Bound states in superconducting nanodevices 2023
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Topologically protected and scalable quantum bits (TOPSQUAD)

and

Andreev qubits for scalable quantum computation (ANDQC)

Bound states in superconducting nanodevices

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Talk Abstracts

11 – 14 June 2023

Conference Centre

Margaret Island (Margitsziget)

Budapest, Hungary

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Josephson junctions of two-dimensional time-reversal invariant superconductors: Signatures of the topological phase

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We determine the current-phase relation (CPR) of two-terminal configurations of Josephson junctions containing two-dimensional (2D) time-reversal invariant topological superconductors (TRITOPS), including TRITOPS-TRITOPS, as well as junctions between topological and nontopological superconductors (TRITOPS-S). We focus on wide junctions for which several channels intervene in the tunneling coupling. We derive effective Hamiltonians to describe the topological edge modes for different TRITOPS models, including Hamiltonians with p-wave pairing and Hamiltonians combining s-wave pairing with spin-orbit coupling. We also derive effective low-energy Hamiltonians to describe the Josephson junction. These can be solved analytically and explain the contribution of the edge states to the Josephson current as a function of the phase bias. We find that edge modes yield peculiar features to the CPR for both junction types. The primary effects occur for the response of the Majorana zero modes at half-flux quantum phase $\phi\approx\pi$ in TRITOPS-TRITOPS junctions and for integer flux quantum phase $\phi\approx0$ for TRITOPS-S junctions, respectively. The former effect is particularly strong for two-component nematic superconductors. The second effect leads to a spontaneously broken time-reversal symmetry in the TRITOPS-S junction and to a breakdown of the bulk-boundary correspondence [1]. We analyze in this case the role of the phase fluctuations and the localized states generated in pinned vortices within the junction [2].

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Unidimensional Andreev bound states using quantum Hall edges

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A supercurrent flow in a superconductor-normal metal-superconductor junction is made possible via resonances of normal charge carriers (electrons and holes): Andreev bound states, transmitting Cooper pairs in the superconductors. Engineering superconductivity in the quantum Hall regime is a promising route to create novel electronic states [1,2], but, in this regime different carriers move on opposite device sides which necessitates a tedious coupling between distant edges to achieve small supercurrents [3-5].

Here we present a new geometry where quantum Hall edge states are carried along narrow domain walls (DWs) at the centre of the device allowing localised Andreev bound states insensitive to the magnetic field [6]. At magnetic fields as high as 8 T, we observe Josephson coupling with relatively large critical currents. We find superconducting interferences between domain walls and Fabry-Pérot oscillations in individual DWs, effects attributed unambiguously to a 1D nature.

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Andreev bound state fusion

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Semiconductor-superconductor hybrid structures form the basis for a large variety of novel quantum electronic devices, for example as a source of entangled electron pairs with anti-correlated spins [1]. However, the electrical control is often hampered by inhomogeneous or badly reproducible tunnel barriers. Recently, in-situ grown, atomically sharp and gate tunable barriers in InAs nanowires (NWs) were shown to form very stable and reproducible quantum dots (QDs) [2], used, for example, for tunnel spectroscopy of normal state lead states [3], but also to observe how the superconducting proximity effect is established in NW segments [4], or to investigate magnetic field *in*dependent subgap states [5].

Here, we use such built-in barriers to divide a NW into three segments, with superconducting contacts on the outer ones and a QD in between. In a sequence of tunneling spectroscopy measurements we show intermediate states in the process of merging individual Andreev bound states (ABSs) while the barrier height is lowered. For large barriers, the QD couples weakly to the two NW segments carrying individual ABSs, or “Andreev atoms”. For lower barrier strengths, these ABSs sequentially hybridize with the central QD, forming different types of “Andreev molecules”, with zero-bias conductance peaks as precursors of the Josephson effect. For very low barriers, we finally find gate tunable Josephson currents, suggesting ABSs spanning the complete NW, states one might call "fused" ABS or “Andreev helium”. Our results illustrate the merging of subgap states and may serve as a guide in future fusion experiments of topologically non-trivial bound states.

This work was supported by the Swiss National Science Foundation, the QuantEra project SuperTop, the Horizon 2020 projects AndQC and QUSTEC, the Swiss Nanoscience Institute, the Knut and Alice Wallenberg Foundation and the Swedish Research Council.

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Josephson junctions with topological interlayers - Tutorial

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In order to experimentally study Majorana and parafermionic quasiparticles a platform is needed that combines superconductivity and topology. A candidate platform is a Josephson junction with standard s-wave superconductors as leads and a topological interlayer in which electron spin is coupled to momentum direction.

In this tutorial, we will review results for junctions based on topological materials with transport in 3D bulk Dirac semimetals, 2D topological surface states, vortex arrays, as well as 1D higher order topological hinge states, progressively reducing the number of non-topological additional modes. We will discuss the use and limitations of several dc and microwave experiments as well as experimental challenges towards future braiding experiments.

Probing Andreev bound states with circuit quantum electrodynamics

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Andreev bound states (ABSs), the quantum many-body electronic states that are localized at Josephson weak-links, provide a platform to explore the interplay of superconductivity, spin-orbit interaction, Coulomb interaction, and magnetism, including in topological regimes. ABS carry supercurrent and are thus suited to being probed by the circuit quantum electrodynamics (cQED) toolset, which offers high-resolution, high-bandwidth microwave-domain measurement and manipulation of quantum states. In this talk, I will describe our implementation of cQED to reveal the spectrum, dynamics, and potential applications of quasiparticles trapped in ABSs hosted in a Josephson semiconductor nanowire.

After an introduction to ABS, I will describe our use of superconducting resonators for quantitative measurement of microwave response functions and spectroscopy in the presence of non-equilibrium state populations. With this tool, we developed insights on Coulomb interaction in ABSs[1,2], which are conventionally regarded as chargeless states. Second, I will describe the influence of spin-orbit interaction on ABSs[3,4] and how we leveraged that interaction to realize the Andreev spin qubit, a supercurrent-carrying spin degree of freedom[5,6]. I will conclude with an outlook regarding the status of Andreev spin qubits and the immediate challenges ahead.

