a conventional tunnel junction, unit efficiency is achievable while maintaining a large supercurrent. Moreover, the relative phase between the two driving tones determines the directionality of the diode, which can be tuned in situ.

TT 25.5 Wed 10:30 H32

Spin-Resolved Josephson Diode Effect in Strongly Polarized SFS Junctions — •Danilo Nikolić, Niklas L. Schulz, and Matthias Eschrig — Institut für Physik, Universität Greifswald, Felix-Hausdorff-Strasse 6, 17489 Greifswald, Germany

We present a systematic study of equal-spin Cooper pair formation at the interface between a superconductor (S) and a helical ferromagnet (F) [1]. The theory is done in the framework of the quasiclassical Green's function formalism [2-4]. However, assuming the large splitting between the spin bands in F, the standard quasiclassical approach cannot be applied directly and requires a modified description [5-8]. Applying this approach, we account for the long-ranged (equal-spin) Josephson current-phase relation (CPR) in an SFS weak link considering a helimagnetic state in F. Remarkably, the CPR takes a nontrivial form leading to both the anomalous and Josephson diode effects. These effects have clear physical interpretations based on the coupling between the superconducting phase and the adiabatic spin gauge field (geometric phase) induced by inhomogeneous magnetization of F.

[1] A. Spuri *et al.*, Phys. Rev. Res. **6**, L012046 (2024).
[2] G. Eilenberger, Z. Phys. **214**, 195 (1968).
[3] A.I.Larkin, Yu.N.Ovchinnikov, Sov. Phys. JETP **28**, 1200 (1969).
[4] A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005).
[5] M. Eschrig, Phys. Rev. B **80**, 134511 (2009).
[6] R. Grein *et al.*, Phys. Rev. Lett. **102**, 227005 (2009).
[7] M. Eschrig, Rep. Prog. Phys. **78**, 104501 (2015).
[8] I. V. Bobkova *et al.*, Phys. Rev. B **96**, 094506 (2017).

TT 25.6 Wed 10:45 H32

Spin and Charge Josephson Diode Effect in Diffusive Superconductor-Ferromagnet Heterostructures — •Niklas L. Schulz, Danilo Nikolić, and Matthias Eschrig — Institut für Physik, Universität Greifswald, Felix-Hausdorff-Strasse 6, 17489 Greifswald, Germany

Long-range equal-spin triplet supercurrents in the presence of a nontrivial spin texture are of fundamental importance for applications of superconducting spintronics [1]. In this work we investigate quantum geometric phases in a Josephson trilayer consisting of a strongly spin-polarized ferromagnet connected to BCS superconductors by ferromagnetic insulating barriers. For non-coplanar spin textures of the device, spin-geometric phases arise, which enter the current-phase relation additionally to the superconducting phase difference [2]. In general, such spin-geometric phases are induced by gauge fields entering the transport equation [3] and in the considered case these are caused by spin-dependent U(1) gauge fields. The resulting current-phase relation in such devices allows for the observation of a Josephson diode effect in the charge current for symmetric systems and a diode effect in the spin current for asymmetric configurations. In certain cases, the device also allows to switch between fully spin-polarized supercurrents across the ferromagnet by reversing the Josephson phase.

[1] M. Eschrig, Rep. Prog. Phys. **78**, 104501 (2015)

[2] R. Grein et al., Phys. Rev. Lett. **102**, 227005 (2009)
[3] I. V. Bobkova et al., Phys. Rev. B **96**, 094506 (2017)

15 min. break

TT 25.7 Wed 11:15 H32

Josephson diode fabricated by a focused He-Ion beam in a $YBa_2Cu_3O_7$ thin film. — •Edward Goldobin, Alireza Jozani, Christoph Schmid, Reinhold Kleiner, and Dieter Koelle — Universität Tübingen, Germany

We report on the fabrication of a Josephson diode with high asymmetry and size $\approx 1\,\mu m^2$. The device is fabricated from $YBa_2Cu_3O_7$ thin films by creating nano-patterns using a focused He-ion beam (He-FIB). He-FIB irradiation of different doses allows us to "write" both Josephson barriers as well as amorphous resistive walls (circuit boundaries) on a sub-micron scale [1]. We have fabricated sub-μm Josephson junctions of in-line geometry that have rather skewed $I_c(H)$ dependences. At the optimal value of the applied magnetic field H, the ratio of positive and negative critical current I_c reaches ≈ 7. Such a high asymmetry is key for achieving good figures of merit, e.g. a wide rectification window, large stopping forces and a high rectification efficiency [2]. The rectification of an ac current into an average dc voltage $\langle V\rangle$ was investigated experimentally by measuring rectification curves $\langle V\rangle(I_{ac})$ at $T = 4.2\,K$. Average dc voltages as high as $212\,\mu V$ were achieved for the optimum value of the driving amplitude I_{ac}. Further, the diode was loaded, which allowed us to measure the input and the output power and, therefore, experimentally demonstrate the efficiency, which reaches 80% in some regimes [3].

[1] B. Müller et al., Phys. Rev. Applied **11**, 044082 (2019).
[2] E. Goldobin et al., Phys. Rev. E **94**, 032203 (2016).
[3] C. Schmid, et al., arXiv: 2408.01521 (2024).

