POSTER ABSTRACTS

RELEVANT INFORMATION:

The poster sessions will take place in the same room as the coffee breaks, i.e. in Sala de Música. In each poster session, a dedicated committee will rank 3 best posters for a 1st, a 2nd, and a 3rd places and announce the winners the next day, shortly before the lunch break. The best-poster prizes are sponsored by Nature Reviews Materials.

Tuesday, September 6

16:45–19:15  Poster session A

Group A can hang their posters in Sala de Música on Tuesday morning. The posters will then need to be removed during the lunch break on Wednesday to free the space for Group B.

Wednesday, September 7

12:35–12:45  committee

Award of prizes for best posters of Poster session A

Thursday, September 8

16:45–19:15  Poster session B

Group B can hang their posters in Sala de Música on Wednesday during lunch break.

Friday, September 9

12:35–12:45  committee

Award of prizes for best posters of Poster session B
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Group A

poster session on Tuesday, 16:45–19:15
Electrical and magnetic tuning of Andreev levels in a hybrid superconductor-semiconductor quantum dot

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In recent years, there has been a growing interest in the interaction of magnetic impurities and superconductors. This is partly motivated by theoretical proposals that suggest that chains of such impurities can result, under appropriate conditions, in a topological superconductor [1-9]. A semiconductor quantum dot coupled to a superconductor represents a versatile platform to investigate, in a controllable and quantitative manner, the physics of the corresponding single-impurity limit. Accordingly, we have employed nanowire-based quantum dots, coupled strongly to a superconductor and weakly to a normal metal probe, to spectroscopically study the sub-gap states, commonly referred to as Andreev levels. These levels stem from a competition between superconductivity proximity effect, Kondo correlations and Coulomb blockade, which defines the ground state of the system: a spin singlet or a magnetic doublet. We demonstrate, by properly adjusting the coupling of the quantum dot to the superconductor, electrically-tunable quantum phase transitions between singlet and doublet ground states. We further exploit the electrical control over device parameters to obtain an experimental phase diagram of the possible ground states, which shows a remarkable agreement with numerical renormalization group calculations [10]. In parallel, we have studied the magnetic properties of the Andreev levels. We demonstrate that the Zeeman effect results in a splitting of the sub-gap states only when the ground state is a spin singlet. In this case, the applied magnetic field can also lead to a quantum phase transition to a spin-polarized ground state [11]. The herein demonstrated electrical tuning of Andreev levels as well as their spin-polarization could be harnessed to pursue proposals of realizing a topological superconductor using quantum dot arrays [7-9].

[10] Lee et al., in preparation.
Transport signatures of interacting fermions in quasi-one-dimensional topological superconductors
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A topological superconducting wire with an effective time reversal symmetry is known to have a Z8 topological classification in the presence of interactions. The topological index $|n| \leq 4$ counts the number of Majorana end states, negative $n$ corresponding to end states that are odd under time reversal. If such a wire is weakly coupled to a normal-metal lead, interactions induce a Kondo-like correlated state if $|n| = 4$. We show that the Kondo-like state manifests itself in an anomalous temperature dependence of the zero-bias conductance and by an anomalous Fano factor for the zero-temperature normally-reflected current at finite bias. We also consider the splitting of the effective Kondo resonance for weak symmetry-breaking perturbations.
From an array of quantum wires to three-dimensional fractional topological insulators

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The coupled-wires approach has been shown to be useful in describing two-dimensional strongly interacting topological phases. We extend this approach to three-dimensions, and construct a model for a fractional strong topological insulator. This topologically ordered phase has an exotic gapless state on the surface, called a fractional Dirac liquid, which cannot be described by the Dirac theory of free fermions. Like in non-interacting strong topological insulators, the surface is protected by the presence of time-reversal symmetry and charge conservation. We show that upon breaking these symmetries, the gapped fractional Dirac liquid presents unique features. In particular, the gapped phase that results from breaking time-reversal symmetry has a halved fractional Hall conductance of the form \( \sigma_{xy} = \frac{e^2}{2mh} \) if the filling is \( \nu = 1/m \). On the other hand, if the surface is gapped by proximity coupling to an s-wave superconductor, we end up with an exotic topological superconductor. To reveal the topological nature of this superconducting phase, we partition the surface into two regions: one with broken time-reversal symmetry and another coupled to a superconductor. We find a fractional Majorana mode, which cannot be described by a free Majorana theory, on the boundary between the two regions. The density of states associated with tunneling into this one-dimensional channel is proportional to \( \omega^{m-1} \), in analogy to the edge of the corresponding Laughlin state.
Signatures of topological Josephson junctions

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Quasiparticle poisoning and diabatic transitions may significantly narrow the window for the experimental observation of the 4\pi-periodic dc Josephson effect predicted for topological Josephson junctions. Here, we show that switching current measurements provide accessible and robust signatures for topological superconductivity which persist in the presence of quasiparticle poisoning processes. Such measurements provide access to the phase-dependent subgap spectrum and Josephson currents of the topological junction when incorporating it into an asymmetric SQUID together with a conventional Josephson junction with large critical current. We also argue that pump-probe experiments with multiple current pulses can be used to measure the quasiparticle poisoning rates of the topological junction. The proposed signatures are particularly robust, even in the presence of Zeeman fields and spin-orbit coupling, when focusing on short Josephson junctions. Finally, we also consider microwave excitations of short topological Josephson junctions which may complement switching current measurements.
Current Correlations in a Majorana Beam Splitter

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We study current correlations in a T-junction composed of a grounded topological superconductor and of two normal-metal leads which are biased at a voltage $V$. We show that the existence of an isolated Majorana zero mode in the junction dictates a universal behavior for the cross correlation of the currents through the two normal-metal leads of the junction. The cross correlation is negative and approaches zero at high bias voltages as $-1/V$. This behavior is robust in the presence of disorder and multiple transverse channels, and persists at finite temperatures. In contrast, an accidental low-energy Andreev bound state gives rise to non-universal behavior of the cross correlation. We employ numerical transport simulations to corroborate our conclusions.


