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Topologically protected spin and valley currents via mass inversion in Dirac materials

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We demonstrate the general principle that inversion of the band mass in Dirac-like condensed matter systems will drive the formation of topologically protected interface modes which may carry spin or valley current. As examples, we discuss buckled two-dimensional hexagonal lattices such as silicene or germanene, and transition metal dichalcogenides such as MoS2. The common features among these systems in the bulk are a Dirac-like low energy effective Hamiltonian, a mass gap, and spin-orbit coupling. If spatial variation of the mass gap can be controlled to the extent that the sign of the mass is reversed, the bulk states on each side of the transition will carry different topological invariants which implies that linearly dispersing interfaces states must be present near the region where the mass is zero. The details of the spin-orbit coupling will then dictate the nature of the resulting topologically protected edge currents.

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Disorder-mediated Kondo effect in graphene

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We study the emergence of strongly correlated states and Kondo physics in disordered graphene. Diluted short range disorder gives rise to localized midgap states at the vicinity of the system charge neutrality point. We show that long-range disorder, ubiquitous in graphene, allows for the coupling of these localized states to an effective (disorder averaged) metallic band. The system is described by an Anderson-like model. We use the numerical renormalization group (NRG) method to study the distributions of Kondo temperatures P(TK). The results show that disorder can lead to long logarithmic tails in P(TK), consistent with a quantum Griffiths phase.

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Persistent charge and spin currents in the long wavelength regime for graphene rings

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We address the problem of persistent charge and spin currents on a Corbino disk built from a graphene sheet. We consistently derive the Hamiltonian including kinetic, intrinsic (ISO) and Rashba spin-orbit interactions in cylindrical coordinates. The Hamiltonian is carefully considered to reflect hermiticity and covariance. We compute the energy spectrum and the corresponding eigenfunctions separately for the intrinsic and Rashba spin-orbit interactions. In order to determine the charge persistent currents we use the spectrum equilibrium linear response definition. We also determine the spin and pseudo spin polarizations associated with such equilibrium currents. For the intrinsic case one can also compute the correct currents by applying the bare velocity operator to the ISO wavefunctions or alternatively the ISO group velocity operator to the free wavefunctions. Charge currents for both SO couplings are maximal in the vicinity of half integer flux quanta. Such maximal currents are protected from thermal effects because contributing levels plunge ($\sim$1K) into the Fermi sea at half integer flux values. Such a mechanism, makes them observable at readily accessible temperatures. Spin currents only arise for the Rashba coupling, due to the spin symmetry of the ISO spectrum. For the Rashba coupling, spin currents are cancelled at half integer fluxes but they remain finite in the vicinity, and the same scenario above protects spin currents.

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Valley polarization in graphene-silicene-graphene heterojunction

Man Shen, Yan-Yang Zhang, Xing-Tao An, Jian-Jun Liu, Shu-Shen Li

Considering the difference of energy bands in graphene and silicene, we put forward a new model of the graphene-silicene-graphene (GSG) heterojunction. In the GSG, we study the valley polarization properties in a zigzag nanoribbon in the presence of an external electric field. We find the energy range associated with the bulk gap of silicene has a valley polarization more than 95%. Under the protection of the topological edge states of the silicene, the valley polarization remains even the small non-magnetic disorder is introduced. These results have certain practical significance in applications for future valley valve.

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Majorana Fermions in Semiconducting Nanowires on the Top of Fulde-Ferrell Superconductor

Jia Liu, Chun Fai Chan, Ming Gong

The novel idea that spin-orbit coupling (SOC) and s-wave pairing can lead to induced p-wave pairing at strong magnetic limit has stimulated widespread interests in the whole community for the searching of Majorana Fermions (MFs), a self-hermitian particle, in semiconductor-superconductor hybrid structures. However, this system has several inherent limitations that prohibit the realization and identification of MFs with the major advances of semiconductor nanotechnology. We show that these limitations can be resolved by replacing the s-wave superconductor with type-II Fulde-Ferrell (FF) superconductor, in which the Cooper pair center-of-mass momentum plays the role of renormalizing the in-plane Zeeman field and chemical potential. As a result, the MFs can be realized for semiconductor nanowires with small Land\'e g factor and high carrier density. The SOC strength directly influences the topological boundary, thus the topological phase transition and associated MFs can be engineered by an external electric field. Almost all the semiconductor nanowires can be used to realize MFs in this new platform. In particular, we find that InP nanowire, in some aspects, is more suitable for the realization of MFs than InAs and InSb nanowires. This new platform therefore can integrate the advances of semiconductor nanotechnology to the realization and identification of MFs in this hybrid structure.

