Topologically protected and scalable quantum bits
(TOPSQUAD)
and

Andreev qubits for scalable quantum computation
(ANDQC)

Bound states in superconducting nanodevices

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Poster Abstracts

In alphabetical order

(last name)

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Relation between normal state rectification and the superconducting diode effect due to magnetochiral anisotropy

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When both inversion and time-reversal symmetry are broken, the energy spectrum of a system can exhibit magnetochiral anisotropy (MCA). In the presence of MCA the conductivity of the normal state of a material or device can depend on the direction of current, resulting in an intrinsic rectification effect. Similarly, in a superconductor, MCA of the energy spectrum results in a critical current that depends on the direction of current flow, an effect known as the superconducting (SC) diode effect. Here, we consider one-dimensional and two-dimensional systems where MCA of the energy spectrum is present. We show that both the SC diode effect and normal state rectification can be related to the curvature of the energy spectrum and show that the relationship between these two effects is primarily governed by the ratio of superconducting gap and Fermi-energy. In addition we discuss the impact of temperature and the extension of our relationship to higher dimensions. Our results demonstrate that materials with sizable MCA rectification effects are ideal for producing hybrid superconducting devices with large superconducting diode effects.

Aharonov-Bohm-type oscillations in phase-pure core/shell GaAs/InAs nanowires

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The transport properties of epitaxially-grown core-shell GaAs/InAs nanowires are determined by angular momentum states in the InAs shell formed around a high-resistive GaAs core (Fig. 1a) [1]. In the presence of an axial magnetic field, regular h/e-periodic Aharonov-Bohm type oscillations are observed in the magnetoconductance. For GaAs/InAs core/shell nanowires equipped with superconducting electrodes, phase-coherent Andreev reflections lead to a corresponding period of h/2e [2]. However, only polymorphic GaAs/InAs core/shell nanowires have been realized so far. In contrast, we report on phase-pure core/shell nanowires consisting only of wurtzite crystal structure and therefore, providing enhanced uniformity in their electrical, mechanical, and optical properties due to the absence of a crystallographic disorder [3]. We carried out low-temperature magnetotransport measurements under an axial magnetic field to assess the suitability of such nanowires for flux-controlled nanowire-based Josephson junctions [4,5]. Pronounced Aharonov-Bohm-type oscillations in the conductance are observed (Fig. 1b). Significantly higher oscillation amplitudes are found for measurements at different gate voltages compared to polymorphic core/shell nanowires. Measurements at various temperatures show the robustness of these oscillations against high temperatures as a consequence of reduced disorder (Fig. 1b). The exponential decrease in oscillation amplitude indicates that the carrier transport occurs in the quasi-ballistic transport regime (Fig. 1c). Our study demonstrates that phase-pure core/shell nanowires are a promising weak-link element for realizing flux-controlled Andreev-bound states in corresponding Josephson junctions [4,5].

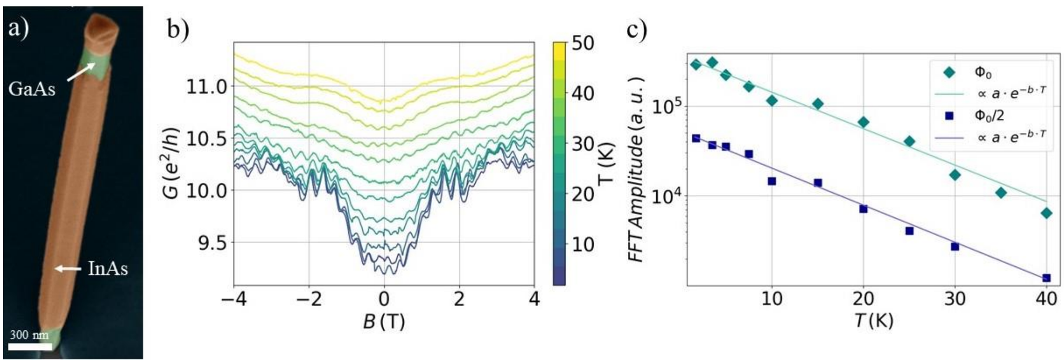

Figure 1 a) Electron micrograph of a GaAs/InAs core/shell nanowire. b) Magnetoconductance oscillations at various temperatures. c) Amplitude of Aharonov-Bohm oscillations vs. temperature and fit according to a quasi-ballistic transport regime.

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Gate tunable supercurrent in the epitaxial superconducting shell in Ta/InAs, Al/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 [1-4]. In this work, we studied gate tunable supercurrents in Ta and Al superconducting shells epitaxially grown on the top of of InAs nanowires. The investigated device switches from superconducting state to normal state by applying ~ ±10 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. With noise measurements on the Al samples it is demonstrated that the suppression of the supercurrent by the gate electrode and the leakage current between the wire and the gate electrode seem not to be independent. By examining the voltage noise measured on the wire and the noise of the leakage current it can be shown that in the gate voltage interval where the suppression of the critical current happens the coherence between the two noise signals increases significantly. We are the first to present detailed analysis of the cross spectrum and coherence in such systems. Our findings indicate that the leakage current and the suppression of the supercurrent by the gate voltage are closely related. With the help of this finding, we can get closer to the understanding of this phenomenon, which is essential for future practical use.

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Crossed Andreev Coupling in Parallel InAs Nanowires

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Parallel InAs nanowires connected by an epitaxially grown superconductor (SC) shell recently became available to create hybrid nanostructures[1]. The defect-free SC-semiconductor interface and the vicinity of two quasi-one-dimensional channels can enhance the crossed Andreev reflection (CAR) between quantum dots (QD) formed in the separate wires. These properties allow high-efficient Cooper pair splitting (CPS)[2], can lead to the strong hybridization of the QDs resulting in an Andreev molecule[3], or create a SC island-semiconductor hybrid QD[4], which are milestones toward more exotic states, like Majorana or parafermions[5]. We demonstrate the experimental realization of CPS, Andreev molecule, and SC island-QD hybrid in different parallel nanowire-based nanocircuits (see Fig. 1). The CAR-mediated interaction between parallel QDs is characterized, while the electron transport in the CPS and Andreev limit is analyzed theoretically and matched to the measurements.

