Novel Quantum Phases in Superconducting Heterostructures

769. WE-Heraeus-Seminar

30 May - 02 Jun 2022
Hybrid at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 769. WE-Heraeus-Seminar

The phenomenon of superconductivity is a central element in the development of novel quantum technologies. On the one hand, the most elementary quantum units are realized, investigated and manipulated in superconducting heterostructures, while on the other hand superconducting detection technologies explore the ultimate limits. Novel superconducting materials, such as two-dimensional crystals or synthetic magnet-superconductor compounds, illustrate the enormous possibilities that are currently being explored. The resulting novel quantum phases are characterized using the full range of experimental techniques, from scanning tunneling spectroscopy, to transport properties, as well as in their magnetic response. Accompanied by theories using state-of-the-art nonequilibrium quantum field theory methods, a synergistic progress towards new insights and applications is emerging.

Quantum technologies are shaping today's modern solid-state physics and motivate to construct, study, characterize, and control novel quantum phases. For example, two-dimensional van der Waals heterostructures are assembled from an almost infinite variety of two-dimensional crystals, giving rise to synthetic materials that exhibit properties not found in single layers. A recent example is twisted bi-layer graphene with specific angles creating moiré superstructures with flat bands and unique correlated phases. Magnetic crystals can be used to introduce either a ferromagnetic, an antiferromagnetic, or even noncollinear magnetic order into a two-dimensional superconductor enabling new pairing states and spin-polarized supercurrents. Spin-orbit coupling can control fundamental pairing mechanisms and produce unusual Ising superconductivity. In general, strong spin-orbit coupling at interfaces produces novel superconducting phases characterized, e. g., by a paramagnetic Meissner response. These effects have recently been experimentally unveiled by sophisticated methods.

Scientific Organizers:

Prof. Dr. Elke Scheer	Universität Konstanz, Germany E-mail: elke.scheer@uni-konstanz.de
Prof. Dr. Christoph Strunk	Universität Regensburg, Germany E-mail: christoph.strunk@physik.uni-regensburg.de
Prof. Dr. Wolfgang Belzig	Universität Konstanz, Germany E-mail: Wolfgang.Belzig@uni-konstanz.de

Program

Program

Sunday, 29 May 2022

17:00 – 21:00	Registration	
From 18:30	BUFFET *SUPPER / Informal get together*	

Monday, 30 May 2022

08:00	*BREAKFAST*	
08:50 – 09:00	Scientific Organizers	**Opening remarks**
09:00 – 09:40	Katharina Franke	**Quantum spins and hybridization in artificially-constructed chains of magnetic adatoms on superconducting 2H-$NbSe_2$**
09:40 – 10:20	Sebastian Bergeret	**Magnetoelectric effects and non-reciprocal transport in superconducting systems with spin-orbit coupling and spin-splitting fields**
10:20 – 10:45	Saulius Vaitiekenas	**Semi-super-ferro hybrids: A new platform for unconventional superconductivity**
10:45 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Ewelina Hankiewicz	**Thermal versus electric response of superconducting topological materials; are Majorana states more widespread than expected?**
11:50 – 12:30	Alexandra Palacio Morales	**Misfit Layer Compounds: A Platform for Heavily Doped 2D Transition Metal Dichalcogenides**
12:30	*LUNCH*	

Program

Monday, 30 May 2022

14:30 – 15:10	Alexander Buzdin	**Spontaneous currents and vortex generation at S/F interfaces**
15:10 – 15:35	Denis Kochan	**Anisotropic vortex squeezing in Rashba superconductors: a manifestation of Lifshitz invariants**
15:35 – 16:00	*COFFEE BREAK*	
16:00 – 16:40	Dimitri Roditchev	**Resonant transmission of Josephson current in Nb-$Bi_2Te_{2.3}Se_{0.7}$-Nb junctions via Andreev bound states**
16:40 – 17:20	Beena Kalisky (online)	**Hidden magnetism and spontaneous vortices in 4Hb-TaS_2**
17:20 – 17:35	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
17:35 – 19:35	**Poster Session I**	
19:40	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, with complimentary drinks)*	

Program

Tuesday, 31 May 2022

08:00	*BREAKFAST*	
09:00 – 09:40	Julia Meyer	**Diode effect in topological Josephson junctions**
09:40 – 10:20	Landry Bretheau	**Weyl Josephson Circuits**
10:20 – 10:45	Julien Basset	**Gate-assisted phase fluctuations in all-metallic Josephson junctions**
10:45 – 11:10	*COFFEE BREAK*	
11:10 – 11:50	Sophie Gueron	**Signatures of Higher Order Topology in Bismuth-based Josephson Junctions**
11:50 – 12:30	Angelo Di Bernardo	**Spectroscopic evidence for unconventional superconducting and magnetic states**
12:30	*LUNCH*	
14:30 – 15:10	Charis Quay	**Tunnelling spectroscopy of few-monolayer $NbSe_2$ in high magnetic field: Ising protection and triplet superconductivity**
15:10 – 15:35	Yoichi Ando	**Proximity-induced superconductivity in bulk-insulating topological insulators**
15:35 – 16:00	*COFFEE BREAK*	

Program

Tuesday, 31 May 2022

16:00 – 16:40	Patrik Recher	**Transport signatures of Majorana edge modes in two-dimensional topological insulator - chiral topological superconductor junctions**
16:40 – 17:05	Magdalena Marganska	**Two-gap Ising superconductivity from Coulomb interactions in monolayer $NbSe_2$**
17:05 – 17:30	Hannes Weisbrich	**Higher-dimensional topological states of matter in superconducting systems**
18:00	*DINNER*	
20:00 – 20:50	Silke Bühler-Paschen	**Strange metal behavior and unconventional superconductivity in heavy fermion compounds and beyond**

Posters

Posters 1

1	Antognini Silva	**First principles analysis of Yu-Shiba-Rusinov states caused by an iron impurity in bulk lead**
2	Masoud Bahari	**Topological phase transition away from the Fermi surface in multiband superconductors**
3	Lorenz Bauriedl	**Supercurrent diode effect in few-layer NbSe2 nanowires**
4	Philip Beck	**Tuning the spin-orbit coupling in 1D magnetic structures on superconducting surfaces**
5	Johanna Berger	**Influence of in-plane and out-of-plane magnetic fields on quantum interference in a 1d array of three-terminal Josephson junctions**
6	Andreas Costa	**Spin-orbit coupling assisted transport phenomena in superconducting magnetic tunnel junctions**
7	Christian Eckel	**Fabrication and measurements for a deeper investigation of charge density waves in 1T-TaS2 devices**
8	Jacob Fuchs	**Supercurrent oscillations in 3D topological insulator nanowire Josephson junctions**
9	Mohammad Rasoul Hemmati Nafar	**Ab initio study of the Van der Waals Superconductor NbSe2.**
10	Richard Hess	**Prevalence of trivial zero-energy sub-gap states in non-uniform helical spin chains on the surface of superconductors**
11	Alberto Hijano	**The anomalous Andreev interferometer**

Posters 1

12	Wolfgang Himmler	**Tunable 4π-periodic supercurrent in HgTe-based topological nanowires**
13	Niklas Hüttner	**Current phase relation of HgTe nanowire Josephson junctions in an axial magnetic field**
14	Stefan Ilic (online)	**Theory of the supercurrent diode effect in Rashba superconductors with arbitrary disorder**
15	Eugene Kogan	**The kinks, the solitons and the shocks in series connected discrete Josephson transmission lines**
16	Olivér Kürtössy	**Crossed Andreev Coupling in Parallel InAs Nanowires**
17	Henry Legg	**Majorana bound states and giant magnetochiral anisotropy in topological insulator nanowires**
18	Roberto Lo Conte	**Coexistence of Antiferromagnetism and Superconductivity in pseudomorphic Mn ultra-thin films on Nb(110)**
19	George Moethrath	**Flux periodic oscillations and phase-coherent transport in GeTe nanowires**
20	Danilo Nikolic	**Calorimetry and thermometry of a quantum phase slip**
21	David Christian Ohnmacht	**Full counting statistics of multiterminal Josephson junctions**
22	Jon Ortuzar Andres	**Yu-Shiba-Rusinov states in 2D superconductors with arbitrary Fermi contours**

Posters 2

23	Sourabh Patil	**Ising superconductors: The signatures of triplet pairings on the density of states and vanishing of the "mirage" gap**
24	Lea Pfaffinger	**High Precision Impedance Measurements of the Berezinski-Kosterlitz-Thouless Transition in Strongly Disordered Superconductors**
25	Priyana Pulyuappara Babu	**Optimisation of Sr2RuO4 thin films and devices based on single-crystals flakes**
26	Panch Ram	**Escape rate problem in driven Josephson junctions**
27	Hannes Riechert	**Towards coherent manipulation of Andreev Bound States in ultraclean carbon nanotubes**
28	Leon Ruf	**Exploring the electrical gating-effect in different kinds of superconductors**
29	Philipp Rüßmann	**Density functional Bogoliubov-de Gennes calculations for a topological superconductor**
30	Deividas Sabonis	**Parity switching in a semiconductor-based transmon qubit**
31	Harald Schmid	**Quantum Yu-Shiba-Rusinov dimers**
32	Jaydean Schmidt	**Experimental signatures of Lifshitz-invariants in the kinetic inductance of Rashba superconductors**
33	Rubén Seoane Souto (online)	**Magnetism and spin-polarized bound states in semiconductor-superconductor-ferromagnetic wires**
34	Julian Siegl	**A particle conserving approach to transport in AC-DC driven interacting quantum dots with superconducting leads**

Posters 2

35	Laura Sobral Rey	**Interplay between charging effects and superconducting transport in a tunable SET**
36	Alfredo Spuri	**Signatures of superconducting proximity effects in two-dimensional (2D) superconductor/ferromagnet bilayers with a helimagnetic metal**
37	Annika Stellhorn	**Polarized Grazing Incidence Small Angle Neutron Scattering – Application to ferromagnet-superconductor heterostructures**
38	Dhavala Suri	**Large Enhancement of Critical Current in Superconducting Devices by Gate Voltage**
39	Máté Sütő	**Characterization of GaAs-based near-surface InAs 2DEGs with an epitaxial Al layer**
40	Aleksandr Svetogorov	**Enhancement of Kondo effect in S-QD-S Josephson junction based on full-shell nanowire**
41	Khai Ton That	**Correlation of Magnetism and Disordered Shiba bands in Fe Monolayer Islands on Nb(110)**
42	Martina Trahms	**Phase dynamics in current-biased Josephson junctions in the presence of Yu-Shiba-Rusinov bound states**
43	Stefano Trivini	**Many-body Excitations of a Quantum Spin on a Proximitized Superconductor**
44	Alexander Wagner	**Bloch Oscillations in Josephson Junctions**
45	Grace Lu	**Proximity Effect Induced Superconductivity in Sb2Te3 Nanowire**

Abstracts of Lectures

(in alphabetical order)

Proximity-induced superconductivity in bulk-insulating topological insulators

Yoichi Ando[1]

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In this talk, I will present our efforts to induce superconductivity in the surface states of bulk-insulating topological insulators through proximity effects and to elucidate its topological nature. The first part will be about the Josephson junctions made on exfoliated flakes of bulk-insulating $BiSbSeTe_2$ (BSTS): We have previously reported a high transparency achieved in Al/BSTS Josephson junctions [1], and recently we identified an anomalous current-phase relation in Nb/BSTS Josephson junctions by employing asymmetric SQUID devices. The second part will be about the devices in which proximity-induced superconductivity is achieve by the self-formation of $PdTe_2$ superconductor in bulk-insulating $(Bi_{1-x}Sb_x)_2Te_3$ (BST) thin films via Pd diffusion [2]. Interestingly, this self-formation process can be used to fabricate a structure in which a BST nanowire is sandwiched by $PdTe_2$ superconductors on the sides [3]; in the ac Josephson effect observed in such a horizontal sandwich Josephson junction, the first Shapiro step is missing at low frequency, low power, and low temperature, giving evidence for the formation of 4π-periodic Majorana bound states [3].

This work was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 741121) and was also funded by the German Research Foundation (DFG) under CRC 1238 - 277146847 as well as under Germany's Excellence Strategy - Cluster of Excellence Matter and Light for Quantum Computing (ML4Q) EXC 2004/1 - 390534769.

References

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Gate-assisted phase fluctuations in all-metallic Josephson junctions

Julien Basset[1], **Ognjen Stanisavljevi´c[1], Marko Kuzmanovi´c[1], Julien Gabelli[1] , Charis H. L. Quay[1], Jérôme Estève[1] , and Marco Aprili[1]**

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We study the reduction of the supercurrent by a gate electrode in a purely metallic superconductor–normal metal–superconductor Josephson junction by performing, on the same device, a detailed investigation of the gate-dependent switching probability together with the local tunneling spectroscopy of the normal metal. We demonstrate that high energy electrons leaking from the gate trigger the reduction of the critical current which is accompanied by an important broadening of the switching histograms. The switching rates are well described by an activation formula including an additional term accounting for the injection of rare high energy electrons from the gate. The rate of electrons obtained from the fit remarkably coincides with the independently measured leakage current. Concomitantly, a negligible elevation of the local temperature in the junction is found by tunneling pectroscopy which excludes stationary heating induced by the leakage current as a possible explanation of the reduction of the critical current. This incompatibility is resolved by the fact that phase dynamics and thermalization effects occur at different timescales [1].

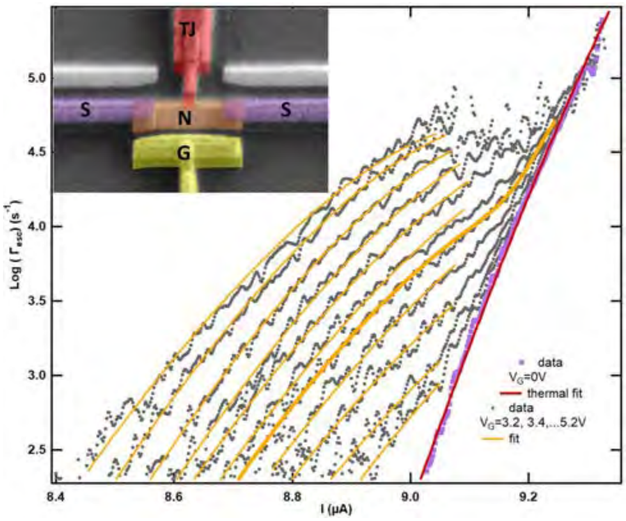

Figure 1: Colorized scanning electron microscope picture of the sample showing the superconducting contacts S, the normal metal N, the tunnel junction electrode TJ, and the gate G. Escape rates for different V_G as a function of current bias I and the corresponding fits.

