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Helical edge transport in the presence of a magnetic impurity

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Two-dimensional topological insulators (2D TIs) are in the focus of recent interest due to existence of two helical edge states inside the band gap [1, 2]. Because of spin-momentum locking caused by strong spin-orbit coupling, electrical current transfers helicity along the edge [3, 4]. This "spin" current is a hallmark of the quantum spin Hall effect, and it has been detected experimentally in HgTe/CdTe quantum wells [5–9]. If only elastic scattering is allowed, and in the absence of time-reversal symmetry breaking, the helical state is a realization of the ideal transport channel with conductance of $G_0 = e^2/h$. This prediction was questioned by the experiments in HgTe/CdTe [5, 10–12] and InAs/GaSb [13, 14] quantum wells. Therefore, studies of mechanisms which can lead to the destruction of the ideal helical transport are important.

A local perturbation breaking the time-reversal symmetry, e.g., a classical magnetic impurity, leads to backscattering of helical edge states and reduction of the edge conductance [15, 16]. Electron-electron interactions along the edge can promote edge reconstruction and, consequently, spontaneous time-reversal symmetry breaking at the edge [17]. Furthermore, even in the absence of time-reversal symmetry breaking, electron-electron interactions may induce backscattering [18], resulting in the suppression of the helical edge conductance at finite temperatures (see [19] and references therein). A combination of electron-electron interactions and magnetic impurities can significantly modify the picture of ideal helical edge transport [20–24].

In the absence of electron-electron interactions along the edge, the ideal transport along the helical edge may still be affected (at finite temperatures) by its time-reversal symmetric interaction with a "quantum impurity", that is, an impurity which has its own quantum dynamics, e.g. a charge puddle that acts as an effective spin-1/2 impurity [25, 26], or a quantum magnetic impurity with spin $S = 1/2$ [15, 16] or $S \geqslant 1/2$ [27, 28].

In this Letter we study theoretically a modification of the ideal current-voltage characteristics of the helical edge in 2D TI by *weak* scattering off a single magnetic impurity. As a physical realization of such system we have in mind the (001) CdTe/HgTe/CdTe quantum well (QW) with a Mn impurity that possesses spin $S = 5/2$. Contrary to the previous works, we consider a general structure of the matrix $\mathcal{J}_{jk}$ describing exchange interaction between magnetic impurity and edge states. For $S = 1/2$ we find an analytical expression for the backscattering current at arbitrary voltage. For larger spin, $S > 1/2$, we obtained analytical expressions for the backscattering current at low and high voltages.

An example of the dependence of the backscattering correction to the differential conductance $\Delta G(V)$ on the voltage for the different values of the impurity spin S is shown in Fig. 1. For $S > 1/2$ the differential conductance is non-monotonous, with extrema at $V \sim |\mathcal{J}_{jk}|T$ and $V \sim T$ (indicated by triangles in Fig. 1). The first extremum is the consequence of competition between the effective magnetic field acting on the impurity spin and the relaxation. The extremum at $V \sim T$ is the consequence of the dependence of the effective temperature on the voltage. In contrast with the higher spins, for $S = 1/2$ the differential conductance saturates already at $V \sim |\mathcal{J}_{jk}|T$ instead of $V \sim T$. Finally, we mention that in the case of $|V| \ll |\mathcal{J}_{jk}|T$ the ratio $\Delta G(V)/\Delta G(0)$ is independent of S.

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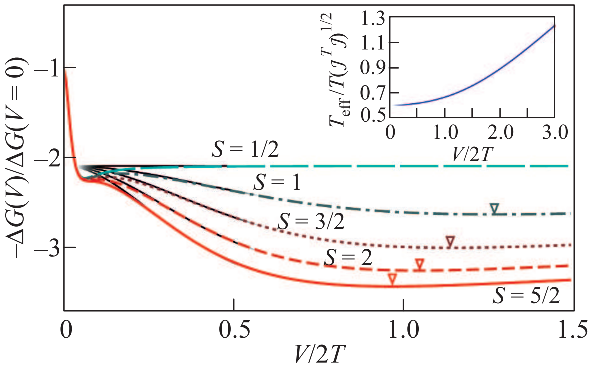

Fig. 1. (Color online) $-\Delta G(V)/\Delta G(0)$ versus $V/2T$ for different values of S. The exchange couplings were chosen as $\mathcal{J}_{xx} = \mathcal{J}_{yy} = 10^{-2}$, $\mathcal{J}_{xz} = 0.8\mathcal{J}_{xx}$, $\mathcal{J}_{zx} = 0.3\mathcal{J}_{xx}$, $\mathcal{J}_{zz} = 0.9\mathcal{J}_{xx}$, while the other couplings vanish. Black thin curves correspond to the approximate analytic solutions with the Gibbs-like reduced density matrix for the magnetic impurity which is parametrized by the effective temperature $T_{\rm eff}$. The empty triangles indicate the positions of additional minima. Inset: the dependence of $T_{\rm eff}$ on V

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