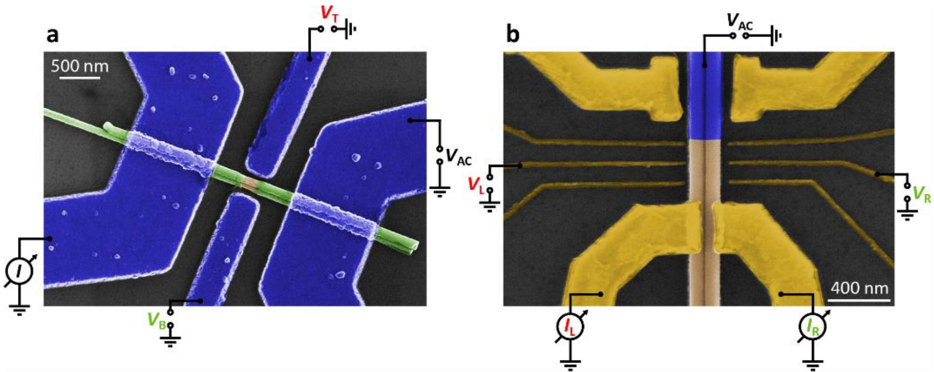

Fig. 1. Scanning electron micrographs of the devices in which **a** an Andreev molecule, **b** CPS were captured with strong capacitive (C) and superconducting coupling.

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

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The search for Majorana zero modes in hybrid semiconductor-superconductor devices has been a topic of great interest in the field of topological quantum computing [1, 2, 3, 4]. Despite multiple claims of Majorana detection through tunneling or Coulomb blockade spectroscopy, these findings remain disputed. Our study [5] presents an experimental protocol that enables both types of measurement on a single hybrid island by adjusting its charging energy through tunable junctions to the normal leads. By checking the consistency between Coulomb blockade spectroscopy and zero-bias peaks in non-blockaded transport, this approach reduces ambiguities in Majorana detections. Specifically, we observed even-odd modulated, single-electron Coulomb blockade peaks in InAs/Al hybrid nanowires, without accompanying low-bias peaks in tunneling spectroscopy, which we theoretically interpreted as low-energy, longitudinally confined island states rather than overlapping Majorana modes. Our study emphasizes the importance of combined measurements on the same device for the reliable identification of topological Majorana zero modes.

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High-fidelity two-qubit gates of hybrid superconducting-semiconducting singlet-triplet qubits

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Hybrid systems comprising superconducting and semiconducting materials are promising architectures for quantum computing. Superconductors induce long-range interactions between the spin degrees of freedom of semiconducting quantum dots [1]. These interactions are widely anisotropic when the semiconductor material has strong spin-orbit interactions [2]. We show that this anisotropy is tunable and enables fast and high-fidelity two-qubit gates between singlet-triplet (ST) spin qubits [3]. Our design is immune to leakage of the quantum information into non-computational states and removes always-on interactions between the qubits, thus resolving key open challenges for these architectures. Our ST qubits do not require additional technologically-demanding components nor fine-tuning of parameters. They operate at low magnetic fields of a few milli Tesla and are fully compatible with superconductors. In realistic devices, we estimate infidelities below 10^{-3}, that could pave the way toward large-scale hybrid superconducting-semiconducting quantum processors.

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Towards Andreev molecules in semiconducting nanowires

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Semiconducting Josephson junctions have recently attracted attention due to the interesting physics they present as a combination of superconducting and semiconducting properties [1] and, particularly, for their suitability in Quantum Information [2-4]. The main role in this kind of devices is played by the Andreev bound states, which are fermionic states created in the weak link as a consequence of electron-hole Andreev reflections at the semiconductor-superconductor interfaces.

It has been experimentally proven that Andreev bound states in a single semiconductor Josephson junction can be used to realize a qubit [5-6]. Such a result pushes towards the investigation of devices with two or more weak links where Andreev bound states can couple each other, the so-called Andreev molecules.

In this poster, we present a two-semiconducting junctions device inductively coupled to a resonator and embedded in a double superconducting loop. The chemical potential in each junction is controlled by two electrostatic gates, while the phase across them can be tuned with an external flux piercing the superconducting loops. Device response as a function of gates and flux, together with single tone and two-tone spectroscopy around an anti-crossing point are shown.

Our preliminary results validate our fabrication process and demonstrates that Andreev levels are coherently coupled to the readout resonator. Also, our data allow us to improve our design for the next generation devices.

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Catastrophes in Weyl Josephson circuits

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Weyl Josephson circuits (WJC) [1] are superconducting devices which can emulate electronic band structures; therefore, they can host Weyl points (WP), robust spectral degeneracies which cannot be split with small perturbations, they are protected by their non-zero topological charge. For larger perturbations, WPs can disappear with pairwise annihilation, where two oppositely charged WPs merge, and the resulting neutral degeneracy disappears. The neutral degeneracy is unstable, meaning that it requires the finetuning of the perturbation. An advantage of the WJCs is the high tunability which enables the investigation of such merging processes.

Finetuning of more than one parameter can lead to more exotic WP mergers. The mergers also require the coexistence of nearby WPs, which is satisfied as the Weyl points are born from a nodal line which acts as an infinite source of WPs upon breaking [2]. In this work, we show that the WP merging processes define universal features (fold, cusp, swallowtail [3]) in the phase diagram in the control parameter space of the perturbations. We argue that those universal features can be derived from catastrophe theory. Our findings provide a novel connection between catastrophe theory and physics.