References

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Magnetoelectric effects and non-reciprocal transport in superconducting systems with spin-orbit coupling and spin-splitting fields.

Stefan Ilić[1], Ilya Tokatly[2,3] , Pauli Virtanen[4], Elia Strambini[5], Tero Heikkilä[4], Francesco Giazotto[5], Sebastian Bergeret[1,3]

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I will discuss the interplay between superconductivity and spin-dependent fields. First, I will introduce a theoretical framework to describe superconducting systems with spin-orbit coupling. It is based on the quasiclassical kinetic equations, which, in the diffusive case, have been derived from a non-linear sigma model [1]. I will then discuss different effects related to spin-orbit coupling. These include the anomalous supercurrent in Josephson junctions [2], the paramagnetic response of Rashba[3] superconductors, and the superconducting diode-effect[4].
Finally, I will discuss a tunnel diode with a spin-split superconductor in contact with a ferromagnet [5]. The direction-selective propagation of the charge is due to the broken electron-hole symmetry induced by the spin-selective transport. I will contrast the results of our theory with recent experiments on Cu/EuS/Al and EuS/Al/Co tunnel junctions which achieve a significant current rectification (up to ∼40%) [6].

References:

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Weyl Josephson Circuits

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Multiterminal superconductor-normal-superconductor junctions have been a focus of theoretical and experimental work due to their potential topological properties, but so far, they remain far out of experimental reach due to lack of microscopic control. Here we propose an alternative approach based on standard Josephson tunnel junction circuits, immediately enabling experimental pursuit. We find that these circuits can be designed to simulate Weyl band structures, which can mimic the properties of massless ultra-relativistic particles known as Weyl fermions. We dubbed these Weyl Josephson circuits.

In this work, we first explain a general approach to construct small quantum circuits that exhibit topological band structures of a desired symmetry class, and which are governed by a designable set of controllable parameters. We then construct and analyze in detail a six-junction device that produces a 3D Weyl Hamiltonian with broken inversion symmetry and in which topological phase transitions can be triggered *in situ*. Finally, we propose specific experiments probing the topological character of Weyl Josephson circuits which are readily accessible using standard nanofabrication and measurement techniques.

This work breaks open a field of research that merges the technological readiness and theoretical clarity of superconducting circuits with the notions of quantum geometry and band topology.

References

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Strange metal behavior and unconventional superconductivity in heavy fermion compounds and beyond

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Heavy fermion compounds are a versatile platform for exploring quantum phases and fluctuations in the regime of extreme correlation strength [1-3]. Unconventional superconductivity is ubiquitous in their (temperature vs non-thermal control parameter) phase diagrams. It typically appears as a "dome" centered around a quantum critical point (QCP), and is thus considered to be an emergent phase stabilized by quantum critical fluctuations. In some cases, the superconducting pairing is attributed to critical spin fluctuations associated with the continuous suppression of a magnetic order parameter at the QCP. However, of particular interest today are materials – from cuprates and other transition metals oxides, through kagome metals and twisted bilayer graphene, to heavy fermion compounds – that go beyond this order-parameter paradigm and where the pairing mechanism is yet to be identified. The similar phenomena they exhibit, most notably "strange metal" linear-in-temperature electrical resistivities, suggest that a common mechanism may be at play. I will discuss this physics from the perspective of heavy fermion compounds, using the prototype material $YbRh_2Si_2$ as an example, and show the growing evidence for Kondo destruction is this case. But whether this mechanism is universal across all materials classes is an outstanding question. New approaches are needed to quantify the strange metal state, and evaluating the role of entanglement seems to be an interesting way forward.

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Spontaneous currents and vortex generation at S/F interfaces

L. Olthof[1], S. Mironov[2], J. Robinson[1], A. Samokhvalov[2], and A. Buzdin[3]

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Rashba spin-orbit interaction at the interface between a superconductor and a ferromagnet is at the origin of the linear over the gradient term in the Ginzburg-Landau free energy. This term modifies the expression for the superconducting current and results to the helical superconducting ground state. In the uniform system the spontaneous current in such a helical state is absent.

The situation drastically changes in the case of the non-uniform systems (where the spin-orbit coupling varies in space). We discuss the mechanisms of the spontaneous current generation and its distribution in these systems. The current-carrying states may appear close to a magnetic island on a thin-film superconductor [2] or near an S/F interface within a distance of the London penetration depth of the interface [3]. In thick superconducting films Rashba spin-orbit coupling at the S/F interface produces a spontaneous current in the atomic thickness region near the interface. This current is counterbalanced by the superconducting screening current.

Another example of the spontaneous current generation is provided by a ferromagnetic strip on the top of a thin supercomputing [4]. In this case even a relatively weak spin-orbit coupling is enough for the Abrikosov vortex generation.

Finally, spontaneous currents emerge within a thin superconducting loop that is partially proximitized by a ferromagnet [5]. They provide sizable shifts in Little-Parks oscillations and made the critical temperature of the loop dependent on the orientation of magnetization. The superconducting region above the ferromagnet play a role of a “phase battery” and so offers a new device concept for superconducting spintronics.

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Spin transport in a conventional superconductor

Chiara Ciccarelli

I will give an overview of our work in collaboration with the Department of Materials Science and Metallurgy in Cambridge [1-5] on the spin pumping into a Nb thin film. Unlike conventional spin-singlet Cooper pairs, spin-triplet pairs can carry spin. Triplet supercurrents were discovered in Josephson junctions with metallic ferromagnet spacers, where spin transport can occur only within the ferromagnet and in conjunction with a charge current. Ferromagnetic resonance injects a pure spin current from a precessing ferromagnet into adjacent non-magnetic materials. For spin-singlet pairing, the ferromagnetic resonance spin pumping efficiency decreases below the critical temperature (Tc) of a coupled superconductor. Here we present ferromagnetic resonance experiments in which spin sink layers with strong spin–orbit coupling are added to the superconductor. We show that the induced spin currents, rather than being suppressed, are substantially larger in the superconducting state compared with the normal state and show that this cannot be mediated by quasiparticles and is most likely a triplet pure spin supercurrent. By carrying angular dependence studies of the Gilbert damping we are able to link the generation of a triplet condensate with the Rashba spin-orbit coupling.

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Recent developments in the understanding of Yu-Shiba-Rusinov bound states

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The competition between magnetism and superconductivity is one of the most fundamental problems in condensed matter physics. The ability of the scanning tunneling microscope (STM) to manipulate individual magnetic atoms and molecules has enabled to study this competition at the atomic scale. One of the most interesting manifestations of the interplay between these two antagonistic phases of matter is the appearance of the so-called Yu-Shiba-Rusinov (YSR) bound states in the spectrum of a single magnetic impurity coupled to a superconductor. Numerous STM-based experiments on single magnetic impurities on surfaces of conventional superconductors have reported the observation of these superconducting bound states [1]. Those experiments have elucidated many basic aspects of the YSR states, but there are still many open questions.

In this talk, I will present our recent advances in the understanding of YSR states obtained as a result of a close collaboration between experiment and theory. In particular, I will report on three different topics: (i) the electron tunnelling between individual YSR states [2,3], (ii) the Josephson current as a tool to probe quantum phase transitions in systems featuring YSR states [4,5], and (iii) the interplay between multiple Andreev reflections and YSR states [6,7].

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Electric field effects on superconductors: π-pairing, orbital vortex phases and novel phenomena

M. Cuoco[1]

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In this seminar I talk about the effects that an electrostatic field induces on thin film metallic superconductors. I start by focusing on the physical mechanisms for achieving an electrical control of conventional spin-singlet superconductivity in thin films by focusing on the role of inversion symmetry breaking and orbital Rashba coupling. Assuming a multi-orbital metallic state the electric field acts by modifying the strength of the surface potential yielding non-trivial orbital-Rashba coupling. [1] We demonstrate that, by varying the strength of the electric field, the superconducting phase can undergo a 0−π transition with the π-phase being marked by non-trivial sign change of the superconducting order parameter between different bands [1]. This phase exhibits a weak influence of the magnetic field on the critical electric field that identifies the transition from the superconducting state to a phase with vanishing critical supercurrent [2]. Such multi-orbital π-pairing can account for the suppression of the supercurrent, as well as for the weak dependence of the critical magnetic fields on the electric field. Then, I discuss the emergence of unconventional pair density waves on the surface of a superconductor due to applied electric field including electric gradients [3]. Breaking of time-reversal and point-group spatial symmetries can have a profound impact on superconductivity. I will show that in two-dimensional spin-singlet superconductors with unusually low degree of spatial symmetry content, vortices with supercurrents carrying angular momentum around the core can form and be energetically stable [3]. The vortex has zero net magnetic flux since it is made up of counter-propagating Cooper pairs with opposite orbital moments. I show that the orbital vortex is stable and has a characteristic pattern with a pronounced angular anisotropy that deviates from the profile of conventional magnetic vortices. These findings unveil a rich scenario to design heterostructures with superconducting orbitronics effects.

This research receives support by the EU's Horizon 2020 research and innovation program under Grant Agreement nr. 964398 (SUPERGATE).

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Spectroscopic evidence for unconventional superconducting and magnetic states

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The combination of different materials into complex heterostructures often stems from the discovery of unconventional states either in the elemental materials or at their interfaces. A typical example is the formation of odd-frequency spin-triplet states at the interface of superconductor (S) and ferromagnet (F) materials, which has led to the development of superconducting spintronics [1].

Low-energy muon spin rotation (LE-μSR) is an ideal spectroscopy technique to discover novel states in elemental and hybrid material systems, since it can resolve extremely small magnetic fields (< 0.1 Gauss) with nanometre depth resolution. Evidence for odd-frequency spin-triplet states was already found in LE-μSR studies on S/F (Nb/Ho) thin film multilayers, where we observed an inverse (paramagnetic) Meissner effect due to spin-triplet correlations [2].

After briefly reviewing the basics of LE-μSR spectroscopy, I will discuss recent studies that we have carried out using LE-μSR. In the first study [3], we find that the conventional Meissner screening of Nb thin films is significantly modified upon adsorption of non-magnetic chiral molecules (ChMs) on their surface, in a way that is consistent with the emergence of odd-frequency spin triplet states at the ChMs/Nb interface. These results suggest that ChMs/S system can be used for the generation and manipulation of spin-triplet states similar to S/F hybrids.

In the second study [4], we demonstrate evidence for unconventional magnetism due to orbital loop currents at the reconstructed surface of the superconductor Sr_2RuO_4 in its normal state. The presence of these magnetic states raises questions on their interplay with superconductivity in Sr_2RuO_4 and it can be crucial to address the open questions on the symmetry of the superconducting state in this compound.

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Spin physics in superconducting junctions

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The interplay between exchange, spin-orbit, and superconducting coupling is a source of fascinating physics. I will discuss our theoretical works on quasiparticle and superconducting transport in tunnel junctions comprising ferromagnets and superconductors, in view of some recent experimental discoveries. I will cover several themes: (i) The interplay of spin-orbit and exchange coupling as manifested in transport magnetoanisotropies in SFS Josephson junctions, especially pronounced close to the 0-pi transitions [1], and in FSF junctions, where the effect is giant compared to the normal transport counterpart [2], as also seen in an experiment [3], and can also be manifested by triplet pairing [4]. (ii) The emergence of zero-energy Yu-Shiba-Rusinov states in the magnetic superconducting junctions is correlated with the appearance of the 0-pi transitions in ferromagnetic Josephson junctions [5]. (iii) The spin-orbit interaction leads to the appearance of transverse supercurrents as a result of conventional and Andreev skew scattering. As with magentoanistropy, this effect can be giant (compared to the classical counterpart) due to constructive addition of various transport channels [6]. (iv) Finally, I will report on our recent realistic simulations of the superconducting diode effect discovered in highly transparent lateral Josephson junctions based on InAs quantum wells [7].

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Quantum spins and hybridization in artificially-constructed chains of magnetic adatoms on superconducting 2H-$NbSe_2$

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Magnetic adatom chains on superconducting substrates constitute a fascinating platform to study the interplay of quantum magnetism and superconductivity. Here, we investigate magnetic adatom chains in the “dilute” limit. This means that the atoms are sufficiently far spaced that direct hybridization of their d orbitals is negligible, but close enough for sizeable substrate-mediated interactions. We build these chains from individual Fe atoms on a 2H-$NbSe_2$ substrate. Using scanning tunneling microscopy and spectroscopy we first characterize the exchange coupling between the magnetic adatoms and the superconductor by detecting their Yu-Shiba-Rusinov states within the superconducting energy gap. We then use the tip of the STM to assemble dimers, trimers and chains of these Fe atoms. In each step, we track the evolution of the Yu-Shiba-Rusinov states and identify magnetic interactions, hybridization and band formation [1].

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The T-SQUIPT: Thermal Superconducting Quantum Interference Proximity Transistor

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Superconducting materials are known to be good thermal insulators at sufficiently low temperatures thanks to the presence of the energy gap in their density of states (DOS). Yet, the proximity effect allows to tune the local DOS of a metallic wire by controlling the phase biasing imposed across it. As a result, the wire thermal resistance can be largely tuned by phase manipulation. In this talk I will show the experimental implementation of efficient control of thermal current by phase tuning the superconducting proximity effect. This is achieved by using the magnetic flux-driven modulation of the DOS of a quasi one-dimensional aluminum nanowire forming a weak-link embedded in a superconducting loop [1]. Moreover, phase-slip events occurring in the nanowire are able to induce a hysteretic dependence of its local DOS on the direction of the applied magnetic field. Thus, we also demonstrate the operation of the nanovalve as a phase-tunable *thermal* memory [1, 2], thereby encoding information in the local temperature of a metallic electrode nearby connected. Besides quantum physics, our results are relevant for the design of innovative phase-coherent caloritronics devices such as thermal valves and temperature amplifiers, which are promising nanostructures for the realization of heat logic architectures.

