TT 6: Focus Session: Emerging Phenomena in Superconducting Low Dimensional Hybrid Systems I

Low-dimensional superconducting hybrid systems belong to the most intensively studied nanoelectronic devices and building blocks to date. On one hand they reveal and allow to study in detail a plethora of novel transport phenomena discovered only recently. These include, among others, studies of stacked two-dimensional hybrid systems, phenomena arising from the interplay between superconducting and magnetic order, single-particle or spin excitations excitations in zero- or one-dimensional systems, the competition of superconductivity and charging phenomena, Majorana bound states, or Ising superconductivity. On the other hand, some of these novel phenomenal are already under discussion for quantum information applications. This focus session aims at addressing selected aspects of the field thereby mainly focussing on the fundamental physical mechanisms rather than on the application aspects.

Organizers: Elke Scheer and Wolfgang Belzig (Konstanz University)

Time: Tuesday 10:00–12:45 Location: H7

Invited Talk TT 6.1 Tue 10:00 H7

Spin Triplet Superconductivity within Superconductors as Determined by FMR Spin pumping — •Lesley Cohen — Blackett Laboratory Imperial College London

Superconductor (SC)/ ferromagnet (FM) interfaces are of great interest as potential candidates to exploit the spin degree of freedom in superconducting phenomena, leading to potential applications for cryogenic memory and novel computing technologies. Over the last decade, experimental and theoretical studies have established that long-range spin polarized triplet supercurrents can be generated in superconducting/ferromagnetic heterostructures in the presence of magnetic inhomogeneities (e.g. spatially varying magnetization) via the proximity effect in combination with spin mixing and spin rotation processes. Separately it has been predicted that spin-orbit coupling in combination with the ferromagnetic exchange interaction can also generate conditions for the formation of spin triplet superconductivity. In this talk I will introduce the use of ferromagnetic resonance to inject a pure spin current in an interfacial material in close proximity, when that material is a superconductor. At a clean interface spin currents should be blocked from entering the superconductor by the Andreev process. I will discuss the conditions where the opposite appears to be the case and aspects we have learnt so far about using this technique to determine the strength of the spin triplet current within the superconductor under these conditions.

TT 6.2 Tue 10:30 H7

Tunneling Spectroscopy of Layered Superconductors — •Hadar Steinberg — Hebrew University of Jerusalem, Jerusalem, Israel

Tunnel junctions consisting of van der Waals (vdW) materials are realized by placement of thin barriers on top layered superconductors such as $NbSe_2$, TaS_2, and others. The atomic mating of the tunnel barrier and superconductor gives rise to a stable junction, which allows probing of the spectrum at high resolution, revealing clear signatures of the quasiparticle structure and of the sub-gap features. I will show how the use of such devices allows us to differentiate between dynamic properties of carriers in multi-gap superconductors. At ultrathin superconductors, we are able to track the evolution of the gap function up to very high in-plane magnetic field, where the gap feature hints at the onset of a triplet order. I will also show how defects in the barriers can give rise to quantum dot states, which can couple to the superconductor, forming Andreev bound states, and can be utilized as energy probes. Finally, I will show new data demonstrating the use of $NbSe_2$ as a source-drain electrode in a graphene-based Josephson device, which can sustain high in-plane fields.

15. min. break

TT 6.3 Tue 11:15 H7

Interplay of magnetism and Ising superconductivity: mirage gap and Josephson junction — •Gaomin Tang[1], Rafael L. Klees[2], Christoph Bruder[1], and Wolfgang Belzig[2] — [1]Department of Physics, University of Basel, Switzerland — [2]Fachbereich Physik, Universität Konstanz, Germany

Superconductivity is commonly destroyed by a magnetic field due to orbital or Zeeman-induced pair breaking. Surprisingly, the spin-valley locking in an Ising superconductor makes the superconducting state resilient to large magnetic fields. In the presence of an in-plane magnetic field, the emerging finite-energy pairing correlations manifest themselves in the occurrence of "mirage" gaps: at (high) energies of the order of the spin-orbit coupling strength, a gaplike structure in the spectrum emerges that mirrors the main superconducting gap. These mirage gaps are signatures of the equal-spin triplet finite-energy pairing correlations.

In a Josephson junction formed by two Ising superconductors that are in proximity to ferromagnetic layers, the supercurrent due to the triplet pairing correlations is controlled by the magnetic exchange fields. We show that both the charge and spin supercurrents can be modulated by the exchange fields.

