Resistance at the edge: imperfect conductance quantization in 2D topological insulators

Helical edge resistance introduced by charge puddles
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Recommended with a commentary by Jason Alicea, Caltech

The ability of electrons to conduct usually depends on the purity of the medium through which they propagate. In some materials, however, scattering events stemming from defects can be frozen out entirely, leading to conductance quantization. Quantum Hall systems stunningly illustrate this phenomenon: measurements reveal Hall resistances quantized to rational fractions of h/e^2, sometimes to an accuracy of parts per billion or better [1]. One can intuitively understand this remarkable result from the perspective of edge states. In the simplest quantum Hall phases, an incompressible bulk is accompanied by a single chiral edge mode that allows one-way transport around the sample perimeter. An electron propagating along the edge can then not backscatter upon encountering an impurity because low-energy modes moving in the opposite direction simply do not exist. Chirality thus breeds immunity against disorder, providing one mechanism for quantized transport.

In a seminal 2005 paper Kane and Mele predicted conductance quantization of subtler origin in 2D topological insulators [2]—time-reversal-invariant cousins of quantum Hall phases first observed in HgTe quantum wells by König *et al.* [3] Such states possess an inert bulk, as in the quantum Hall effect, but host *counterpropagating* edge modes composed of Kramers pairs. Despite their non-chiral nature scattering among these modes is again restricted, in this case by symmetry. More precisely, time-reversal prevents non-magnetic impurities from elastically backscattering a 'right'-moving edge electron into its 'left'-moving Kramers partner (and vice versa). This property underlies an appealing fingerprint of 2D topological insulators. In a two-terminal measurement, as temperature $T \to 0$ the 'top' and 'bottom' edges behave as perfectly transmitting wires that together yield a $2e^2/h$ conductance.

König *et al.* and subsequently other groups measured conductances in HgTe quantum wells roughly in agreement with this prediction, though the observed quantization accuracy pales in comparison to that seen in the quantum Hall effect. For one, values near $2e^2/h$ appeared only in sufficiently small samples, and even then deviations on the several percent level are clearly visible (see Fig. 1). Why the glaring contrast with quantum Hall? The likely culprit is the weaker immunity against impurities that 2D topological insulator edge modes possess: whereas time-reversal symmetry precludes elastic backscattering, *inelastic* processes generically do occur at finite temperature yielding imperfect quantization. This crucial point was appreciated by Kane and Mele and further explored by various authors [4]. The dominant inelastic scattering mechanism in experiment, however, remains an interesting open question.

Väyrynen, Goldstein, and Glazman chime in on this important issue, introducing a compelling new scenario that is likely to shed light on the experimental situation. Their key insight is that even if the bulk remains essentially insulating it need not serve as a mere spectator insofar as transport is concerned. To illustrate why, it is useful to first peer into the electronic environment of a HgTe quantum well. In such a narrow-gap semiconductor charged dopants produce a random potential landscape

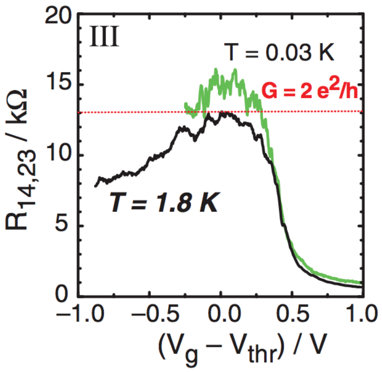

FIG. 1: Resistance of a HgTe quantum well, adapted from Ref. [3]. The horizontal axis represents a gate voltage used to access the topological insulator phase. Though a conductance close to $2e^2/h$ appears in this regime, appreciable fluctuations are evident.

that generally leads to the formation of quantum dots—or 'puddles'—interspersed throughout the bulk. An electron migrating along the edge can tunnel onto a nearby puddle, where it experiences Coulomb interactions characteristic of the dot. These interactions can, in turn, mediate inelastic processes that send the electron back in the direction from which it arrived. Hence even if the puddles are sufficiently rare that they impact bulk transport negligibly, they can still efficiently catalyze inelastic backscattering amongst the topological insulator edge modes.

This intuitive picture is complemented by quantitative predictions both for short samples (where deviations from quantized conductivity are obtained) and long samples (for which a resistivity $\sim T^3$ arises). Notably, Väyrynen *et al.* show that the scaling of conductance with temperature distinguishes their mechanism from previously discussed sources of inelastic scattering—e.g., phonons or interactions intrinsic to the edge which tend to produce stronger T-dependence. Systematic experiments to disentangle various mechanisms based on these predictions would thus be extremely well-motivated, not only in HgTe but also in other topological insulator candidates such as InAs/GaSb. After all, a thorough understanding of edge transport is likely a prerequisite for harnessing the vast technological promise that topological insulators possess in areas ranging from spintronics to Majorana fermions.

[1] As an interesting aside, such quantization accuracy has even been observed in graphene; see A. Tzalenchuk, S. Lara-Avila, A. Kalaboukhov, S. Paolillo, M. Syväjärvi, R. Yakimova, O. Kazakova, T. J. B. M. Janssen, V. Fal'ko and S. Kubatkin, Nature Nanotechnology **5**, 186 (2010)

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