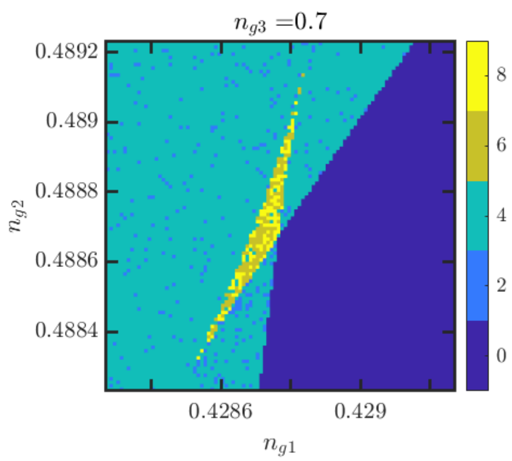

Figure 1. Number of Weyl points in the magnetic flux parameter space of a Weyl Josephson circuit with respect to offset charge perturbations. This shows the merging processes of 4 Weyl points nearby which draws a swallowtail singularity.

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Anomalous Phase Shifts in Planar Josephson Junctions

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Planar Josephson junctions (JJs) in hybrid materials are a promising platform for gate-tunable superconducting [1], spin [2] and topological [3] qubits. We investigate the characteristics of planar JJs in an InAs/Al heterostructure with strong spin-orbit interaction [4] when subjected to an in-plane magnetic field $B_{\parallel}$. Current-phase relation (CPR) and tunnelling spectroscopy measurements were performed on the same device. At small $B_{\parallel}$, an anomalous phase shift was observed as a function of the JJ top-gate voltage V_{TG} consistent with a φ_0-junction [5]. The large measured φ_0-shift was compared with tunnelling spectroscopy of Andreev bound states (ABSs), and was found to match the phase shift of the highest transmission ABSs in the JJ. At large $B_{\parallel}$ the switching current showed a minimum and then revival for further increase in $B_{\parallel}$, for all top-gate voltages. The switching current minimum was concurrent with a phase shift of the CPR, measured with respect to a reference device on the same chip. Tunnelling spectroscopy showed that the superconducting gap was suppressed at the re-entrant field, and then re-opened at larger in-plane fields. These observations were compared in devices with different superconducting lead size, which demonstrated that the re-entrant field scaled with the characteristic dimensions of the lead. This is consistent with a phase transition in the planar JJ [6] induced by orbital effects in the superconducting leads.

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Trivial Andreev band mimicking topological bulk gap reopening in the nonlocal conductance of long Rashba nanowires - arXiv:2210.03507v2

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We consider a one-dimensional Rashba nanowire in which multiple Andreev bound states [1,2,3] in the bulk of the nanowire form an Andreev band. We show that, under certain circumstances, this trivial Andreev band can produce an apparent closing and reopening signature of the bulk band gap in the non-local conductance of the nanowire. Furthermore, we show that the existence of the trivial bulk reopening signature (BRS) in non-local conductance is essentially unaffected by the additional presence of trivial zero-bias peaks (ZBPs) in the local conductance at either end of the nanowire, see Fig. 1. The simultaneous occurrence of a trivial BRS and ZBPs mimics the basic features required to pass the so-called 'topological gap protocol' [4,5]. Our results therefore provide a topologically trivial minimal model by which the applicability of this protocol can be benchmarked.

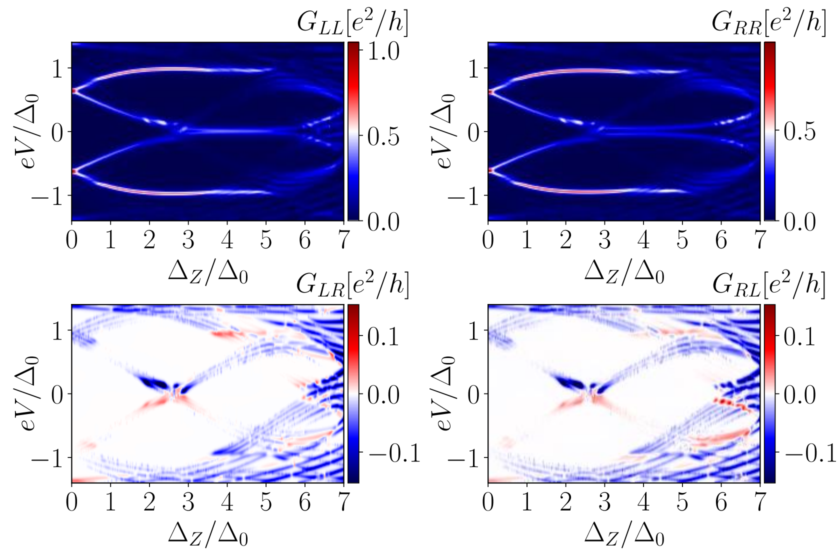

Fig. 1: Local and non-local conductance of a system hosting an Andreev band and trivial zero-energy states as a function of the Zeeman field strength.

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Flip-chip-based microwave spectroscopy of Andreev bound states in a planar Josephson junction

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We demonstrate a flip-chip-based approach to microwave measurements of Andreev bound states in a gate-tunable planar Josephson junction using inductively-coupled superconducting low-loss resonators[1]. By means of electrostatic gating, we present control of both the density and transmission of Andreev bound states. Phase biasing of the device shifted the resonator frequency, consistent with the modulation of supercurrent in the junction. Two-tone spectroscopy measurements revealed an isolated Andreev bound state consistent with an average induced superconducting gap of 184 μeV and a gate-tunable transmission approaching 0.98. Our results represent the feasibility of using the flip-chip technique to address and study Andreev bound states in planar Josephson junctions, and they give a promising path towards microwave applications with superconductor-semiconductor two-dimensional materials.