The prospect of coupling a two-dimensional (2D) semiconductor heterostructure to a superconductor opens new research and technology opportunities, including fundamental problems in mesoscopic superconductivity, scalable superconducting electronics, and new topological states of matter. For instance, one route toward realizing topological matter is by coupling a 2D electron gas (2DEG) with strong spin-orbit interaction to an $s$-wave superconductor [1]. Previous efforts along these lines have been hindered by interface disorder and unstable gating. For InAs nanowires, this problem has been recently overcome by growing an epitaxial Al film \textit{in-situ}, i.e. directly in the InAs growing chamber [2].

We will present transport experiment performed on an InAs/Al heterostructures, where the superconductive Al film is epitaxially matched and grown \textit{in-situ} on InAs, allowing for a pristine semiconductor-superconductor interface [3]. The Al film is only a few nanometers thick, resulting in an in-plane critical field exceeding 1.5 T. The InAs 2DEG is gate tunable and characterized by strong spin-orbit coupling.

Experiments conducted on Josephson junctions demonstrated gate tunable supercurrents and an unprecedented interface transparency for a 2D system. Multiple Andreev reflection (MAR) are used to measure a near-unity junction transmission and an induced superconducting gap of 180 $\mu$eV, close to that of Al, indicating a high quality superconductor-semiconductor interface.

Most notably, transport measurement performed on a semiconductor – quantum point contact (QPC) – superconductor device [5] confirm the long standing prediction of the Andreev doubling of quantized conductance [4]. Operating the QPC in the tunneling regime, we directly measure the density of states below the Al. For the first time in a hybrid 2D system, we probe a hard superconductive gap of 180 $\mu$eV, comparable to the state-of-the-art nanowire devices [6].

We will finally present our current efforts in creating Majorana modes in these structures by top-down lithography of one-dimensional nanowires. This approach could allow, in the future, the realization of complex T-junctions and Majorana networks [7].

A.6

Detecting Topological Superconductivity with $\phi_0$ Josephson Junction

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Topological superconductivity can emerge in conventional superconductors in the presence of spin-orbit interaction and magnetic fields. Remarkably, the recent experimental discovery of $\phi_0$ Josephson junctions by Szombati et al., Nat. Phys. 12, 568 (2016), characterized by a finite phase offset in the supercurrent, require the same ingredients as topological superconductors, which suggests a profound connection between these two distinct phenomena. Here, we theoretically show that a quantum dot $\phi_0$ Josephson junction can serve as a new qualitative indicator for topological superconductivity: Microscopically, we find that the phase shift in a junction of $s-$wave superconductors is due to the spin-orbit induced mixing of singly occupied states on the quantum dot, while for a topological superconductor junction it is due to singlet-triplet mixing. Because of this important difference, when the spin-orbit vector of the quantum dot and the external Zeeman field are orthogonal, the $s$-wave superconductors form a $\pi$ Josephson junction while the topological superconductors have a finite offset $\phi_0$ by which topological superconductivity can be distinguished from conventional superconductivity. Our prediction can be immediately tested in nanowire systems currently used for Majorana fermion experiments and thus offers a new and realistic approach for detecting topological bound states.
Edge effects in ballistic InAs Josephson junctions

Folkert K. de Vries, Jasper van Veen, Tom Timmerman, Arjan J.A. Beukman, Fanming Qu, Binh-Minh Nguyen, Wei Yi, Jacob Thorp, Marko Sokolich, Michael J. Manfra, Charles M. Marcus, and Leo P. Kouwenhoven

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Previous observations of finite size Josephson junctions show the influence of edge scattering in the magnetic interference patterns [1,2]. Here we study the edge effects in long ballistic NbTiN – InAs 2DEG – NbTiN Josephson junctions with highly transparent contacts. The switching current is investigated under the influence of an electrostatic gate, perpendicular magnetic field and radio frequency radiation. The InAs quantum well is expected to have trivial edge conduction resulting from Fermi level pinning at the surface [3]. Electrostatic gating enables us to change the electron density as well as the ratio of bulk versus edge conduction. This crossover regime is studied with magnetic interference measurements of the switching current. The measurements will be compared to recent theoretical simulations on the effect of edge scattering in the long Josephson junctions[4]. Furthermore signatures of a non-sinusoidal current phase relation are obtained in the radio frequency response of the supercurrent. This work could give insight in the understanding of proximitized edge states, for example in quantum Hall or quantum spin Hall systems.

Majorana modes without free fermions
Graham Kells, Dganit Meidan, and Niall Moran

\textsuperscript{1}DIAS
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The concept of a Majorana quasi-particle is rooted in the mean-field/free-fermion picture. We will discuss some of the 1D interacting regimes where the notion of a Majorana mode also makes sense. Moreover we will show how disorder can be used to extend the parameter space where this happens.
Interplay of topology and interactions in quantum Hall topological insulators: U(1) symmetry, tunable Luttinger liquid, and interaction-induced phase transitions

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We consider a class of quantum Hall topological insulators: topologically nontrivial states with zero Chern number at finite magnetic field, in which the counter-propagating edge states are protected by a symmetry (spatial or spin) other than time-reversal. HgTe-type heterostructures and graphene are among the relevant systems. We study the effect of electron interactions on the topological properties of the system. We particularly focus on the vicinity of the topological phase transition, marked by the crossing of two Landau levels, where the system is a strongly interacting quantum Hall ferromagnet. We analyse the edge properties using the formalism of the nonlinear $\sigma$-model. We establish the symmetry requirement for the topological protection in this interacting system: effective continuous U(1) symmetry with respect to uniaxial isospin rotations must be preserved. If U(1) symmetry is preserved, the topologically nontrivial phase persists; its edge is a helical Luttinger liquid with highly tunable effective interactions. We obtain explicit analytical expressions for the parameters of the Luttinger liquid. However, U(1) symmetry may be broken, either spontaneously or by U(1)-asymmetric interactions. In either case, interaction-induced transitions occur to the respective topologically trivial phases with gapped edge charge excitations.

