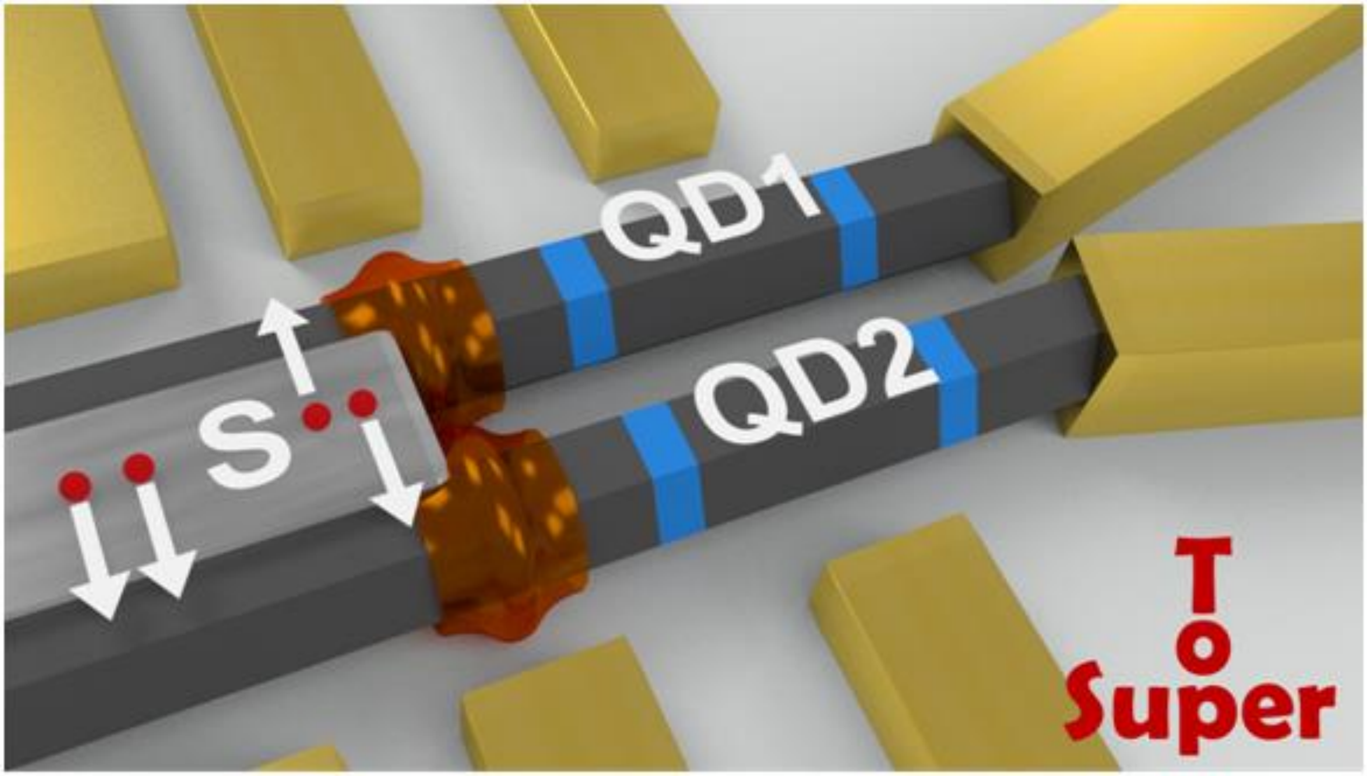
Supertop Workshop



Budapest, 9-11.05.2022

Organized by the Nanoelectronics group of the Budapest University of Technology and Economics:

Szabolcs Csonka

Péter Makk

András Pályi

MŰEGYETEM 1782

Quantum Information National Laboratory HUNGARY

SuperTop workshop, 2022		
Monday		
19:00	**Conference dinner**	
Tuesday		
8:30-8:55	**Registration**	
8.55-9:00	Szabolcs Csonka (BME)	Opening
09:00 - 9:30	Kasper Grove-Rasmussen (Niels Bohr Institute)	Superconducting island systems defined in double and single Al-InAs nanowires
9:30 - 10:00	Marco Valentini (IST Wien)	Majorana-like Coulomb spectroscopy in the absence of zero bias peaks
10:00 - 10:30	Attila Geresdi (Chalmer Uni.)	Progress with InSb nanoflag-based devices
	Coffee Break	
11:00 - 11:30	Fabrizio Nichele (IBM Zürich)	Large Quantum Fluctuations in Planar Josephson Junctions
11:30 - 12:00	Srijit Goswami (QuTech Delft)	Controllable Cooper-pair splitting in two-dimensional electron gases
12:00 - 12:30	Andreas Baumgartner (Uni. Basel)	Spin correlation experiments in a Cooper pair splitter
	Lunch, photo	
14:00 - 14:30	Maria Spethmann (Uni. Basel)	*Coupled superconducting spin qubits*
14:30 - 15:00	Simon Zihlmann (CEA Grenoble)	Coherent coupling of a microwave photon to a hole spin
	Coffee Break	
15:30-16:00	Matthieu Delbecq (Ecole Normale Superieure, Paris)	Universal fluctuations of the induced superconducting gap in an elemental nanowire
16:00 - 16:30	Ramon Aguado (ICMM-CSIC Madrid)	Singlet-doublet parity transitions in hybrid superconductor/semiconductor nanowires containing quantum dots
	Coffee Break	
17:00 - 17:30	Christian Prosko (QuTech, Delft)	On-demand single Cooper pair splitting in hybrid quantum dot systems
17:30 - 18:00	Thomas Schäpers (Peter Grünberg Institute, Forschungszentrum Jülich)	Topological-Insulator-Superconductor Networks
18:00-18:30	Marko Kuzmanovic (Aalto and University Paris-Saclay)	Tunneling spectroscopy of few-monolayer NbSe2 in high magnetic field: triplet superconductivity and Ising protection
19:00 - 21:00	**Free evening**	

