MA 20: PhD Focus Session: Symposium on "Strange Bedfellows – Magnetism Meets Superconductivity" (joint session MA/AKjDPG)

At first sight, it seems that the phenomena of magnetism and superconductivity do not go along, as indicated by the Meissner effect, when a magnetic field is completely expelled from the interior of a conventional superconductor. However, the synergy of these two manifestations of nature in condensed matter does occur and can be rather interesting! Theoretical works have predicted the existence of exotic states at the interface between a superconductor and a magnet, such as the sought-after Majorana fermions and spin-triplet superconductivity. The first have been predicted to route an efficient way to implement quantum computers (currently a European scientific flagship), while the latter allows the creation of spin-polarized supercurrents, opening up fundamentally new possibilities for spintronics. Therefore, our symposium aims at putting together experts to provide a fundamental and practical understanding of the subject to discuss most recent developments from the theoretical and experimental sides, and to show perspectives for applications.

Organizers: Flaviano José dos Santos, Markus Hoffmann, Annika Stellhorn – (Forschungszentrum Jülich and Peter Grünberg Institut)

Time: Tuesday 9:30–13:00 Location: HSZ 04

Invited Talk MA 20.1 Tue 9:30 HSZ 04

Magnetism and superconductivity: building new physics one atom at a time — •Alexander Balatsky — Nordita and University of Connecticut

In this tutorial I will review the effects of magnetism and electronic defect in conventional and unconventional superconductors. The extreme case of quantum engineering where one builds magnetic and electronic features one atom at a time has proved to be a versatile approach. Impurities and defects are pair breakers in superconductors. I will discuss how defects can also enable new features in superconductors like intragap resonances, topological Majorana modes and seed new superconducting phases. Looking forward I will discuss how we might induce novel physics in superconductors with precise quantum impurity band engineering.

MA 20.2 Tue 10:15 HSZ 04

Magnetic Impurities and Anisotropic Multiband Superconductors — •Tom Saunderson[1], Gábor Csire[3], James Annett[1], Balázs Úfalussy[2], and Martin Gradhand[1] — [1]HH Wills Laboratory, University of Bristol, UK — [2]Wigner Research Centre for Physics, PO Box 49, H-1525 Budapest, Hungary — [3]Catalan Institute of Nanoscience and Nanotechnology (ICN2), Barcelona, Spain

Scanning tunnelling microscopy for superconductors has seen a flourish of activity in the last few years. It has become a powerful tool for determining the underlying fundamental properties of the gap structures in unconventional superconductors within the presence of impurities [1]. It has also been interesting to observe the pair-breaking effects that magnetic impurities have in conventional superconductors which lead to bound states [2]. Such states are even a possible source of Majorana Fermions [3]. We present the implementation of the Bogoliubov-de Gennes (BdG) equation into a Green's function (KKR) first principles method [4]. This method combines the full complexity of the underlying electronic structure and Fermi surface geometry with a simple phenomenological parametrisation for the superconductivity, whilst also being ideal to model impurities and interfaces. We present various test cases of simple superconductors in the presence of magnetic impurities, and assess the orbital character of the ensuing bound states.

[1] Ø. Fischer *et al*, Rev. Mod. Phys., **79**, 353 (2007)
[2] B. W. Heinrich *et al*, Prog. Surf. Sci., **93**, 1 (2018)
[3] S. Nadj-Perge *et al*, Science, **346**, 1259327 (2014)
[4] T. G. Saunderson *et al*, arXiv:1911.04163

Invited Talk MA 20.3 Tue 10:30 HSZ 04

Yu-Shiba-Rusinov states of single magnetic atoms and nanostructures probed by scanning tunneling spectroscopy — Eva Liebhaber[1], Michael Ruby[1], Benjamin W. Heinrich[1], Gaël Reecht[1], Kai Rossnagel[2,3], Felix von Oppen[1,4], and •Katharina J. Franke[1] — [1]Freie Universität Berlin, Berlin, Germany — [2]Christian-Albrechts-Universität Kiel, Kiel, Germany — [3]Deutsches Elektronen Synchrotron, Hamburg, Germany — [4]Dahlem Center for Complex Quantum Systems, Berlin, Germany

The exchange coupling of individual magnetic atoms with the Cooper pairs of a superconducting substrate leads to Yu-Shiba-Rusinov (YSR) bound states inside the superconducting energy gap. Their bound state energy and spatial extent can be probed by scanning tunneling spectroscopy [1-4]. Chains of magnetic adatoms have attracted particularly strong attention due to the formation of Majorana bound states at their terminations [5].