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Superconducting proximity effect in topological metals

Kyungmin Lee, Abolhassan Vaezi, Mark H. Fischer, Eun-Ah Kim

Much interest in the superconducting proximity effect in 3D topological insulators (TIs) has been driven by the potential to induce exotic pairing states at the interface. Most candidate materials for 3D TI, however, are bulk metals, with bulk states at the Fermi level coexisting with well-defined surface states exhibiting spin-momentum locking. In such topological metals, the proximity effect can differ qualitatively from that in TIs. By studying a model topological metal-superconductor (TM-SC) heterostructure within the Bogoliubov-de Gennes formalism, we show that the pairing amplitude reaches the naked surface, unlike in a topological insulator-superconductor (TI-SC) heterostructure where it is confined to the interface. Furthermore, we predict vortex-bound-state spectra to contain a Majorana zero-mode localized at the naked surface, separated from the bulk vortex-bound-state spectra by a finite gap in such a TM-SC heterostructure. These naked-surface-bound modes are amenable to experimental observation and manipulation, presenting advantages of TM-SC over TI-SC.

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Rashba-Zeeman-effect-induced spin filtering energy windows in a quantum wire

Xianbo Xiao, Zhaoxia Chen, Wenjie Nie, Guanghui Zhou, Fei Li

We perform a numerical study on the spin-resolved transport in a quantum wire (QW) under the modulation of both Rashba spin-orbit coupling (SOC) and a perpendicular magnetic field (MF) by adopting the developed Usuki transfer-matrix method in combination with the Landauer-Buttiker formalism. Wide spin filtering energy windows can be achieved in this system for a spin-unpolarized injection. In addition, both the width of these energy windows and the magnitude of the spin conductance within these energy widows can be tuned by varying the Rashba SOC strength, which can be apprehended by analyzing the energy dispersions and the spin-polarized density distributions inside the QW, respectively. Further study also demonstrates that these Rashba-SOC-controlled spin filtering energy windows show a strong robustness against disorders. These findings may not only benefit to further understand the spin-dependent transport properties of the QW in the presence of external fields but also provide a theoretical instruction to design a spin filter device.

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Detection of entanglement by helical Luttinger liquids

Koji Sato, Yaroslav Tserkovnyak

A Cooper-pair or electron-hole splitter is a device capable of spatially separating entangled fermionic quasiparticles into mesoscopic solid-state systems such as quantum dots or quantum wires. We theoretically study such a splitter based on a pair of helical Luttinger liquids, which arise naturally at the edges of a quantum spin Hall insulator. Equipping each helical liquid with a beam splitter, current-current cross correlations can be used to construct a Bell inequality whose violation would indicate nonlocal orbital entanglement of the injected electrons and/or holes. Due to Luttinger-liquid correlations, however, the entanglement is exponentially suppressed at finite temperatures.

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Majorana fermions in an antiferromagnetic chain in proximity to a superconductor

Andreas Heimes, Panagiotis Kotetes, Gerd Schön

We propose a new Majorana fermion platform based on an antiferromagnetically ordered chain of atoms in proximity to a conventional superconductor. This hybrid system can be driven into a topologically non-trivial phase by the combination of a supercurrent flow and a weak Zeeman field. Both can be finely tuned providing a platform with enhanced functionality for applications. Remarkably, the electronic spin-polarization of the arising edge Majorana fermions depends on the parity of the number of magnetic moments. The resulting even-odd effect should be measurable and could serve as a signature of the Majorana fermions. We introduce the basic concepts on a model level and confirm them by a microscopic analysis.

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Quantum transport of disordered Weyl semimetals at the nodal point

Björn Sbierski, Gregor Pohl, Emil J. Bergholtz, Piet W. Brouwer

Weyl semimetals are paradigmatic topological gapless phases in three dimensions. We here address the effect of disorder on charge transport in Weyl semimetals. For a single Weyl node with energy at the degeneracy point and without interactions, theory predicts the existence of a critical disorder strength beyond which the density of states takes on a nonzero value. Predictions for the conductivity are divergent, however. In this work, we present a numerical study of transport properties for a disordered Weyl cone at zero energy. For weak disorder our results are consistent with an RG flow towards an attractive pseudoballistic fixed point with zero conductivity and a scale-independent conductance; for stronger disorder diffusive behavior is reached. We identify the Fano factor as a signature that discriminates between these two regimes.

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Realizing Majorana Zero Modes by Proximity Effect between Topological Insulators and d-wave High-Temperature Superconductors

Zi-Xiang Li, Cheung Chan, Hong Yao

We theoretically study superconducting proximity effect between a topological insulator (TI) and a high-temperature d-wave superconductor (dSC). When the TI-dSC heterostructure violates 90 degree-rotation and certain reflection symmetries, we show that a sizable s-wave pairing, coexisting with a d-wave one, emerges in the proximity-induced superconductivity in the TI's top surface states. Weak disorder further suppresses d-wave pairing but not s-wave one in the TI's surface states. More importantly, the pairing gap in surface states is found to be nodeless and nearly-isotropic when the Fermi pocket of surface states is relatively small. Our theoretical results qualitatively explain recent experimental evidences of a nearly-isotropic pairing gap on surface states of Bi_2Se_3 induced by proximity with high-T_c cuprate Bi_2Ca_2Cu_2O_{8+\delta}. We also demonstrate convincing evidences of Majorana zero modes in a magnetic hc/2e vortex core, which may be detectable in future experiments.