[1] G. Tang, C. Bruder, W. Belzig, Phys. Rev. Lett. 126, 237001 (2021)

TT 6.4 Tue 11:30 H7

A Josephson junction supercurrent diode — •Christian Baumgartner[1], Lorenz Fuchs[1], Andreas Costa[1], Simon Reinhardt[1], Sergei Gronin[2], Geoffrey Gardner[2], Tyler Lindemann[2], Michael Manfra[2], Paulo Faria Junior[1], Denis Kochan[1], Jaroslav Fabian[1], Nicola Paradiso[1], and Christoph Strunk[1] — [1]University of Regensburg — [2]Purdue University

The combination of Rashba spin-orbit interaction and superconductivity leads to the appearance of an anomalous phase shift (φ_0) in the current phase relation (CPR) of Josephson junctions, as experimentally demonstrated by several groups in recent years. However, if the CPR is sinusoidal, the φ_0 shift does not affect the symmetry between positive and negative branch of the CPR. Here, we demonstrate that in short ballistic Josephson junctions application of an in-plane field perpendicular to the current induces an asymmetry between positive and negative branch of the CPR. Such magnetochiral anisotropy (MCA) is at the basis of the so-called supercurrent diode effect, here shown for the first time in Josephson junctions. We quantify MCA by measuring the kinetic inductance, whose in-plane field dependence allows us to determine the MCA coefficient for the superfluid. The experimental value compares well with the results of tight-binding simulations based on realistic material parameters for epitaxial Al/InAs 2DEGs.

TT 6.5 Tue 11:45 H7

Majorana bound states in magnetic impurity chains on conventional superconductors — •Annica Black-Schaffer — Uppsala University, Uppsala, Sweden

Magnetic impurities on the surface of spin-orbit coupled but otherwise conventional superconductors offer the possibility to create topological phases with Majorana bound states (MBSs) without having to apply an external magnetic field. In this talk I will present some of our resent results in modeling both magnetic impurity wires and islands on the surface of spin-orbit coupled superconductors, including a self-consistent treatment of the superconductivity, which results in a local π-shift of superconducting order parameter near magnetic impurities. In particular, I will show how MBSs at wire end points very strongly hybridize with in-gap Yu-Shiba-Rusinov (YSR) states, causing large oscillations in the MBSs energies that are significantly enhanced within the self-consistent treatment. Still, by treating the MBSs as topological boundary modes dependent only on the effective mass gap,

we can arrive at a fully parameter-free fitting of the Majorana localization length, which stays very short. I will also show how the wire end point MBSs are very robust against disorder within a self-consistent treatment, despite individual YSR states being extremely sensitive to disorder. Finally, despite the importance of a self-consistent treatment of superconductivity for the properties of the MBSs, I will show how the π-shift cannot easily be measured using the Josephson effect.

TT 6.6 Tue 12:15 H7

Evidence for p-wave pairing and precursors of Majorana modes in artificial Shiba chains — •Jens Wiebe — Department of Physics, Universität Hamburg, Hamburg, Germany

Magnetic chains on s-wave superconductors hosting spin spirals or spin-orbit coupling may realize one-dimensional topological superconductors with Majorana modes on their edges. We study artificial spin chains built atom-by-atom [1] with respect to such phenomena. By variation of substrate and adatom species and interatomic distances in the chain [2-5], we adjust the energies of multi-orbital Yu-Shiba Rusinov states induced by the adatoms [2,3], their hybridizations [4], as well as the chains' spin structures [5]. This enables to tailor the emerging multi-orbital Shiba bands such that p-wave gaps open [6]. We measure the length dependent energy oscillations of precursors of Majorana modes in short chains [7].

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[1] D.-J. Choi *et al.*, Rev. Mod. Phys. **91**, 041001 (2019)
[2] L. Schneider *et al.*, npj Quantum Materials **4**, 42 (2019)
[3] L. Schneider *et al.*, Nature Commun. **11**, 4707 (2020)
[4] P. Beck *et al.*, Nat. Commun. **12**, 2040 (2021)
[5] L. Schneider *et al.*, Science Advances **7**, eabd7302 (2021)
[6] L. Schneider *et al.*, Nat. Phys. (2021) https://doi.org/10.1038/s41567-021-01234-y
[7] L. Schneider *et al.*, arXiv:2104.11503 (2021)