Here, we investigate individual magnetic atoms on Pb and $2H$-$NbSe_2$ substrates. We observe intriguing patterns of YSR states around the adatoms, which are determined by the adatom's d-levels as well as local symmetries of the adsorption potential. When the adatoms are sufficiently close, the YSR states hybridize, eventually giving rise to YSR bands in atomic chains.

[1] Yazdani *et al.*, Science 275, 1767 (1997); [2] Ji *et al.*, Phys. Rev. Lett. 100, 226801 (2008); [3] Franke *et al.*, Science 332, 940 (2011); [4] Ménard *et al.*, Nature Phys. 11, 1013 (2015); [5] Nadj-Perge *et al.*, Science 346, 602 (2014).

MA 20.4 Tue 11:00 HSZ 04

Symmetric and antisymmetric combinations of Yu-Shiba-Rusinov states in antiferromagnetic dimers — •Philip Beck, Lucas Schneider, Levente Rósza, Jens Wiebe, and Roland Wiesendanger — Department of Physics, University of Hamburg, Jungiusstraße 9-11, 20355 Hamburg

Magnetic atoms coupled to the Cooper pairs of a superconductor give rise to excitations in the superconductor's energy gap, so-called Yu-Shiba-Rusinov (YSR) states [1]. Theoretical proposals and experimental results have shown that, for ferromagnetically coupled atoms, the in-gap states hybridize and form symmetric and antisymmetric linear combinations.[2-4]

In our scanning tunneling spectroscopy study we reveal the evolution from multi-orbital YSR states of single transition metal atoms placed on an elemental superconductor to the YSR states of artificially constructed dimers with different interatomic separations and orientations. Even though the coupling in particular dimers, as calculated by DFT, is antiferromagnetic, we still observe a splitting of some of their orbital YSR states into symmetric and antisymmetric combinations. This unexpected behavior will be discussed and explained by advanced theoretical models.

We acknowledge funding by the ERC via the Advanced Grant ADMIRE (no. 786020) and by the SFB925 of the DFG.

[1] A. Rusinov, JETP **9**, 85 (1969). [2] D. K. Morr *et al.* PRB **67**, 020502 (2003). [3] M. Ruby *et al.* PRL **120**, 156803 (2018). [4] D.-J. Choi *et al.* PRL **120**, 167001 (2018).

Invited Talk MA 20.5 Tue 11:15 HSZ 04

Majorana bound states in magnetic skyrmions — •Jelena Klinovaja — Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

Magnetic skyrmions are highly mobile nanoscale topological spin textures. A magnetic skyrmion of an even azimuthal winding number placed in proximity to an s-wave superconductor hosts a zero-energy Majorana bound state in its core, when the exchange coupling between the itinerant electrons and the skyrmion is strong [1]. This Majorana bound state is stabilized by the presence of a spin-orbit interaction. We propose the use of a superconducting tri-junction to realize non-

Abelian statistics of such Majorana bound states.

Antiferromagnetic skyrmion crystals are magnetic phases predicted to exist in antiferromagnets with Dzyaloshinskii-Moriya interactions. Their spatially periodic noncollinear magnetic texture gives rise to topological bulk magnon bands characterized by nonzero Chern numbers [2,3]. We find topologically-protected chiral magnonic edge states over a wide range of magnetic fields and Dzyaloshinskii-Moriya interaction values. Edge states appear at the lowest possible energies, namely, within the first bulk magnon gap. Thus, antiferromagnetic skyrmion crystals show great promise as novel platforms for topological magnonics.

[1] G. Yang, P. Stano, J. Klinovaja, and D. Loss, Phys. Rev. B 93, 224505 (2016). [2] S. Diaz, J. Klinovaja, and D. Loss, Phys. Rev. Lett. 122, 187203 (2019). [3] S. Diaz, T. Hirosawa, J. Klinovaja, and D. Loss, arXiv:1910.05214.

