First sighting of a quantum anomalous Hall effect in a magnetically-doped topological insulator

"Experimental observation of the quantum anomalous Hall effect in a magnetic topological insulator", Science **340**, 167 (2013)
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Recommended with a Commentary by Leonid Glazman, Yale University

The theoretical discovery of 2D and 3D topological insulators has been swiftly followed by the creation of MBE-grown 2D heterostructures and of chemically synthesized 3D semiconductors which displayed some of the predicted properties [1, 2]. This success emboldened experimentalists to search for even more exotic states of matter. The paper of Cui-Zu Chang *et al* reports observations consistent with the properties of magnetic topological insulators. The key observation was the measurement of an almost rectangular hysteresis loop in Hall resistance ρ_{xy}, with the value of $\rho_{xy} = h/e^2$ and coercive field of about $H_c \approx 0.1$T. Such behavior can be attributed to an anomalous quantum Hall insulator, which is expected to have, in the limit of low temperature, quantized Hall conductance $\sigma_{xy}(H) = \pm e^2/h$ and vanishingly small $\sigma_{xx}(H)$ at $H \to \pm 0$ (in fact, this behavior should persist in some range of fields around $H = 0$).

The possibility of "quantum Hall effect without Landau levels" was envisioned in Ref. [3] in a model of spinless fermions of charge e on a honeycomb lattice having finite next-nearest neighbors (NNN) hopping matrix elements. The breaking of time-reversal symmetry was achieved in Ref. [3] by placing ferromagnetically ordered magnetic dipole moments at the center of each hexagonal cell. Clearly, the moments create zero net magnetic flux through each cell, while endowing the NNN hopping matrix elements with phase factors due to the vector potential of the magnetic field. As the result, the Dirac spectrum of electrons acquires a gap. The analysis of the effect of an infinitesimally small external field H yields $\sigma_{xy} = \pm e^2/h$ with the sign depending on the direction of the magnetic dipoles.

An alternative mechanism of realizing the anomalous quantum Hall insulator was suggested in Refs. [4, 5]. It relies on the exchange interaction of electron spins in a topological insulator (TI) with localized and ferromagnetically ordered magnetic moments embedded in the host matrix. One may view the quenching of the electron spins by the exchange interaction, combined with the spin-orbit interaction inherent for a TI as a source of a "synthetic" vector potential which introduces phases in the electron hopping and leads to $\sigma_{xy} = \pm e^2/h$ in the absence of external field. The prediction of Ref. [5] was the theoretical guidance for Cui-Zu Chang *et al*.

Cui-Zu Chang *et al* used the $(Bi_{1-x}Sb_x)_2Te_3$ system which unlike Bi_2Se_3 tends to have low bulk conductivity. The material was doped with Cr to form $Cr_{0.15}(Bi_{0.1}Sb_{0.9})_{1.85}Te_3$. Measurements were performed on a Hall bar made of a gated film with a thickness of 5 quintuple layers. The $H \to 0$ value of σ_{xy} (depicted in Fig. 2D) at $T = 30$mK was remarkably close to e^2/h around the gate voltage $V_g = -1.5$V identified with the charge neutrality point. The value of σ_{xx} at that voltage was fairly low, $\sigma_{xx} \sim 0.1 \cdot e^2/h$ and attributed to some unidentified residual dissipative channels. A later theoretical work [6] associates these channels with gapless non-chiral states found by first-principle band structure calculations [6].

The low-temperature dependence of ρ_{xy} on H at $|H| > H_c$ turns out to be remarkably weak ($d\rho_{xx}/dH \to 0$ with non-quantized values of ρ_{xx}), even when the system is far from the neutrality point, $|V_g| \gg 1.5$V. At these high gate voltages, and relatively high ($H \sim 0.4$T) magnetic fields ρ_{xx}, surprisingly, does not reveal neither the presence of Landau levels, nor signatures of a "normal" Hall effect. Cui-Zu Chang *et al* checked that the data is robust with respect to changing the aspect ratio of the Hall bar. All the samples apparently were of the same thickness. In that context, it is worth noting that the band structure calculation [7] actually indicates the oscillatory nature of the 3D-to-2D topological insulator crossover in films of Bi_2Te_3.

To conclude, the experimental data presented in the paper by Cui-Zu Chang *et al* is tantalizing and calls for more measurements and more detailed transport theory.

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