Wednesday		
09:00 - 09:30	Stephan Heun (NEST, Pisa)	Supercurrent Diode Effect in High Mobility Free- Standing InSb Nanoflags
09:30 - 10:00	Zoltán Scherübl (BME, Budapest)	Andreev molecule and crossed Andreev reflections in double nanowires
10:00 - 10:30	Ville Maisi (NanoLund)	Real-time observation of Cooper pair splitting showing strong non-local correlations
	Coffee Break	
11:00 - 11:30	László Oroszlány (ELTE, Budapest)	Topological superconductivity in the presence of correlations at the edge of topological insulators: a DMRG perspective
11:30 - 12:00	Jelena Klinovaja (Uni. Basel)	Majorana bound states in topological insulators without a vortex
12:00 - 12:30	Gergely Zaránd (BME, Budapest)	Kondo cloud in a superconductor
	Lunch	
14:00-14:30	Christian Baumgartner (Uni. Regensburg)	Supercurrent diode and magnetochiral effects in symmetric Josephson junctions
14:30-15:00	Andreas Pöschl/Alisa Danilenko (Niels Bohr Institute)	Superconductor-semiconductor hybrid devices: from Andreev bound states to quantum dots
	Coffee Break	
15:30-16:00	Marcello Goffman (CEA Saclay)	Effects of Spin and Coulomb interactions on Andreev states in hybrid weak links
16:00-16:05	Szabolcs Csonka	Closing remarks

Venue

Workshop:

Budapest University of Technology and Economics, Műegyetem rakpart 3.
Building K (main building)
Pécsi Eszter room (First floor, Nr. 95)

Dinner on Monday

Trófea Grill restaurant, Király street 30

Superconducting island systems defined in double and single Al-InAs nanowires

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We present recent activities on hybrid superconductor-semiconductor double and single nanowire devices, which are of particular interest for studying phenomena related to Yu-Shiba-Rusinov (YSR), Andreev and Majorana sub-gap states. The double nanowire material system consists of two closely grown InAs nanowires covered by an in-situ metalized half/full epitaxially-matched Al shell [1]. We show three types of hybrid double nanowire devices, parallel double quantum dot Josephson junctions [2], Little-Parks devices [3] and superconducting islands [4] with focus on measurements of the latter devices. Furthermore, we present measurements on a quantum dot (QD)-superconducting island (SI) system defined in single aluminum-InAs nanowires, realizing a spin coupled to a superconductor with tunable charging energy [5]. The YSR sub-gap states can be tuned to the Coulombic limit as the charging energy of the superconducting island is increased. The measurements also reveal the tunable nature of the nanowire SI-QD and even SI-QD-SI system, which is promising for making entangled chains of the QD-SI unit [6].

References

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Majorana-like Coulomb spectroscopy in the absence of zero bias peaks

Marco Valentini[1], Maksim Borovkov[1], Elsa Prada[2], Sara Marti-Sanchez[3], Marc Botifoll[3], Andrea Hofmann[1,5], Jordi Arbiol[3,4], Ramon Aguado[2], Pablo San-Jose[2], Georgios Katsaros[1]

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Hybrid semiconductor-superconductor devices hold great promise for realizing topological quantum computing with Majorana zero modes. However, multiple claims of Majorana detection, based on either tunneling or Coulomb spectroscopy, remain disputed. Here we devise an experimental protocol that allows to perform both types of measurements on the same hybrid island by adjusting its charging energy via tunable junctions to the normal leads. This method reduces ambiguities of Majorana detections by checking the consistency between Coulomb spectroscopy and zero bias peaks in non-blockaded transport. Specifically we observe junction-dependent, even-odd modulated, single-electron Coulomb peaks without concomitant low-bias peaks in tunneling spectroscopy. We provide a theoretical interpretation of the experimental observations in terms of low-energy longitudinally confined island states rather than overlapping Majorana modes. Our method highlights the importance of combined measurements on the same device for the identification of topological Majorana bound states.

References

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Progress with InSb nanoflag-based devices

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In this talk, I will report on our efforts of investigating quantum interference in InSb nanoflags. Grown by chemical beam epitaxy, these devices reach approximately a µm lateral sizes while being less than 150 nm thick, facilitating few-channel quantum transport. Additional, fine control of the quantum confinement can then be reached by using the combination of wet etching and electrostatic gating. Furthermore, loop geometries required for the investigation of the Aharonov-Bohm effect or for making superconducting quantum interference devices (SQUIDs) can be created by this technique. After discussing the fabrication of these devices, I will provide an overview of our recent and ongoing experiments.

Large Quantum Fluctuations in Planar Josephson Junctions

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We investigate the stochastic phase dynamics of hybrid Josephson junctions (JJs) in an InAs/Al planar heterostructure [1]. We show that our JJs are characterized by prominent quantum fluctuations, resulting in a mean switching current which is a small fraction of the JJ critical current. In JJs with small critical current, the suppression of the mean switching current is strong enough for phase-diffusion effects to dominate at low-temperature.

We further show that embedding a JJ in an asymmetric superconducting quantum interference device (SQUID), an approach intensively pursued for realizing topological states, alleviates the impact of quantum fluctuations. Consequently, the mean switching current may significantly vary when a JJ is measured in isolation or in a SQUID (by a factor of 2.5 or higher, in the present case). The dominant phase-escape mechanism is further tuned via temperature, gate voltages and fluxes threading the SQUID. Contrary to conventional metallic JJs, no indication of thermal phase activation is observed.

Characteristic experimental features are reproduced with a Monte Carlo simulation of the phase dynamics. Our observations contribute to the understanding of high-quality planar JJs, both in isolation and within SQUID loops, and guide towards the realization of novel quantum architectures.

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Controllable Cooper-pair splitting in two-dimensional electron gases

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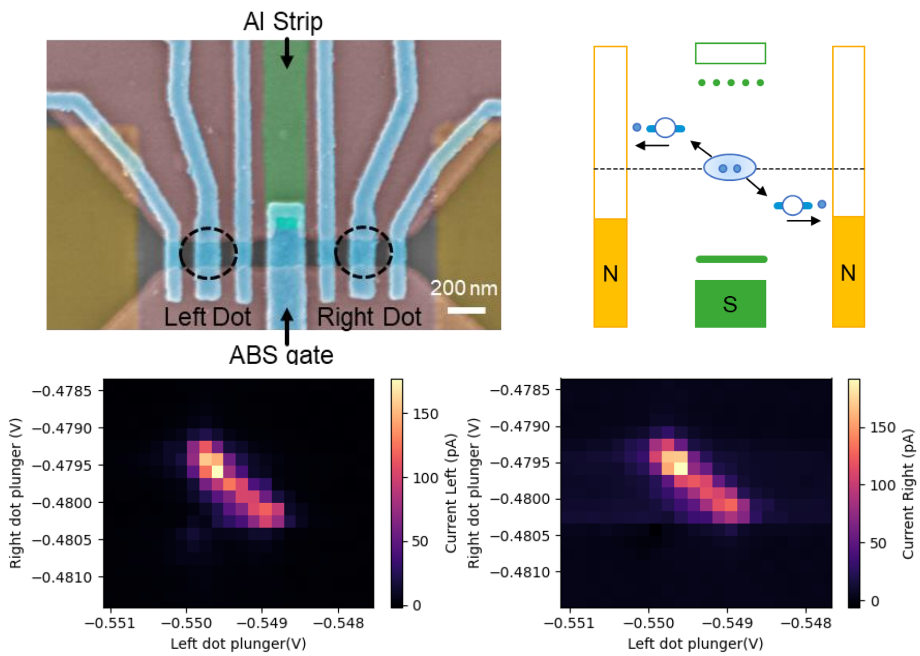
In recent years superconductor-semiconductor hybrids have received attention in the context of engineering topological superconductivity. I will outline some of these efforts, with a focus on studies in two-dimensional electron gases (2DEGs). In particular, I will discuss our efforts towards creating a Kitaev chain in InAsSb 2DEGs, where quantum dots are coupled via Andreev bound states (ABSs). We show two specific realizations of these hybrid structures; in the first the ABS energy is tunable by gate voltages, and in the second, via magnetic flux through a superconducting loop. Using these devices we can clearly distinguish between crossed Andreev reflection (Cooper-pair splitting) and elastic co-tunneling, and demonstrate control over their relative amplitudes.