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4. Hays, M. *et al.* Continuous monitoring of a trapped superconducting spin. *Nat. Phys.* **16**, 1103–1107 (2020).
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Half-integer Shapiro steps in InSb/Nb Josephson junctions

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InSb is a high-quality narrow band gap semiconductor with strong spin-orbit coupling, which makes it the ideal platform to develop architectures able to coherently induce new states of matter with topological properties when proximitized with superconductors. Here we present transport data on hybrid Josephson junctions made from InSb nanoflags with Nb contacts. The InSb nanoflags have a typical length 2.8 µm, width 500 – 700 nm, and thickness 100 nm. A mobility of 29.500 $cm^2/(Vs)$ at an electron density of 8.5×10^{11} cm^{-2} is measured, which results in an electron mean free path ℓ_e ~ 500 nm [1]. At variance to previous work [1-3], in the junctions presented here the Nb is directly deposited on the S-passivated InSb nanoflags.

The junction discussed in this presentation has a length L of 80 nm and a width W of 700 nm. Since $\ell_e > L$, the transport in the junction is ballistic. The Nb has a critical temperature of ~ 8.9 K. This corresponds to a BCS gap of ~ 1.3 meV, so that the induced superconducting coherence length exceeds L, which places the device in the short-junction limit. At 30 mK, the junction shows a critical current above 100 nA. The temperature dependence of the critical current above 500 mK is well described by a short-junction model with excellent interface transparency 0.8. However, a detailed analysis of the full temperature range suggests that the current in the junction flows in both a short and a long channel regime, the latter characterized by a path length of about 5 µm (Fig. 1). This result is consistent with the quantitative analysis of the anomalous Fraunhofer pattern measured on the same junction (Fig. 2). Finally, irradiating the junction with microwaves, half-integer Shapiro steps are observed (Fig. 3), which are robust in temperature and persist up to 1 K. Possible explanations for these observations will be discussed in the seminar.

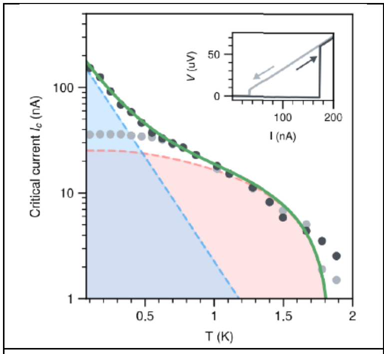

Fig. 1: Temperature dependence of the critical current.

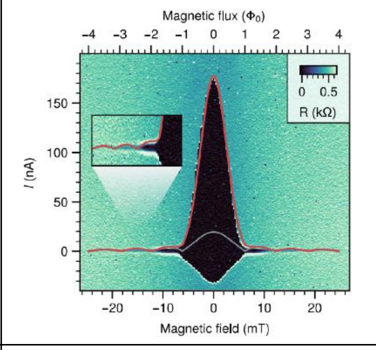

Fig. 2: Anomalous Fraunhofer pattern.

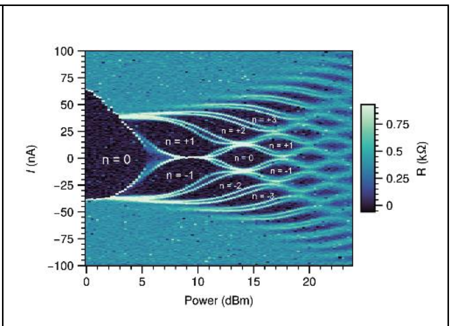

Fig. 3: Half-integer Shapiro steps.

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Helpful discussions with Michal Nowak are gratefully acknowledged. Furthermore, we acknowledge funding by the FET-OPEN project AndQC (H2020 Grant No. 828948) and the EU's Horizon 2020 research and innovation program under Grant Agreement No. 800923 (SUPERTED) and No. 964398 (SUPERGATE).

Semiconductor core-shell nanowires and superconductor hybrid nanostructures

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The control and the manipulation of topological superconductivity may lead in the future in the development of novel quantum bits less sensitive to decoherence than traditional qubits. Among the different strategies proposed to create topological superconductivity, one of them consists in interfacing a superconductor, typically Al, with a one-dimensional semiconductor having a large spin-orbit coupling. In devices based on this combination of materials, superconductivity emerges in the semiconductor via the proximity effect. In theory, topological superconductivity appears in those devices via symmetry breaking in the presence of a magnetic field or a magnetic material. However, a clear observation of topological superconductivity is still missing and two reasons have been advanced: (1) the devices function in the strong coupling regime in which Andreev bound states live and (2) disorder in the materials, in particular at the surface of the semiconductor, are responsible for the presence of unintentional states unrelated to topological effects.

I will present the efforts we are pursuing in Grenoble to tackle those challenges. Our research focuses on the growth and the structural characterization of nanoscale interfaces in nanowires and in planar surfaces. The nanowires grow in a molecular beam epitaxy reactor and we use X-ray diffraction and transmission electron microscopy (TEM) to evaluate and optimize the properties of our core-shell nanowires.

First, the very promising InSb/Sn system will be presented. Hybrid nanowire devices based on this system have shown excellent low temperature electronic properties, in terms of large superconducting gap and 2-e parity charging in Sn superconducting islands. [1] We studied the properties of Sn films grown at cryogenic temperatures on InSb substrates and on nanowires by X-ray diffraction. It appears that post-growth capping plays an important role for the structure of the Sn films. [2] Next, Sn crystalline phases differ when grown on planar surfaces and on nanowires under our growth conditions.

Then, I will show our first data on the growth of II-VI shells around InAs nanowires. Those shells can act as intermediate tunnel barriers between a superconductor outer shell and the core nanowire to tune the proximity effect in the semiconducting core and reach the weak coupling regime in superconductor-semiconductor nanowire devices. [3] Preliminary TEM analyses demonstrate a perfect epitaxial relationship between the II-VI semiconductor and InAs [4].

Overall, our efforts in developing hybrids nanowires have led to a constant improvement of their quality, through the careful optimization of the growth conditions and structural properties. In the future, we will correlate their low temperature transport properties with their crystalline structure and evaluate their suitability for quantum devices.