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Heating effects in mesoscopic superconducting InAs-Al islands

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Mesoscopic superconducting islands defined in hybrid superconductor-semiconductor nanowires have received a lot of interest in the past years in the context of topological superconductivity. On the one hand, they have been employed as a way to detect zero-energy states by Coulomb blockade [1]. In addition, they have been proposed as a geometry for carrying out fusion rule experiments of Majorana modes and for demonstrating a topological qubit [2]. In a recent work [3], we have shown that heating effects can be important in hybrid superconductor-semiconductor nanowires, owing to the poor thermal conductivity of superconductors at low temperatures. Here, we extend that study to the case of mesoscopic islands defined in hybrid InAs-Al nanowires. To this end, we study the superconductor-to-normal transition of the epitaxial Al shell induced by the Joule effect. Such transitions manifest as dips in the differential conductance reflecting the suppression of the excess current [3, 4], and can be used to study the heat transport in the above devices. Surprisingly, we show that the islands turn normal at relatively low powers of ~100 pW, owing to severe heat bottlenecks. Importantly, this implies that the temperature of the island can already be substantial even at voltages much lower than at the transition to the normal state and, in some cases, below the superconducting gap.

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Magnetic field dependence of the quasiparticle parity lifetime in 3D transmons with thin-film Al-AlOx-Al Josephson junctions

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As the overall lifetime of superconducting qubits has increased, quasiparticle losses have become a more significant source of decoherence [1]. As such, an improved understanding of the mechanisms that impact quasiparticle lifetime is essential for further development of such qubits [2]. Additionally, the magnetic field dependence of the quasiparticle parity lifetime is of interest for future topological qubits, which involve both a superconducting circuit and a magnetic field.

Placing a thin-film aluminum transmon qubit in a 3D copper cavity [3], we can measure its quasiparticle parity lifetime using Ramsey- or Rabi-like pulse sequences. We can do so in magnetic fields of up to 400 mT in-plane – about half of the estimated critical field. While the magnetic field does not affect the charging energy, it reduces the Josephson energy E_J by two separate mechanisms: by suppressing the gap, and by Fraunhofer interference. The reduction in E_J not only influences the parity lifetime, but also increases the parity splitting within the transmon energy levels. At lower fields, the splitting of the first excited state does not suffice for parity measurements. To resolve this issue, we use a variety of pulse sequences involving the second excited state.

We observe an increase of the parity lifetime at fields up to 150 mT, followed by a decrease at higher fields. We show that the difference in film thickness between the two aluminum layers of the Josephson junction plays an essential role here. As the field approaches 150 mT, the difference in the superconducting gap becomes similar to the qubit frequency, causing a significant increase in quasiparticle tunneling. As the field increases further, the two frequencies diverge and the quasiparticle lifetime is largely restored.

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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 [1,2] and superconductivity in graphene simultaneously. We apply a measurement setup consisting of two Josephson junctions connected in a SQUID geometry [3]. 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.

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Superconducting microwave resonators to probe Andreev bound states in InAs quantum well

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Among the many types of superconducting qubits, the Andreev qubit has attracted increasing interest in recent years. Coherent control of Andreev bound states (ABSs) has already been shown in superconducting atomic contacts [1], InAs nanowires [2] and recently, superconducting quantum point contacts (SQPCs) realized in a proximitized two-dimensional electron gas (2DEG) [3,4]. The 2DEG platform investigated in this work surpasses both the atomic contacts and the nanowires systems in terms of scalability thanks to the possibility of fabricating devices with standard top-down techniques. The flip chip technique has also been used recently to couple SQPCs in the InAs 2DEG system to a coplanar transmission line resonator (CTR) on a silicon chip [5]. Here we look at the possibility of realizing the resonator directly on the InP chip for ease of fabrication.

We fabricated resonators of different designs, geometries, and materials on polished InP substrates to study the dependence of their quality factor. Fabrication is done via e-beam lithography and lift-off technique. The microstrip line design offers the advantage of a small footprint when high kinetic inductance materials are used. The CTR on the other hand has a higher internal quality factor (Q_i) and is well controlled. We designed and optimized the operating parameters of the resonators using high-frequency simulations and measured the transmission and reflection characteristics. In conclusion, we find that the best and more reproducible results are obtained with a CTR made with thermally evaporated Aluminum. This design shows a Q_i of 1600 when a DC line is inductively coupled to the resonator. This on-chip circuit QED architecture approach will give access to ABSs spectroscopy and allow qubit manipulation and control [6].

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Building blocks of Kitaev chains: First principle theory of magnetic adatoms on the superonducting Nb(110) surface