Cooper pair splitting in InAsSb 2DEGs: (Top) Scanning electron micrograph of two quantum dots coupled via a hybrid segment, and energy level diagram for Cooper pair splitting. (Bottom) Current through left/right dot, demonstrating a resonant CAR process

Spin correlation experiments in a Cooper pair splitter

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Semiconducting nanowires (NWs) coupled to superconducting contacts are a very fruitful platform, for example to investigate the formation and coupling of Andreev bound states [1,2]. However, assessing the spin degree of freedom in such hybrid systems is very challenging. To avoid problematic ferromagnetic electrical contacts, we use ferromagnetic split-gates (FSGs) to individually polarize the spin states in semiconductor quantum dots (QDs) [3], which then act as electronic spin filters. The working principle we demonstrate in a double QD spin valve [4], with individual QD spin polarizations of up to 80%. We then implemented such spin filters in a Cooper pair splitting (CPS) device [5,6] with two FSG/QD elements coupled in parallel to a superconducting reservoir to demonstrate a negative correlation between the spin currents emitted from the 'splitting' of spin-singlet Cooper pairs. Both, in direct experiments and in double QD transconductance experiments, we find a strong negative spin correlation of about -1/3 [7], which deviates from the ideal value of -1 mainly due to the finite spin polarizations of the QD states. Such QD spin filters are suitable for various other applications, for example to investigate spin structures in Rashba nanowires [8], to demonstrate possible equal spin Andreev reflection [9] at Majorana-type bound states, or to measure entanglement and perform Bell tests in electronic systems [10].

References

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Coupled superconducting spin qubits

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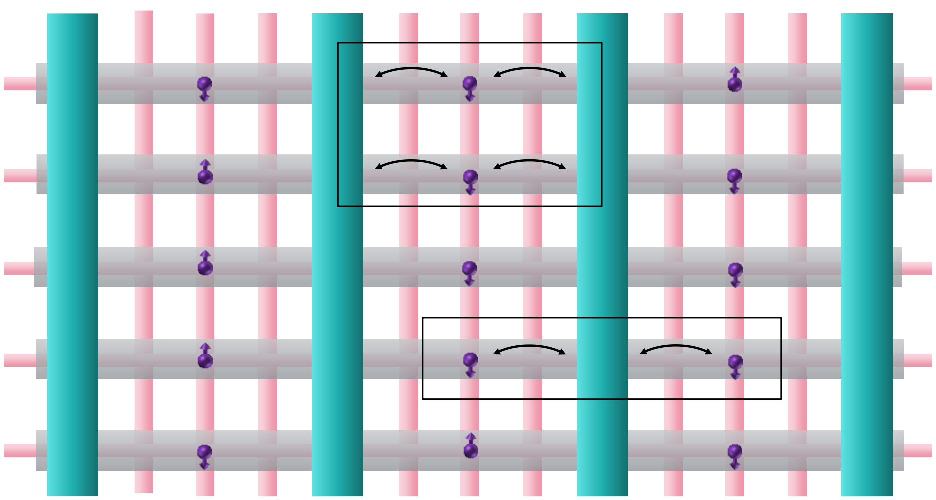
Superconducting spin qubits, also known as Andreev spin qubits, can be coupled to each other via Cooper pairs to implement two-qubit quantum gates [1]. This coupling mechanism is closely related to the formation of Andreev molecules which were observed in recent experiments [1,2]. We theoretically investigate the interaction between superconducting spin qubits in the weak tunneling regime and concentrate on the effect of spin-orbit interaction, which can be large in semiconductor-based quantum dots and thereby offers an additional tuning parameter for quantum gates. We find analytically that the interaction between superconducting spin qubits consists of anisotropic Ruderman-Kittel-Kasuya-Yosida and Dzyaloshinskii-Moriya interaction and is tunable by the superconducting phase difference, the tunnel barriers, and the spin-orbit parameters. We demonstrate that this interaction can be used for fast controlled phase-flip gates with a fidelity >99.99%. Using our results, we propose a scalable network of superconducting spin qubits that is suitable for implementing the surface code.



Network of superconducting spin qubits. *Spins (violet) in quantum dots are weakly tunnel coupled to superconductors (green). This gives rise to an indirect Cooper-pair-mediated coupling between superconducting spin qubits. Electric gates (pink) confine the spins in the nanowires (grey), control the tunnel barriers and the spin-orbit interaction.*

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Coherent coupling of a microwave photon to a hole spin

Simon Zihlmann[1], **C.Yu**[1], **J. C. Abadillo-Uriel**[2], **V. Michal**[2], **B. Bertrand**[3], **N. Rambel**[3], **H. Niebojewski**[3], **T. Bedecarrats**[3], **E. Dumur**[1], **M. Filippone**[2], **M. Vinet**[3], **S. De Franceschi**[1], **Y.-M. Niquet**[2], **and R. Maurand**[1]