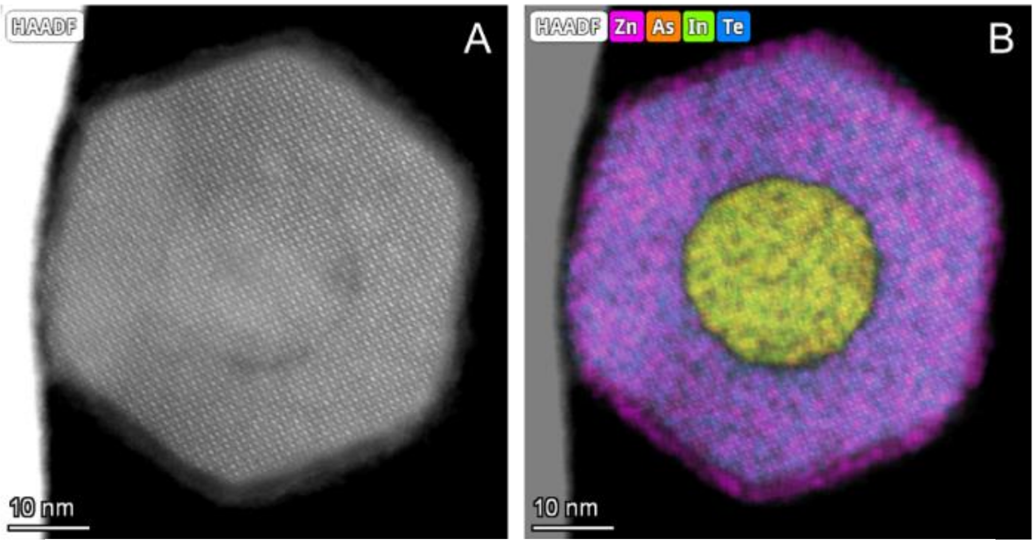

Figure: *Cross-section of a II-VI/III-V core-shell nanowire.* ***A.*** *High Angle Annular Dark Field TEM image.* ***B.*** *Chemical mapping obtained by HAADF/ energy dispersive X-ray spectroscopy.*

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Parity protected superconducting diode effect in topological Josephson junctions

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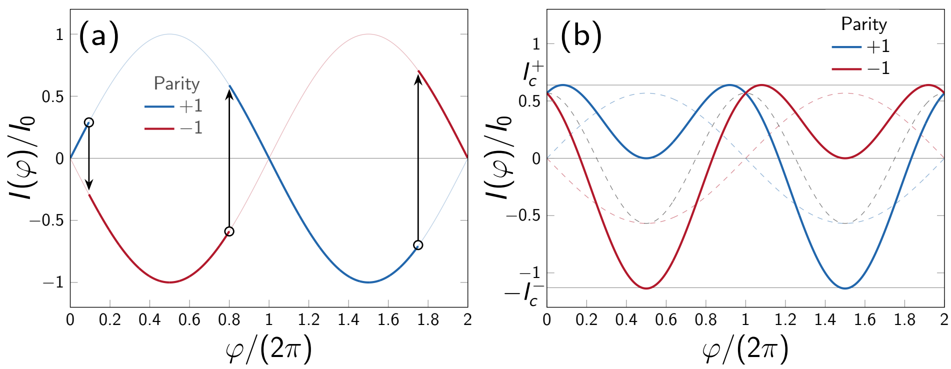
In bulk superconductors or Josephson junctions formed in materials with spin-orbit interaction, the critical current can depend on the direction of current flow or of applied magnetic field, an effect known as the superconducting (SC) diode effect. Here, we consider the SC diode effect in Josephson junctions in nanowire devices. We find that the 4π-periodic contribution of Majorana bound states (MBSs) to the current phase relation (CPR) of individual junctions results in a significant enhancement of the SC diode effect when the device enters the topological phase. Crucially, this enhancement of the SC diode effect is independent of the parity of the junction and therefore protected from parity altering events, such as quasiparticle poisoning, which have hampered efforts to directly observe the 4π-periodic CPR of MBSs. We show that this effect can be generalized to superconducting interference devices (SQUIDs) and that, in such devices, the parity-protected SC diode effect can provide a highly controllable probe of the topology in a Josephson junction. Our results enable a protocol, capable of implementation in current state-of-the-art devices, to use the parity-protected SC diode effect to probe the topology of a Josephson junction.



Parity protected SC diode effect in topological Josephson junctions. **(a)** Schematic showing the impact of parity altering events in CPR from MBSs. Since measurement of the full CPR cannot be done faster than the rate of parity altering events, such as quasiparticle poisoning, measurement of the theoretical 4π-periodic CPR of the MBSs in a topological Josephson junction is rendered effectively 2π-periodic. **(b)** The interference between the 2π-periodic CPRs of ABSs and the 4π-periodic CPR of MBSs, here both of amplitude I_0, can lead to a significant SC diode effect in both a single junction and SQUID. The full CPR remains parity dependent (indicated by red and blue lines, individual bound state CPR contributions are indicated by dashed lines). In contrast, however, the size and sign of the SC diode effect, governed by $I^+_c - I^-_c$, is protected from parity altering events and can therefore be used as a measure of junction topology.

Dynamical parity selection in superconducting weak links

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Excess quasiparticles play a crucial role in superconducting quantum devices ranging from qubits to quantum sensors. In this work we analyze their dynamics for phase-biased finite-length weak links with several Andreev subgap states, where the coupling to a microwave resonator allows for parity state (even/odd) readout. Our theory shows that almost perfect dynamical polarization in a given parity sector is achievable by applying a microwave pulse matching a transition in the opposite parity sector. Our results qualitatively explain key features of recent experiments on hybrid semiconducting nanowire Josephson junctions [1] and provide theoretical guidelines for efficiently controlling the parity state of Andreev qubits.