Measurement of the channel’s transmissions of an InAs Josephson junction

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Semiconductor nanowires in good contact with superconductors allow obtaining Josephson junctions with low electron density and strong spin-orbit interaction, which are used in particular in the quest of Majorana physics. An important issue is the determination of the number of transport channels and of their transmissions. Here, we present measurements of the current-voltage ($I-V$) characteristics of Josephson junctions obtained from epitaxial InAs–Al semiconductor–superconductor nanowires [1] in which an Al shell has been etched away over 150nm. A pair of metallic side gates is used to deplete the InAs and modulate the $I-V$ characteristics. The number of channels of the junction and their transmissions are obtained by fitting the $I$-$V$s, assuming that their non-linearities are due to Multiple Andreev Reflections (MAR) [2]. It is found that the number of channels can be tuned from 4 to 1, with transmissions sometimes approaching unity. However, the MAR fits do not always reproduce all the observed features, in particular the asymmetry of the $I$-$V$s.

The aim of the poster is to trigger discussions on the validity of the description of these preliminary results in terms of MAR, and on possible extensions of the theory.

InAs Josephson junction: InAs nanowire covered with epitaxial Al, except in the 150-nm-long central region. Bright fingers are metallic gates.


Cavity quantum electrodynamics techniques have turned out to be instrumental to probe or manipulate the electronic states of nanoscale circuits. [1] Recently, cavity QED architectures have been extended to quantum dot circuits. These circuits are appealing since other degrees of freedom than the traditional ones (e.g. those of superconducting circuits) can be investigated. I will show how one can use carbon nanotube based quantum dots in that context. In particular, we design electronic circuits based on a Cooper pair splitters architecture, which could be used to study spin entanglement in condensed matter. I will focus on the coherent coupling of a non-local Cooper pairs to cavity photons. We observe a vacuum Rabi splitting of the photonic mode when brought in resonance with transitions of the Cooper pair splitter.

We have very recently extended such an architecture to induce topological superconductivity in carbon nanotube, with the help of an additional artificial spin-orbit coupling. I will present preliminary results on the coupling of such systems to microwave cavity photons.

Self-organized topological superconductivity in magnetic adatom lattices

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Motivated by recent experiments [1-3], we study lattices of magnetic adatoms exchange coupled to the surface of a conventional s-wave superconductor. We show that a variety of collective magnetic and electronic phases emerge in this system, due to the interplay between ferromagnetism and superconductivity. In particular, an adatom chain on a bulk (2d or 3d) superconductor can order into a magnetic spiral state leading to, and stabilized by, the opening of a topological superconducting gap within the band of Shiba states induced by the adatoms [4]. The spiral wave-vector increases sharply as the Shiba energy is lowered from the quasiparticle continuum, due to a strong spin-spin exchange interaction mediated through the band of sub-gap Shiba states. As the Shiba band enters the topological phase, the wave-vector exhibits a peak and is thereafter driven down towards ferromagnetism due to Shiba state double-exchange. We provide the range of Shiba energies and adatom spacing where these phases exist for adatoms on a 3d superconductor in Fig. 1. The possibility of non-coplanar magnetism in a 2d adatom lattice, associated with the opening of a topological $p+ip$ superconducting gap in the corresponding 2d Shiba lattice, is also explored.

Fig. 1 Groundstate phase diagram of a magnetic adatom chain on a 3d superconductor as a function of chain lattice spacing $a$ and single Shiba energy $\epsilon$ [4]. The general structure of the phase diagram repeats for integer $n$ ($n=15$ shown). The regions denoted by AF represent antiferromagnetism, while S denotes a magnetic spiral whose wavevector is shown schematically in gray-scale. The topologically nontrivial and distinct superconducting TS$^\pm$-regions are bounded by the red curves.

Tomography of Majorana Fermions with STM tips

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We investigate numerically the possibility to detect the spatial profile of Majorana fermions (MFs) modeling STM tips that are made of either normal or superconducting material. In both cases, we are able to resolve the localization length and the oscillation period of the MF wavefunction. We show that the tunneling between the substrate and the tip, necessary to get the information on the wave function oscillations, has to be smaller in the case of a superconducting STM. In the strong tunneling regime, the differential conductance saturates making it more difficult to observe the exponential decay of MFs. The temperature broadening of the profile is strongly suppressed in case of the superconducting lead resulting, generally, in better resolution.
Fano Resonances in Majorana Bound State - Quantum Dot Systems

Alexander Schuray,¹ Luzie Weithofer,¹ and Patrik Recher¹

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Majorana bound states (MBS) have received a lot of attention in the last years and first experiments with nanowires in proximity to a superconductor [1] possibly present first experimental evidence for their existence. Systems in which MBS are coupled via a quantum dot to normal leads are also gaining interest, as the parameters of the dot provide an interesting handle for transport signatures [2]. In contrast to previous studies, here we consider two MBS with non-zero overlap coupled to a lead on one side and a quantum dot on the other side. Using the Keldysh formalism we derive the cumulant generating function (CGF) for the tunnel currents in the leads. We show that this setup exhibits a Fano-resonance which we interpret as resulting from interference of two different transport channels. Finally, we validate numerically that our result for this simple model is also applicable to a realistic setup of quantum wire and dot.

Breaking time-reversal symmetry at the topological insulator surface by metal-organic coordination networks

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We propose a new way to break the time-reversal symmetry at the surface of a three-dimensional topological insulator. Based on the possibility of organizing an ordered array of local magnetic moments by inserting them into a two-dimensional matrix of organic ligands, we study the magnetic coupling and electronic structure of such metal-organic coordination networks on a topological insulator surface from first principles. In this way, we find that both Co and Cr centers, linked by the tetracyanoethylene-like organic ligand, are coupled ferromagnetically and, depending on the distance to the topological insulator substrate, can yield a magnetic proximity effect. This latter leads to the Dirac point gap opening indicative of the time-reversal symmetry breaking.
Two-dimensional centrosymmetric topological insulators constructed from BiTeI trilayers: 
*ab initio* calculations and related model Hamiltonians

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The unique transport properties of two-dimensional (2D) topological insulators (TI) trigger a search of robust and easily fabricated materials. The thinnest known film of three-dimensional (3D) TI that can demonstrate topologically nontrivial properties consists of at least two structural elements—quintuple or septuple layers—and has a band gap of ~100 meV [1].