MA 20.6 Tue 11:45 HSZ 04

Interplay of Shiba and Majorana states in nanostructures deposited on superconducting surfaces — •Uriel A. Aceves-Rodriguez, Filipe S. M. Guimarães, and Samir Lounis — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

Majorana Bound States (MBS) are zero-energy modes that have become one of the leading candidates for the next generation of qubits, due to their topological protection and exchange statistics [1]. In pursuance of handling these entities, we implemented a multi-orbital tight-binding scheme, offering a realistic description of the electronic structure, to solve the Bogoliubov-de Gennes equations self-consistently. We investigate in-gap states, such as Shiba states, emerging from various nanostructures on typical superconducting substrates. Additionally, we examine the occurrence of MBS at superconducting/non-superconducting interfaces of nanowires deposited on superconducting surfaces.

This work was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC-consolidator Grant No. 681405-DYNASORE).

[1] J. Alicea, Rep. Prog. Phys. 75 (2012) 076501

Invited Talk MA 20.7 Tue 12:00 HSZ 04

Orbital selective superconductivity in iron-based superconductors — •Pengcheng Dai — Rice University

Superconductivity in iron-based superconductors emerges from long-range ordered antiferromagnetic phase with nematic order that breaks four-fold rotational symmetry of the underlying lattice. In spite of considerable work over the past decade, much is unclear concerning the microscopic origin of superconductivity and its relationship with magnetism, nematicity, and orbital order. In this talk, I will summarize our recent inelastic neutron scattering studies of iron-based superconductors, focusing on studying the relationship between magnetism, nematic order, and superconductivity. We find that orbital selective magnetic excitations and superconductivity are central to a microscopic understanding of these materials.

MA 20.8 Tue 12:30 HSZ 04

Inductive detection of field- and damping-like inverse spin-orbit torques in superconductor/ferromagnet heterostructures — •Manuel Müller[1,2], Lukas Liensberger[1,2], Luis Flacke[1,2], Hans Huebl[1,2,3], Akashdeep Kamra[4], Wolfgang Belzig[5], Rudolf Gross[1,2,3], Mathias Weiler[1,2], and Matthias Althammer[1,2] — [1]Walther-Meissner-Institut, Bayerische Akademie der Wissenschaften, Garching, Germany — [2]Physik-Department, Technische Universität München, Garching, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), München, Germany — [4]Norwegian University of Science and Technology, Trondheim, Norway — [5]Fachbereich Physik, Universität Konstanz, Konstanz, Germany

Proximity effects at superconductor(SC)/ferromagnet(FM) interfaces provide novel functionality in the field of superconducting spintronics. We present experiments, where we probe the angular momentum transport across the SC/FM interface using a phase resolve broadband ferromagnetic resonance (bbFMR) technique that allows to measure both field- and damping-like inverse spin orbit torques (iSOT)[1]. We extend this iSOT analysis to make it applicable for SC/FM-bilayers and study iSOTs in a series of multilayers based on $NbN/Ni_{80}Fe_{20}$ as a function of temperature. We observe distinct changes in damping-like and field-like iSOT at the superconducting transition temperature T_c. Our findings reveal symmetry and strength of iSOTs at the SC/FM interface and provide guidance for future superconducting spintronics devices. [1] A. Berger. Phys. Rev. B. **97**: 94407. (2018).

MA 20.9 Tue 12:45 HSZ 04

Electronic and magnetic character of UTe_2 unconventional superconductor — Alexander B. Shick[1] and •Warren E. Pickett[2] — [1]Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic — [2]Department of Physics, University of California-Davis, Davis, California, USA

The interplay between ferromagnetism and superconductivity is a challenging problem in the coupling between the two major states of condensed matter. We report density functional theory plus Hubbard U calculations for recently discovered the orthorhombic uranium dichalcogenide superconductor [1]. The UTe_2 displays superconductivity below 1.7 K, with the anomalous feature that the specific heat coefficient does not vanish at zero temperature limit, but rather weakly diverges, suggesting very low energy ungapped quantum fluctuations. The analysis of the experimental data indicates that this actinide compound is a nearly ferromagnetic spin-triplet superconductor. The DFT+U calculations for ferromagnetic alignment [2] reveal that the states are dominated by the j=5/2 configuration, with the $j_z = \pm 1/2$ sectors being effectively degenerate and half-filled. The Fermi surfaces are large and strongly metallic, and display low-dimensional features, reminiscent of the ferromagnetic superconductor UGe_2. Our calculations can provide a platform for modeling unusual behavior of UTe_2.
[1] S. Ran et al., Science 365, 684 (2019); [2] A. B. Shick, and W. E. Pickett, PRB 100, 134502 (2019).