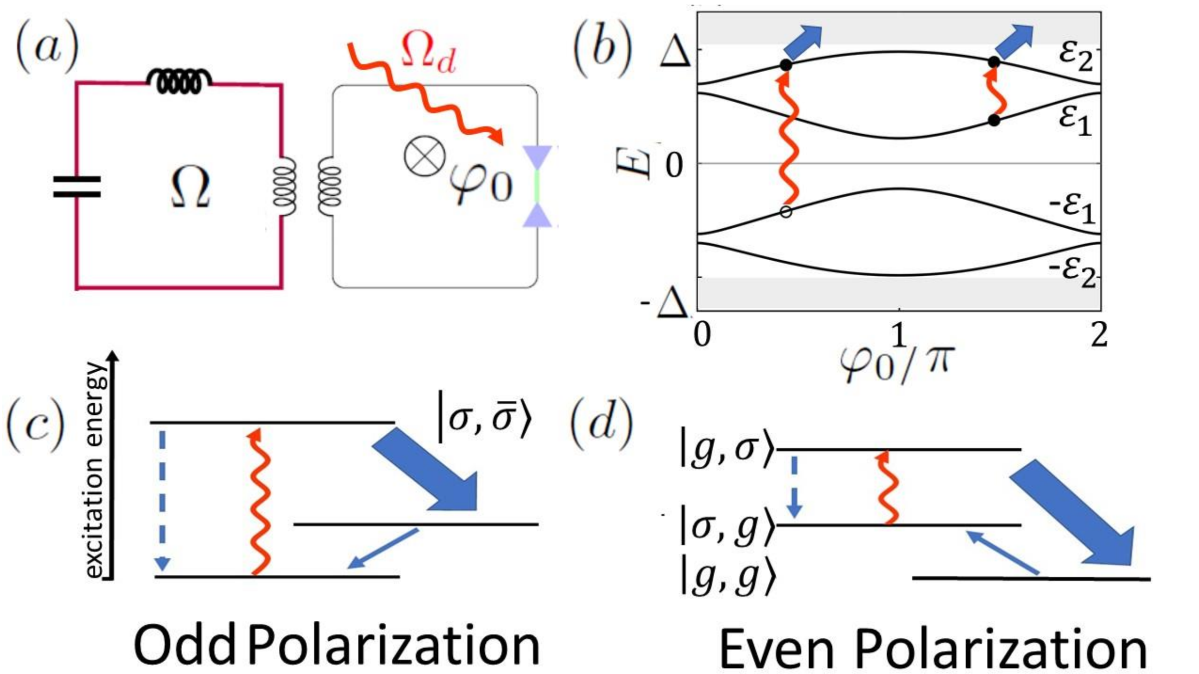

Fig: *(a) Schematic setup: phase biased weak link coupled to a microwave resonator (b) Subgap states as a function of phase for a finite length weak link (c-d) Excitation of even/odd many-body states leading to polarization in the odd/even parity sector.*

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Investigation of graphene-based multi-terminal Josephson junctions

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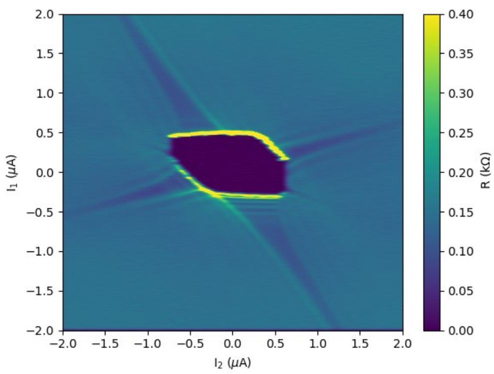
The Andreev spectrum of an N-terminal Josephson junction is expected to host Weyl singularities in the (N-1)-dimensional space of the individual superconducting phases, thus mimicing the band structure of topological materials [1]. Graphene is an ideal platform to realize such multiterminal junctions, where high quality Josepshon junctions can be formed in a planar geometry.

First we will show the realization of high quality graphene based Josephson junctions and characterize their behavior using CPR measurements. Afterwards, we investigate a 3-terminal Josephson junction containing hBN-encapsulated graphene as the weak link connecting the terminals. We characterize the junction by DC transport measurements and apply RCSJ simulations to understand the multi-terminal behaviour. By applying current bias to 2 different leads, we obtain a differential resistance map with several complex features and observe the coexistence of normal and superconducting current paths in the graphene region [2,3,4]. Furthermore, we perform switching current distribution measurements to probe the switching mechanism in this multiterminal system.



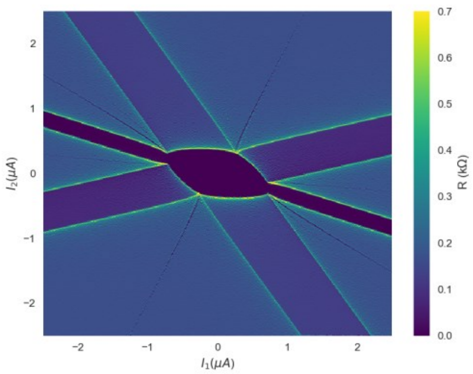


Figure 1: Differential resistance of a 3-terminal Josephson junction (measurement – left and simulation on the right).

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[3] N. Pankratova et al., Phys. Rev. X 10 (2020)

Josephson Quantum Mechanics at Odd Parity

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Embedding a Josephson junction into an electromagnetic environment results in quantum fluctuations of the superconducting phase. This opened up the field of Josephson Quantum Mechanics with its numerous opportunities to engineer and fabricate the practical quantum devices[1].

We concentrate on the tunnel junctions with few conduction channels. Such junction may be in a stable odd parity state when a single quasiparticle is trapped in the lowermost Andreev bound state.[2] This is called quasiparticle poisoning and completely cancels supercurrent in the corresponding channel.

Despite such cancellation, embedding the odd parity junction into an electromagnetic environment gives rise to a special quantum mechanics of superconducting phase, very distinct from the conventional one [3] as far as the underlying theoretical structure is concerned. We investigate it theoretically covering several most representative cases and predict a set of spectacular experimentally observable effects. We show that the poisoning is incomplete in low-impedance environment. We demonstrate four-fold degeneracy of the odd-parity ground state in high-impedance environment. For a Coulomb island, the odd parity junction provides overlap and hybridization of the charging states of different parities. We study how this affects phase slips in the junction.