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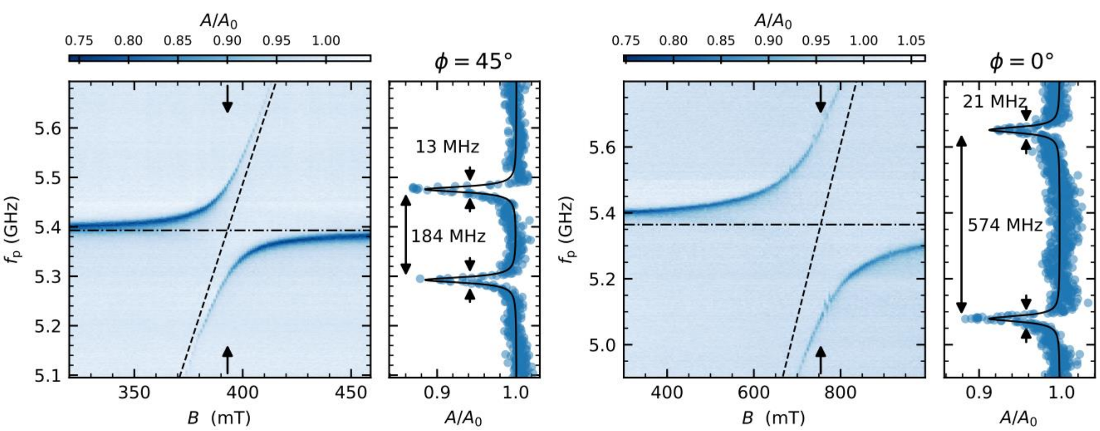
Recently, hole spins in silicon and germanium have shown increasing interest for quantum information processing owing to the advantage of manipulating their state with electric instead of magnetic microwave fields [1,2]. This is possible due to the strong spin-orbit interaction intrinsically present in the valance band of these materials. Spin-orbit coupling should as well offer the possibility to couple a hole spin to the electric field component of a microwave photon.

Here we show a strong hole spin-photon interaction on a CMOS compatible platform. We find a coupling strength of 300 MHz, exceeding the spin decoherence rate and the photon decay rate by a factor 27. Our coupling largely exceeds the best figures reported so far in the case of electrons in silicon [3, 4], opening the door to the achievement of high-fidelity two qubits gate with distant spins.



Strong spin-photon coupling: *Normalized transmission as a function of probe frequency (f_p) and magnetic field (B) for two different magnetic field orientations. When the spin transition frequency (black dashed line) equals the bare resonator frequency (black dashed-dotted line), an avoided crossing is observed. This is attributed to the strong coupling of a single hole spin to a single microwave photon. Line cuts through at the position indicated by the arrows show a vacuum Rabi mode splitting of $2g_s/2\pi =$ 184 MHz and 574 MHz, respectively.*

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Universal fluctuations of the induced superconducting gap in an elemental nanowire

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Proximity induced superconductivity in a normal conductor is a rich field of experimental and theoretical investigations in many systems. In the last decade, it has been particularly at the heart of the quest for realizing topological modes in hybrid superconductor-nanowire nanodevices. Yet it turns out that there was a lack of investigations in elemental systems, in particular as a function of magnetic field. In this work we therefore investigate an ultra-clean carbon nanotube coupled to a superconducting lead. We observe for the first time a long standing prediction of random matrix theory (RMT), dating back to 2001, that mesoscopic fluctuations of the mini-gap in a conductor follow a universal distribution [1]. The statistical distribution of the mini-gap over recorded over 60 charge states in our device unambiguously demonstrate a universal behavior with a clear transition when time reversal symmetry is broken, as predicted by RMT. Interestingly, mesoscopic fluctuations of the minigap were precisely predicted to lead to ubiquitous nontopological edge states clustering towards zero energy. We do indeed observe ubiquitous and robust zero bias conductance peaks under magnetic field in our device that cannot host topological modes by design. The RMT predictions that are compatible with our observations are very general and should be present in any system showing disorder, even if it is weak. It therefore calls for alternative probes than transport measurement to identify Majorana modes in 1D systems with microwave photons in a cavity as a promising powerful platform [2].

References

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Singlet-doublet parity transitions in hybrid superconductor/semiconductor nanowires containing quantum dots

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An interacting quantum dot coupled to a superconducting contact is an artificial analogue of a quantum impurity in a superconductor. The physics of such system is governed by the fermionic parity and spin of the two possible ground states, doublet or singlet, and their corresponding Yu-Shiba-Rusinov subgap excitations. Changes in the fermionic parity of the ground state occur as a quantum phase transition where the energy of the subgap excitations crosses zero energy. After an introduction about such excitations and their Zeeman splitting in hybrid superconductor/semiconductor nanowires [1-4], I will focus on full shell nanowires. In this geometry, the role of the external magnetic flux needs to be taken into account. Specifically, the Little-Parks modulation of the pairing and the winding of the superconducting phase around the shell (fluxoid) may result in robust zero-bias peaks owing to subgap levels close to zero energy and flattening of fermionic parity crossings. Such features could be easily misinterpreted as originating from Majorana zero modes [5,6].

In the second part of the talk, I will explain how microwave spectroscopy in a transmon circuit allows to probe the ground state parity of a quantum dot Josephson junction as a function of gate voltages, external magnetic flux, and magnetic field [7]. The measured parity phase diagram is in very good agreement with that predicted by the single-impurity Anderson model. Furthermore, continuous time monitoring of the circuit allows to resolve the quasiparticle dynamics of the quantum dot Josephson junction across the phase boundaries. Away from the transition, in either the singlet or doublet phase, the lifetime in the ground state sector is of the order of several milliseconds, exceeding that of the excited state by more than an order of magnitude. These results hold promise towards realizing Andreev qubits, which benefit from long parity lifetimes.

References

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On-demand single Cooper pair splitting in hybrid quantum dot systems

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TBA

Topological-Insulator-Superconductor Networks

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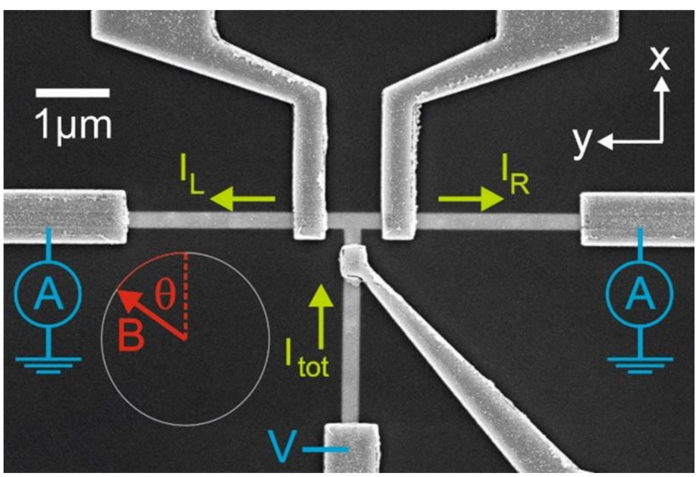
Networks of three-dimensional nanoribbons of topological insulators (TI) in combination with superconducting electrodes are promising building blocks for topoelectronic applications and topological quantum computations. In our approach, these structures are fabricated by a dedicated fabrication method that uses selective-area growth in combination with in situ shadow evaporation of the superconducting electrodes. On single straight TI nanoribbons, we have found pronounced Aharonov-Bohm oscillations in magnetoresistance, indicating transport via topologically protected surface states. In three-terminal TI nanoribbon junctions, a dependence of the current on the in-plane magnetic field has been observed, with the current in the surface state being clearly steered toward a preferred output at different magnetic field orientations. The origin of this steering effect is interpreted in terms of orbital effects. Finally, the interplay of the Josephson supercurrent in the different branches of a multi-terminal TI hybrid junction is discussed.