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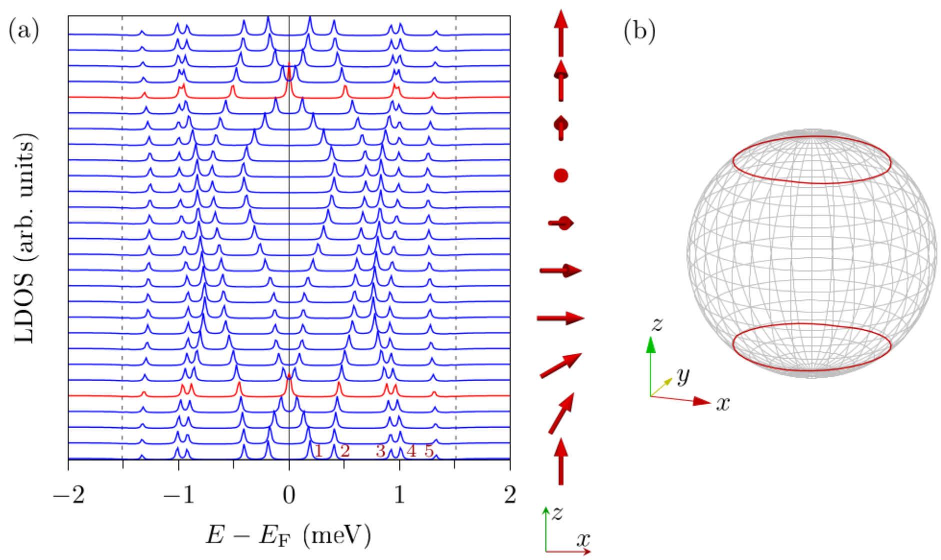
Recently, we developed a first principles based theoretical approach for calculating the spectral properties of magnetic clusters on superconducting surfaces.[1,2] This theory provides a material specific description of the Yu—Shiba—Rusinov (YSR) states. As a first step, we investigate the properties of single magnetic 3d elements on the top of Nb(110) surface. We found that the local density of states in the normal state plays a key role in the formation of the YSR states: for the Cr and Mn adatoms the occupation of the majority spin channel and the disoccupation of the minority spin channel lead to large magnetic moments, which shift the YSR states to the edge of the superconducting gap. In the case of the Fe and Co adatoms, the majority spin channel is totally and the minority spin channel is partially occupied, leading to smaller magnetic moment and to that the YSR states lie in the interior of the superconducting gap. Moreover, we found that the rotation of the magnetic moment shifts the energy of the YSR states as a consequence of the spin orbit coupling. In some cases, during this rotation, the YSR sates cross the Fermi energy, meaning that at certain orientations of the magnetic moment there is a zero bias peak.



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Majorana bound states in germanium utilising only phase control

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Germanium (Ge) has been one of the most highly utilised materials in superconducting electronics and the large interest has resulted in an extremely high quality material [1]. In Ge heterostructures, spin-orbit interaction that is cubic in momentum (CSOI) can be the dominant form of SOI and very strong [2-4]. Within experimentally accessible chemical potentials CSOI can result in spin-split Fermi-surfaces with large mismatches in Fermi-momentum and Fermi-velocity.

However, the very small g-factor of Ge [1] is a considerable obstacle to most proposals to realise MBSs because these often require a significant Zeeman energy. Recently, it was shown that utilising only the two phase differences in a planar SNSNS Josephson junction and Rashba SOI can result in MBSs utilizing potentially only extremely small magnetic fields to tune the phase differences [5]. However, this proposal requires a significant mismatch in Fermi-velocities of the inner and outer spin-orbit split Fermi-surfaces, which is difficult to achieve using standard Rashba SOI that is linear in momentum [5].

We show that SNSNS Josephson junctions with CSOI can achieve topological superconductivity utilising only superconducting phase differences. We find the existence of parameter ‘sweet spots’ that enable a significant topological region of phase space. Utilising realistic parameters for planar Ge Josephson junctions, we show that recent advances in superconductor-Ge devices [6,7] should enable MBSs to be realised in an experimentally accessible regime and for junctions with reasonable transparencies. We also demonstrate how the influence of an in-plane magnetic field can provide an additional fingerprint of the topological phase.

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Local parity flipping Andreev transitions

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We analyze microwave measurements of an InAs hybrid nanowire Josephson junction close to the pinch-off. As in the case of a quantum dot Josephson junction [1], the frequency shift of a resonator coupled to the system [2,3] indicates singlet/doublet alternation over certain gate voltage range. Surprisingly, the corresponding microwave induced transitions display sharp dips reaching zero energy close to the phase boundaries, suggesting that these transitions connect the singlet and the doublet: while parity flipping transitions are typical in transport experiments (e.g. [4]), they are forbidden when induced by microwave radiation, which can only excite a quasiparticle or break a Cooper pair to create two of them.

We show that these transitions can be theoretically understood by means of an additional localized state isolated in the junction [5], which acts as a reservoir for an electron, thus allowing a local parity flip in the main subsystem.

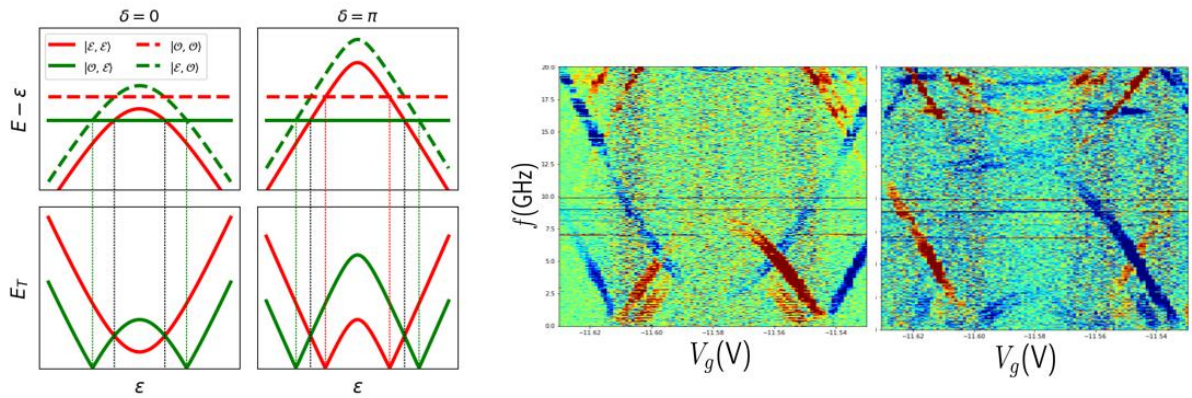

Fig. 1. Left: model of the junction and the ancillary level (top row: energies of the many-body states with even/odd parity in each subsystem; bottom row: corresponding allowed transitions). Right: Two-tone spectroscopy over gate.