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Hybridisation of Andreev bound states in three-terminal Josephson junctions

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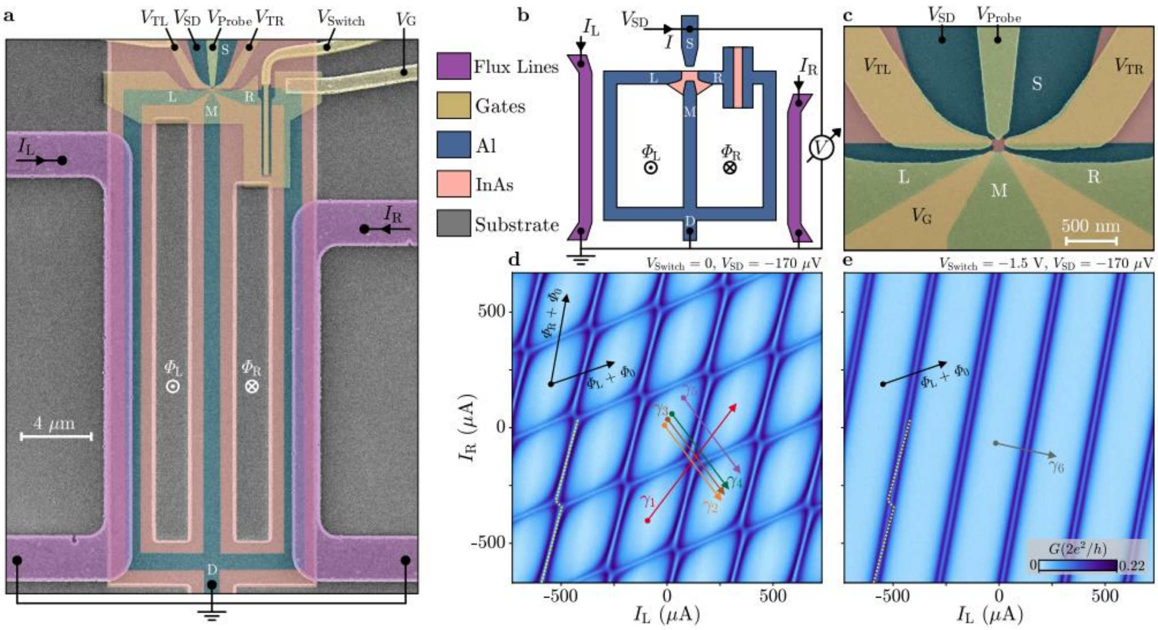
Hybrid Josephson junctions with three or more superconducting terminals coupled to a semiconducting region are expected to exhibit a rich variety of phenomena. Andreev bound states (ABSs) arising in such multiterminal devices have been predicted to form unconventional energy band structures, which can be engineered by controlling superconducting phase differences between the individual terminals. Here we report tunnelling spectroscopy measurements of three-terminal Josephson junctions (3TJJs) realised in a gate-tunable InAs/Al heterostructure. The three terminals are connected to form two loops where phase differences are independently controlled. Our results provide a demonstration of phase control over a novel Andreev band structure. Signatures of hybridisation between ABSs, consistent with their overlap in the 3TJJ region, are observed in the form of avoided crossings in the spectrum and are well explained by a numerical model. Future extensions of this work could focus on addressing spin-resolved energy levels, ground state parity transitions and Weyl bands in multiterminal geometries.



Nanowire platforms for hybrid quantum dot systems

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Superconductor-semiconductor nanowires have been established as an essential platform for research in quantum devices, notably used in the search for novel bound states in hybrid systems [1]. In this talk we firstly discuss the excitations and correlations arising in short chains of coupled quantum dots and superconducting islands in Al/InAs nanowires [2].

We then take a look beneath the surface of these devices, addressing advances in materials science where epitaxial growth, in situ fabrication and implementation of various superconductors have expanded the available parameter space for hybrid devices [3,4]. We will finally focus on new opportunities arising from in situ fabrication of multiple coupled nanowires [5,6,7].

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Topological superconductivity by phase tuning

Omri Lesser and Yuval Oreg

Topological superconductivity in one dimension requires time-reversal symmetrybreaking, but at the same time, it is hindered by the necessity for large external magneticfields. We introduce a scheme in which a systematic manipulation of the phases of threesuperconducting pads tunes the system into a topological state. This scheme requires a tinyfield that could be even less than a microtesla or current bias of the phases of thesuperconductors. The scheme is operational for several platforms and materials, includingwires with strong spin-orbit coupling, planar 2D, certain transition metal dichalcogenides,and two layers of 2D systems. If time permits, I will discuss extensions to topologicalsuperconductivity in two dimensions based on the same methodology.

Yu-Shiba-Rusinov states in proximitized quantum dots

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In this tutorial, I will discuss the Andreev bound states, which are induced by Coulomb blockaded quantum dots contacted by superconducting leads. With normal metallic leads, the paradigmatic *Coulomb diamonds* demarcate regions of suppressed conductance except for pronounced zero-bias *Kondo resonances* for odd-occupied, spinful ground states. Correspondingly, with superconducting leads, the quantum dot states are gapped by proximity effect, except for pronounced Yu-Shiba-Rusinov (YSR) sub-gap states for odd-parity, spinful ground states. In both cases, the hybridization between dot and leads serves to screen the local magnetic moment by means of dynamical singlet formation. This compromise between Kondo screening and induced Cooper pairing will be illustrated in terms of simple effective models and a selection of exemplary experiments.

Braiding-based quantum control of a Majorana qubit built from quantum dots

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Topology-related ideas might lead to noise-resilient quantum computing. For example, it is expected that the slow spatial exchange (`braiding') of Majorana zero modes in superconductors yields quantum gates that are robust against disorder. Here, we report our numerical experiments [1], which describe the dynamics of a Majorana qubit built from quantum dots controlled by time-dependent gate voltages [2,3,4]. Our protocol incorporates non-protected control, braiding-based protected control, and readout, of the Majorana qubit. We use the Kitaev chain model [5] for the simulations, and focus on the case when the main source of errors is quasistatic charge noise affecting the hybridization energy splitting of the Majorana modes [6,7]. We provide quantitative guidelines to suppress both diabatic errors and disorder-induced qubit dephasing, such that a fidelity plateau is observed as the hallmark of the topological quantum gate. Our simulations predict realistic features expected in future braiding experiments with Majorana zero modes in quantum-dot-based devices [8].

This research was supported by the Ministry of Culture and Innovation of Hungary and the National Research, Development and Innovation Office (NKFIH) within the Quantum Information National Laboratory of Hungary (Grant No. 2022-2.1.1-NL-2022-00004), and by the NKFIH via the OTKA Grant No. FK 132146.