Here we demonstrate that a centrosymmetric sextuple layer (SL) constructed from two BiTeI trilayers with facing Te-layer sides and a typical van-der-Waals spacing $d_{vdW}$ is a 2D TI with the gap of 70 meV at $\Gamma$'. With increasing $d_{vdW}$, this SL becomes topologically trivial. We derive an eight-band $k\cdot p$ Hamiltonian $H_{kp}^{SL}$ that involves Rashba-split valence and conduction bands of BiTeI and show that due to the bonding-antibonding splitting the inversion occurs between one of the Te-related valence bands and one of the conduction bands formed by Bi orbitals.

We consider the above SL as a structure element, a repetition of which along the $z$-axis results rapidly in gapless Dirac surface states. The topological invariant $v$ of the films is found to “oscillate” with the number of SLs. The corresponding bulk system is a 3D TI with the band gap of 234 meV at $\Gamma$. This TI turns out to be described by the same four-band $k\cdot p$ Hamiltonian $H_{kp}^{bulk}$ as that for Bi$_2$Se$_3$ (to within a unitary transformation) [2]. For the $k\cdot p$ description of the films, we use a four-band $H_{kp}^{slab}$ accurate up to $k^2$.

We derive the Hamiltonians within an original approach from *ab initio* bulk or slab wave functions $\Psi_n$ obtained with the all-electron full-potential linearized augmented plane-wave method. This approach allows us to show how $H_{kp}^{bulk}$ relates to $H_{kp}^{slab}$ and to what extent the behavior of parameters of $H_{kp}^{slab}$ as a function of thickness correlates with the thickness-dependence of $v$.

This work was supported by the Spanish Ministry of Economy and Competitiveness MINECO (Project No. FIS2013-48286-C2-1-P) and Saint Petersburg State University (Grant No. 15.61.202.2015).
Excitonic insulators are a condensate phase of matter investigated since the sixties [1]. They remain so far an elusive phase in solid-state systems. Recent experiments hints at the observation of a semi-metallic/excitonic insulator phase in HgTe quantum wells with a width of circa 20 nm [2]. Proposal of combining excitonic insulators with superconductors should show evidence of Andreev processes due to the combination of two different types of condensates [3].

Inspired by recent experiments where HgTe quantum wells where analyzed in combination with superconductors [4] we have analyzed the transport property of a hybrid junction composed of a semi-metallic-electrode, an excitonic insulator and a superconductive electrode. We have simulate the superconductive electrode by proximizing a semi-metal. By playing with the length of the excitonic insulator region [5], we can show that the current in the semi-metal electrode can be due either to holes coming from standard Andreev reflection and to electrons coming from Rontani-Sham reflection [6].

Majorana fermions detected in the vortex of Bi$_2$Te$_3$/NbSe$_2$ topological insulator-superconductor heterostructure

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Majorana fermions (MFs) have been intensively studied for many years because of their importance to both fundamental science and potential applications in topological quantum computing. MFs are predicted to exist in a vortex core of superconducting topological insulators. Here, we made the topological insulator/superconductor heterostructure by growing of Bi$_2$Te$_3$ on the top of NbSe$_2$ [1]. Then, we proved the surface states of Bi$_2$Te$_3$ are superconducting, i.e., Bi$_2$Te$_3$/NbSe$_2$ heterostructure is an artificial topological superconductor [2]. Finally, all three features of MFs, zero energy, cone-like spatial distribution and spin selective Andreev reflection were observed at the center of the vortex in Bi$_2$Te$_3$/NbSe$_2$. And most importantly, all the evidences are self-consistent, i.e., while the MF appears, the intensity of the zero bias peak is high, the zero bias peak splits off at a finite distance away from the vortex center and spin selective Andreev reflection is observed. While the MF is destroyed by the interaction between vortices, all the three phenomena disappear at the same time [3,4]. Our work provides definitive evidences of Majorana fermions and also suggests a possible route to manipulating them. It will stimulate the MFs research on their novel physical properties, hence a step towards their statistics and application in quantum computing.

References

Characterising unconventional superconductors from the spin structure of impurity-induced bound states

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Cooper pairs in two-dimensional unconventional superconductors with broken inversion symmetry are in a mixture of an even-parity spin-singlet pairing state with an odd-parity spin-triplet pairing state. We study the magnetic properties of the impurity bound states in such superconductors and find striking signatures in their spin polarisation which allow to unambiguously discriminate a non-topological superconducting phase from a topological one. Moreover, we show how these properties, which could be measured using spin-polarised scanning tunneling microscopy (STM), also enable to determine the direction of the spin-triplet pairing vector of the host material and thus to distinguish between different types of unconventional pairing.
Conductance of a quantum point contact realized in a semiconductor-superconductor heterostructure is predicted to be quantized in multiples of twice the conductance quantum [1]. This results from Andreev reflection at the normal-superconductor interface and hence doubling of the charge that is transported through the constriction. Only very recently this phenomenon has been demonstrated experimentally [2,3]. However, the measurements reveal an unexpected - but independent on the system geometry – feature: conductance drop after the first enhanced plateau. In this work we explain that this indicates mixing between the lowest subbands of the transport channel. We simulate numerically the nanowire geometry of Ref. [2] and show that the dip structure depends on the disorder strength and the shape of the quantum point contact. Van Hove singularity at the subband bottom strongly enhances the mode mixing near the opening of the next transport channel and results in the appearance of the dip even for systems with a residual disorder. Notably, despite the fact that the mode mixing leaves a strong imprint on the conductance governed by the Andreev reflection, it still allows for a perfect quantization of the conductance for energies above the superconducting gap.

Group B

poster session on Thursday, 16:45–19:15
Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry
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By coupling the kinetic moment of the electron to its spin, spin-orbit (SO) interactions provide a fundamental tool to transform electronic currents into spin currents and vice-versa, a basic ingredient of spintronic devices. Coupling strong SO materials to superconductors is expected to induce new phenomena, such as spin-dependent supercurrents, supercurrents at zero phase difference (phi_0 junctions), topologically protected zero-energy states, etc... So far, these ideas were explored experimentally with semiconducting nanowires (InAs or InSb). New heterostructures have also been engineered from high spin-orbit elements, exploiting crystalline symmetries and boundary conditions to induce original bandstructure: Such are the 2D and 3D topological insulators, famed for the striking properties of their edge states, such as the quantum spin Hall regime in HgTe/HgCdTe and InAs/GaSb quantum wells. Adding superconducting contacts has led to the observation of supercurrents carried by the helical edge states.

