Spin-helical transport in normal and superconducting topological insulator materials

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Abstract

This work is focused on transport phenomena in topological insulators (TIs). Unlike conventional insulators, these novel nanomaterials (e.g. based on HgTe, Bi2Se3, Bi2Te3 etc.) exhibit nontrivial conduction properties originating from metallic-like edge or surface states. These boundary states are topologically protected and characterized by spin helicity whereby the direction of the electron spin is locked to the momentum direction. In this contribution, we demonstrate, both theoretically and experimentally, that the spin helicity leads to several unusual transport phenomena in HgTe-based TIs:

(i) Single-valley Dirac-fermion transport [1]. Using the band-structure calculations, we show that zero-gap HgTe quantum wells possess a single-valley Dirac-like dispersion [see Fig.1 (left)]. In a magnetic field, the system exhibits the quantum Hall effect with odd plateaus, characteristic of Dirac fermions [Fig. 1(middle)]. Also, the conductivity at the Dirac point (so called minimal conductivity) and its temperature dependence can be understood from the single-valley Dirac physics [Fig. 1(right)]. These results pave the way to study effects related to spin coherence of Dirac fermions.

(ii) Weak anti-localization [2]. As well known, in low-dimensional conventional systems electronic states tend to be localized by static disorder (e.g. due to impurities). Remarkably, this never happens for helical carriers in TIs because of spin *Berry phases* that hinder contructive quantum interference in the random disorder potential [see Fig. 2 (left)]. Moreover, we find that HgTe-based TI materials exhibit weak anti-localization observable via a positive magnetoresistance effect [see Fig. 2 (right)].

(iii) Zero-bias anomaly [3] and topological midgap states in Josephson junctions [4]. We also investigate transport in HgTe TIs with superconducting contacts. We observe and theoretically explain a zero-bias anomaly (pronounced resistance drop) resulting from Andreev reflection and the induced superconductivity on the TI surface [Fig. 3]. Furthermore, we identify theoretically midgap Andreev bound states [Fig. 4] which are intimately related to topological Majorana states. These findings show that HgTe is a promising material to search for the signatures of the Majorana fermions in TI transport.

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References

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Figures

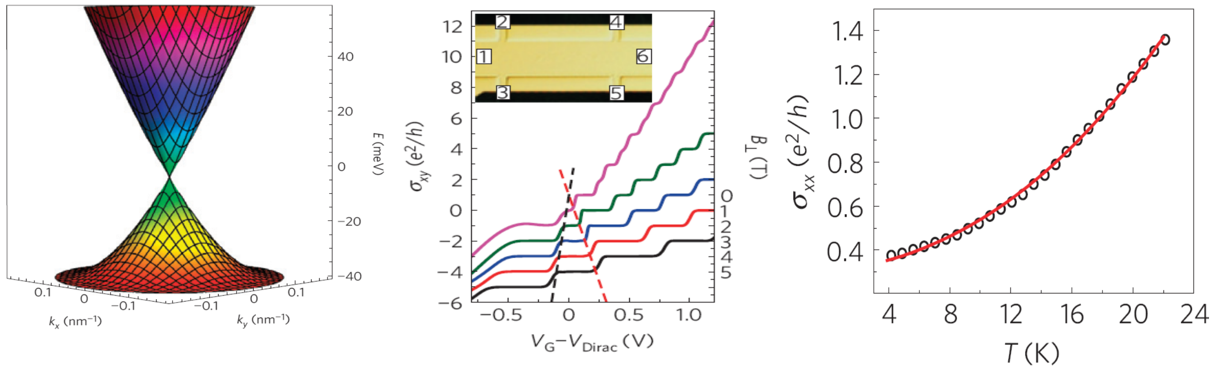

Fig. 1 (left) Theoretical single-valley Dirac-like dispersion of 2D HgTe system, (middle) measured Hall conductivity with predicted odd plateaus, and (right) temperature dependence of the conductivity at the Dirac point: circles – experiment, read line – theoretical fit based on quantum Kubo formula (from [1]).

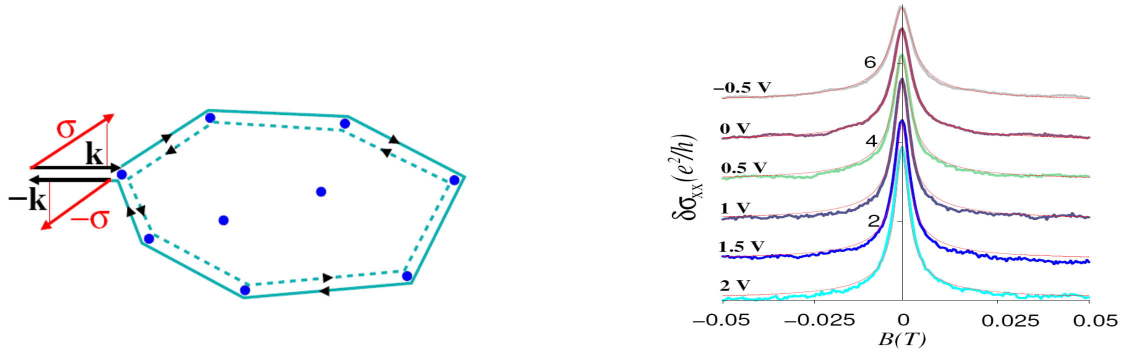

Fig 2. (left) Schematic of interfering electron trajectories giving rise to weak anti-localization in disordered topological insulators. Trajectories involve opposite spins **σ** and -**σ** as a result of Berry phase of π . (left) Magnetic-field dependence of the WAL magnetoconductivity.

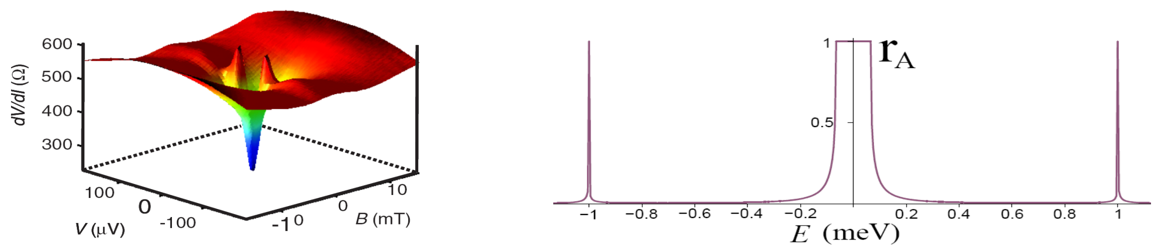

Fig. 3 (left) Measured differential resistance dV/dI versus bias V and magnetic field B, and (right) Theoretical Andreev reflection probability $r_A(E)$ versus energy E. Three maxima in the energy dependence $r_A(E)$ correspond exactly to the minima in the bias dependence dV/dI(V), as expected for proximity induced superconductivity (from [3]).

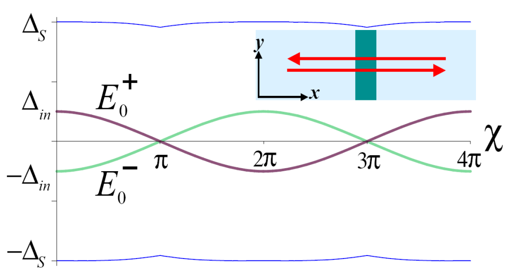

Fig. 4 Topological 4π-periodic Andreev bound states in a TI Josephson junction. At superconducting phase difference χ = π midgap Majorana states appear (from [4]).