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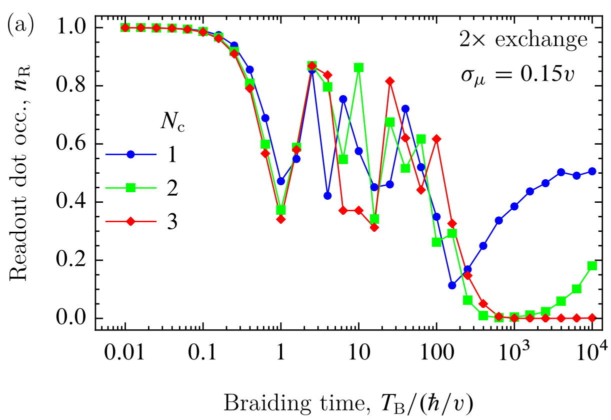

Figure 1. Numerical demonstration of topological protection of the braiding-based quantum-logical gate. Readout dot charge occupation as a function of the braiding time, for various system sizes (N_c). With increased system size (N_c = 3), a plateau emerges for long braiding times, signalling topological protection of the braiding-based quantum logical gate.

Caroli-de Gennes-Matricon analogs in full-shell nanowires

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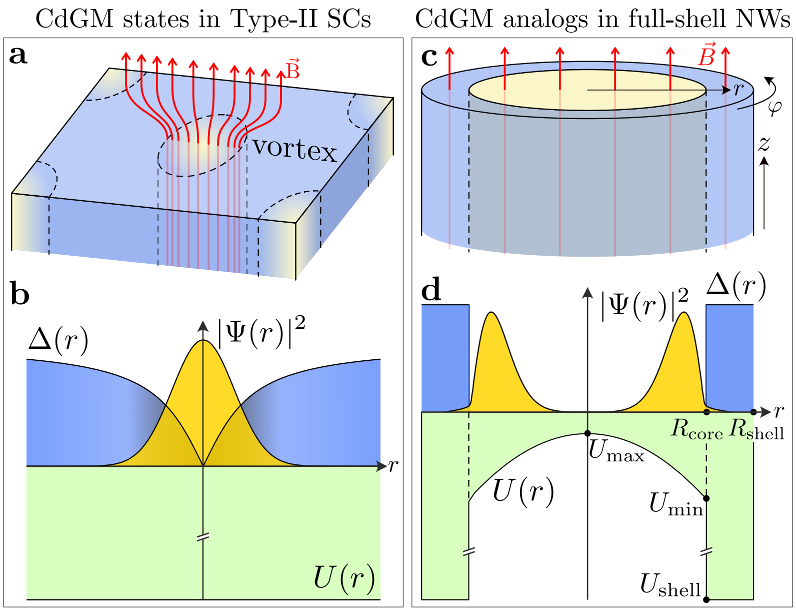
In the search for Majorana bound states in hybrid nanowires, an alternative design with favorable and appealing properties was recently proposed, known as a full-shell nanowire [1]. These new type of hybrid nanostructures consist of a semiconducting core fully surrounded by an epitaxial superconducting shell, which forms a doubly-connected geometry. When subject to an external magnetic flux, these wires exhibit the Little-Parks (LP) phenomenon [2] of flux-modulated superconductivity, an effect connected to the physics of Abrikosov vortex lines in type-II superconductors [3]. In this seminar I will show [4] that full-shell nanowires can host subgap states that are a variant of the Caroli–de Gennes–Matricon (CdGM) states in vortices. These CdGM analogs are shell-induced Van Hove singularities in propagating core subbands. We elucidate their structure, parameter dependence and behavior in tunneling spectroscopy through a series of models of growing complexity. We find that CdGM analogs exhibit a characteristic skewness towards higher flux values inside non-zero LP lobes, as has been observed in recent experiments. Our analysis provides a transparent interpretation of the nanowire spectrum that allows to extract microscopic information of the encapsulated semiconducting core, which is otherwise inaccessible, by measuring the number and skewness of CdGM analogs with a local tunneling probe [4].



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Strong nonlocal tuning of the current-phase relation of an Andreev molecule

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Recent advances in hybrid superconducting – semiconducting structures allows for well-controlled fabrication of complex nanodevices. Placing two Josephson junctions next to each other, closer than the superconducting coherence length, the Andreev bound states hybridize into an Andreev molecular state. Here we investigate the scenario where the Josephson junctions are formed of a quantum dot. Similar molecular states were theoretically investigated in ballistic channels, in the absence of electron-electron interactions, where the non-local tunability of the supercurrent was argued [1-2]. In quantum dots, the presence of the Coulomb interaction and the possibility of electrostatic gating allows for a more versatile tunability. First of all, doublet ground states are only possible with finite Coulomb interactions.

In this contribution we discuss how the molecular state is formed and how the supercurrent of a given junction is affected by the control parameters of the other junction, namely the level position and the superconducting phase difference. Besides the usual parity driven 0-π transition we identified 0 and π regions within the same ground state. We demonstrate a large, strongly tunable φ_0 phase in the absence of spin-orbit interaction. Furthermore exotic current phase relations and superconducting diode effect are discussed. The non-local tunability of these effects are the smoking gun features of the Andreev molecular state. This work opens the way of a better understading of complex hybrid devices.

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Current-Phase Relation of Hybrid Semiconductor-Superconductor Gatemon Devices

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The current-phase relationship (CPR) [1], as one of the most fundamental properties of a Josephson junction, contains information about the Andreev bound state (ABS) spectrum in weak links and can serve as a powerful tool to explore physical phenomena like π-junction physics due to electron-electron interactions [2], 4π-periodicity due to topology [3] and other phase-effects caused by spin-orbit interaction combined with magnetic Zeeman fields.[4]

Here we report CPR measurements for Josephson junctions based on Ge/Si core/shell nanowires, embedded in a superconducting quantum interference device (SQUID) geometry. The Josephson junctions are fabricated by annealing Al into the Ge core.[5] With electrical side gates, we individually tuned the critical current in each arm. In an asymmetrical supercurrent configuration, we find a non-reciprocal critical current when changing the current bias direction, often described as the Josephson diode effect. This effect can be understood as caused by the non-sinusoidal CPR of a highly transmissive junction together with an applied flux bias that leads to an effective non-reciprocal critical current.[6] Most intriguingly, we find an anomalous CPR with a dominant cos(2φ) dependence for selected gate voltages, an effect we currently investigate in more detail.

If time permits, we will report on similar results in another material platform, in hybrid devices fabricated in a proximitized quantum well structure.

We acknowledge funding from the EC, the Swiss NSF, the SNI and fruitful collaborations with the TU-Twente, TU-Eindhoven, the Qdev team at Niels-Bohr Copenhagen and inspiring discussions with G. Katsaros and A. Levy-Yeyati.