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Growth and characterization of MBE-grown $Pb_{1-x}Sn_xTe$ nanowires

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Topological Insulators (TIs) are very interesting for their topological surface states, which hold great promise for scattering-free transport channels. In addition, topological qubits have potential for fault-tolerant quantum computing [1].
Here, we present the growth and characterization of the topological crystalline insulator (TCI) $Pb_{1-x}Sn_xTe$ in MBE, which is predicted to be topological for x>35% [2,3]. The nanowires are grown catalyst-free from holes in a patterned mask using a vapor-solid growth mechanism as can be seen in Fig. 1(a). We show that the nanowires are mono-crystalline with atomically flat [100] facets. Nanoflakes, which grow simultaneously with the nanowires and are easier to contact, are exploited to determine the carrier density of the nano-objects using Van de Pauw measurements (Fig. 1b). We find carrier densities for the nano-objects in the same order of magnitude as for thin films[3]. This indicates that we can grow exotic shapes with a similar level of defects as thin films. Finally, signatures of spin-polarization are measured by observing a potential difference between a state where the magnetization of a third ferromagnetic contact is aligned with the expected spin-polarization of the surface states (negative B-fields) and a state of misalignment (positive B-fields), indicating the presence of topological surface states as can be seen in Fig. 1(c). These results are a big step towards measuring and harnessing the topological surface states in the TCI material class with electronic devices.

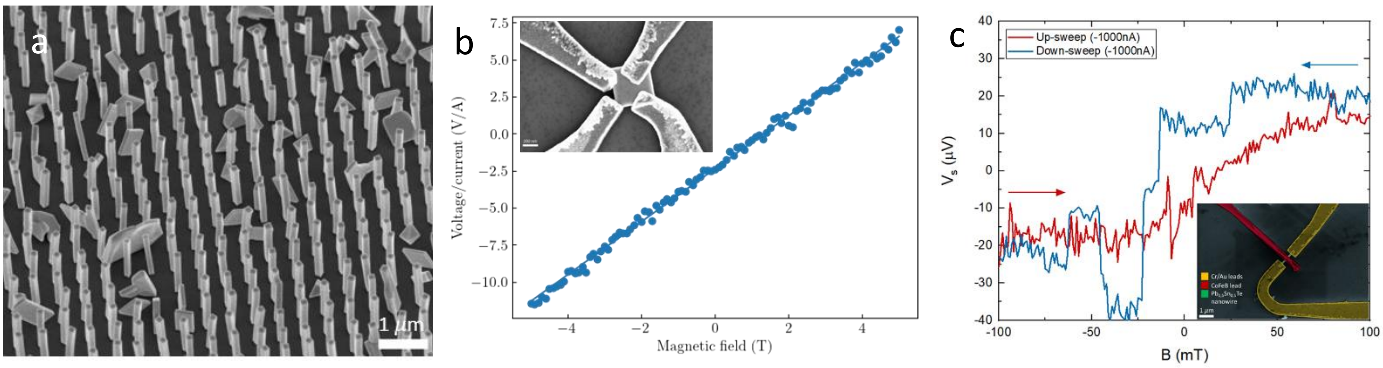

Fig. 1 (a) A representative SEM image of $Pb_{1-x}Sn_xTe$ nanowires grown from a patterned mask. (b) A magnetoconductance graph of a $Pb_{1-x}Sn_xTe$ nanoflake measured in the Van de Pauw configuration. The inset shows a SEM image of the measured flake. (c) The tunnel voltage measured between the ferromagnet and a metal contact as a function of the magnetic field. The inset shows a false-color SEM image of the measured device

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Tunnel spectroscopy of Andreev bound states in phase-biased topological insulator Josephson junctions

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Quasiparticle excitations that obey non-Abelian exchange statistics, such as Majorana zero modes, can serve as basis for topological quantum computation [1]. Such states are predicted to be formed at the boundaries of topological superconductors [2]. In their 2008 paper, Fu and Kane propose that a topological superconducting state is formed on the surface of a three-dimensional topological insulator when placed in close proximity to a conventional s-wave superconductor [3]. We experimentally investigate this platform using tunnelling spectroscopy. Our system is based on a planar Josephson junction (JJ) made by putting superconducting Al electrodes on the surface of the bulk-insulating topological insulator $BiSbTeSe_2$. Measuring the differential conductance at a tunnel junction made on the JJ gap in response to a wide parameter space of chemical potential, phase difference across the junction, and in-plane magnetic field allows us to study the dispersion of the states within the junction to confirm their predicted properties. For a certain range of controllable parameters, our results agree with the one-dimensional gapless mode with 4π-periodicity predicted by Fu and Kane [3]. Thus, the present work delivers results that are consistent with topological superconductivity in the surface states of a three-dimensional topological insulators with an approach that has not been used so far.

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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 challenging. 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]. Simple arguments for a strong triplet blockade are provided in the large-gap [4], and the strong-Coulomb-repulsion limit, furthermore we also outline a process-counting argument that supports partial triplet blockade in the intermediate regime, using perturbation theory [5]. We also present experimental data showing the triplet blockade predicted by the theory [1]. The triplet blockade mechanism could provide a coupling mechanism between spin qubits, and (topological or non-topological) superconducting qubits.