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Long-lived Andreev states in a bismuth nanoring Josephson junction: Evidence for topological hinge modes

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A three-dimensional Second-Order Topological Insulator is a 3D material with insulating bulk and surfaces, but topologically protected 1D states which conduct current along the hinges between the crystal surfaces. Those hinge states are Quantum Spin Hall states, i.e. counter-propagating helical states in which the spin orientation is locked to the propagation direction. Such states open many possibilities, from dissipationless charge and spin transport to new avenues for quantum computing. Bismuth has been shown to belong to this class of materials [1,2,3]. Adding superconducting contacts to bismuth nanowires has allowed us to reveal the ballistic character of the Andreev states at the hinges, via the sawtooth-shaped supercurrent-versus-phase relation [1,2]. We also recently demonstrated the topological nature of those states in an ac-squid configuration, thanks to the tell-tale high frequency signature of protected Andreev level crossings, a peaked absorption at phase pi [3].
In this talk, I will present our current investigation of how helical Andreev edge states differ from spin-degenerate Andreev states of a non-topological ballistic wire. [4]. In particular, I will present our use of the full statistical distribution of the switching current of a bismuth nanoring Josephson junction to probe the relative occupation probability of different possible states (ground or excited) of the hinge Andreev modes. Using a phenomenological model, we determine the relative relaxation times of pairs and quasiparticles. In striking contrast with non-topological systems for which the pair relaxation is orders of magnitude faster, we find a relatively slow pair relaxation, which we attribute to the spatial separation of the helical hinges, and hence the SOTI character of bismuth. This experiment thus provides insight into how Cooper pairs must split into spatially separate helical Andreev modes to travel through a SOTI.

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Thermal versus electric response of superconducting topological materials; are Majorana states more widespread than expected?

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In this talk, we will discuss different Josephson junctions based on semimetals, metals and topological insulators proximitized with s-wave superconductors. We show that thermal response can be more sensitive to Majorana bound states than an electrical response [1,2,3]. Moreover, due to the 4pi periodicity of topological Josephson junctions, the thermal engines built on them are more efficient as the ones on the classical Josephson junctions [4].

Furthermore, we predict that the s-wave superconductivity proximitized j=3/2 particles in 2D Luttinger materials are able to host Majorana bound states even in the absence of BIA and Rashba spin-orbit couplings [5]. This originates from the hybridization of the light and heavy hole bands of the j=3/2 states in combination with the superconducting pairing. We predict that Majorana bound states should be seen in many classes of materials like p-doped GaAs, bulk HgTe, as well as many half-Heusler compounds [5].

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Hidden magnetism and spontaneous vortices in 4Hb-TaS_2

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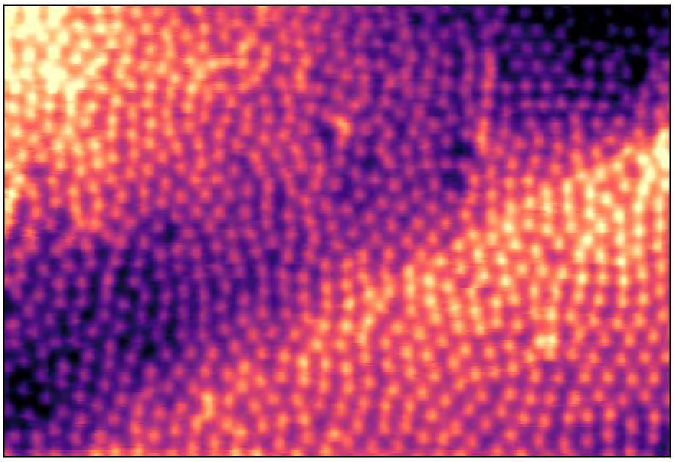
Van der Waals heterostructures provide a unique opportunity to examine proximity effects between materials with vastly different ground states. 4Hb-TaS_2 naturally realizes this opportunity as its structure is an alternate stacking of two lattice structures, 1T and 1H, a Mott insulator and a superconductor. I will show scanning SQUID data mapping the magnetic landscape of this compound. The data reveal magnetic history that affects the superconducting state, and survives in the normal state. Our results indicate that the coupling between the two constituent layers generates a new unconventional ground state.



Ultrasensitive thermal detection by a proximitized nano-calorimeter in superconducting quantum circuits

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We present a nano-calorimeter, whose key elements are an ultrasensitive tunnel junction-based proximity supercurrent thermometer (ZBA thermometer) and a nanosized proximitized normal metal absorber [1,2]. Due to the very low dissipation in the supercurrent regime at low bias voltage and the very small heat capacity of the electronic absorber coupled weakly to a phonon bath, the detector reaches the ultimate noise level dictated by the fundamental thermal fluctuations [3,4]. Based on these features we estimate favorably the potential of this sensor to detect single microwave photons in a continuous manner. A scheme of coupling a superconducting qubit to this calorimeter is presented [5]. To boost the signal-to-noise ratio, we propose theoretically splitting of the photon to two uncorrelated absorbers and performing a cross-correlation measurement of the two temperatures [6]. At the end we present the current experimental status of the proposed measurement scheme.

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Anisotropic vortex squeezing in Rashba superconductors: a manifestation of Lifshitz invariants

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Most of 2D superconductors are of type II, i.e., they are penetrated by quantized vortices when exposed to out-of-plane magnetic fields. In a presence of a supercurrent, a Lorentz-like force acts on the vortices, leading to a drift and dissipation. The current-induced vortex motion is impeded by pinning at defects. Usually, the pinning strength decreases upon any type of pair-breaking interaction that perturbs a system and destroys the superconducting coherence.

In the talk I will discuss surprising experimental evidences showing an unexpected enhancement of pinning in synthetic Rashba 2D superconductors when exposed to an in-plane magnetic field. When rotating the in-plane component of the field with respect to the driving current, the vortex inductance turns out to be highly anisotropic and squeezed. We explain this phenomenon as a direct manifestation of the Lifshitz invariant, a term that is allowed in the Ginzburg-Landau free energy when space-inversion and time-reversal symmetries are broken. As demonstrated in our experimental-theory work [arXiv:2201.02512], the elliptic squeezing of vortices---an inherent property of the non-centrosymmetric superconducting condensate---can provide an access to fundamentally new property of the Rashba superconductors, and can offer an entirely novel approach to the vortex manipulation.

Breaking the Clogston-Chandrasekhar limit via flat bands and giant anisotropy in antiferromagnetic Josephson junctions

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The Chandrasekhar-Clogston limit normally places stringent conditions on the magnitude of the spin-splitting field that can coexist with spin-singlet superconductivity, restricting the critical induced Zeeman shift to a fraction of the superconducting gap. Here, we consider a model system where the spin-singlet Cooper pairing in a dispersive band crossing the Fermi level is boosted by an additional flat-band located away from the Fermi level. Moreover, considering a different system, we predict that the amplitude of the Josephson current through an antiferromagnetic weak link changes by several orders of magnitude upon rotation of the Néel order parameter characterizing the staggered magnetic order. This occurs due the presence of spin-orbit coupling arising from structural inversion asymmetry which makes the band gap in the antiferromagnet highly sensitive to Néel vector direction.

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Proximity Effect Induced Superconductivity in Sb_2Te_3 Nanowire

J. Zhang, A. Jalil, J. Kölzer, T. Schäpers and J.G. Lu

Topological insulator when combined with superconducting electrodes are systems which are considered as very promising building blocks for achieving topological quantum bits based on Majorana fermions.[1-3] In order to create Majorana fermions, one-dimensional structures of topological insulators are required. To form the required topological superconducting state in the topological insulator, it has to be proximitized by an s-type superconductor. In many cases, topological insulators are grown by molecular beam epitaxy or thin layers are prepared by exfoliation. However, in both cases it is rather difficult to form one-dimensional structures since the required etching step often deteriorates the material. As an alternative approach, quasi one-dimensional structures can be created by chemical vapor deposition technique.

We would like to present the transport properties of Sb_2Te_3 topological insulator nanoribbon/superconductor hybrid structures. These hybrid structures are thoroughly characterized at low temperatures, in order to gain information on the inducted proximity effect in the topological insulator nanoribbon.[4] All measurements are performed in a four-terminal configuration. We find a clear signature the Josephson effect in the current-voltage characteristics. Its occurrence is due to two proximitized regions connected by a weak link formed by the connecting topological insulator nanoribbon bridge. After exceeding the critical current, we observe an enhanced conductance, which we attribute to the remaining proximitized regions directly underneath the superconducting electrodes. The transport studies are complemented by measurements in a magnetic field. As we can unambiguously show that the topological insulator nanoribbon becomes superconducting due to the proximity effect, it renders an essential step towards the realization of Majorana fermions.

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Superconductivity in double nanowires: Cooper pair splitting and Andreev molecule

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Hybrid nanostructures consisting of two parallel InAs nanowires connected by an epitaxially grown superconductor (SC) shell recently became available [1]. The defect-free SC-semiconductor interface and the vicinity of two quasi-one-dimensional channels can be utilized to enhance crossed Andreev reection (CAR) between quantum dots (QD) formed in the separate wires. These properties allow not only a highly-efficient spatial separation of entangled electrons in the so-called Cooper pair splitting process (CPS) [2], but can lead to the strong hybridization of the QDs resulting in an Andreev molecule [3], as a milestone towards more exotic states, like Majoranna or parafermions [4].
We demonstrate the experimental realization of both CPS and Andreev molecule in different parallel nanowire-based nanocircuits (see Fig. 1). At ultra-low temperature, we characterize the electrostatic and the CAR-mediated interaction between parallel QDs. The electron transport in both systems is analyzed theoretically showing good agreement with the measurements.

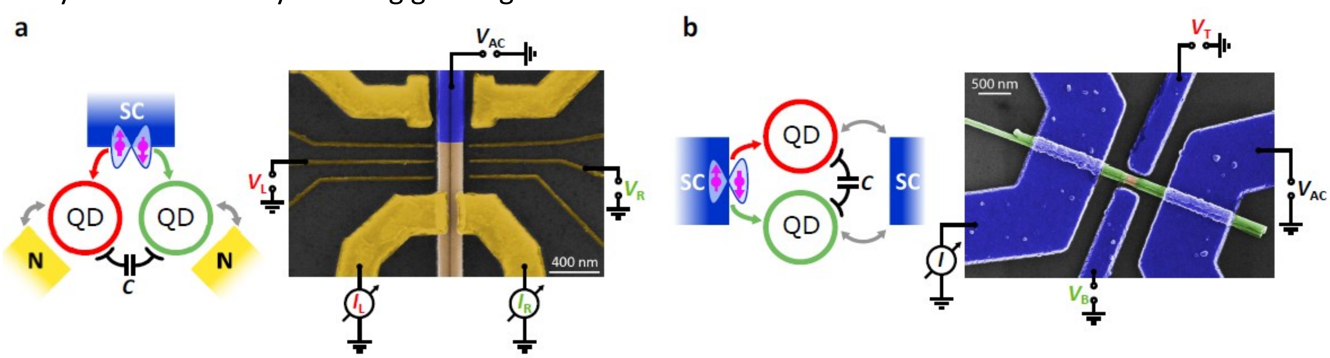

Figure 1: *Schematics and scanning electron micrographs of the devices in which **a** CPS and **b** Andreev molecule were captured with strong capacitive (C) and superconducting coupling.*

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Two-gap Ising superconductivity from Coulomb interactions in monolayer $NbSe_2$

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In conventional materials the presence of repulsive Coulomb interactions is in general detrimental to superconductivity. Nevertheless, it has long been known that when the Coulomb interaction, in addition to repulsive short-range scattering processes, generates also long-range attractive processes, the superconductivity can still arise [1]. More recently, Roldan et al [2] have proposed another mechanism which may act in materials with fragmented Fermi surface, such as transition metal dichalcogenides (TMDCs). The competition between short and long range processes, both of them repulsive, can lead to an effective attraction which again induces superconducting pairing. This idea has been strongly developed by Shaffer et al [3], who have shown theoretically that, even with purely repulsive interactions, the application of the magnetic field and/or Rashba spin-orbit coupling can drive TMDCs such as $NbSe_2$ into a multitude of non-trivial superconducting phases.

In the present work we follow the original idea of Roldan et al., starting from the premise of repulsive interactions and disjoint Fermi surfaces around the K points in $NbSe_2$. Using a microscopic multiband BCS approach we derive and self-consistently solve the gap equation. We find two distinct superconducting gaps, one for the outer and one for the inner Fermi pockets, both consisting of a mixture of s-wave and f-wave components. The presence of two gaps is consistent with the recent observation of a collective Leggett mode in monolayer $NbSe_2$ [4]. Further, our results for the dependence of the gaps on temperature, as well as for the critical in-plane field as a function of temperature, are consistent with various sets of existing experimental data.

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Diode effect in topological Josephson junctions

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A topological Josephson junction formed by connecting two superconductors through the helical edge states of a quantum spin-Hall insulator provides a simple model system that, in the presence of a Zeeman field along the spin quantization axis, displays a so-called diode effect, where the critical currents in opposite directions are different [1]. Here we show that parity constraints, inherent to the topological character of the junction, enhance this effect.

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Superconductor Heterostructures Displaying Unusual Behavior

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One of the major fundamental phenomena in condensed matter physics that continues to evolve over the decades displaying exotic properties is superconductivity. Its richness and complexity are evident in many of the recent studies. This includes our recent Majorana zero mode (MZM) pair in the superconducting gold surface state - a topological superconductor; coexistence of superconductivity and ferromagnetism; as well as the nonreciprocal critical current flow in superconductor heterostructures. For example, seeking MZM we approached the problem based on the theoretical prediction by A. Potter and P. Lee that large (~ 110meV) Rashba spin-orbit split Shockley surface states in gold could host the MZM. Our studies show the classic example of surfaces and interfaces playing a pivotally defining role in superconductor heterostructures for many of the topologically driven nontrivial quantum phenomena. We will discuss MZM and other two phenomena in the talk.

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Misfit Layer Compounds: A Platform for Heavily Doped 2D Transition Metal Dichalcogenides

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Transition metal dichalcogenides (TMD) display a rich variety of correlated states such as spin and charge orders, superconductivity and topological properties. In the monolayer limit, TMD's Fermi level is easily tunable by electric gates and adatom deposition [1], thus the competition between correlated states. In addition, TMD break inversion symmetry which, combined with the presence of large spin-orbit interaction, give rise to out-of-plane spin-momentum locking at K and K' corners of the Brillouin zone and unconventional Ising pairing. This pairing leads to strong magnetic in-plane critical fields, well beyond the paramagnetic limit as observed in $NbSe_2$ [2]. Moreover, recent theoretical studies support the emergence of topological superconductivity carried out by the spin polarized bands thanks to the fine tuning of the doping [3].

A new alternative platform to exceed the electric-field doping limit is obtained by TMD-based misfit layer compounds. Here, I present the misfit $(LaSe)_{1.14}(NbSe_2)_2$: a compound formed from the alternation of blocks of 2H-$NbSe_2$ and unit cells of LaSe rock salt. Its band structure behaves as monolayer $NbSe_2$ with a rigid doping of 0.55-0.6 electrons per Nb in agreement with DFT calculations. Contrary to the 3x3 charge density wave (CDW) order in the monolayer $NbSe_2$ [4], $(LaSe)_{1.14}(NbSe_2)_2$ exhibits a CDW order with a 2x2 periodicity and very short coherence length [5]. In addition, STS and quasiparticle interference measurements show that large doping in $(LaSe)_{1.14}(NbSe_2)_2$ introduces signatures of unconventional pairing.