By contrast, edge states in semiconducting or semimetallic quantum wires have not yet been detected through transport measurements, even though scanning tunnelling spectroscopy has given strong indications of their existence. One difficulty is to distinguish them from bulk or surface states, that also contribute to transport.

In the presentation, we will report on our use of proximity-induced superconductivity through monocrystalline bismuth nanowires to reveal one dimensional, ballistic states at the edges of (111) facets. The one-dimensional character was previously inferred from the subsistance of the supercurrent at high (Tesla-order) fields and from modulation of the Josephson current by the magnetic flux through the facets [Li]. We have more recently demonstrated the ballistic nature of the 1D states, via the measurement of the characteristic sawtooth-shaped supercurrent-Vs-phase relation when the bismuth nanowire is inserted as part of an asymmetric SQUID. We find that the magnetic field orientation and amplitude modulate the phase of the supercurrent-Vs-phase relation, producing phi_0 junctions as well as 0-pi transitions, thereby demonstrating the dephasing by the Zeeman energy of Andreev pairs created from spin-orbit-split Andreev levels.

The helical gap in interacting Rashba wires at low electron densities

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Rashba spin-orbit coupling and a magnetic field perpendicular to the Rashba axis have been predicted to open a partial gap ("helical gap") in the energy spectrum of noninteracting or weakly interacting one-dimensional quantum wires. By comparing kinetic energy and Coulomb energy we show that this gap opening typically occurs at low electron densities where the Coulomb energy dominates. To address this strongly correlated limit, we investigate Rashba wires using Wigner crystal theory. To interplay of Rashba spin-orbit coupling and a magnetic field leads to an effective spiral magnetic field. We find that the helical gap exists even in the limit of strong interactions but its dependence on electron density differs significantly from the weakly interacting case. In particular, we find that the critical magnetic field for opening the gap becomes an oscillatory function of electron density.

Figure 1: Left: Critical magnetic field as a function of density for the noninteracting (blue line) and the interacting (red line) case. In the interacting case, $B_{\text{crit}} = 0$ whenever the particle density is commensurate with the pitch of the effective spiral magnetic field. Examples for commensurate densities are shown in the right panel, where the dots denote the electron positions and the spiral indicates the effective magnetic field. Right: Comparison of electron density and Rashba length for a general incommensurate density.

We present the spectroscopy and the quantum manipulation of Andreev states in an elementary superconducting weak-link: a single atom contact between two superconductors [1]. The experiments rely on a circuit-QED architecture, in which the phase-biased contact is coupled to the electromagnetic field of a microwave resonator. We show that it is possible to create a long-lived excitation (lifetime of several microseconds) by promoting two quasiparticles into a sub-gap discrete spin-degenerate bound state. We also demonstrate coherent superpositions of this excited state and the ground state.

The same methods could be employed to detect and characterize topological junctions in which a non-degenerate subgap state is obtained from the hybridization of two Majorana states [2].

Interplay between phonons and band topology in Dirac materials

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The discovery of topological phases in three dimensional crystals has culminated in a new classification scheme for solids that is based on quantum mechanics and topology. In topological phases, the momentum-space geometry of electronic energy bands and wave functions is described by nonzero integers known as topological invariants.

Although the allure of topological materials has ignited a spark of research activity, almost all theoretical studies thus far have focused on closed quantum systems, wherein electrons are isolated from their environments. Yet, the assumption of isolated electrons is not realistic in principle. In real crystals, electrons constitute open quantum systems coupled to various baths, of which the most ubiquitous are lattice vibrations (phonons).

In the first part of the poster, I will show that electron-phonon interactions can alter the topological properties of Dirac insulators and semimetals, at both zero and nonzero temperature. Contrary to the common belief that increasing temperature always destabilizes topological phases, our results highlight instances in which phonons may lead to the appearance of topological surface states above a crossover temperature in a material that has a topologically trivial ground state [1, 2].

In the second part of the poster, I will turn the tables and will explore the backaction of topological invariants on phonons. I will show that, for a centrosymmetric Dirac insulator coupled to phonons, the linewidths of bulk optical phonons can reveal electronic band inversions [3]. Long the same lines, I will discuss my ongoing work on how the chiral anomaly of Weyl semimetals modifies the lattice dynamics as well as the interaction between electrons and polar optical phonons [4].

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**References**

4. P. Rinkel and I. Garate, *in progress*
New Fermions

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In quantum field theory, we learn that fermions come in three varieties: Majorana, Weyl, and Dirac. In this paper, we show that this is not a complete classification. We find the types of crystal symmetry-protected free fermionic excitations that can occur in condensed matter systems, going beyond the classification of Majorana, Weyl, and Dirac particles. We exhaustively classify linear and quadratic 3-, 6- and 8- band crossings stabilized by space group symmetries in solid state systems with spin-orbit coupling and time-reversal symmetry. Several distinct types of fermions arise, differentiated by their degeneracies at and along high symmetry points, lines, and surfaces. For each new class of fermion, we analyze its topological properties by constructing the low-energy effective Hamiltonian and comment on any possible experimental signatures. Some notable consequences of these fermions are the presence of Fermi arcs in non-Weyl systems, the fermionic spin-1 generalization of a Weyl fermion, and the existence of Dirac lines. In addition, we present 18 candidate materials that should realize these exotic fermions, as verified by ab-initio calculations. Finally, we comment on experimental investigations that are currently underway.
Transport in Majorana nanowires
Javier Osca, Jong Soo Lim, Rosa López, and Lorenz Serral

1. Abstract

The electrical resistance expression is obtained for a Majorana nanowire. The sign of the total current is determined by means of the Keldysh Green function formalism. Our main result is that the AC transport on a Majorana nanowire cannot be modeled by an equivalent RC circuit. On the other hand, we calculate the AC and quasi-particle transmission. In the presence of a perpendicular component of the magnetic field, the current flows in the quantum tunneling without a preferred orientation. Oppositely, when a perpendicular component of the magnetic field is present, the quasi-particle current circulates surrounding the Majorana density peak with an orientation established by the magnetic field.