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Superconductor-semiconductor hybrid devices for quantum science and technology

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When a semiconductor is brought into proximity with a superconductor, superconductivity can leak into the semiconductor (superconducting proximity effect). The resulting superconducting state can inherit several interesting properties from the semiconductor, such as large g-factors, strong spin-orbit coupling and the ability to tune the density of Cooper pairs with a gate voltage. In my presentation, I will discuss how to engineer these properties by choosing appropriate superconducting and semiconducting materials, and by controlling the geometry of the hybrid structures. I will also discuss how to exploit the properties of superconductor-semiconductor hybrid structures in new types of superconducting circuits and quantum devices, including qubits. A particular focus has been on reaching a topological superconducting phase, where Majorana bound states occur at edges and defects. I will discuss the prospect of reaching a topological superconducting phase in systems with proximity-induced magnetism [1 – 3], as well as in chains of strongly interacting quantum dots [4 – 6].

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Towards realization of protected qubits using topological superconductivity

Javad Shabani

A central goal in quantum computing researchis to protect and controlquantuminformation from noise. This talk will provide recent progress on thedeveloping field of topological superconductivity where we can encode informationin spatially separated Majorana zero modes (MZM). We show that topologicalsuperconductivity can be achieved in certain hybrid materials where thetopological properties are not found in the constituent materials. These specialMZMs are formed at the location of topological defects (e.g. boundaries, domainwalls,..) and manifest non-Abelian braiding statistics that can be used in noise-freeunitarygate operations. We show by engineering a reconfigurable domain wallson a Josephson junction we can create a scalable platform to study MZMproperties and their applications in quantuminformation science.

Tunable superconductivity and engineered current-phase relation in planar Germanium

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III-V materials, like InAs and InSb, are the leading platforms for the realization of gatemons and for the quest of Majorana zero modes. Here we investigate Germanium as an alternative platform [1]. In the past years, dramatic progress has been made in inducing superconductivity in planar Germanium either by enhancing the proximity effect using a double layer of superconductors [2] or by creating a low-disorder interface between the germanium hole gas and an annealed germanosilicide superconductor [3]. Here, we show that we can reliably induce superconductivity in a Germanium hole gas by evaporating aluminum on top of a thin $Si_{0.3}Ge_{0.7}$ spacer which separates the superconductor from the quantum well. We estimate transparencies close to unity and we reveal a superconducting hard gap which can be tuned by the $Si_{0.3}Ge_{0.7}$ spacer. Finally, we show the exchange of pairs of Cooper pairs between two superconducting leads, highlighting the potential of Germanium quantum well as protected qubit [4].

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Microwave spectroscopy of Majorana vortex modes

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Majorana zero modes have been predicted to be hosted in vortices of certain iron-based topological superconductors. Recent observations of zero-bias conductance peaks in vortex cores of such superconductors have sparked renewed interest in vortex-bound Majorana states. However, progress toward a vortex-based topological qubit is hindered by our inability to measure the topological quantum state of a non-local vortex Majorana state, i.e., the charge of a vortex pair. Here, we theoretically propose a microwave-based charge parity readout of the Majorana vortex pair charge. We study the coupling between electrons in the iron-based superconductor and the photons from a microwave resonator above the superconductor. The frequency-dependent transmission of the resonator allows for a dispersive readout of the Majorana parity. Our technique may also be used in vortices in conventional superconductors and allows one to probe the lifetime of vortex-bound quasiparticles, which is currently beyond existing scanning tunneling microscopy capabilities.

This material is based upon work supported by the Office of the Under Secretary of Defense for Research and Engineering under award number FA9550-22-1-0354.

Signatures of Majorana modes leaking into double quantum dot systems

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We analyze the spectral and transport properties of a strongly-correlated double quantum dot attached to metallic contacts and to a topological superconducting nanowire, hosting Majorana bound states. We show that, depending on the device geometry, the Majorana modes can leak into the both quantum dots, giving rise to fractional values of conductance and revealing a subtle interplay between the Kondo screening and the half-fermionic nature of Majorana quasiparticles. In particular, in the case when only one quantum dot is directly attached to metallic leads, the interference with the Majorana modes lifts the suppressed conductance due to the two-stage Kondo effect from zero to a fractional value of $e^2/2h$. Moreover, the coupling to topological superconductor is also found to enhance the second-stage Kondo temperature. On the other hand, when both quantum dots are attached to external leads, we show that the presence of Majorana mode gives rise to unique features visible in the local density of states in the $SU(4)$ Kondo regime. It also greatly modifies the gate voltage dependence of the linear conductance, leading to new fractional values of the conductance. Finally, we study the case when the leads are subject to a thermal gradient, focusing on the behavior of thermopower and revealing new sign changes in the temperature dependence of the Seebeck effect due to the presence of Majorana bound states.

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We acknowledge support from the National Science Centre in Poland through the Project No. 2018/29/B/ST3/00937.

Andreev states in Ge-Si core-shell nanowire Josephson devices

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Ge-Si core-shell nanowires feature one-dimensional confinement, low disorder and strong 'first order' Rashba spin-orbit interaction (SOI) [1]. Additionally, when combined with an s-wave superconductor and a sufficiently large Zeeman field, Ge-Si nanowires should undergo a topological phase transition that hosts Majorana bound states [2]. Here, we use gate-tunable nanowire Josephson devices (Figure 1a) to explore Andreev bound states and topological transition conditions in the wire. A novel contacting recipe gives us control over the tunnel coupling between superconductor and semiconductor and contributes to the observation of a rich subgap spectra in a Josephson device (Figure 1b). Furthermore, changing the Si shell thickness gives us control over the induced superconducting gap and thus over the coupling to the superconductor. Optimizing this coupling strength prevents renormalization of the SOI and g-factor towards the bulk Al value; an essential step towards realizing a topological phase transition[3].