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Topological phenomena in Josephson tunnel junction circuits

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Promising topological properties have been predicted in multi-terminal Josephson junctions [1], but so far they remained out of experimental reach due to lack of microscopic control over the normal weak link. Here we discuss an alternative approach based on two-terminal Josephson tunnel junctions [2,3]. In these circuits, topology naturally appears in the form of robust level crossings in the dispersion of charge states as a function of superconducting phase differences and charge offsets.
We first give a recipe for finding robust topological band crossings in simple Josephson circuits, and extend the discussion to more complex circuits with degeneracies in higher dimensions. We then present the results of a circuit-QED spectroscopy experiment of a three-junction circuit, the BiSQUID. We show that it simulates a Weyl semi-metal with robust linear band crossings in a unit cell of its three-dimensional parameter space.
This work shows that Josephson tunnel junction circuits are a promising platform to simulate topological properties inaccessible in regular condensed matter systems and to realize protected quantum devices.

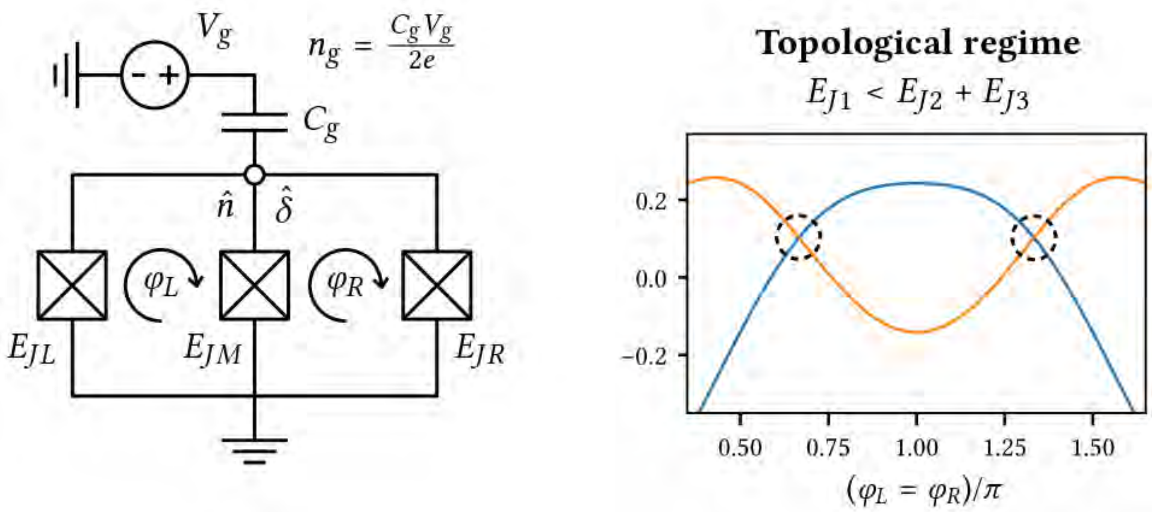

Figure: A BiSQUID circuit, formed by three Josephson junctions in parallel (left), is a simple topological circuit with Weyl nodes of opposite topological charges (right).

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Signatures of interactions in the Andreev spectrum of nanowire superconducting weak links

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In a non-superconducting material linking two superconductors, discrete quasiparticles states are formed as electrons and holes are "transmuted" into each other through successive Andreev reflection processes at both interfaces. The energy of these Andreev bound states depends on the phase difference between the complex order parameters of the superconductors. As a result, such a "weak link" carries a supercurrent and behaves as an inductance that depends on the occupation of the Andreev states.

I will review a series of experiments performed on semiconducting nanowire weak links [1,2,3] relying on the techniques of "circuit Quantum Electrodynamics", which consist in probing a quantum circuit through a coupled resonator [4]. They reveal the rich physics of Andreev Bound States, from the basics to the effects of spin-orbit coupling and of Coulomb interactions.

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Tunnelling spectroscopy of few-monolayer $NbSe_2$ in high magnetic field: Ising protection and triplet superconductivity

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Triplet superconductivity are expected to arise in systems with superconducting correlations in which non-colinear magnetic fields exist, perhaps most notoriously in magnetic textures. Odd-parity equal-spin triplet pairs (ESTPs) have recently been predicted to arise in superconductors with Ising (or valley Zeeman) spin-orbit coupling (ISOC), such as NbSe2, due to the non-colinearity between the Ising field, which pins Cooper pair spins out-of-plane, and an applied in-plane magnetic field. Using van der Waals tunnel junctions, we perform spectroscopy of superconducting NbSe2 flakes, of thicknesses ranging from 2--25 monolayers, measuring the quasiparticle density of states as a function of applied in-plane magnetic field up to 33T, the first spectroscopy measurements on TMDs at these fields. In flakes up to \approx\ 15 monolayers thick, we find that the density of states is well-described by a single band superconductor. In these thin samples, the magnetic field acts primarily on the spin (vs orbital) degree of freedom of the electrons, and superconductivity is further protected by ISOC. We extract the superconducting energy gap as a function of the applied magnetic field from our tunnelling data. In bilayer NbSe2, close to the critical field (up to 30T, much larger than the Pauli limit), superconductivity appears to be even more robust than expected if only ISOC is considered. Our data are well-explained by the above-mentioned equal-spin triplet pairs. These ESTPs are revealed by the magnetic field, which also couples them to the dominant singlet order parameter.

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Transport signatures of Majorana edge modes in two-dimensional topological insulator - chiral topological superconductor junctions

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Topological states are recent concepts in condensed matter physics that have important implications for example in metrology, due to their robust transport properties and also in topological quantum computation through the braiding of Majorana bound states. In this talk, we propose and analyze detection schemes for the presence of chiral Majorana edge modes in Normal-Superconductor (NS) - and Josephson (SNS) junctions using spin-momentum locked helical edge states of two-dimensional topological insulators. We theoretically show that such junctions can be implemented and probed in real materials using a four-band model (BHZ-model) for the topological insulator, including Rashba- and Dresselhaus spin-orbit coupling and the proximity effect due to an s-wave superconductor. We employ numerical Green-function techniques as well as analytical scattering approaches to unveil how the relative strength of the different Andreev reflection processes (local Andreev reflection processes involving a single helical edge vs crossed Andreev reflection processes involving both helical edges) depends on the presence of the chiral Majorana edge modes, and, consequently, influences the transport properties of the setups considered.

Supercurrent diode and magnetochiral effects in symmetric Josephson junctions

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We study Josephson junctions in hybrid aluminum/InGaAs/InAs structures. Using a cold resonator technique, we measure the Josephson inductance as well as DC transport properties. We find that our junctions are in the ballistic limit, featuring a current phase relation with near-unity transmission [1]. When applying in-plane magnetic fields, the Josephson inductance reveals a presence of cosine contributions to the current phase relation, which allows us to directly derive the supercurrent magnetochiral anisotropy coefficient. Moreover, we observe a pronounced superconducting diode effect of the critical current far below the superconducting transition temperature [2, 3].

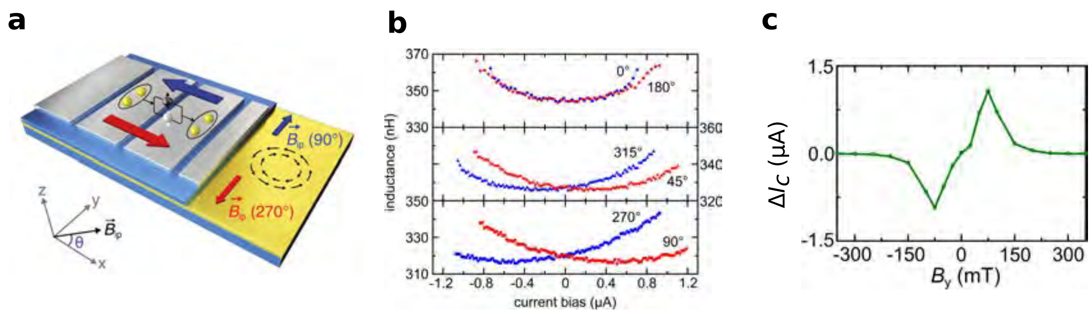

Figure 1: **a,** Sketch of Josephson junction array formed by a chain of Al islands (grey) on top of an InAs quantum well (yellow). Red and blue arrows denote the spontaneous supercurrents flowing at zero phase difference via spin-split pairs of Andreev bound states. **b,** Josephson inductance as a function of current bias for an applied in-plane magnetic field of 100mT. The magnetochiral effect is maximal for a magnetic field applied perpendicular to the current (bottom graph). **c,** Difference of $|I_c|$ for the two bias polarities as a function of applied in-plane magnetic field B_y for zero out-of-plane magnetic field B_z.

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Observation of microwave Higgs-Anderson modes in superconducting Titanium nanostructures

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The Higgs-Anderson mode in superconductors is known to be difficult to observe because of its weak coupling to the electromagnetic field. A recent theory [1] predicted a huge increase of this coupling in the presence of a DC supercurrent, which should translate into an anomaly in the complex conductivity at frequencies of the order of twice the superconducting gap Δ. This phenomenon has been experimentally confirmed in macroscopic NbN films exposed to THz radiations at a temperature of 5K [2].

In order to better control, and investigate in more depth Higgs mode properties, it would be very useful to be able to work at much lower frequencies, thus much lower temperature. Our experiment aims at providing such a step towards detecting and manipulating Higgs mode in a microwave circuit.

We studied Titanium samples for which 2Δ is of the order of 10-30 GHz and can be tuned with the sample thickness and temperature. We implemented a calibrated, cryogenic microwave reflectance setup, with which we measured the complex impedance vs. frequency and temperature of superconducting wires of various dimensions. In the absence of DC current we compare our results with BCS theory at equilibrium. Adding a current results in the appearance of an anomaly at frequency 2Δ on both the real and imaginary parts of the complex impedance. This feature behaves as predicted in [1], however it is much broader in frequency.

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Resonant transmission of Josephson current in Nb-$Bi_2Te_{2.3}Se_{0.7}$-Nb junctions via Andreev bound states

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A new type of resonant oscillations of the critical Josephson current in the magnetic field is observed in DC-transport response of ballistic Nb-$Bi_2Te_{2.3}Se_{0.7}$-Nb proximity junctions at temperatures below 500 mK [1]. The unexpectedly fine (~ 1 Oe) period of oscillations along with the upwards peaked maxima are attributed to the resonant transmission of quasiparticles through low-lying Andreev bound states forming at the superconductor-topological insulator interfaces owing to the p-wave component of the induced superconducting order [2].

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Semi-super-ferro hybrids: A new platform for unconventional superconductivity

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Recently developed semiconducting InAs nanowires with epitaxial superconducting Al and ferromagnetic insulator EuS shells display induced superconductivity with Zeeman-like splitting at zero external magnetic field [1]. The intricate interplay between spin-orbit coupling, magnetic domains, and superconducting coherence gives rise to unique ground states and corresponding electrical properties. In this talk, I will discuss our latest experiments on spin-polarization of the induced superconductivity [2,3].

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Higher-dimensional topological states of matter in superconducting systems

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Many robust physical phenomena in quantum physics are based on topological invariants, which are intriguing geometrical properties of quantum states. A prime example is the 2D quantum Hall effect with its quantized quantum Hall effect protected by the respective 2D topology. In general however these topological states of matter are theoretically not restricted to low-dimensional systems, as in the 2D quantum Hall effect, but can also emerge in higher-dimensional spaces in which control parameters play the role of extra synthetic dimensions. Unfortunately current implementations in the area of condensed matter rarely enable for implementations of higher-dimensional topological systems that by design are often restricted to three spatial dimensions.

In this work, we theoretically demonstrate how higher dimensional topological states of matter can be implemented in superconducting systems by using the synthetic dimensions of superconducting phase differences. In principle such implementation allows to construct exotic topological phases such as a 4D non-Abelian topological state of matter in a double quantum dot system coupled to superconductors [1] or a 4D Berry curvature tensor monopole using superconducting systems [2].

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Enhanced Spin-Triplet Superconductivity: From Spintronics to Majorana States

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While spin-triplet pairing remains elusive in nature, there is a growing effort to realize proximity-induced equal-spin triplet superconductivity in junctions with magnetic regions or an applied magnetic field and s-wave superconductors. Since such triplet is related to equal-spin Andreev reflection [1], to enhance its contribution, it is expected a weak interfacial barrier and strong spin-orbit coupling (SOC) are desirable. Intuitively, a weak interfacial barrier enables a robust proximity-induced superconductivity and strong SOC promotes spin mixing, converting singlet into triplet superconductivity. In contrast, we reveal a non-monotonic triplet contribution with the strength of the interfacial barrier and SOC [2,3]. This enhanced triplet superconductivity is consistent with the measured huge increase in the conductance magnetoanisotropy [4,5]. A similar proximity-induced triplet superconductivity also supports topologically-protected Majorana bounds states (MBS) for fault-tolerant quantum computing. We discuss our proposal for realizing such MBS in 2D platforms using magnetic textures to induce effective SOC and the challenges for their experimental demonstration [6,7]. Our studies of experimentally realizing proximity-induced topological superconductivity and phase measurements in Josephson junctions with gate-tunable SOC coupling [8] provide novel opportunities for controlling MBS [9] and probing their non-Abelian statistics through fusion [10].

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Abstracts of Posters

(in alphabetical order)

First principles analysis of Yu-Shiba-Rusinov states caused by an iron impurity in bulk lead

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Topological superconductors have the potential to realize long-sought Majorana zero modes (MZM) in solid state systems. These can be used as the building blocks for topological qubits which are robust against certain types of disorder and decoherence. Materials that combine magnetism, spin-orbit interaction and conventional s-wave superconductivity are a suitable platform to study these exotic states of matter [1]. Magnetic impurities in superconductors on the other hand offer a pair breaking potential to singlet Cooper pairs which leads to localized Yu-Shiba-Rusinov (YSR) states at the impurity [2]. Understanding YSR states and their interplay with MZMs is crucial in achieving topological quantum computers in the future.