T-junction device: *Scanning electron microscopy image of a selectively grown Bi_2Te_3 T-junction device.*

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

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In conventional Bardeen-Cooper-Schrieffer superconductors, singlet Cooper pairs of electrons form the ground state. Equal spin triplet pairs (ESTPs) are of great interest for superconducting spintronics and topological superconductivity, yet remain elusive. Recently, odd-parity ESTPs were predicted to arise in (few-)monolayer superconducting $NbSe_2$ [1], from the non-colinearity between the out-of-plane Ising spin-orbit field (due to the lack of inversion symmetry in monolayer NbSe2) and an applied in-plane magnetic field. These ESTPs couple to the singlet order parameter at finite field.

Using van der Waals tunnel junctions, we perform spectroscopy of superconducting $NbSe_2$ flakes, 2–25 monolayer thick, measuring the quasiparticle density of states (DOS) as a function of applied in-plane magnetic field up to 33T. In flakes less than ~15 monolayers thick the DOS is that of 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 the Ising field. The superconducting energy gap, extracted from our tunneling spectra, decreases as a function of the applied magnetic field. However, in bilayer $NbSe_2$, close to the critical field (up to 30T, much larger than the Pauli limit), superconductivity appears to be more robust than expected from Ising protection alone. Our data can be explained by a field induced ESTP order parameter.

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Supercurrent Diode Effect in High Mobility Free-Standing InSb Nanoflags

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High-quality III–V narrow bandgap semiconductor materials with strong spin–orbit coupling and large Landé g-factor provide a promising platform for next-generation applications in the field of high-speed electronics, spintronics, and quantum computing. InSb offers a narrow bandgap, high carrier mobility, and small effective mass and, thus, is very appealing in this context. In fact, this material has attracted tremendous attention in recent years for the implementation of topological superconducting states. An attractive pathway to obtain two-dimensional (2D) InSb layers is the growth of freestanding single-crystalline InSb nanoflags [1]. We have demonstrated fabrication of ballistic Josephson-junction devices based on these InSb nanoflags with Ti/Nb contacts that show a gate-tunable proximity-induced supercurrent and a sizable excess current [2]. The devices show clear signatures of subharmonic gap structures, indicating phase-coherent transport in the junction and a high transparency of the interfaces. In an applied in-plane magnetic field, the device is driven into a non-reciprocal transport regime, where we observe an asymmetry between the critical current in opposite directions (see Fig. 1), modulated by the angle between in-plane field and current direction. This supercurrent diode effect is promising for superconducting electronic circuits and places InSb nanoflags in the spotlight as a versatile and convenient 2D platform for advanced quantum technologies.

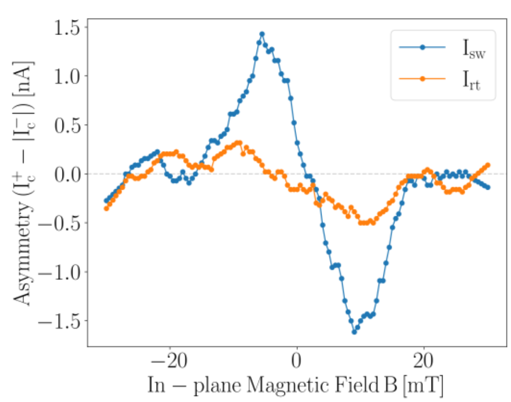

Figure 1: *Asymmetry in switching and retrapping current as a function of the applied in-plane magnetic field.*

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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 high-e_cient 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 which is matched to the measurements.

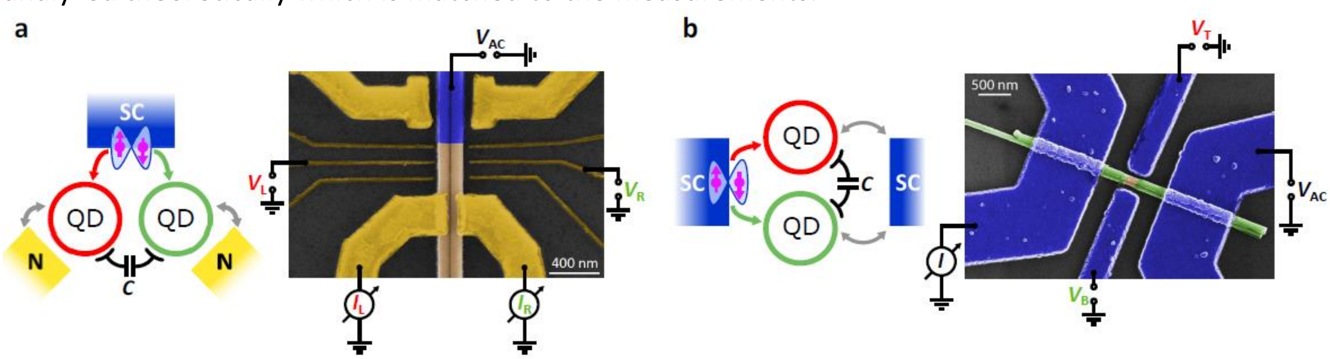

Figure 1: *Schematics and scanning electron micrographs of the devices in which **a** CPS and **b** Andreev molecule were captured with strong capacitive (C) and superconducting coupling.*

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Real-time observation of Cooper pair splitting showing strong non-local correlations

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Splitting Cooper pairs from a superconductor provides entangled electrons at separate locations. In this talk, I present experiments where charge readout with two detectors resolve the splitting of individual Cooper pairs in real time [1,2]. This approach yields direct access to the time-resolved statistics of Cooper pair splitting enabling us to determine the correlation statistics arising from two-electron processes and find a pronounced second-order correlation peak that is two orders of magnitude larger than the background [1]. Our experiment thereby allows to unambiguously pinpoint and select split Cooper pairs with 99% fidelity, as well as identify and study other competing processes such as elastic cotunneling and local Andreev tunneling [2]. The results open an avenue for performing experiments that tap into the spin-entanglement of split Cooper pairs.