2. Majorana AC admittance calculation

- Step 1. The time-dependent current is calculated as the electron number variation in the context of the

\[ \frac{dN(t)}{dt} = \frac{1}{\hbar} \left( \frac{\partial}{\partial \phi} \mathcal{K}_{\text{Majorana}} \right) \]

- Step 2. The admittance is given by the function of the electron Hamiltonian:

\[ Y(t) = \int \frac{dx}{\hbar} \mathcal{K}_{\text{Majorana}} \]

- Step 3. The current is calculated as follows:

\[ I(t) = \int \frac{dx}{\hbar} \mathcal{K}_{\text{Majorana}} \]

- Step 4. The admittance and current are calculated using the parametric expressions.

3. Admittance frequency response \( \omega = \frac{1}{\hbar} \)

\[ \text{Current} = \int \frac{dx}{\hbar} \mathcal{K}_{\text{Majorana}} \]

\[ \text{Admittance} = \int \frac{dx}{\hbar} \mathcal{K}_{\text{Majorana}} \]

4. Majorana junction: not equivalent to an RC circuit

\[ A \text{ quasi-particle current} \]

\[ B \text{ Majorana junction} \]

5. SpatialHamiltonian variation

\[ \text{Semi-infinite nanowire density function} \]

\[ \text{A zero eigenvalue of } \mathcal{H} \text{ is a Majorana signature} \]

6. Majorana local quasi-particle current

- Currents follow closed trajectories
- No preferred direction of circulation in a no magnetic field parallel propagator
- Circulation around the Majorana \( \mathcal{H} \) propagator component present.

7. Conclusions

- We calculated the admittance and AC response of the Majorana state.
- We showed that a Majorana junction is not equivalent to a RC circuit.
- We calculated the local current associated with the Majorana state.
- We have shown the difference in the current in presence of absence of a perpendicular component of the magnetic field.

8. References

Quasiparticle poisoning in semiconductor-superconductor nanowires

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Superconductor-semiconductor structures can be driven into a topological regime by application of an external magnetic field, in which Majorana zero modes emerge. Although spectral properties of these bound states have been investigated by several groups [1-4,8], their dynamical properties are of utmost importance for applications as topological qubits. Our work extends recent work on quasiparticle poisoning times in superconducting structures [6,7], by developing nanowire-based double-island devices in which the Josephson coupling between islands can be quickly manipulated using gate electrodes, whereas the charge of islands can be measured with high-bandwidth proximal charge sensors and rf-reflectometry. These devices will allow the direct measurement of quasiparticle poisoning dynamics, as well as demonstrations of parity-to-charge conversion and related steps towards initialization and readout of a double-island Majorana qubit [9].

Spin-orbit interaction in dual gated InAs/GaSb quantum wells

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InAs/GaSb heterostructures have attracted much attention because of the prediction that they can host the quantum spin Hall insulator phase when their band structure is inverted [1]. Recently it has been shown that in a dual gated geometry the band structure in these quantum wells can be tuned between inverted and non-inverted [2]. An important difference between the two regimes is that in the inverted regime electrons and holes coexist whereas in the non-inverted regime only one charge carrier is present. Here we study the spin-orbit interaction (SOI) in InAs/GaSb quantum wells both in the two carrier as in the electron (only) regime by analyzing the beating pattern in the Shubnikov-de Haas oscillations, see figure 1.

We observe that in the electron regime the zero field spin splitting (ZFSS) can be tuned by 20% when the gates are varied along a constant electron density line. The observed beating pattern in this regime is described by a model which includes Rashba as well as linear and cubic Dresselhaus SOI. In the two carrier regime we observe an oscillating pattern of regions in gate space that show the beating pattern. Also we observe that the ZFSS increases when the Fermi level is tuned towards the hybridization gap. Both these observation are consistent with our band structure calculations.

![Figure 1: Experimental data showing the beating in the Shubnikov-de Haas oscillations in the electron regime at various gate voltages along a constant electron density line.](image)

Chern numbers and chiral anomalies in Weyl butterflies

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The Hofstadter problem—the competition between the periodicities imposed by the lattice and by an external magnetic field—is a cornerstone of condensed matter physics. In this work we introduce and characterize the Weyl butterfly; using an experimentally motivated model for cold atomic systems we solve the Weyl-Hofstadter problem numerically for finite lattices. We find that Weyl nodes reemerge at commensurate fluxes and propose how to use the dynamics of wavepackets to reveal their chirality. Moreover, we show that the chiral anomaly, the non-conservation of chiral charge that is the hallmark of the Weyl semimetal state, is no longer proportional to magnetic field but rather inherits a fractal structure of linear regimes as a function of the external flux. The slope of each linear regime is determined by the difference of two Chern numbers and can be measured experimentally with time-of-flight spectra that we compute.
Topological Phases of Inhomogeneous Superconductivity
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We theoretically consider the effect of a spatially periodic modulation of the superconducting
order parameter on the formation of Majorana fermions induced by a one-dimensional system
with magnetic impurities brought into close proximity to an $s$-wave superconductor. When the
magnetic exchange energy is larger than the inter-impurity electron hopping we model the
effective system as a chain of coupled Shiba states. While in the opposite regime, the effective
system is accurately described by a quantum wire model. Upon including a spatially
modulated superconducting pairing, we find, for sufficiently large magnetic exchange energy,
the system is able to support a single pair of Majorana fermions with one Majorana fermion
on the left end of the system and one on the right end. When the modulation of
superconductivity is large compared to the magnetic exchange energy, the Shiba chain returns
to a trivially gapped regime while the quantum wire enters a new topological phase capable of
supporting two pairs of Majorana fermions.

Majorana fermions in superconducting nanowires via the interplay of orbital and Zeeman effects

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Recent experiments involving InSb [1] and InAs [2] nanowires in proximity to conventional superconductors have provided strong evidence of Majorana fermions (MFs). The prototypical mechanism responsible for MFs relies on the Zeeman coupling of the nanowire electrons to a sufficiently strong applied magnetic field [3, 4]. The above picture is relevant for single-channel nanowires, while it becomes incomplete for the multi-channel case where the orbital field effects also set in and can significantly influence the topological phase diagram [5]. Moreover, it has been theoretically demonstrated that such multi-channel hybrid devices can be driven to the topologically non-trivial regime with MFs, solely by the presence of the orbital effects [6,7].