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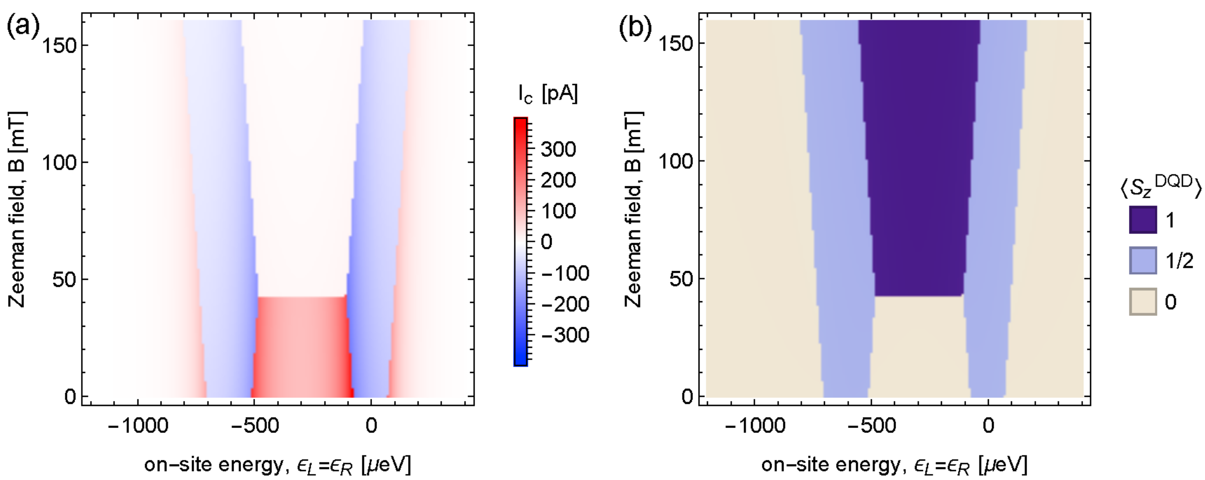

Figure 1. (a) Magnetic stability diagram of the double quantum dot Josephson junction; (b) Ground state expectation value of the z-component of the total double quantum dot spin reveals that the supercurrent is blockaded in the triplet configuration.

A Microscopic Model of a Quantum Dot Embedded in a Transmon

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Transmons can be made controllable by embedding a quantum dot within the Josephson junction. This exploits the full microscopic degrees of freedom by coupling the excitations of the QD level to the transport of Cooper pairs across the junction.

Modelling both the quantum dot and Josephson physics coherently is not possible with standard methods. The main problem is accounting for the charging energy in the superconductors.

We present a flat-band, charge conserving model that accounts for the interacting quantum dot, superconducting charging energy and phase dynamics in the Josephson junction. It can be diagonalised exactly, allowing for time evolution and non-equilibrium calculations.

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Theory of Caroli-de Gennes-Matricon analogs in full-shell hybrid nanowires

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We show that full-shell hybrid nanowires can host subgap states similar to teh Caroli-de Gennes- Matricon (CdGM) states in vortices, which are shell-induced Van Hove singularities in propagating core subbands.The CdGM analgos exhbit a characteritic skewness towards higher flux values inside non-zero Little-Parks (LP) lobes, resulting from the interplay of three ingredients: orbital copuling to the field, coalescence into degeneracy points, and the average radii of all CdGM analog wavefunctions inside the core. An approximation to realistic parameters is controlled by the electrostatic band bending at the core/shell interface. The analysis provides a transparent interpretation of the nanowire spectrum and allows for the extraction of microscopic information by measuring the number and skewness of CdGM analogs. Moreover, it allows for the derivation of an efficient Hamiltonian of the full-shell nanowire in terms of a modified hollow-core at the average radius of the CdGM wave functions.

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Towards semi-super qubits in planar Germanium

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Semiconductor-superconductor qubits combine the flexibility of superconducting circuits with the tunability of semiconductors, opening a new door for novel qubit designs [1, 2]. Finding a platform for them is a formidable task since it requires a microwave-compatible substrate and a transparent semiconductor-superconductor interface. So far only III-V material platforms have overcome the challenge [3].

Here, we present the initial steps towards realizing a gate-tunable superconducting qubit using planar Ge. We prove the microwave compatibility of our SiGe/Ge heterostructures by fabricating coplanar waveguide resonators exhibiting $Q_i \approx 10^4$ at the single photon power level. Induced superconductivity in germanium was achieved by evaporating aluminum on top of a thin $Si_{0.3}Ge_{0.7}$ spacer which separates the superconductor from the quantum well. We define Josephson junctions by selectively removing the aluminum above the hole gas. The Josephson junctions are embedded in an Xmon circuit [4] and capacitively coupled to a $\lambda/4$ transmission line resonator. With standard cQED techniques we demonstrate that the gate-tunable critical current of the Josephson junction allows the voltage tuning of the qubit.

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Magnetoconductance oscillations in topological crystalline insulator $Pb_{1-x}Sn_xTe$ nanowires

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SnTe is a topological crystalline insulator (TCI) with gapless surface states [1]. However, electrically probing these states is a challenge due to the large charge carrier density in the bulk. Therefore, we use the ternary alloy $Pb_{1-x}Sn_xTe$, for which x can be varied to reduce the carrier density but at the same time undergoes a topological to trivial phase transition for $x \approx 0.35$ [2]. Here, we report the fabrication and characterization of $Pb_{1-x}Sn_xTe$ nanowire field-effect devices with local bottom gates. Magnetoconductance measurements on a nanowire with $x = 0.4$ show periodic oscillations of the conductance as a function of in-plane magnetic field, which are reproducible even after multiple thermal cycles. The magnitude of the oscillations is on the order of one conductance quantum $2e^2/h$. The Fourier spectrum after subtracting the background shows three distinct sets of peaks. For the nanowire diameter d = 53±2 nm (measured using atomic force microscopy (AFM)), the three peaks correspond to flux values of *h/e*, *h/2e* and *h/3e*. This indicates the Aharonov-Bohm (AB) effect and Altschuler-Aronov-Spivak (AAS) effect with an additional higher harmonic, which have previously been reported for topological insulator (TI) nanowires [3,4]. From the temperature dependence of the *h/2e* peak, we extract a coherence length of $L_\phi \sim 3.5$ µm at 50 mK. These results indicate that $Pb_{1-x}Sn_xTe$ nanowires provide a suitable platform for electrically probing the topological states in a TCI in quantum transport experiments.