TT 25.8 Wed 11:30 H32

Investigation of Josephson junctions with Weyl-Kondo semimetals — •Ronja Fischer-Süsslin[1], Roman Hartmann[1], Thành Tran[1], Diana Kirschbaum[2], Xinlin Yan[2], Andrey Prokofiev[2], Angelo Di Bernardo[1,3], Silke Paschen[2], and Elke Scheer[1] — [1]FB Physik, Universität Konstanz, Konstanz, Deutschland — [2]Institut für Festkörperphysik, TU Wien, Wien, Österreich — [3]Dipartimento di Fisica, Università di Salerno, Fisciano, Italy

A superconducting diode, i.e., a device with a polarity dependent supercurrent amplitude, would provide new functionalities for superconducting circuits. The superconducting diode effect (SDE) was observed in 2020 [1] in an artificial superlattice with inversion symmetry breaking and is now investigated in both Josephson junctions and junction-free superconductors. We have fabricated and investigated Josephson junctions composed of Nb electrodes and the Ce-based Weyl-Kondo semimetals $Ce_3Bi_4Pd_3$ [2] and $CeRu_4Sn_6$ [3] as weak links. These topologically nontrivial materials are promising candidates to investigate the SDE due to their noncentrosymmetry and strong spin-orbit coupling, which are also responsible for the purely electric-field-driven nonlinear spontaneous Hall response [2,3].

[1] F. Ando et al., Nature **584**, 373-376 (2020).
[2] S. Dzsaber et al., PNAS **118**, e2013386118 (2021).
[3] D.Kirschbaum et al., arXiv:2404.15924 (2023).

TT 25.9 Wed 11:45 H32

Cooper pair diode in Coulomb blockade Pb islands on graphene — •Stefano Trivini[1,3], Jon Ortuzar[1], Katerina Vaxevani[1], F Sebastian Bergeret[3,4], and Jose Ignacio Pascual[1,2] — [1]CICnanogune, Donostia, Spain — [2]Ikerbasque, Basque Foundation for Science, Bilbao, Spain — [3]Centro de Física de Materiales (CFM),San Sebastián, Spain — [4]Donostia International Physics Center (DIPC), Donostia-San Sebastián, Spain

Non-reciprocity, essential for current rectification in electronics, is challenging to achieve in superconducting devices without external magnetic fields. Current methods rely on non-centrosymmetric materials or magnetochiral effects, limiting their versatility. We investigate small Pb islands on graphene where Coulomb and superconducting correlations coexist. Approaching the STM tip to Josephson regimes, we observe Resonant Cooper Pair Tunneling (RCT) peaks in the current-voltage characteristics. RCT values change with gating. We test this in a current-biased STM junction and find a CP current asymmetric with polarity. This is a realization of non-reciprocal transport of CP, tunable with a gate.

TT 25.10 Wed 12:00 H32

Magnetoelectric phenomena and radial Rashba diode effect in non-centrosymmetric superconductors — •Denis Kochan — Department of Physics, National Cheng Kung University, Tainan, Taiwan — Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia

The superconducting diode effect is a magneto-electric phenomenon where an external magnetic field imparts a non-zero center-of-mass momentum to Cooper pairs, either facilitating or hindering the flow of electric current depending on its direction. One possible mechanism leading to SDE is a lack of inversion symmetry that facilitates spin splitting of the electronic bands by the underlying spin-orbit coupling (SOC). When breaking also the time-reversal by a weak magnetic/exchange field the Cooper pairs condensate displays intriguing magneto-electric and magneto-chiral effects.

This talk will present a theoretical overview and key experimental observations, particularly supercurrent diode effect and Josephson inductance anisotropy in InAs-quantum well-based junctions [1], zero-pi-like transitions and anomalous Josephson effect in non-centrosymmetric systems [2], enhanced vortex pinning and squeezing in Rashba-based superconductors [3]. The new kid on the block is the radial Rashba SOC giving rise to a novel Radial Rashba spin-diode effect [4].

[1] Nat. Nanotech. 17, 39 (2022).
[2] Nat. Nanotech. 18, 1h266 (2023).
[3] Phys. Rev. X 12, 041020 (2022).
[4] Phys. Rev. Lett. 133, 216201 (2024).

TT 25.11 Wed 12:15 H32

The Josephson diode effect with Andreev and Majorana states — •Sayan Mondal[1], Pei-Hao Fu[2], and Jorge Cayao[1] — [1]Department of Physics and Astronomy, Uppsala University, Box 516, S-751 20 Uppsala, Sweden — [2]Science, Mathematics and Technology, Singapore University of Technology and Design, Singapore 487372, Singapore

We consider a Josephson junction formed by Rashba superconductors and investigate the Josephson diode effect as the system transitions from a trivial to a topological phase under an applied external Zeeman field [1]. The component of the Zeeman field parallel to the spin-orbit axis introduces asymmetry in the Andreev bound states, which in turn leads to an asymmetry in the Josephson current, giving rise to the diode effect. In this study, we analyze the forward and backward currents, which differ due to the presence of the parallel Zeeman field. We discover that the diode's efficiency as a function of the Zeeman field exhibits a rich structure strongly dependent on the Andreev bound states. This dependence reveals clear signatures of the topological phase of transition. Notably, in the topological phase, the diode efficiency develops an oscillatory pattern reflecting Majorana bound states' formation. We have also verified that the functionality of the obtained Josephson diode is robust against finite temperatures, below the superconducting gap. Our findings help us understand the realization of Josephson diodes in topological superconductors and can also be useful for identifying the emergence of Majorana bound states.

[1] S. Mondal, P. -H. Fu, and J. Cayao, In preparation.