TT 10: Focus Session: Superconductivity in 2d-Materials and their Heterostructures

Two-dimensional crystals have become important throughout condensed matter physics. Only a few of them are intrinsic superconductors, most of these containing heavy elements. Hence, Cooper pairing is strongly affected by spin-orbit interactions that lead to exotic features like Ising pairing and mixed singlet-triplet correlations. The unconventional pairing offers novel degrees of freedom and integrates superconductivity with topological and even higher-order topological edge and hinge states. Moreover, proximity induced superconductivity displays characteristic features owing to the ballistic character and the Dirac dispersion relation of today's high-quality hexagonal boron nitride/graphene heterostructures. This makes graphene-based heterostructures an interesting platform for Andreev billiards and similar systems.

Organizers: Christoph Stampfer, RWTH Aachen University and Christoph Strunk, University of Regensburg

Time: Tuesday 9:30–13:15 Location: H3

Invited Talk TT 10.1 Tue 9:30 H3

Two-fold symmetric superconductivity in few-layer $NbSe_2$ — •Vlad Pribiag — University of Minnesota, USA

Few-layer samples of transition metal dichalcogenides (TMDs) feature a wide array of properties such as layer-dependent inversion symmetry, valley-contrasted Berry curvatures, and strong spin-orbit coupling (SOC). Among the superconducting TMDs, $NbSe_2$ is profoundly affected by Ising SOC. Ising SOC not only helps stabilize the superconducting state against large in-plane magnetic fields, but in conjunction with other forms of SOC, it could also give rise to exotic superconducting states such as nodal topological superconductivity. This talk will discuss recent transport measurements of few-layer $NbSe_2$, and $NbSe_2/CrBr_3$ junctions, studied under in-plane external magnetic fields. Surprisingly, although the crystal lattice has a three-fold symmetry, the magneto-resistance and critical field show a two-fold anisotropy, which is absent in the normal state. We will discuss these results in the context of a competition between the conventional s-wave pairing instability characteristic of the bulk and a competing d- or p-wave instability that emerges in the few-layer limit. These results [1] suggest an unconventional character for superconducting pairing in $NbSe_2$ and open the possibility for further discoveries, such as nontrivial topologies, in few-layer TMDs.

[1] A. Hamill et al., Nat. Phys. 17, 949 (2021)

Invited Talk TT 10.2 Tue 10:00 H3

Spin-orbit coupling and triplet pairing in mesoscopic superconductors — •marco aprili[1], marko kuzmanovic[1], tom dvir[2], david leboeuf[3], stefan ilic[4], menashe haim[2], maxim khodas[2], julia meyer[4], hadar steinberg[2], and charis quay[1] — [1]Laboratoire de Physique des Solides, Bâtiment 510, Université Paris-Saclay 91405 Orsay, France — [2]Racah Institute of Physics, Hebrew University of Jerusalem, Givat Ram, Jerusalem 91904 Israel — [3]Laboratoire National des Champs Magnétiques Intenses, CNRS, Grenoble, France — [4]Université Grenoble Alpes, CEA, Grenoble INP, 38000 Grenoble, France

The spin-orbit coupling which is present in in 2D materials because of inversion breaking symmetry allows a triplet component of the superconducting order parameter to appear.

In presence of an external magnetic field acting on the spin degree of freedom of the electron pairs forming the condensate, this spin-orbit coupling originates a spontaneous supercurrent and hence a phase difference. In a monolayer of a superconducting transition-metal-dichancogenides such as NbSe2, the lack of in-plane crystal inversion symmetry, results instead in a large valley Zeeman splitting which pins the spins out-of-plane and protects in fact superconductivity. Adding an external magnetic field results in a mix singlet-triplet superconducting state where the two order parameters are linearly coupled by the field. The triplet is an equal spin paring state. In this talk I'll present a series of quantum transport and tunneling spectroscopy experiments in mesoscopic superconductors that address these issues.