The purpose of the present work is to explore and design new hybrid devices in which orbital effects dominate and drive the topological transition. In particular, we restrict ourselves to InAs nanowires with wurtzite structure [2] and geometries with wide crossection, in which significant values of flux can build up without the requirement of large fields. In addition, we consider different orientations of the growth axis that allow us to modify the spin-orbit interaction, consisting of both Dresselhaus and Rashba types. Our approach builds upon a microscopic continuum Hamiltonian for a cylindrical nanowire geometry, projected on the three energetically lowest channels, owing a structure reminiscent of the $s$, and $p_x \pm ip_y, p_x$ atomic orbitals. As we show, the mechanism for orbitally-induced MFs relies on maximizing the asymmetry between the channel-hybridization matrix elements $s - p_x + ip_y$ and $s - p_x - ip_y$. Finally, by employing a $Z_2$ invariant we extract the detailed topological phase diagram and demonstrate the interplay of orbital and Zeeman effects in these systems.

Strong Electronic Correlation in a Quantum Dot in Contact with a Majorana Bound State: Non-Crossing Approximation Approach

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In many experimental realizations of Majorana bound states at the edge of nanowires, a quantum dot is formed in between the topological part of the wire and its normal region, creating a Majorana bound state-Quantum Dot-Normal metal junction. The interplay between the Kondo correlations on the dot and the localized Majorana state, which also allow for Andreev reflections, give rise to new and interesting physics.

We use the non-crossing approximation to study the behavior of such a junction in the regime where the electrons on the dot are strongly correlated. The effects of the coupling to the Majorana bound state on the strong correlations on the dot are investigated under different coupling strengths and temperatures, and different types of Majorana bound states are considered. Using our approach we are able to study the setup both in thermal equilibrium and out-of-equilibrium, and to calculate physical observables such as the electronic density of states, magnetic polarization and electronic conductance.
Realizing all so(N)$_1$ quantum criticalities in symmetry protected cluster models

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We show that all so(N)$_1$ universality class quantum criticalities emerge when one-dimensional generalized cluster models are perturbed with Ising or Zeeman terms. Each critical point is described by a low-energy theory of N linearly dispersing fermions, whose spectrum we show to precisely match the prediction by so(N)$_1$ conformal field theory. Furthermore, by an explicit construction we show that all the cluster models are dual to non-locally coupled transverse field Ising chains, with the universality of the so(N)$_1$ criticality manifesting itself as N of these chains becoming critical. This duality also reveals that the symmetry protection of cluster models arises from the underlying hidden Ising symmetries and it enables the identification of local representations for the primary fields of the so(N)$_1$ conformal field theories.

For the simplest and experimentally most realistic case, that corresponds to the original one-dimensional cluster model with local three-spin interactions, our results show that the su(2)$_2$ ≈ so(3)$_1$ Wess-Zumino-Witten model can emerge in a local, translationally invariant and Jordan-Wigner solvable spin-1/2 model. Our results pave the way classifying critical behavior between distinct symmetry-protected topological states.

Spatial distribution of density and current in 2D Majorana nanowires

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We discuss the description of Majorana states in hybrid semi-super conductor 2D nanowires solving the Bogoliubov-deGennes equation in position space. The wave function is obtained with grid techniques combined with methods of plane waves of complex wavenumbers. We focus on the orbital effects due to a magnetic field tilted from the nanowire axis \cite{1,2}. The phase diagram with tilting angle and magnetic field intensity, with analytical boundaries, is discussed. Our method yields the spatial distribution of the density and current for quasiparticle probability and charge \cite{3}. We show the formation of current vortices due to the Majorana state, in both closed and open Majorana nanowires. The influence of barriers and different junction shapes is also discussed.

Figure caption: a) sketch of a 2D Majorana nanowire in tilted field. b) Phase diagram with tilting angle and field intensity. (c) and (d) show current distributions in parallel and tilted fields.

\cite{1} J. Osca, D. Ruiz, L. Serra, Effects of tilting the magnetic field in one-dimensional Majorana nanowires, Physical Review B 89, 245405 (2014).


Topologically protected fermionic quasiparticles appear in metals, where band degeneracies occur at the Fermi level, dictated by the band structure topology. While in some metals these quasiparticles are direct analogues of elementary fermionic particles of the relativistic quantum field theory, other metals can have symmetries that give rise to quasiparticles, fundamentally different from those known in high-energy physics. Here we report on a new type of topological quasiparticles – triple point fermions – realized in metals with symmorphic crystal structure, which host crossings of three bands in the vicinity of the Fermi level protected by point group symmetries [1,2]. We find two topologically different types of triple point fermions – type-A and type-B —, differing by their nodal line structure and both distinct from any other topological quasiparticles reported to date. We provide examples of existing materials that host triple point fermions of both types, and discuss a variety of physical phenomena associated with these quasiparticles, such as the occurrence of topological surface Fermi arcs, transport anomalies and topological Lifshitz transitions.

Fig. 1. Two types of triple point excitations. (a) Type-A triple points are connected by a single nodal line, where conduction and valence bands are degenerate (shown in black). (b) Type-B triple points are accompanied by four such nodal lines, shown in black, green, blue and red. The latter three occur in the mirror-symmetric planes in momentum space. (c)(d) Band structure around a type-A (type-B) triple point along a $C_3v$ axis. Here $\Lambda_6$ represents the double degenerate band (double representation of $C_{3v}$), while $\Lambda_{1,5}$ correspond to two one-dimensional representations. The black lines in (c) and (d) mark the region of the band structure that produces the nodal lines shown in black in panels (a) and (b).