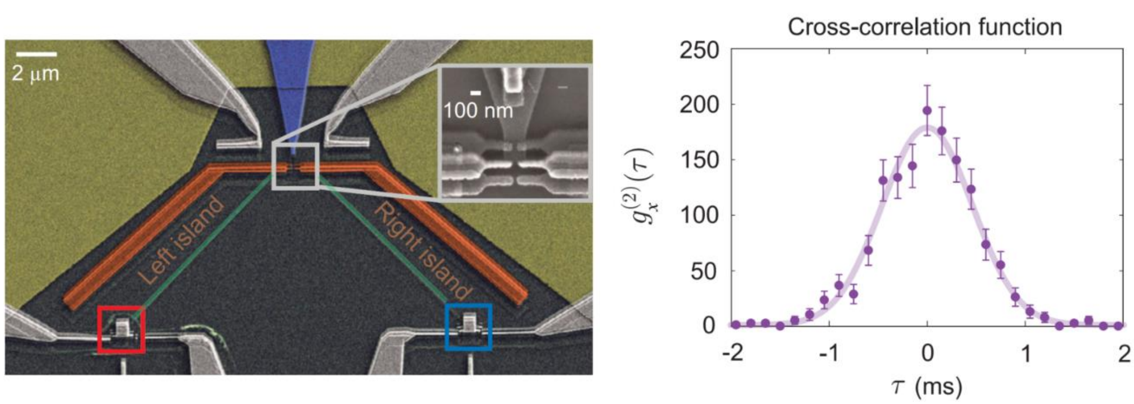

Fig. 1: Cooper Pair Splitter with charge detection. *A Cooper pair from the blue superconducting island splits into two electrons located on the normal metal island in orange. Two charge detectors, indicated with red and blue boxes, detect the electron tunneling events and yield access to the second order correlation function measurement on the right. Points are measurement data, and the solid line is a theory calculation. Figure adapted from Ref. 1.*

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Topological superconductivity in the presence of correlations at the edge of topological insulators: a DMRG perspective

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The edge states of two dimensional topological insulators proximitized with superconducting and magnetic domains were proposed to host zero energy Majorana bound states at the domain boundary. In these systems time reversal symmetry is explicitly broken by the magnetic domains. A pair of domain walls host a pair of Majorana fermions and thus the system has a twofold degenerate ground state. This degeneracy can be used to define a highly non-local qubit which is resilient to local perturbations. Interactions can gap the edge modes without breaking time reversal symmetry explicitly. Based on low energy bosonized calculations it is expected that zero energy bound states in this case are also localized at domain walls between interacting and superconducting regions. However, opposed to the two fold degenerate ground state of devices where time reversal is explicitly broken, in this case degeneracy is fourfold. This fourfold degenerate ground state can be understood in terms of parafermions rather than Majorana zero modes. Studies investigating this setup have mainly employed low energy effective field theoretical approaches based on a bosonized language. Microscopic models allow for studying properties of these localized states which go beyond the bosonized description, for example decoherence during a braiding process induced by the excited states.

In my talk I will describe a simple microscopic model where the edge states of topological insulators in the presence of superconductivity and interactions can be studied within the framework of matrix product states and the density matrix renormalization group algorithm.

Majorana bound states in topological insulators without a vortex

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In our work, we consider a three-dimensional topological insulator (TI) wire with a nonuniform chemical potential induced by gating across the cross section [1-3]. This inhomogeneity in chemical potential lifts the degeneracy between two one-dimensional surface state subbands. A magnetic field applied along the wire, due to orbital effects, breaks time-reversal symmetry and lifts the Kramers degeneracy at zero momentum. If placed in proximity to an s-wave superconductor, the system can be brought into a topological phase at relatively weak magnetic fields. Majorana bound states (MBSs), localized at the ends of the TI wire, emerge and are present for an exceptionally large region of parameter space in realistic systems. Unlike in previous proposals, these MBSs occur without the requirement of a vortex in the superconducting pairing potential, which represents a significant simplification for experiments. In my talk, I will also discuss metallization effects caused by a coupling between a thin layer of an s-wave superconductor and a TI nanowire [3-5]. In the strong coupling limit, required to induce a large superconducting pairing potential, we find that metallization results in a shift of the TI nanowire subbands ($\sim$20 meV) as well as it leads to a small reduction in the size of the subband gap opened by a magnetic field applied parallel to the nanowire axis. Surprisingly, we find that metallization effects in TI nanowires can also be beneficial. Most notably, coupling to the superconductor induces a potential in the portion of the TI nanowire close to the interface with the superconductor, this breaks inversion symmetry and at finite momentum lifts the spin degeneracy of states within a subband. As such coupling to a superconductor can create or enhance the subband splitting that is key to achieving topological superconductivity. This is in stark contrast to semiconductors, where it has been shown that metallization effects always reduce the equivalent subband-splitting caused by spin-orbit coupling. We conclude that, unlike in semiconductors, the metallization effects that occur in TI nanowires can be relatively easily mitigated, for instance by modifying the geometry of the attached superconductor or by compensation of the TI material.

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Kondo Cloud in a Superconductor

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Magnetic impurities embedded in a metal are screened by the Kondo effect, signaled by the formation of an extended correlation cloud, the so-called Kondo or screening cloud,

$$C(\mathbf{r}) = \langle\, \mathbf{S}\cdot\boldsymbol{\sigma}\,(\mathbf{r})\rangle.$$

In a superconductor, the Kondo state turns into subgap Yu-Shiba-Rusinov states, and a quantum phase transition occurs between screened and unscreened phases once the superconducting energy gap Δ exceeds sufficiently the Kondo temperature, T_K . Naively, one may think that the Kondo cloud ceases to exist in the doublet (or unscreened) phase, since there the impurity remains free.

We show by combining simple theoretical arguments and field theoretical calculations, combined with detaailed DMRG and NRG simulations, that this naive expectation is not correct. Although the Kondo state does not form in the unscreened phase, the Kondo cloud does exist in both quantum phases. However, while screening is *complete* in the screened phase, it is only *partial* in the unscreened phase.