Invited Talk TT 10.3 Tue 10:30 H3

Supercurrent diode effect in few-layer $NbSe_2$ — Lorenz Bauriedl[1], Christian Bäuml[1], Lorenz Fuchs[1], Christian Baumgartner[1], Nicolas Paulik[1], Jonas M. Bauer[1], Kai-Qiang Lin[1], John M. Lupton[1], Takashi Taniguchi[2], Kenji Watanabe[2], Christoph Strunk[1], and •Nicola Paradiso[1] — [1]Institut für Experimentelle und Angewandte Physik, University of Regensburg, Regensburg, Germany — [2]International Center for Materials Nanoarchitectonics, National Institute for Materials Science, Tsukuba, Japan

Current rectifiers are devices which display a largely different resistance for the two opposite bias polarities. Recent seminal works on Rashba superconductors have demonstrated that a simultaneous breaking of time- and inversion-symmetry leads to supercurrent rectification, where for one direction the resistance is strictly zero. Owing to the symmetry of the Rashba spin-orbit interaction, the effect is controlled by the in-plane field. In this work, we report on a supercurrent diode effect in few layer-thick $NbSe_2$ constrictions. As predicted by theory for valley Zeeman spin-orbit interaction (SOI), the observed supercurrent rectification is controlled by the *out-of-plane* field B_z. Remarkably, the in-plane field does play a role: it determines a preferred direction for the out-of-plane field, making the rectification effect asymmetric in B_z. Such asymmetry is in contrast to theory expectations for pure valley Zeeman spin-orbit. Instead, it points toward the presence of an additional Rashba SOI component in $NbSe_2$.

15 min. break

Invited Talk TT 10.4 Tue 11:15 H3

Superconducting devices in magic-angle twisted bilayer graphene — •Folkert de Vries[1], Elias Portoles[1], Giulia Zheng[1], Shuichi Iwakiri[1], Kenji Watanabe[2], Takashi Taniguchi[2], Thomas Ihn[1], and Klaus Ensslin[1] — [1]Laboratory for Solid State Physics, ETH Zurich, Otto-Stern-Weg 1,Zurich, Switzerland — [2]National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

In situ electrostatic control of two-dimensional superconductivity is commonly limited due to large charge carrier densities, and gate-defined superconducting devices are therefore rare. Magic-angle twisted bilayer graphene (MATBG) has recently emerged as a versatile platform that combines metallic, superconducting, magnetic and insulating phases in a single crystal. Here we use multilayer gate technology and physical etching to create devices based on distinct phases in adjustable regions of MATBG. We electrostatically define the superconducting and insulating regions of a Josephson junction and observe tunable d.c. and a.c. Josephson effects. Futhermore, we form a ring shaped geometry with two Josephson junctions known as a superconducting quantum interference device. We observe the expected coherent oscillations of the supercurrent and extract characteristics such as the current phase relation and inductance. These works are an initial steps towards devices where gate-defined correlated states are connected in single-crystal nanostructures. We envision applications in superconducting electronics and quantum information technology.

Invited Talk TT 10.5 Tue 11:45 H3

Minigap and Andreev bound states in ballistic graphene — •Luca Banszerus[1,2], Florian Libisch[3], Andrea Ceruti[1], Stefan Blien[4], Kenji Watanabe[5], Takashi Taniguchi[5], Andreas Hüttel[4], Bernd Beschoten[1], Fabian Hassler[1], and Christoph Stampfer[1] — [1]RWTH Aachen University, Germany — [2]Forschungszentrum Jülich, Germany — [3]TU Vienna, Austria — [4]University of Regensburg, Germany — [5]National Institute for Materials Science, Japan

A finite-size normal conductor, proximity-coupled to a superconductor has been predicted to exhibit a so-called minigap, in which quasiparticle excitations are prohibited. In this talk, we demonstrate the direct observation of such a minigap through transport measurements on partially gated ballistic graphene, coupled to superconducting MoRe contacts [1]. The minigap is probed by finite bias spectroscopy through a weakly coupled junction in the graphene region and its value is given by the dimensions of the device. Besides the minigap, a distinct peak in the differential resistance is observed, which we attribute to weakly coupled Andreev bound states (ABS) located near the superconductor-graphene interface. For weak magnetic fields, the phase accumulated in the normal-conducting region shifts the ABS in quantitative agreement with predictions from tight-binding calculations based on the Bogolioubov-de Gennes equation as well as with an analytical semiclassical model.

[1] arXiv:2011.11471

TT 10.6 Tue 12:15 H3

Competition of Density Waves and Superconductivity in Twisted Tungsten Diselenide — •Lennart Klebl[1], Ammon Fischer[1], Laura Classen[2], Michael M. Scherer[3], and Dante M. Kennes[1,4] — [1]Institut für Theorie der Statistischen Physik, RWTH Aachen University and JARA-Fundamentals of Future Information Technology, D-52056 Aachen, Germany — [2]Max Planck Institute for Solid State Research, D-70569 Stuttgart, Germany — [3]Institut für Theoretische Physik III, Ruhr-Universität Bochum, D-44801 Bochum, Germany — [4]Max Planck Institute for the Structure and Dynamics of Matter, Center for Free Electron Laser Science, D-22761 Hamburg, Germany