In the field of solid state physics, the Korringa-Kohn-Rostoker (KKR) method is a powerful density functional theory-based method to study the electronic structure of crystals. The Green's function variant of this method is also very convenient for materials with reduced symmetry, such as impurities embedded into crystalline solids [3]. However, the KKR Green's function method needs to be extended with the Bogoliubov-de Gennes (BdG) formalism in order to allow calculations with superconducting materials [4]. In our work, we implement the BdG formalism in the juKKR impurity code (https://iffgit.fz-juelich.de/kkr/jukkr.git), and apply it to an iron impurity embedded in a bulk lead. We compute the impurity's local density of state in the normal and superconducting state, and analyze the YSR states that emerges from the magnetic defect. We further comment on the importance on spin-orbit coupling for the YSR states in the heavy metal superconductor Pb.

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Topological phase transition away from the Fermi surface in multiband superconductors

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We show theoretically that the formation of odd-parity interband Cooper pairing at finite excitation energies can be accompanied by a topological phase transition, shown in Figs.1 (a) and (b). It happens in directions where the inter- and intra-band pairings are finite and vanishing, respectively. The emergent topological surface states are dispersive in energy away from the transition direction as depicted in Figs.1 (c). To capture the underlying mechanism, we develop a generic theory in the interband representation of the Bogoliubov-de Gennes Hamiltonian valid for weakly interacting systems. We apply our theory to j=3/2 systems.

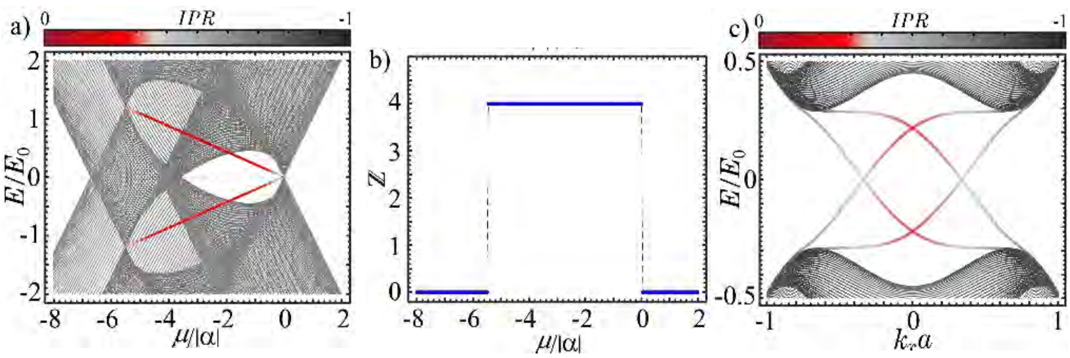

Figure 1. (a) Excitation energy along the direction [0,0,1] in the presence of septet J=3 pairing. (b) Topological index corresponding to the panel (a). (c) Dispersive spectrum in the k_x direction.

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Supercurrent diode effect in few-layer $NbSe_2$ nanowires

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A superconductor formed from a metallic superlattice with strong Rashba spin-orbit coupling exhibits anisotropy in its critical currents when applying a magnetic field resulting in a diode where current flows non-dissipative only in one direction [1].

We report here on the superconducting diode effect in $NbSe_2$ nanowires obtained by patterning a constriction in few-layered $NbSe_2$ crystals. The observed rectification efficiency of these two-dimensional crystals can be as large as 60%, more than one order of magnitude larger compared to devices based on bulk Rashba superconductor. As predicted for valley-Zeeman spin-orbit coupling [2], we find that the diode effect is driven by an out-of-plane magnetic field component, cf. Fig. 1. In an IV characteristic the critical currents for positive and negative bias are offset by the magnetic field. Inverting B_z also inverts the offset. Remarkably, the maximum of I_c^+ and I_c^- are shifted to finite field values. This excludes, that the rectification is simply an effect of resistive magnetochiral anisotropy due to vortices. Moreover, we show that the in-plane field plays a role as well: when applied perpendicular to the current, it renders the diode effect asymmetric in the out-of-plane dependence. This effect is unexpected for 2D systems with purely out-of-plane spins and may signal the presence of an additional Rashba component in the spin-orbit interaction.

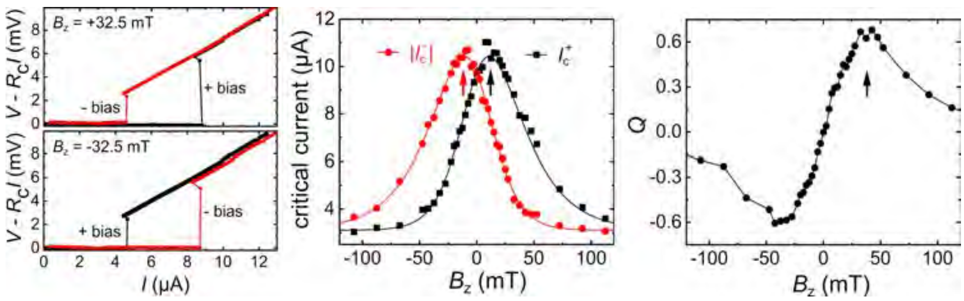

Figure 1: Diode effect in few-layer $NbSe_2$. Left: Magnitude of critical currents swap under magnetic field inversion. Contact resistance R_c $\approx$1kΩ has been subtracted. Middle: Critical currents show maximum at finite field. Right: The rectification efficiency, Q=2$\cdot$(I_c^++I_c^-)/($|I_c^+|$+$|I_c^-|$), can become as large as 60%.

* Supported by the European Union's Horizon 2020 program under grant agreement number 862660/QUANTUM E LEAPS.

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Tuning the spin-orbit coupling in 1D magnetic structures on superconducting surfaces

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The realization of Majorana bound states (MBS) in a hard topological gap remains one of the key goals in current solid state physics research. One approach features the construction of 1D chains of magnetic impurities on an *s*-wave superconductor, using the tip of a scanning tunneling microscope (STM) to tailor in-gap bands of Yu-Shiba-Rusinov (YSR) states [1]. Recent experiments have demonstrated the band formation of YSR states and their experimental measurement [2] as well as the energy-oscillations of precursors of MBS [3] in Mn chains on Nb(110). With these tools at hand, the remaining challenge to tailor MBS has evolved to a material science issue, as the requirements for the superconducting substrate are versatile: (i) High T_C and a correspondingly large superconducting gap, (ii) high spin-orbit coupling (SOC) to induce a large topological gap, (iii) ultrahigh quality of the substrate to enable minimally disordered bands and STM tip-induced atom manipulation of chains. Here we present an STM study of artificial magnetic structures on tailored substrates meeting the requirements above, which are elemental superconductors with larger atomic mass than Nb and heterostructures of a high-*Z* material deposited on Nb(110) (e.g. [4]). We utilize scanning tunneling spectroscopy of artificially constructed magnetic chains with tunable length to resolve their in-gap band structure and, thereby, shine light on the influence of the substrate's SOC on the physical properties of the adatom chains.

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Influence of in-plane and out-of-plane magnetic fields on quantum interference in a 1d array of three-terminal Josephson junctions

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We present DC transport measurements of an 1d array of three-terminal Josephson junctions based upon an epitaxial Al-InAs heterostructure. Two terminals are connected via a superconducting loop. Under the influence of perpendicular magnetic fields the critical current displays a superposition of a Fraunhofer pattern-like envelope and SQUID oscillations. In the presence of an in-plane magnetic field this pattern becomes asymmetric with respect to magnetic field and current polarities: The interference patterns show clear supercurrent diode behavior [1] as well as a markedly asymmetry of the side maxima of the envelope. The latter means, that with increasing in-plane magnetic field the critical current is enhanced for one polarity of the perpendicular magnetic field. Unlike the Diode effect this asymmetry is not suppressed at higher fields.

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Spin-orbit coupling assisted transport phenomena in superconducting magnetic tunnel junctions

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Superconducting magnetic tunnel junctions exhibit fascinating physical phenomena, making them essential building blocks for modern technologies like quantum computing. Particularly attractive are multicomponent junctions in which the broken space-inversion symmetry rises strong spin-orbit coupling (SOC). Pairing the interplay of the two most important spin interactions---ferromagnetic exchange and SOC---with superconducting coherence has already been demonstrated to lead to unique signatures in spectroscopy and transport, and is furthermore expected to induce topological superconductivity potentially hosting Majorana states.

This poster will characterize some of the most intriguing transport ramifications of SOC in superconducting magnetic junctions, covering giant transport magnetoanisotropies [1], the possibility to generate sizable transverse anomalous (Josephson) Hall effects [2, 3], as well as nonreciprocal transport and supercurrent-diode characteristics in proximitized 2DEG Josephson junctions [4, 5]. After briefly sketching the details of the applied theoretical approaches, we will mostly focus on the experimental consequences of our findings and relate them to recent measurements to illustrate the robustness of our theoretical predictions.

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Fabrication and measurements for a deeper investigation of charge density waves in 1T-TaS_2 devices

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Two dimensional materials are a current, interesting research field where novel quantum phases can arise due to the dimensionality constraints. For instance, transition metal dichalogenides (TMDCs) with their monolayered heterostructure exhibit manifold phases. The coupling of the charges to the displacement of the lattice atoms, known as charge density waves (CDW), is one mechanism in 2D-materials which leads to new phases in such systems. Our work focuses on novel phases generated by CDW in the prototypical 1T-TaS_2 TMDC. With different device designs as freestanding and hBN encapsulated ones we will be able to perform magnetotransport measurements on high quality samples combined with SNOM and IR-spectroscopy to investigate layer thickness dependency and controlled phase switching via electrical pulses. Additionally, using ultrafast low-energy electron diffraction and ultrafast transmission electron microscope techniques allows to investigate time-resolved evolution of the CDW-phases. Preliminary work will be presented and an outlook of the upcoming measurements will be discussed.

Supercurrent oscillations in 3D topological insulator nanowire Josephson junctions

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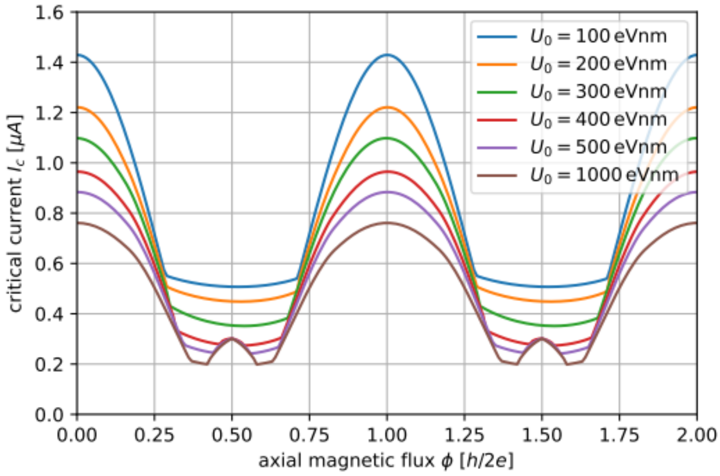
We investigate Josephson junctions from 3D topological insulator nanowires hosting surface states. The two superconducting contacts are placed on top such that only a part of the wire circumference becomes superconducting by the proximity effect. We calculate the critical current and examine it's dependence on the axial magnetic field. The critical current shows oscillations with an unexpected Fraunhofer-like pattern showing peaks when the flux through the wire cross section is h/4e, h/2e etc., see the figure below. A semiclassical treatment explains how these oscillations occur reveals which trajectories are responsible for them.



Ab initio study of the van der Waals Superconductor

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Transition metal dichalcogenides (TMDCs) are a very versatile material class in which a plethora of physical phenomena can be realized. This ranges from 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 NbSe2 is an example of a superconducting TMCD which shows the unconventional Ising superconductivity that is particularly robust against magnetic fields. We study NbSe2 on the basis of first principles calculations within the Korringa-Kohn-Rostoker Green function method which allows to combine 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.

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Prevalence of trivial zero-energy sub-gap states in non-uniform helical spin chains on the surface of superconductors

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Helical spin chains, consisting of magnetic (ad-)atoms, on the surface of bulk superconductors are predicted to host Majorana bound states (MBSs) at the ends of the chain. Here, we investigate the prevalence of trivial zero-energy bound states in these helical spin chain systems [1]. The existence of trivial zero-energy bound states can prevent the conclusive identification of MBSs and, given the limited tunability of atomic spin chain systems, could present a major experimental roadblock. First, we show that the Hamiltonian of a helical spin chain on a superconductor can be mapped to an effective Hamiltonian reminiscent of a semiconductor nanowire with strong Rashba spin-orbit coupling [2]. In particular, we show that a varying rotation rate between neighbouring magnetic moments maps to smooth non-uniform potentials in the effective nanowire Hamiltonian. Previously it has been found that trivial zero-energy states are abundant in nanowire systems with smooth potentials [3]. Therefore, we perform an extensive search for zero-energy bound states in helical spin chain systems with varying rotation rates. Although bound states with near zero-energy do exist for certain dimensionalities and rotation profiles, we find that zero-energy bound states are far less prevalent than in semiconductor nanowire systems with equivalent non-uniformities. In particular, utilising varying rotation rates, we do not find zero-energy bound states in the most experimentally relevant setup consisting of a one-dimensional helical spin chain on the surface of a three-dimensional superconductor, even for profiles that produce near zero-energy states in equivalent one- and two- dimensional systems. Although our findings do not rule them out, the much-reduced prevalence of zero-energy bound states in long non-uniform helical spin chains compared with equivalent semi-conductor nanowires, as well as the ability to measure states locally via STM, should reduce the experimental barrier to identifying MBSs in such systems.

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The anomalous Andreev interferometer

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Josephson junctions (JJs), where both time-reversal and inversion symmetry are broken, exhibit a phase shift f_0 in their current-phase relation. This allows for an anomalous supercurrent to flow in the junction even in the absence of a phase bias between the superconductors. We show that a finite phase shift also manifests in the so-called Andreev interferometers - a device that consists of a mesoscopic conductor coupled to the f_0-junction. Due to the proximity effect, the resistance of this conductor is phase-sensitive - it oscillates by varying the phase of the JJ. As a result, the quasiparticle current I_{qp} flowing through the conductor has an anomalous component, which exists only at finite f_0. Thus, the Andreev interferometry could be used to probe the f_0 effect.

We consider two realizations of the f_0-junction and calculate I_{qp} in the interferometer: a superconducting structure with spin-orbit coupling and a system of spin-split superconductors with spin-polarized tunneling barriers.

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Tunable 4π-periodic supercurrent in HgTe-based topological nanowires

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Topological insulator nanowires (TINW) in proximity to conventional superconductors were suggested as possibility to observe topological superconductivity (TSC) and Majorana zero modes [1]. Given the non-abelian statistics and topological protection of these quasiparticles, TINW present a tunable platform for fault tolerant quantum computing [2]. Using an axial magnetic flux ϕ the system can be tuned from trivial at $\phi = 0$ to topologically nontrivial when half a magnetic flux quantum $\phi = \phi_0/2 = h/2e$ threads the wire's cross-section.