To quantify partial screening, we introduce *compensation*

$$\kappa \sim \int \mathrm{d}^3\mathbf{r}\, C(\mathbf{r}),$$

a quantity characterizing the integrity of the cloud. We show that $\kappa(\Delta/T_K)$ is universal, and is related to the magnetic impurities' g-factor, $\kappa = 1 - g$, the latter possibly monitored experimentally by bias spectroscopy. We discuss consequences for gapless superconductors, and puzzling relations with long-ranged tunneling into Yu-Shiba-Rusinov states [2].

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Supercurrent diode and magnetochiral effects in symmetric Josephson junctions

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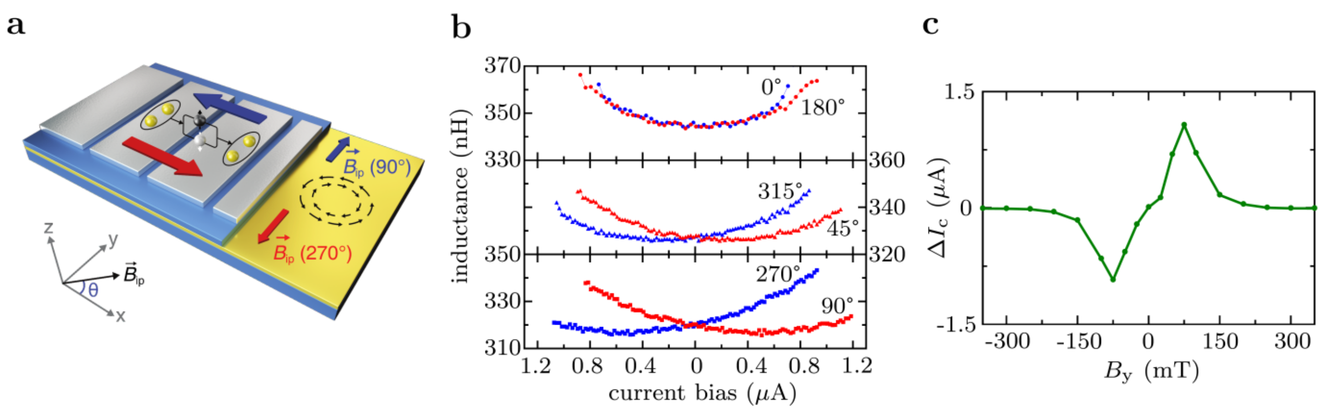
Our work focuses on Josephson junctions based on an InAs 2D electron gas (2DEG) proximitized by epitaxial Al. We measure the Josephson inductance as well as the DC transport properties by using a cold resonator technique. With this technique we show the ballistic behaviour of our junctions and obtain the current-phase relation with a near-unity transmission [1]. In the presence of in-plane magnetic fields, cosine contributions lead to a distortion of the current-phase relation, which allows us to determine the magnetochiral anisotropy coefficient for supercurrents. Surprisingly, this coefficient changes sign when the Zeeman energy coincides with the size of the superconducting gap in the InAs. Furthermore, we observe a strong superconducting diode effect of the critical currents far below the superconducting transition temperature [2, 3].



Supercurrent Diode effect: **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,** Current bias dependence of the Josephson inductance for an applied in-plane field perpendicular to the current (bottom graph). **c,** Difference of $|I_c^+|$ and $|I_c^-|$ as a function of applied in-plane magnetic field B_y for zero out-of-plane magnetic field B_z.

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Superconductor-semiconductor hybrid devices: from Andreev bound states to quantum dots

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Superconductor-semiconductor hybrid devices based on two-dimensional heterostructures offer the possibility of combining semiconducting and superconducting properties in advanced device structures. This allows for measurements which provide increasingly detailed information about the quantum states in these systems, namely Andreev bound states (ABS) and quantum dots.

In this talk, we discuss various designs for quasi-1D hybrid nanowires based on gate-confined 2D InAs/Al heterostructures. Multiple side probes along the nanowire length allow for tunneling spectroscopy. ABSs can be controlled in the nanowire by electrostatic gating. We present local and nonlocal conductance measurements to probe the properties of these states, including their electron-hole character given by their Bardeen–Cooper–Schrieffer charge [1,2]. We discuss the use of quantum dots as probes of ABS properties, starting from a regime in which strong hybridization between a dot and an ABS gives us insight to the nonlocal character of the bound state [3], and progressing to a strongly decoupled regime in which a single quantum dot level can be used as a spectrometer [4], while providing both spin and charge resolution.

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Effects of Spin and Coulomb interactions on Andreev states in hybrid weak links

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The Josephson supercurrent that flows through a non-superconducting material linking two superconductors is governed by quasiparticle states localized at the “weak link”: the Andreev bound states. The energy of these fermionic states depends on the phase difference between the superconductors, and their occupation determines the properties of the weak link.

Using circuit-QED techniques, we measure the microwave absorption spectrum of the Andreev states in phase-biased semiconducting nanowire weak links. The spectra display a “fine structure” resulting from the spin-orbit coupling [1], and reveal the signature of Coulomb interactions among quasiparticles [2].

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Posters

Capacitive dispersive probing of InAs quantum dots using superconducting inductors

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Utilizing radio-frequency techniques for nanoelectronic investigations has flourished in the recent years. One of these techniques is the so called gate reflectometry, during which a carefully designed resonator is coupled to a gate electrode of the device under investigation. Then probing the changes in the reflected high frequency signal from the setup the quantum properties of the sample can be extracted through the measured impedance. In order to enhance the sensitivity of the readout it is favorable to minimize the parasitic losses of the resonant circuit, that can be achieved by using superconducting inductors with no DC resistance.
Hereby we present a radio-frequency gate reflectometry measurement carried out on quantum dots formed by electrostatic potential in In/As nanowires. The resonant circuit embedding a NbTiN high kinetic inductance inductor was coupled to a plunger gate of the device and a capacitance change of around 20 aF was observed between the Coulomb-blockaded and conducting states of the device.

Current—phase relation measurements of graphene-based Josephson junctions

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One of the most fundamental properties of a Josephson junction is its current—phase relation (CPR), the relation between the critical current of the junction and the difference of the macroscopic phases of the two superconducting leads. For example, CPR can give us insight into the transmission properties of the junction. Here, we employ CPR measurements to investigate the interplay between superconductivity and spin—orbit coupling (SOC) in graphene. We present CPR measurements of Josephson junctions containing graphene/WSe2 Van der Waals heterostructures. Combining single- or bilayer graphene with WSe2 in Josephson junctions enables us to induce a large SOC and superconductivity in graphene simultaneously. We apply a measurement setup consisting of two Josephson junctions connected in a SQUID geometry. By operating the SQUID in a highly asymmetric configuration, we can directly measure the CPR of one of the junctions. We investigate the effect of SOC on the CPR by measuring heterostructures built up of different combinations of graphene and WSe2 layers.