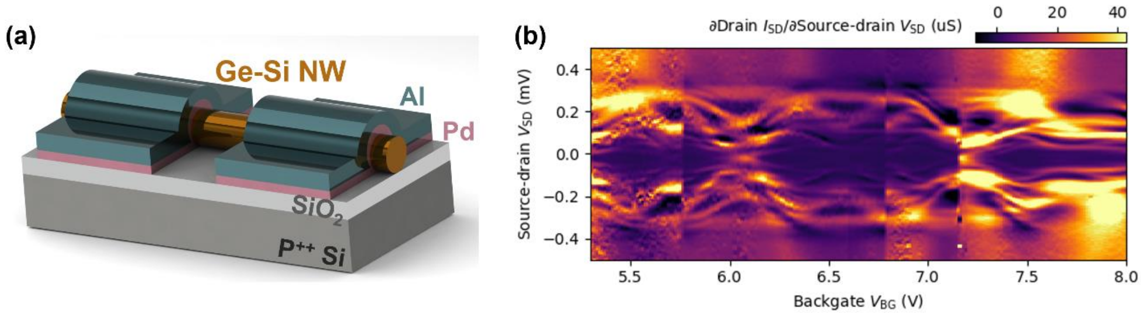

Figure 1 (a) Schematic overview of a gate tunable Ge-Si core-shell nanowire Josephson device. (b) Bias spectroscopy of the subgap states in the device.

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Enhanced Majorana stability in proximitized quantum dots

Francesco Zatelli[1], Tom Dvir[1], David van Driel[1], Di Xu[1], Guanzhong Wang[1], Chun-Xiao Liu[1], Alberto Bordin[1], Bart Roovers[1], Grzegorgz P. Mazur[1], Nick van Loo[1], Jan C. Wolff[1], Sasa Gazibegovic[2], Ghada Badawy[2], Erik P. A. M. Bakkers[2], Michael Wimmer[1], Leo P. Kouwenhoven[1]

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The recent realization of a two-site Kitaev chain [1], and the formation of "Poor man's Majorana" [2] states within, provide a path forward in the field of topological superconductivity [3]. To use such states as the building blocks for a parity qubit and to create longer Kitaev chains, it is necessary to increase the reproducibility of the two-dot system and to increase the robustness of the Majorana states to external perturbations. Here we use two proximitized quantum dots as the basis for the two-site Kitaev chain [4]. We show that in this manner, we enhance the interaction strength between the two quantum dots and form Poor man's Majorana states which are an order of magnitude more stable to gate fluctuations than what was previously reported. This approach does not depend on fine-tuning energy scales to succeed, making it a cross-platform generic approach to forming a Kitaev chain.

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Flux-periodic supercurrent oscillations in GaAs/InAs/Al core/shell/halfshell nanowire Josephson junctions

P. Zellekens[1], R. Deacon[1,2], M. Randall[1,2], P. Perla[3,4], A. Pawlis[3,4], D. Grützmacher[3,4], T. Schäpers[3,4], K. Ishibashi[1,2]

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Mesoscopic nanowire Josephson junctions have been proposed as a potential building block for topological systems. The state-of-the-art realization is based on the combination of a semiconductor with strong spin-orbit interaction such as InAs or InSb with an epitaxially grown superconducting shell [1]. However, one of the main challenges is the creation of separate spin branches in the state spectrum ("helical gap") due to the strong in-plane field that is required to induce a sufficient Zeeman splitting.

To overcome this, several other approaches have been proposed that try to limit the challenges during the actual experiment by exploting more complex device layouts. One of them is based on the so-called Little-Parks effect, whose most famous signature is the formation of supercurrent "lobes" separated by dissipative transport. Even though signatures of this effect have already been observed in nanowires fully surrounded by a superconducting shell [2], many questions regarding the actual formation of the hybridized states and the influence of the system dimensions still need to be addressed.

Here, we use GaAs/InAs/Al core/shell/halfshell nanowires due to the strong localization of the transport within the narrow band gap semiconductor. We use it as a testbed to get more insight into this effect and to study the observed flux-periodic supercurrent oscillations for various field orientations and gate voltages. In addition, we present two-tone spectroscopy measurements of InAs/Al fullshell nanowire Josephson junctions using our Flip-Chip-based superconducting resonator platform [3].

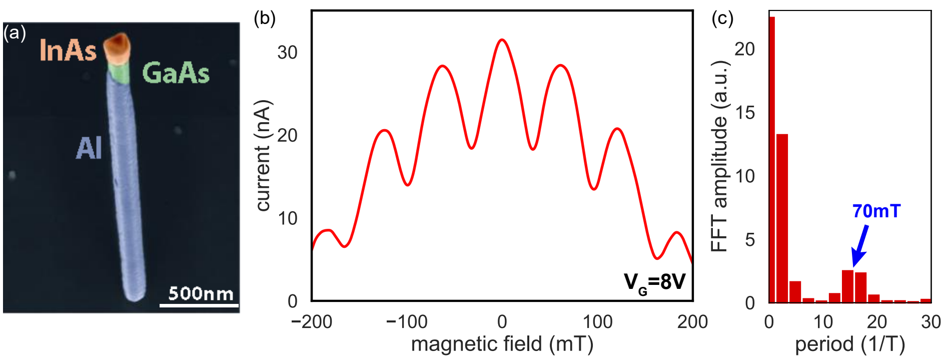

Figure 1 (a) False-colored SEM micrograph of a GaAs/InAs/Al core/shell/halfshell nanowire. (b) Flux-dependent supercurrent oscillations induced by an in-plane magnetic field oriented along the nanowire axis. (c) FFT spectrum of the oscillations), revealing a pronounced and well-defined h/2e period for an effective radius located within the InAs shell.

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Richardson model description of spin-orbit coupling in superconducting islands

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Richardson model, first introduced in nuclear physics as a simplified model of nucleon pairing, is also an appropriate description of a small superconducting island with fixed charge. Complex systems composed of interconnected superconducting islands and interacting quantum dots can be modelled using Hamiltonians that can be transformed into the matrix-product-operator form with small matrices that can be efficiently solved using the density matrix renormalization group [1,2]. This approach allows to include without any approximations the effects of both the exchange interaction (Kondo screening and Yu-Shina-Rusinov subgap states) and the charge repulsion (Coulomb blockade, capacitive coupling) [3] and thereby provide reference results for this family of Hamiltonians that are more general than regular quantum impurity problems. The theory results match well the experimental measurements on hybrid semi-super devices [3,4].

I will describe how this approach can be extended to incorporate two further phenomena, the spin-orbit coupling and the proximity effect leading to level-dependent pairing strength. The combination of the two leads to a degeneracy of even and odd-parity ground states in the regime where the external magnetic field becomes strong enough to generate an increasing number of quasiparticles in the superconducting levels with the weakest pairing strength. This manifests as equal spacing of even and odd states in the charge stability diagrams.

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