In Josephson junctions (JJs), an indication of TSC and emanating Majorana bound-states is a 4π-periodic current-phase relation (CPR) [3]. A way to probe this periodicity of the CPR is the measurement of Shapiro steps. In the trivial situation (2π-periodic CPR) all Shapiro Steps are visible, while the odd ones are supposed to disappear if the CPR is 4π –periodic.

We investigate JJs based on HgTe nanowires with high mobility surface states [4] and probe the Shapiro Step spectrum for different microwave frequencies and intensities at millikelvin temperatures. From the suppression of odd Shapiro Steps, we extract the 4π- and 2π-periodic portion of the supercurrent using a resistively (RSJ) and a resistively and capacitively shunted (RCSJ) model.

The ratio $I_{4\pi}/I_{2\pi}$ of the 4π- and 2π-periodic supercurrents depends strongly on the axial magnetic flux through the wires' cross-section. While the total critical current I_C decreases with increasing flux, $I_{4\pi}/I_{2\pi}$ changes from a few percent at $\phi = 0$ up to a maximum of ~ 40% at $\phi = \phi_0/2$.

The presence of $I_{4\pi}$ at $\phi = 0$ and small magnetic fields indicates that in this trivial regime Landau-Zener transitions between trivial Andreev bound states cause the 4π-periodic current. Our data suggest that this trivial 4π-periodic supercurrent can be suppressed by an in-plane magnetic field, both axial or perpendicular to the wire, but at magnetic fields above $\phi_0/4$, topological 4π-periodic supercurrents take over in the axial configuration only.

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Current phase relation of HgTe nanowire Josephson junctions in an axial magnetic field

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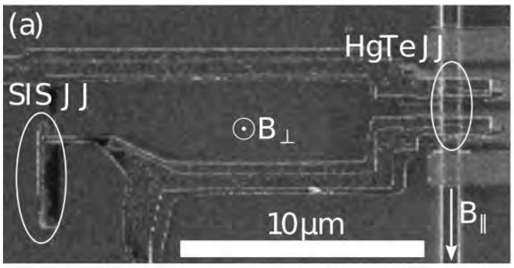
Topological insulators (TIs) such as HgTe nanowires host topological surface states. Their band structure can be tuned to a Dirac shape via the application of an axial magnetic field ($B_{\|}$) [1]. For proximitized nanowires this is expected to tune between trivial and topological supercurrents as recent experiments suggest [2]. Here we present measurements that directly probe the current phase relation (CPR) of a tunable TI Josephson junction.

The TI junction consists of a HgTe nanowire proximitized by superconducting Nb contacts. We embedded the nanowire junction into an asymmetric DC-SQUID together with a conventional Al/AlOx/Al junction see Fig. 1 (a). The nanowire junction turns out to be in the short junction regime [2]. It features a strongly anharmonic CPR see Fig.1 (b) that can be described by the generalized Kulik-Omelyanchuk theory [3,4]. At $B_{\|}$=0 a high average transparency of D≈0.95, an induced gap Δ^*≈0.15meV, and an approximate number of channels n≈10 is obtained [4]. Varying $B_{\|}$ controls the magnetic flux enclosed by the nanowire surface. In the range 0-1.5 Φ_0 we observe a strong modulation of both the critical current and the content of higher harmonics.



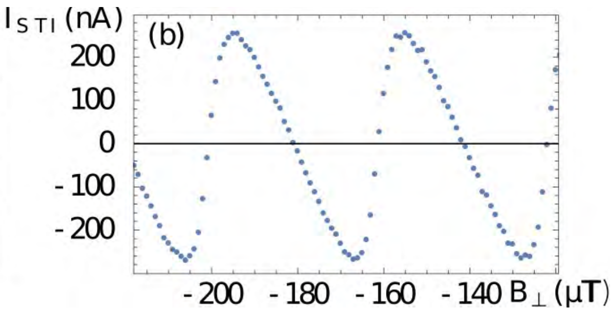


Figure 1: Applying an out of plane magnetic field ($B_{\perp}$) to the SQUID (a) tunes the superconducting phase of the HgTe JJ and reveals a strongly anharmonic CPR (b).

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Theory of the supercurrent diode effect in Rashba superconductors with arbitrary disorder

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We calculate the non-reciprocal critical current and quantify the supercurrent diode effect in Rashba superconductors with arbitrary disorder, using the quasiclassical Eilenberger equation. The non-reciprocity is caused by the helical superconducting state, which appears when both inversion and time-reversal symmetries are broken. In the absence of disorder, we find a very strong diode effect, with the non-reciprocity exceeding 40% at optimal temperatures, magnetic fields and spin-orbit coupling. We establish that the effect persists even in the presence of strong disorder. We show that the sign of the diode effect changes as magnetic field and disorder are increased, reflecting the changes in the nature of the helical state.

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The kinks, the solitons and the shocks in series connected discrete Josephson transmission lines

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We analytically study the localized running waves in the discrete Josephson transmission lines (JTL), constructed from Josephson junctions (JJ) and capacitors.
The quasi-continuum approximation reduces calculation of the running wave properties to the problem of equilibrium of an elastic rod in the potential field. Making additional approximation, we reduce the problem to the motion of the fictitious Newtonian particle in the potential well. We show that there exist running waves in the form of supersonic kinks and solitons and calculate their velocities and profiles. We show that the nonstationary smooth waves which are small perturbations on the homogeneous non-zero background are described by Korteweg-de Vries equation, and those on zero background -- by modified Korteweg-de Vries equation. We also study the effect of dissipation on the running waves in JTL and find that in the presence of the resistors, shunting the JJ and/or in series with the ground capacitors, the only possible stationary running waves are the shock waves, whose profiles are also found.

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Crossed Andreev Coupling in Parallel InAs Nanowires

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Hybrid nanostructures consisting of two parallel InAs nanowires connected by an epitaxially grown superconductor (SC) shell recently became available[1]. The defect-free SC-semiconductor interface and the vicinity of two quasi-one-dimensional channels can be utilized to enhance crossed Andreev reflection (CAR) between quantum dots (QD) formed in the separate wires. These properties allow not only a high-efficient spatial separation of entangled electrons in the so-called Cooper pair splitting process (CPS)[2], but can lead to the strong hybridization of the QDs resulting in an Andreev molecule[3], as a milestone towards more exotic states, like Majoranna or parafermions[4].

We demonstrate the experimental realization of both CPS and Andreev molecule in different parallel nanowire-based nanocircuits. At ultra-low temperature, we characterize the electrostatic and the CAR-mediated interaction between parallel QDs. The electron transport in the systems is analyzed theoretically which is matched to the measurements.

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Majorana bound states and giant magnetochiral anisotropy in topological insulator nanowires

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We consider a three-dimensional topological insulator (TI) nanowire and show that a non-uniform chemical potential across the cross-section of the nanowire lifts the degeneracy between two one-dimensional surface state subbands. Such a non-uniformity in chemical potential can be induced, for example, by gating [1] or the induced potential at the interface to a superconductor [2].

First, we show that a magnetic field *parallel* to the nanowire breaks time-reversal symmetry and, primarily due to orbital effects, lifts the Kramers degeneracy at zero-momentum. As a result, when brought into proximity with an *s*-wave superconductor, Majorana bound states (MBSs), localised at the ends of the TI nanowire, emerge and are present for an exceptionally large region of parameter space in realistic systems[1,2]. Unlike in previous proposals, these MBSs occur without the requirement of a vortex in the pairing potential, representing a significant simplification for experiments.

We also predict that, due to the subband splitting induce by a non-uniform potential, a magnetic field applied *perpendicular* to the TI nanowire axis should result in a large nonreciprocity of resistivity, an effect known as magnetochiral anisotropy. Our result is confirmed by experiments on thin $(Bi_{1-x}Sb_x)_2Te_3$ nanowires in which we observe the largest ever reported MCA rectification coefficient in a normal conductor [3].

Our results open a simple pathway to the realisation of MBSs in TI nanowires and show many of the ingredients necessary are already realised in current devices.

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Coexistence of Antiferromagnetism and Superconductivity in pseudomorphic Mn ultra-thin films on Nb(110)

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In the last few years, pioneering studies of magnet/superconductor hybrid systems have been carried out [1-3], motivated by their potential to host topological superconductivity. A recent investigation of Mn adatoms on top of a clean Nb(110) substrate has shown the emergence of Yu-Shiba-Rusinov (YSR) bound states. In addition, YSR bands as well as the emergence of p-wave superconductivity [4] and interacting Majorana modes [5] have been observed in Mn atomic chains on Nb(110). These results call for the investigation of Mn thin films on top of Nb substrates, where propagating chiral edge states may be stabilized at the 1D boundary of 2D islands.
Here, we report on the structural, magnetic and superconducting properties of single and double atomic layer Mn films and islands on a clean Nb(110) substrate, studied by low-temperature spin-polarized scanning tunneling microscopy and spectroscopy [6]. The Mn thin films are found to grow pseudomorphically on the Nb surface and exhibit a c(2x2) antiferromagnetic ground state. First principles DFT calculations confirm the observed magnetic ground state, which is understood as the consequence of a strong nearest-neighbor antiferromagnetic exchange coupling. Finally, scanning tunneling spectroscopy measurements reveal proximity-induced superconductivity in the Mn thin films and islands and the presence of in-gap states, indicating the formation of YSR bands.

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Proximity Effect Induced Superconductivity in Sb_2Te_3 Nanowire

J. Zhang, A. Jalil, J. Kölzer, T. Schäpers and J.G. Lu

Topological insulator when combined with superconducting electrodes are systems which are considered as very promising building blocks for achieving topological quantum bits based on Majorana fermions.[1-3] In order to create Majorana fermions, one-dimensional structures of topological insulators are required. To form the required topological superconducting state in the topological insulator, it has to be proximitized by an s-type superconductor. In many cases, topological insulators are grown by molecular beam epitaxy or thin layers are prepared by exfoliation. However, in both cases it is rather difficult to form one-dimensional structures since the required etching step often deteriorates the material. As an alternative approach, quasi one-dimensional structures can be created by chemical vapor deposition technique.

We would like to present the transport properties of Sb_2Te_3 topological insulator nanoribbon/superconductor hybrid structures. These hybrid structures are thoroughly characterized at low temperatures, in order to gain information on the inducted proximity effect in the topological insulator nanoribbon.[4] All measurements are performed in a four-terminal configuration. We find a clear signature the Josephson effect in the current-voltage characteristics. Its occurrence is due to two proximitized regions connected by a weak link formed by the connecting topological insulator nanoribbon bridge. After exceeding the critical current, we observe an enhanced conductance, which we attribute to the remaining proximitized regions directly underneath the superconducting electrodes. The transport studies are complemented by measurements in a magnetic field. As we can unambiguously show that the topological insulator nanoribbon becomes superconducting due to the proximity effect, it renders an essential step towards the realization of Majorana fermions.

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Flux periodic oscillations and phase-coherent transport in GeTe nanowires

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We present the phase-coherent phenomena in the magnetotransport of GeTe nanowires. From universal conductance fluctuations measured on GeTe nanowires with Au contacts, a phase-coherence length of about 280 nm at 0.5 K is determined. The distinct phase-coherence is confirmed by the observation of Aharonov–Bohm type oscillations for parallel magnetic fields. We interpret the occurrence of these magnetic flux-periodic oscillations by the formation of a tubular hole accumulation layer. For Nb/GeTe-nanowire/Nb Josephson junctions we obtained a critical current of 0.2 μA at 0.4 K. By applying a perpendicular magnetic field, the critical current decreases monotonously with increasing field; whereas in a parallel field, the critical current oscillates with a period of the magnetic flux quantum confirming the presence of a tubular hole channel.

Calorimetry and thermometry of a quantum phase slip

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Recently it has been observed experimentally that the low-bias anomaly in superconductor-normal-metal (SN) proximity systems can be utilized as an ultrasensitive thermometer for calorimetric measurements. In this presentation, we shall propose and describe a well-defined proximity thermometer based on a diffusive SN proximity junction coupled to an Ohmic electromagnetic environment of certain resistance. By employing the quasiclassical Keldysh Green's formalism in combination with the P(E) theory, we show that low-bias conductance (subgap regime) scales monotonically with temperature and thus can be used as a thermometer. The thermometer does not saturate even at very low temperatures (~10 mK).

In a Josephson junction, which is the central element in superconducting quantum technology, irreversibility arises from abrupt slips of the gauge-invariant quantum phase difference across the contact. A quantum phase slip (QPS) is often visualized as the tunneling of a flux quantum in the transverse direction to the superconducting weak link, which produces dissipation. Recently, the instantaneous heat release caused by a QPS in a Josephson junction has been experimentally detected by using time-resolved electron thermometry on a nanocalorimeter. This presentation will be focused on theoretical aspects of the effect. By employing the quasiclassical Keldysh Green's formalism, first, we shall study the screening supercurrent in the junction, which is directly responsible for the occurrence of phase slips. Then, we shall put a focus on the thermodynamics of the effect by describing the dynamics of the heat transfer, which is mainly due to the electron-phonon cooling channel.

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Full counting statistics of multiterminal Josephson junctions

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We examine the full counting statistics (FCS) of multiterminal Josephson junctions (MJJs) connected by one scattering matrix using the Synman-Nazarov Keldysh action approach [1]. The scattering matrix can be chosen to represent arbitrary quantum channels with variable transmission eigenvalues which enables us to study different types of superconducting circuits.

In the first part, the FCS for a SS junction with non-BCS type superconductors is computed and compared to measurements performed on superconducting single electron transistors. The FCS not only contains information on the current, shot noise and higher-order cumulants of the current but also includes charge-resolved currents caused by (multiple-) Andreev Reflection processes.

In the second part, the FCS will be computed for topological MJJs which exhibit energy-dependent scattering matrices because of the coupling to single-level quantum dots [2]. Our goal is to compute the FCS of these systems to find topological signatures like quantized transconductance or novel features in the charge-resolved currents.