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

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InAs two-dimensional electron gases garnered great interest over the past decades due to their high carrier mobility, great density tunability and exotic topological phases as a consequence of spin-orbit coupling and superconducting proximity from an epitaxial Al layer [1]. This system is promising as a topological quantum computational platform or as a host to Andreev-qubits due to better scalability than semiconductor nanowire-based realizations [2-3]. In this contribution, I present the basic characterization of a new InAs 2DEG structure which is grown on a GaAs crystal by MBE. On the GaAs substrate first a step-graded buffer of InAlAs is used to alleviate the lattice mismatch, which is then followed by a 300 nm thick buffer layer to enhance the wafer properties for high-frequency measurements. We characterized this new heterostructure via low temperature transport measurements such as the observation of Shubnikov-de Haas oscillations, gate tunability measurements in large magnetic fields and Lifshits-Kosevich analysis. We found mobility values to be around 120000 $cm^2/(Vs)$ after the etching of the epitaxial Al layer, which exceeds previously reported values of samples grown on InP by a factor of two [1-3], and matches values measured on samples without the epitaxial Al layer [1]. By defining quantum point contact geometry with local gates, we demonstrate the first quantized conductance plateau. Furthermore, by measuring a Josephson junction in the mK regime we observed large, tunable critical current and Fraunhofer pattern [4]. Furthermore, by using the epitaxial Al layer as base for a superconducting resonator, we are working on the realization and spectroscopy of Andreev bound states, which can be the foundations of Andreev qbits.

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Dynamical parity polarization in a two-level Josephson junction

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We study theoretically dynamical parity polarization of an intermediate-length Josephson junction. We analyze results of a corresponding experiment [1] and develop a theoretical description for the observed effect. We explain why driving the system at specific frequencies increases the probability to find the system in a specific fermion parity sector. We discuss several regimes depending on the power of the drive and show how to optimize the parameters to reach higher polarization, which can be crucial for initializing the Andreev spin (or pair) qubit.

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Development of a semiconductor-superconductor hybrid 2DEG with in-situ Nb.

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The physics of topologically protected states, e.g. Majorana zero-bias modes, has been recently investigated in various semiconductor-superconductor platforms ranging from quasi 1-D nanowires to 2-D electron systems [1][2]. Most of the state of the art experiments rely on MBE-grown InAs combined with in-situ deposited epitaxial Al films [3]. However, promising results were recently shown using other superconductors, e.g. Sn [4], Pb [5] or Nb[6]. In this project we have developed a new hybrid material combination based on Nb as the superconductor. A novel method is implemented to achieve an epitaxial interface between an in-situ magnetron sputtered Nb thin film and a shallow InAs 2DEG by using an Al interlayer. We show optimization of the material stack to form highly transparent interfaces as well as transport measurements of Josephson Junctions fabricated from this material. With these experiments we aim to demonstrate the suitability of this material as a future platform to investigate topologically protected states.

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Assessing Bound States in a One-Dimensional Topological Superconductor: Majorana versus Tamm

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Majorana bound states emerging in topological superconductors seem ideal candidates as qubits to implement revolutionary protocols for fault-tolerant quantum computation. Low-energy models allowing to catch their properties are hence conceptually important. In such models, the standard scenario is that of two gapped phases separated by a gapless topological phase transition. Usually, one of the phases hosts Majorana bound states, while in the other topological bound states are absent. We show that a customary model violates this paradigm: the phase that should not host Majorana fermions supports a fractional soliton exponentially localized at only one end (technically, similar to a so-called Tamm-Shockley state). By varying the parameters of the model, we describe analytically the transition between the fractional soliton and the two Majoranas. We show – also numerically within the quadratic model – that, surprisingly, the Tamm state remains partially localized even when the spectrum becomes gapless. Despite this fact, we demonstrate that the Majorana polarization shows a clear transition between the two regimes, and that the topological properties of the Majorana bound states are not spoiled by the persistence of the Tamm state at the transition. We provide a possible physical implementation of the model and, lastly, we characterize the symmetry of the superconducting pairing, showing that the odd-frequency component closely follows the spatial extension of the Majorana bound states.

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Developing Numerical Renormalization Group for multi-terminal superconductor-dot devices

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With the gradual advance in fabrication of nanodevices, a progressively more complex systems are engineered. Bringing such systems into the contact with superconducting (SC) macroscopic reservoirs leads to quantum phenomena such as Andreev bound states or Josephson currents [1-5]. In the presence of strong Coulombic interactions, theoretical models of Anderson impurity type are typically considered. In such cases, complete understanding via the Numercial renormalization group is possible in the presence of up to two SC leads [6]. However, three and more SC leads the currently intractable by NRG.

Nevertheless, the techniques developed by R. Bulla for pseudo-gap Fermi systems could offer a resolution [7]. For one impurity, one would first extract the corresponding tunneling density of states (TDOS) and apply logarithmic discretization accordingly. The resulting ξ and γ coefficients would then define just one semi-infinite Wilson chain which can easily be solved iteratively by NRG. However, for SC problems the TDOS contains a gap and the discretization procedure fails [8,9]. The direct discretization of the TDOS can be avoided by realizing that the ξ and γ coefficients actually represent the poles and corresponding weights of the discretized TDOS in the current NRG approaches. We then develop a completely new NRG algorithm for SC leads which is of one-cannel nature for arbitrary number of SC leads, which thus overcomes the current limitations.

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