Evidence for correlated insulating and superconducting phases around regions of high density of states was reported in the strongly spin-orbit coupled van-der Waals material twisted tungsten diselenide ($tWSe_2$). We investigate their origin and interplay by using a functional renormalization group approach that allows to describe superconducting and spin/charge instabilities in an unbiased way. We map out the phase diagram as function of filling and perpendicular electric field, and find that the moiré Hubbard model for $tWSe_2$ features mixed-parity superconducting order parameters with s/f-wave and topological d/p-wave symmetry next to (incommensurate) density wave states. Our work systematically characterizes competing interaction-driven phases in $tWSe_2$ beyond mean-field approximations and provides guidance for experimental measurements by outlining the fingerprint of correlated states in interacting susceptibilities.

TT 10.7 Tue 12:30 H3

Tuning lower dimensional superconductivity with hybridization at a superconducting-semiconducting interface — •M. Simonato[1], A. Kamlapure[1], E. Sierda[1], M. Steinbrecher[1], U. Kamber[1], E. J. Knol[1], P. Krogstrop[2,3], M.I. Katsnelson[1], A.A. Khajetoorians[1], and M. Rösner[1] — [1]Radboud University, Institute for Molecules and Materials, Nijmegen, The Netherlands — [2]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark — [3]Microsoft Quantum Materials Lab Copenhagen, Lyngby, Denmark

We demonstrate that the hybrid electronic structure derived at the interface between semiconducting black phosphorus and atomically thin films of lead can drastically modify the superconducting properties of the thin metallic film. Using ultra-low temperature scanning tunneling microscopy and spectroscopy, we observe a strongly anisotropic renormalization of the superconducting gap. To study the effect of hybridization, we develop a hybrid two-band model as an extension to conventional BCS theory in the Nambu-Gorkov formalism. In this model, we obtain analytical expressions for the effective gap and link the hybridization-driven renormalization to a weighting of the superconducting order parameter that quantitatively reproduces the measured spectra. These results illustrate the effect of interfacial hybridization at superconductor-semiconductor heterostructures, and pathways for engineering quantum technologies based on gate-tunable superconducting electronics.

TT 10.8 Tue 12:45 H3

Ab inito study of the van der Waals Superconductor $NbSe_2$ — •Mohammad Hemmati, Philipp Rüssmann, and Stefan Blügel — Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, Jülich, Germany

Transition metal dichalcogenides (TMDCs) are a very versatile material class in which a plethora of physical phenomena can be realized. This ranges from the topological electronic structure in Weyl and Dirac semimetals to magnetic and even superconducting systems that can furthermore be combined due to the intrinsic van der Waals stacking in these materials. The TMDC $NbSe_2$ is an example of a layered superconducting material which shows, for instance, the unconventional Ising superconductivity that is particularly robust against magnetic fields [1]. We study bulk and single-layer $NbSe_2$ on the basis of first-principles calculations within the Korringa-Kohn-Rostoker Green function method which allows combining the accurate description of the electronic structure on the basis of density functional theory with a description of the superconductivity via the Bogoliubov-de Gennes formalism [2,3].

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[1] D. Wickramaratne *et al.*, Phys. Rev. X **10**, 041003 (2020)
[2] https://jukkr.fz-juelich.de
[3] P. Rüßmann, S. Blügel, arXiv:2110.01713 (2021)

TT 10.9 Tue 13:00 H3

Emergence of unconventional proximity effect in $Cr_1/3NbS_2/NbS_2$ heterostructures — •Alfredo Spuri, Roman Hartmann, Elke Scheer, and Angelo Di Bernardo — University of Konstanz

The helimagnetic metal $Cr_1/3NbS_2$ has been reported to host soliton excitations based on magnetransport measurements which have been performed on flakes of this material down to the 2D limit. Investigating the proximity effect between 2D flakes of such a magnetic material and conventional 2D superconductors could lead to the discovery of unconventional spin-triplet superconducting states, with possible applications for superconducting spintronics and quantum computing. Based on these motivations, we have fabricated 2D $Cr_1/3NbS_2/NbSe_2$ and $Cr_1/3NbS_2/NbS_2$ bilayers and investigated their low temperature magnetotransport and spectroscopic properties. In addition, we have also realized $/NbSe_2/Cr_1/3NbS_2/NbSe_2$ Josephson junctions and performed measurements on them. The results obtained give indication for the emergence of an unconventional proximity effect, possibly due to the emergence of spin-triplet pairing correlations.