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Yu-Shiba-Rusinov states in 2D superconductors with arbitrary Fermi contours

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Magnetic impurities on a superconductor induce sub-gap Yu-Shiba-Rusinov (YSR) bound states, localized at the impurity site, and fading away from it for distances up to several nanometers [1,2]. In this article, we present a theoretical method to calculate the spatial distribution of the YSR spectrum of a two-dimensional superconductor with arbitrary Fermi contours (FCs) in the presence of magnetic impurities. Based on the Green's Function (GF) formalism, we obtain a general analytical expression by approximating an arbitrary contour shape to a regular polygon. This method allows us to show the connection between the spatial decay of YSR states and the shape of the FC of the host superconductor. We compare with a tight-binding numerical calculation and find excellent agreement. We further apply this formalism to compute the evolution of YSR states in the presence of a nearby impurity atom [3] and compare the results with Scanning Tunneling Microscopy (STM) measurements on interacting manganese dimers on the β-Bi2Pd superconductor [4]. The method can be easily extended to arbitrary number of magnetically coupled impurities, thus providing a useful tool for simulating the spectral properties of interacting YSR states in artificial atomic nanostructures.

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Ising superconductors: The signatures of triplet pairings on the density of states and vanishing of the "mirage" gap

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The conventional two-dimensional superconductors are governed by the critical in-plane magnetic field above which the superconductivity is destroyed. Monolayer transition-metal dichalcogenides lack inversion symmetry and along with a strong spin-orbit coupling, lead to valley-dependent Zeeman-like spin splitting. This is the Ising spin-orbit coupling (ISOC) which then lifts the degeneracy of the two valleys and enhances the in-plane critical magnetic field. The finite energy pairings are thus obtained in such systems. The main superconducting gap-like feature shifted to finite energy is observed and termed a “mirage” gap [1].
The triplet pairings are introduced by the applied field, which then affects the critical field of Ising superconductors [2]. The equal-spin triplet pairing is always coupled to the singlet pairing thereby affecting the singlet order parameter greatly at higher fields. Importantly, we observe a peculiar feature of the mirage gaps in such systems. As the applied field increases from zero, the mirage gap appears, vanishes at some finite value of the field, and then appears back again as the applied field is increased. This finite value of the field at the mirage gap closing is exactly where the eigenvalues of the BdG Hamiltonian seem to cross each other. The concerned phenomenon in the absence of any disorder can be observed when the triplet critical temperature equals the singlet critical temperature. When the disorder (absent earlier) would be introduced, the vanishing of the mirage gap could also appear, for a range of triplet critical temperatures, different than the singlet critical temperature. The role of topology in such a mirage gap closing would be our topic of further study.

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High Precision Impedance Measurements of the Berezinski-Kosterlitz-Thouless Transition in Strongly Disordered Superconductors

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We investigate the Berezinskii-Kosterlitz-Thouless (BKT) transition in 3 nm thin atomically layer deposited NbN films. This topological phase transition is driven by the thermal unbinding of vortex-antivortex pairs in the quasi-2D limit of superconducting films. It manifests in a discontinuous drop to zero of the superfluid stiffness J_s and the onset of resistance below the mean field BCS critical temperature T_{c0}. Furthermore, the transition temperature T_{BKT} can be identified in current-voltage (IV) characteristics, since the application of a current modifies the attractive potential between vortex and antivortex and leads to power-law behaviour.
The sample is placed inside a RLC-resonator, whose shift in resonant frequency directly correlates to the sample's kinetic inductance $L_K \sim 1/J_s$. A special design enables us to perform measurements of IVs and J_s in the same cooling cycle. Besides two leads required to perform AC measurements in the MHz regime, two additional leads are implemented to investigate DC resistance and IVs in a four-probe setup.
Previous measurements of J_s in ultrathin NbN films via the two-coil method showed early deviation from BCS behaviour and thus a smeared BKT-transition (e.g. [1]). In contrast, we observe a sharp discontinuous jump of J_s at T_{BKT} in agreement with theory. Comparison of the stiffness and the DC resistance measurements reveal quantitative agreement of both T_{BKT} and T_{c0}.
Surprisingly, if a DC current is added to the rf-drive, $J_s(I)$ increases and reaches a pronounced maximum before dropping sharply to zero at a current smaller than the depairing critical current. This behaviour is in disagreement with a Ginzburg-Landau pair-breaking picture and may be tentatively explained as a cut-off of the BKT renormalisation flow by the current.

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Optimization of Sr2RuO4 thin films and devices based on single-crystals flakes

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Since its discovery in 1994, Sr2RuO4 has been the subject of intensive studies aiming at shedding light on the nature of its superconducting order parameter (OP). Despite earlier reports suggesting an unconventional nature of the Sr2RuO4 superconductivity, conflicting results have been recently reported and a definitive conclusion about the superconducting OP symmetry has not been yet achieved.

To address some of the open questions, it is crucial to fabricate superconducting devices based on high-quality superconducting thin films of Sr2RuO4. Thin films of Sr2RuO4 with very low density of defects, high residual resistivity ratio (> 30) and fully metallic down to low temperatures have been grown from single crystal target of Sr3Ru2O7. The growth parameters that can be further optimized to get fully superconducting thin films have also been identified. In parallel, we are also fabricating superconducting devices based on Sr2RuO4 flakes produced by mechanical exfoliation of single crystals. Different fabrication routes involving lithography patterning followed by Inducively Coupled Plasma (ICP) etching and patterning with a helium ion microscope have been successfully employed to fabricate superconducting devices from Sr2RuO4 single-crystal flakes.

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Escape rate problem in driven Josephson junctions

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Josephson effect in a superconductor-insulator-superconductor (SIS) junction is a macroscopic quantum tunneling phenomenon where Cooper pairs tunnel through an insulating barrier without any applied voltage [1-2]. When a Josephson junction is operated in the zero-voltage state with a non-zero bias current (dc and ac) the phase difference between the macroscopic wavefunctions of two superconductors acts as a particle subject to a tilted-washboard potential. The phase particle stuck in this potential can escape via thermal exciton or it can tunnel quantum mechanically. At a very small temperature, the quantum tunneling process dominates [3-5].

I will present on our theoretical study of the escape (tunneling) rate problem for the phase particle in the current biased Josephson junction (CBJJ). We develop a simple quantum mechanical method for the static case (dc bias current) to calculate the position and width of resonances which relate to the tunneling rate. Then we also add a radio-frequency harmonic driving term (ac bias current) and solve the coupled Schrodinger equations to calculate the corresponding tunneling rate out of the ground-state which shows a strong resonant enhancement when the drive frequency matches the excitation energy of the junction.

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Towards coherent manipulation of Andreev Bound States in ultraclean carbon nanotubes

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Coherent manipulation has been achieved for a variety of superconducting devices, recently in particular in Josephson Junctions based on InAs nanowires [1,2]. Similar to nanowires, quantum dots formed by carbon nanotubes host Andreev Bound States [3]. Here we propose a superconducting quantum circuit to coherently control these states. Ultraclean manufacturing of the nanotubes and their intrinsic low-dimensionality promise long coherence times.

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Density functional Bogoliubov-de Gennes calculations for a topological superconductor

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The prospect of Majorana-based quantum computing applications, which have to potential to build topologically protected qubits that are robust against certain types of disorder, has sparked immense research interest in the materials platforms that are suitable to materialize Majorana zero modes. Unconventional Majorana zero modes can be realized in so called topological superconductors and can be engineered in heterostructures of topological insulators and conventional s-wave superconductors. However, to date no Majorana qubit exists and a lot of material research is still needed in order to achieve technological readiness in suitable material platforms. Material specific insights into the physics of the proximity effect from the microscopic atomic and electronic structure can give valuable insights and help overcoming the current material challenges towards the realization of a Majorana qubit.

Here we introduce our recent developments in the JuKKR density functional theory code (DFT) [1] which allows to describe interfaces and heterostructures of different materials from first principles. Recently we have added the possibility to include superconductivity based on solving the Bogoliubov-de Gennes (BdG) equations formulated in the language of density functional theory [2]. We apply this method to study the s-wave superconductor Nb and its (110) surface which is a very important platform in the field around material platforms that allow the formation of Majorana zero modes. We further show BdG-DFT results for the interface of Nb and the topological insulator Bi_2Te_3 where we study the superconducting proximity effect in the electronic structure of the topological insulator at different thicknesses. These insights shed light on the microscopic electronic structure at the superconductor-topological insulator interface and discusses the challenges the material platform faces in the pursuit for Majorana-based quantum computing applications.

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Exploring the electrical gating-effect in different kinds of superconductors

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Superconducting (sc) transistors are promising building blocks for future superconductors by virtue of their low energy consumption and high-end data processing ability. Until now no sc memory devices have been developed. Hence for real applications, sc transistors need to be integrated with memory cells based on the CMOS technology. Some realizations of superconductor/semiconductor hybrid systems, such as Nanocryotrons (nTrons) [1] or thermal driven sc-nanowires (hTron) [2] have already been put forward.

An alternative promising architecture are gate-controlled sc devices. Reversible switching via gate-controlled field effect (FE) has been independently seen for various BCS superconductors, such as Ti [3] and V [4]. Still the origin of the FE is not understood and is under debate [5,6].

To further explore the physical effect and to find suitable materials, we examine different metal and metal-oxide superconductors. By coupling epitaxial piezo-/ferroelectrics to FE-sc devices, we further investigate the *role of strain* and amplification of electric field through these materials on the switching in sc devices.
We present first results of the sample fabrication and characterization of FE devices.

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Parity switching in a semiconductor-based transmon qubit

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Unpaired quasiparticles can adversely affect the performance of superconducting devices, including qubits based on Majorana zero modes. We study charge parity switching in a superconductor-semiconductor nanowire-based transmon device that shows Little-Parks oscillations of its frequency as a function of magnetic field. In the recovery regime, where a single flux quantum threads the cross-section of the wire transport measurements recently revealed signatures compatible with Majorana zero modes.

We read out the charge parity by dispersive monitoring of a readout resonator to which the transmon qubit is coupled. At zero magnetic field, we measure parity switching times in the range of milliseconds. As the magnetic field is increased toward the first closing of the superconducting gap, the switching time is decreased and is consistent with the superconducting gap reduction. In the recovery regime where the gap is re-opened, the switching time is reduced below the sensitivity of our measurement, putting a bound on the minimum observable Majorana hybridization energy in a full-shell nanowire system.

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Quantum Yu-Shiba-Rusinov dimers

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Theoretical descriptions of Yu-Shiba-Rusinov states induced by magnetic adatoms frequently assume classical impurity spins. Experiments on individual adatoms, however, show quantum behavior, as exemplified by Kondo resonances and discrete spin excitations [1-3]. Here, we explore the consequences of this screening for the phase diagrams and subgap excitation spectra of dimers of magnetic adatoms. We specifically account for higher spins, single-ion anisotropy, Ruderman-Kittel-Kasuya-Yosida coupling, and Dzyaloshinsky-Moriya interactions relevant in transition-metal and rare-earth systems. Our flexible approach based on a zero-bandwidth approximation provides detailed physical insight and is in excellent qualitative agreement with available numerical-renormalization group calculations on monomers and dimers. Remarkably, we find that even in the limit of large impurity spins or strong single-ion anisotropy, the phase diagrams for dimers of quantum spins remain qualitatively distinct from phase diagrams based on classical spins, highlighting the need for a theory of quantum Yu-Shiba-Rusinov dimers.

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Experimental signatures of Lifshitz-invariants in the kinetic inductance of Rashba superconductors

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In this work, we demonstrate the interplay of spin-orbit-interaction and in-plane magnetic field in synthetic Rashba superconductors. We investigate the vortex inductance of epitaxially grown Al/InAs heterostructures containing a high-mobility surface-near InAs quantum well covered with an epitaxial layer of aluminum. An ac-current drives vortex oscillation around pinning centers which can be probed via inductance. The vortex inductance was found to be orders of magnitude larger than the kinetic inductance. When applying an in-plane field, the vortex inductance drops in particular for $B_{\|} \perp I_{AC}$ (Fig. 1a) signaling an increase of the pinning force. With respect to the angle between magnetic field and ac-current, a prominent two-fold anisotropy is observed. The unusual behavior of the vortex inductance signals a deformation of the vortex cores and can be theoretically explained by introducing an additional term in the Ginzburg-Landau free energy of a superconductor, resulting from the Rashba spin-orbit interaction [1].

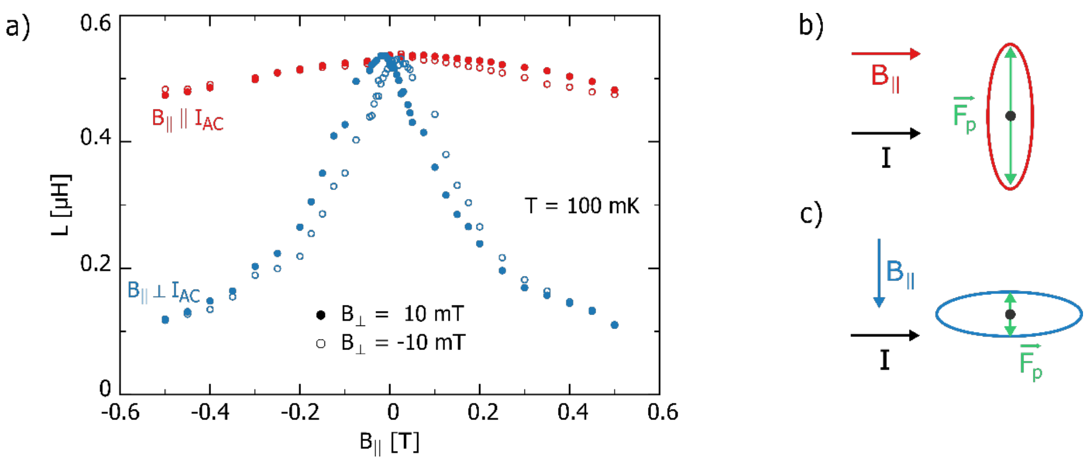

Figure 1: a) Inductance as a function of transverse and parallel magnetic field for $B_{\|}$ $\pm$10 mT. b, c) Contours of $|\Psi|$ = const near vortex cores, with directions of the magnetic field as well as the ac-current

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Magnetism and spin-polarized bound states in semiconductor-superconductor-ferromagnetic wires

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Topological superconductors are attractive platforms for fault-tolerant quantum devices. In 1-dimension, they host well-separated Majorana quasiparticles at their ends, which can encode information in a protected way. The first proposed platforms for topological superconductivity require relatively large magnetic fields, setting constraints on the device's geometries [1]. Ferromagnetic insulating materials (FIM), such as EuS or EuO, can help overcome these limitations, eliminating the requirement of external magnetic fields. Recently, robust zero-energy states have been reported in the semiconductor-superconductor-ferromagnetic insulator platform [2], consistent with the presence of Majorana bound states.