Signature of quantum magnetism in thick rhombohedral graphite

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In low-dimensional quantum magnets antiferromagnetic exchange between spins results in an exceptionally rich behavior with significance from spintronics to high temperature superconductivity. Their theoretical models are simple to formulate, such as the Haldane spin chain, but condensed matter realizations are found in binary, ternary or even more complex compounds, making the realization of defect free materials difficult. Here we show that, one of the simplest compounds, thick rhombohedral graphite (RG) shows signatures of quantum magnetism below 20 Kelvin. By scanning tunneling microscopy we map the surface state charge density of 8 and 10 layers and identify a domain structure emerging from a competition between a sublattice antiferromagnetic insulator and a gapless correlated paramagnet, forming the hallmark degeneracy of a quantum magnet ground state. We perform density-matrix renormalization group calculations, explaining the observed features and demonstrate that the mean-field sublattice-Néel antiferromagnet is not the ground state, just as expected for a quantum magnet. Thick RG offers a simple and tunable materials platform to explore magnetism beyond the mean-field approximation, in a system with itinerant spins.

Development of ultra-low-temperature RF setup and superconducting resonators

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The energy scales of quantum bits used for quantum computation necessitate the use of RF equipment. A cryogenic, low-noise environment is also indispensable as the quantum information is so sensitive, that even absorbing a single photon can be destructive. We built up the capacity to measure nanodevices in such an environment.
The low-temperature environment is provided by the new 3He/4He dilution refrigerator. We developed RF filters to suppress high frequency noise without the limitations of commercially available products. We carried out RF measurements by new instrumentation, and designed and produced NbTiN resonators.

Weyl-point teleportation

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In this work, we describe the phenomenon of Weyl-point teleportation. Weyl points usually move continuously in the configuration parameter space of a quantum system when the control parameters are varied continuously. However, there are special transition points in the control space where the continuous motion of the Weyl points is disrupted. In such transition points, an extended nodal structure (nodal line or nodal surface) emerges, serving as a wormhole for the Weyl points, allowing their teleportation in the configuration space. A characteristic side effect of the teleportation is that the motional susceptibility of the Weyl point diverges in the vicinity of the transition point, and this divergence is characterized by a universal scaling law. We exemplify these effects via a two-spin model and a Weyl Josephson circuit model. We expect that these effects generalize to many other settings including electronic band structures of topological semimetals.

Gate tunable supercurrent in the epitaxial superconducting shell in Ta/InAs nanowires

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Integrated circuits with superconducting building blocks would have several benefits, such as high speed and low power consumption. In recent years, surprisingly, gate control of the supercurrent in all-metallic transistors has been observed. This phenomenon can be used to fabricate gate controlled transistors from superconducting materials, analogous to the field effect transistors. The suppression of the supercurrent was investigated in several materials however there is no scientific consensus on the microscopical explanation [1-3]. In this work, we studied gate tunable supercurrents in Ta superconducting shells epitaxially grown on the top of of InAs nanowires. The investigated device switches from superconducting state to normal state by applying ~ ±5 V on the gate, which is really promising for standard electronical applications. Magnetic field dependence and switching current distribution measurements suggest that the gating effect does not stem from a simple thermal heating. Moreover, electric field driven collapse of superconductivity is not consistent with our experimental findings, however out of equilibrium phonon generation in the substrate is more likely to be the origin of this effect in our device.

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Triplet blockade in a Josephson junction with a double quantum dot

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Topological superconductors are promising building blocks for future quantum computers, although their experimental realization remains a challenging task. Here we present theory results [1] on a Josephson junction with a double quantum dot, a minimal model system toward engineered topological superconductivity based on quantum dot chains [2]. In the (1,1) charge sector of the serially coupled double quantum dot, we illustrate a magnetically induced singlet-triplet ground-state transition via triplet blockade: the Josephson current carried by the triplet ground state at high magnetic field is much suppressed compared to the current carried by the singlet ground state at low magnetic field. The theory results we present are based on the zero-bandwidth approximation [3,4]. We provide simple arguments for a strong triplet blockade in the strong-Coulomb-repulsion limit, using perturbation theory [5]. We also present experimental data (of an InAs nanowire double quantum dot with superconducting leads) showing the triplet blockade predicted by the theory [1]. The demonstrated triplet blockade mechanism could provide a coupling mechanism between spin qubits, and (topological or non-topological) superconducting qubits.

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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 Majorana 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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Crossed Andreev reflection dominated transport through Andreev bound states

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Quantum entangled particles have numerous possible applications in fields such as quantum communications or quantum cryptography. Thus, the practical realization of reproducibly entangled particles is of fundamental interest. Entanglement between electrons is difficult to create in a controlled way, because electron-electron interactions, for example in the Fermi sea of a metal, tend to destroy particle correlations. One of the most promising candidates for creating entangled electron states are spin singlet Cooper pairs, described by the BCS theory of conventional superconductors [1,2]. CPS appears in solid state devices through a process called crossed Andreev reflection (CAR), when an electron from a normal lead N_1 enters a superconductor S, and is non-locally Andreev reflected as a hole particle in another lead N_2.

The high tunability of graphene and the peculiar interplay of the relativistic band structure with superconductivity makes it a great candidate for CPS. It has been shown recently, that CPS is possible in ballistic graphene multiterminal devices [3]. However, in an appropriate setup, the vanishing density of state of graphene at the Dirac point allows for the complete elimination of processes that suppress CAR, such as local Andreev reflection or electron cotunneling [4]. The downside of this setup is that the doping of the graphene has to be controlled very precisely, as it needs to be smaller than the pairing potential Δ of the superconductor. In practice, this is very difficult to achieve. This motivated us to investigate the possibility of CAR in a device where the doping of graphene is substantially larger than Δ.

We study the possibility of CPS in a four terminal device consisting of a *p*-type graphene layer placed on top of a *n*-type graphene layer, with no direct coupling. Superconductors are placed at either side of the graphene layers, creating a geometry similar to Ref. [5]. We study the presence of correlated electron-hole states in the graphene layers, known as Andreev bound states, by determining their spectrum with local density of state calculations. The possibility of CPS is investigated by calculating the non-local, non-equilibrium differential conductance through the device, using two normal leads weakly connected to the graphene layers. We found that CAR dominated transport is robust in a wide parameter range in this setup. Compared to previous studies, the presence of an additional superconducting lead offers the possibility of tuning the differential conductance with the superconducting phases difference.

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