Confined fractional charges at the helical edge

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In the 1980th Jackiw and Rebbi discovered a soliton bound state with a fractional charge as a solution of the Dirac equation by introducing a scalar kinked mass term. We demonstrate, that this model has a direct analogy in condensed matter physics, where the system we investigate is constructed by three magnetic impurities aligned on one dimensional helical edge states of a topological insulator. We show that the total charge of the whole system is always given by integer values, while fractional charges, contained between two magnetic impurities, are proportional to the angle between the two barriers. These fractional charges are sharp (i.e. they do not fluctuate) and can take any value, in the case of infinite magnetic barrier strength. Thus, we consider this setup as a feasible way to confine stable, fractional charges. Moreover, we obtain a physical interpretation of the fractional charges by mapping the Hamiltonian to the one of a Dirac fermion in the presence of an electro-magnetic field which can be easily analyzed in linear response theory.
Signature of Topological Superconductivity in the Meissner state

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An anomalous magnetization signal is reported for superconducting alkali-metal doped Bi2Se3, characterized by an anomalous feature in the ac-susceptibility in the Meissner state, unambiguously related to the superconducting state. The system, that has strong spin-orbit interaction, is believed to additionally show strong 3D Rashba due to broken inversion and mirror symmetry. The superconducting state shows Rashba-induced singlet-triplet admixture and a dominant p-wave contribution drives the system to a time-reversal invariant topological superconducting state [1], with gap of opposite sign and amplitude on the Rashba-split Fermi surface [2]. The anomalous magnetization signal in the Meissner state is attributed to the evolution with external field of the topological surface states and the associated current at the boundary of the system. The presence of two order parameters is consistent with the large field magnetization reported, showing hysteresis, vortex trapping and giant paramagnetic signal, that can be understood in the framework of the so called type 1.5 superconductivity [3,4], characterized by non-monotonic vortex interaction.

Spin-dependent scattering in a nanowire

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We study a quasi-one-dimensional quantum wire in the presence of an impurity and spin-orbit interaction. We solve the problem using a perturbative approach in order to obtain an effective Hamiltonian for the scattering problem. We solve that the scattering problem via the Lippmann-Schwinger equation at the leading order in spin-orbit. We focus on the scattering matrix of a spin-dependent transport setup and elucidate what we believe to be a suitable set of experiments aimed at a scattering matrix tomography.
Time-Reversal Breaking Weyl Fermions In Magnetic Heuslers

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Weyl fermions have recently been observed in several time-reversal invariant semimetals and photonics materials with broken inversion symmetry. These systems are expected to have exotic transport properties such as the chiral anomaly. However, most discovered Weyl materials possess a substantial number of Weyl nodes close to the Fermi level that affect the electronic structure and transport properties. Here we predict for the first time a new family of Weyl systems defined by broken time reversal symmetry, namely, Co-based magnetic Heusler materials XCo2Z (X=V,Zr,Nb,Ti,Hf, Z=Si,Ge,Sn), VCo2Al and VCo2Ga. These compounds are ferromagnetic: using first principle ab-initio calculations we find that the energetically most favorable magnetic axis is [110], consistent with our experimental measurements of the synthesized materials. This has a fundamental effect on the electronic structure of the bands around the Fermi level: a symmetry eigenvalue analysis results in the prediction of low number of Weyl nodes along the magnetic axis, related by inversion symmetry. When alloyed, these materials exhibit only two Weyl nodes at the Fermi level - the minimum number possible in a condensed matter system. The Weyl nodes are separated by a large distance (of order 2π) in the Brillouin zone, giving rise to well-defined Fermi arcs that is also calculated. This discovery provides a way to the realizing
Nodal chain metals

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The band theory of solids is arguably the most successful theory of condensed matter physics, providing the description of the electronic energy levels in a variety of materials. Electronic wavefunctions obtained from the band theory allow for a topological characterization of the system and the electronic spectrum may host robust, topologically protected fermionic quasiparticles. Many of these quasiparticles are analogs of the elementary particles of the Standard Model, but others do not have a counterpart in relativistic high-energy theories. A full list of possible quasiparticles in solids is still unknown, even in the non-interacting case.

In our work [1], we report on a new type of fermionic excitation that appears in metals. This excitation forms a nodal chain -- a chain of connected loops in momentum space -- along which conduction and valence band touch. We prove that the nodal chain is topologically distinct from any other excitation reported before. We discuss the symmetry requirements for the appearance of this novel excitation and predict that it is realized in an existing material IrF4, as well as in other compounds of this material class. Using IrF4 as an example, we provide a detailed discussion of the topological surface states associated with the nodal chain. Furthermore, we argue that the presence of the novel quasiparticles results in anomalous magnetotransport properties, distinct from those of the known materials. In the presence of the sublattice symmetry, the nodal chain is enriched by an additional loop to create a nodal net structure.

Why QSH is robust to magnetic field

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Quantum Spin Hall (QSH) is a topological state of matter that is characterized by quantized conductance $2e^2/h$ [1]. Current is carried by edge states that are helical and topologically protected by time reversal symmetry (TRS). It is expected that magnetic field should break TRS and therefore allow for opening of a gap in edge states that should be visible in transport measurement.

Though QSH was first predicted and observed in HgTe/CdTe quantum wells [2] it was also predicted [3] and observed in InAs/GaSb quantum wells [4]. Surprising fact about experiment [4] is that QSH is very robust to in-plane magnetic field. That robustness cannot be explain in a framework of standard BHZ model.

In our work we investigate effect of magnetic field in semiconductor-based QSH systems, such as HgTe/CdTe or InAs/GaSb, by performing the k.p simulation of the system. We show that robustness to magnetic field can be explain by burying of a Dirac point that occurs naturally in band structure calculations. In addition this effect can be controlled by adding edge potential to the system or inducing strain.

Universal Quantum Computation with Hybrid Spin-Majorana Qubits

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We theoretically propose a set of universal quantum gates acting on a hybrid qubit formed by coupling a quantum dot spin qubit and Majorana fermion qubit. First, we consider a quantum dot tunnel-coupled to two topological superconductors. The effective spin-Majorana exchange facilitates a hybrid CNOT gate for which either qubit can be the control or target. The second setup is a modular scalable network of topological superconductors and quantum dots. As a result of the exchange interaction between adjacent spin qubits, a CNOT gate is implemented that acts on neighboring Majorana qubits, and eliminates the necessity of inter-qubit braiding. In both setups the spin-Majorana exchange interaction allows for a phase gate, acting on either the spin or the Majorana qubit, and for a SWAP or hybrid SWAP gate which is sufficient for universal quantum computation without projective measurements.