In this presentation, I will discuss how FIMs can help inducing topological properties in the device. I will discuss recent Coulomb blockade measurements of semiconducting InAs nanowires, partially covered with Al and EuS shells and tunnel-coupled to normal leads. By comparing experimental results to a theoretical model, we associate inelastic cotunneling features in even-odd periodic Coulomb-blockade spectra with spin-polarized subgap Andreev levels. Our study suggests spin-splitting exceeding the induced superconducting gap at zero magnetic field [3]. I will also discuss the transport properties of spin-polarized Andreev bound states in Josephson junctions, analyzing the role of magnetic domains [4].

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A particle conserving approach to transport in AC-DC driven interacting quantum dots with superconducting leads

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Transport through an interacting quantum dot coupled to superconducting leads and subject to DC and AC-bias is studied within a particle conserving framework. In this formulation, charge conservation during tunneling of an electron out of the dot includes processes where a quasiparticle is destroyed in the superconductor and simultaneously a Cooper pair is created. This possibility gives rise to non vanishing coherences of the density matrix involving Cooper pairs and states with zero or double occupancy in the quantum dot. In the sequential tunneling regime (second order in the tunneling), the *anomalous* contribution to the current due to the coherences is negligible and quasiparticle transport dominates. Here, the combination of AC and DC bias gives rise to stability diagrams whose features cannot be explained within the simple Tien-Gordon theory. At higher orders the coherences are responsible for the supercurrent in the junction.

Interplay between charging effects and superconducting transport in a tunable SET

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A sufficiently small island coupled via a tunnel barrier to two leads and a gate forms a single electron transistor (SET) that shows Coulomb blockade at low temperature. All-superconducting SETs (SSS-SETs) have shown to enable a multitude of possible charge transport processes which are not well understood, in particular in the strong-coupling regime [1]. To disentangle these processes, we study here the conceptually simpler (SSN)-SET, which has never been investigated experimentally before [2]. Electron tunneling (e), Cooper pair tunneling (cp) and (multiple) Andreev reflection ((M) AR) are possible on the S-S mechanically controlled break junction (MCBJ), while on the S-N oxide barrier just e processes are possible. By tuning the MCBJ, it is possible to cover all coupling regimes: from a tunnel contact to a point contact with a small number of highly transmissive transport channels.

Simulations of the system use a master equation approach [3]. In the weak coupling regime, it is valid to use the classical rates for S-N/S-S Josephson junctions. However, this rate for the S-S junction does not account for any type of MAR, and it is also quantitatively not valid when considering junctions with a few channels of high transmission. In order to account for these effects, we include the rates for the individual MAR processes obtained from the full counting statistics of MAR for a single quantum point contact [4] with a transmission that corresponds to the one we measure for the MCBJ, assuming a single channel. We decompose the total current into the contributions from each possible transport process and compare the simulated and experimental current-voltage curves. We discuss the limits of this master equation approach for a SSN-SET with a MCBJ.

Finally, we observe that the charging energy decreases as the coupling of the MCBJ increases. The signatures of Coulomb blockade vanish almost completely when the conductance of the MCBJ exceeds ~ 3-4 G_0.

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Signatures of superconducting proximity effects in two-dimensional (2D) superconductor/ferromagnet bilayers with a helimagnetic metal

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Several studies [1][2] performed on three-dimensional (3D) superconductor/ferromagnet (S/F) structures have shown that a viable route to generate fully spin-polarized (i.e., spin-triplet) superconducting states consists in using F materials with an intrinsically inhomogeneous magnetization [3].

The metallic F $Cr_{1/3}NbS_2$ shows a magnetically inhomogeneous ground state, where the magnetization follows a helimagnetic pattern along the crystallographic *c*-axis. Previous reports on 2D flakes of $Cr_{1/3}NbS_2$ have also shown that the helimagnetic spin texture in this material can be modulated via soliton excitations [4] activated by an in-plane applied magnetic field *H*.

We have fabricated 2D S/F bilayers consisting of $Cr_{1/3}NbS_2$ stacked via van der Waals interactions onto NbS_2 (2D S) and we have characterized their low-temperature magnetotransport properties to find evidence for spin-triplet states. Our results demonstrate strong evidence for a superconducting proximity effect occurring in the $Cr_{1/3}NbS_2/NbS_2$ system which manifests through the emergence of *H*-tunable reentrant resistive states below the superconducting transition of the bilayers and through a non-monotonic variation of the superconducting critical temperature (T_c) with the applied *H*. The latter result is possibly consistent with the generation of long-ranged spin-triplet pairs at the $NbS_2/Cr_{1/3}NbS_2$ interface.

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Polarized Grazing Incidence Small Angle Neutron Scattering

– Application to ferromagnet-superconductor heterostructures

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The magnetic characterization of superconducting heterostructures is a crucial aspect for a successful implementation in novel device structures. Proximity effects in ferromagnet(F)/superconductor(S) or heavy-metal(HM)/superconductor(S) thin films can lead to unknown magnetic phases, with complex magnetic lateral and depth-dependent profiles. Polarized Grazing Incidence Small Angle Neutron Scattering (GISANS) with polarization analysis is a powerful technique to study magnetic materials with non-collinear structures on the nanoscale. This technique requires a high-brilliance neutron source, and will be one of the future key potentials of the European Spallation Source (ESS). Providing polarized GISANS with polarization analysis, the beamline SKADI will be well suited to study such complex magnetic materials.
First, I will present an example of a polarized GISANS study on the heterostructure Nb(S)/FePd(F) with a lateral magnetic domain pattern. In this system, modifications of the superconducting state emerge as stray-field generated domain-superconductivity and spin-triplet superconducting correlations [1-3]. Second, I will report on current development efforts that will support the potential inclusion of polarized GISANS at the ESS.

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Large Enhancement of Critical Current in Superconducting Devices by Gate Voltage

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Significant control over properties of a high-carrier density superconductor via an applied electric field was considered infeasible due to screening of the field over atomic length scales. Recent experiments have proven otherwise demonstrating a decrease in critical current via electrostatic gating in Ti based devices [1]. In this poster, I will review the present status of experiments of gating superconducting devices and the theoretical models proposed for the underlying mechanisms [2]. I will present our experiments that demonstrates an enhancement of up to "30 %" in critical current in a back-gate tunable NbN, micro- and nano superconducting bridges [3]. Our suggested plausible mechanism of this enhancement in critical current based on surface nucleation and pinning of Abrikosov vortices is consistent with expectations and observations for type-II superconductor films with thicknesses comparable to their coherence length. Our work demonstrates an electric field enhancement in a superconducting property in type-II superconductors which is a crucial step towards understanding of field-effects on the fundamental properties of a superconductor.

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Characterization of GaAs-based near-surface InAs 2DEGs with an epitaxial Al layer

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InAs two-dimensional electron gases garnered great interest over the past decades due to their high carrier mobility, great density tunability and exotic topological phases as a consequence of spin-orbit coupling and superconducting proximity from an epitaxial Al layer. This system is promising as a topological quantum computational platform or as a host to Andreev-qubits due to better scalability than semiconductor nanowire-based realizations. In this contribution, I present the basic characterization of a new InAs 2DEG structure which is grown on a GaAs crystal by MBE. On the GaAs substrate first a step-graded buffer of InAlAs is used to alleviate the lattice mismatch, which is then followed by a 300 nm thick buffer layer to enhance the wafer properties for high-frequency measurements. We characterized this new heterostructure via low-temperature transport measurements such as the observation of Shubnikov-de Haas oscillations, gate tunability measurements in large magnetic fields and Lifshits-Kosevich analysis. We found mobility values of 86000 $cm^2/(Vs)$ after the etching of the epitaxial Al layer, which exceeds previously reported values of samples grown on InP by a factor of two, and matches values measured on samples without the epitaxial Al layer. We demonstrate the first quantised conductance plateau by defining quantum point contact geometry with local gates. Furthermore, by measuring a Josephson junction in the mK regime we observed a large, tunable critical current and Fraunhofer pattern. Our results show that GaAs-based InAs 2DEGs are promising novel heterostructures for the realization of Andreev qubits.

Enhancement of Kondo effect in S-QD-S Josephson junction based on full-shell nanowire

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We analyse results of an experiment [PRL **125**, 116803 (2020)] on QD-based Josephson junction in a full-shell nanowire and argue that observed effects cannot be explained by emergence of Majorana bound states but are rather caused by Kondo effect enhancement due to nontrivial geometry (flux through the shell). Moreover, we propose that such setup presents a convenient system to study competition between superconductivity and Kondo effect, which lacks quantitative analytical description, while the setup has significant advantages in comparison to other known approaches, as it does not require additional gates because the important parameter is controlled by the magnetic flux through the full-shell nanowire, which can be significantly varied with small changes of magnetic field.

Correlation of Magnetism and Disordered Shiba bands in Fe Monolayer Islands on Nb(110)

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Two-dimensional (2D) magnet-superconductor hybrid systems are intensively studied due to their potential for realizing model-type 2D topological superconductors with Majorana edge modes. It is theoretically predicted that this quantum state can occur in ferromagnetic or skyrmionic 2D layers with spin-orbit coupling in proximity to an s-wave superconductor. However, recent examples of such 1D and 2D systems suggest, that the requirements for topological superconductivity are complicated by the multi-orbital nature of the magnetic components and disorder effects.

Here, we investigate Fe monolayer islands grown on a surface of the s-wave superconductor with the largest gap of all elemental superconductors, Nb, with respect to magnetism and superconductivity using spin-resolved scanning tunneling spectrosopy. We find three types of Fe monolayer islands which significantly differ by their reconstruction inducing disorder, by the magnetism and the sub-gap electronic states, without any signs of topological gaps or zero energy edge states.

Our work illustrates, that a reconstructed growth mode of magnetic layers on superconducting surfaces is detrimental for the formation of 2D topological superconductivity.

Phase dynamics in current-biased Josephson junctions in the presence of Yu-Shiba-Rusinov bound states

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Magnetic impurities on a superconducting surface are known to locally disturb Cooper-pairs and form Yu-Shiba-Rusinov-states, thereby influencing the superconducting ground-state. We employ current-biased Josephson spectroscopy in a scanning tunnelling microscope to study the phase dynamics of Josephson junctions in the presence of Yu-Shiba-Rusinov-states of single atoms. For that purpose magnetic Mn and Cr adatoms are evaporated on a superconducting Pb(111) surface and investigated with a superconducting Pb tip. We observe switching currents that are significantly larger than the retrapping currents, identifying the junction as underdamped. In the presence of magnetic atoms, a local reduction of switching currents is observed. Additionally, we find that the retrapping currents are not symmetric around zero bias, i.e., the retrapping events depend on whether the current sweep starts at positive or negative bias values. This asymmetry is observed in different forms for both magnetic atoms but not in clean Pb-Pb junction. We suggest a correlation between this observation and the electron-hole asymmetry of the Yu-Shiba-Rusinov-states.

Many-body Excitations of a Quantum Spin on a Proximitized Superconductor

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In magnetic molecules intrinsic magnetic anisotropy breaks spin degeneracy, allowing inelastic spin excitations that can be protected by a superconducting gap [1]. The coupling of the spin to the superconductor induces Yu-Shiba-Rusinov (YSR) states, detected by scanning tunnelling microscopy (STM) as long-lived quasiparticles excitations inside the superconducting gap [2]. YSR states and spin excitations have been usually distinguished as two limiting cases, and when coexisting treated independently from each other [3].
Here, we observe the signature of both described excitations in an Fe-porphyrin adsorbed on a Au/V(100) proximitized superconducting surface. Using the STM tip we modify the exchange interaction between molecule and superconductor, shifting the YSR states throughout the gap and driving the many-body system into a quantum phase transition (QPT) [4]. We found that the STM tip affects in a similar way both in-gap and out-gap states, hint that they are correlated. Solving an effective Hamiltonian of the system [5], we describe the observed signals as multiple excitations of entangled states formed by the molecular spin and superconductor. The energy variation of the spin multiplet with the STM tip allows unequivocal determination of the ground state parity, which is generally elusive. Our work brings fundamental understanding of the many-body picture of YSR states and spin-flip excitations.

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Bloch Oscillations in Josephson Junctions

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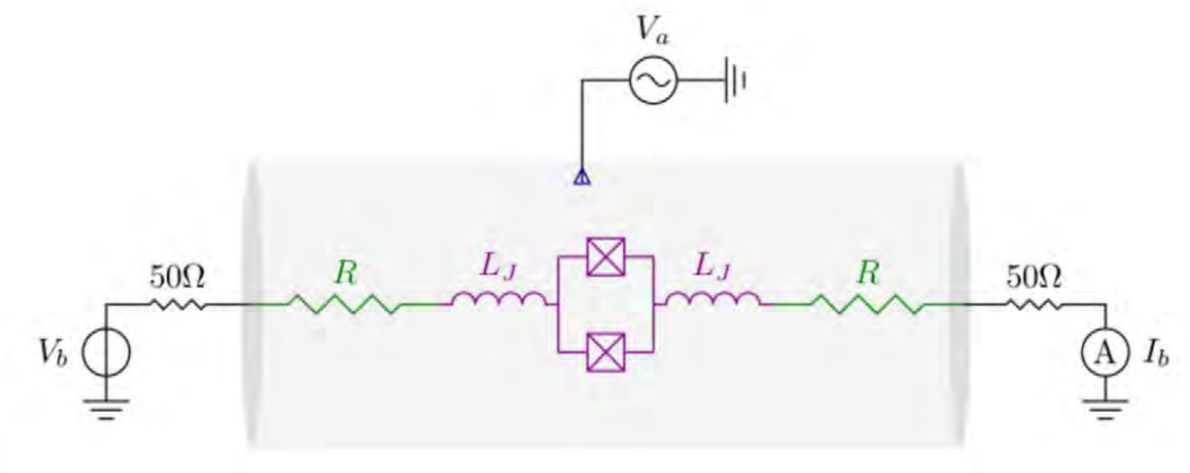
The Josephson effect, describing tunneling of Cooper pairs, is the foundation of superconducting quantum circuits. As a circuit element a Josephson junction can be considered a coherent non-linear inductor with a periodic energy dependence on magnetic flux. The dual to this circuit element, called a phase slip junction[1], would be a coherent non-linear capacitor with a periodic energy dependence on electric charge. Such an element would satisfy all the requirements for a superconducting qubit, and due to the possibility of voltage Bloch oscillations[2], which synchronize charge transfer to a microwave pump cycle, could be incorporated into a quantized current source.
We will fabricate a design for a phase slip junction based on a small Josephson tunnel junction embedded in a high-impedance superconducting cavity and connected to resistive leads. The ultimate goal will be to measure signatures of voltage Bloch oscillations.



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