A River Through Quantum Hall Valleys

Interacting multi-channel topological boundary modes in a quantum Hall valley system
Authors: M. T. Randeria, K. Agarwal, B. E. Feldman, H. Ding, H. Ji, R. J. Cava, S. L. Sondhi, S. A. Parameswaran and A. Yazdani
Nature 566, 363-367 (2019).

Recommended with a Commentary by Liang Fu, MIT

A hallmark of topological phases of matter is the presence of conducting boundary modes with unusual properties. Known examples include chiral edge states of quantum Hall states and unpaired Dirac surface states in topological insulators. Now, the highlighted paper reports the discovery of new one-dimensional topological boundary modes in a multi-valley quantum Hall system, where electron interaction and symmetry breaking play crucial roles and lead to unprecedented many-body topological phenomena.

The authors uses high-resolution scanning tunneling microscopy (STM) to study the (111) surface states of bismuth. On this surface there are six hole pockets in the surface Brillouin zone, related to one another by rotation or time-reversal symmetry (see Fig.1). Therefore, in the presence of a magnetic field, single-particle Landau levels of hole states have six-fold valley degeneracy. Thanks to the exceptional cleanness of bismuth crystal, STM spectroscopy maps shows little spatial variation of Landau level energy over several hundreds of nanometers. This makes bismuth (111) surface a fruitful platform for studying multicomponent quantum Hall physics with STM.

With a magnetic field between 13T and 14T, a set of $N = 3$ Landau levels from six valleys are within a few meV from the Fermi level. Two types of Landau level splittings are found in STM tunneling spectra, with different magnitudes and origins. First, regardless of the filling, there is an energy splitting of about 1meV between two-fold and four-fold degenerate multiplets. This splitting is likely induced by uniaxial strain which lowers the single-particle energy of a pair of valleys. Moreover, when the four-fold degenerate multiplet is tuned to the Fermi level by varying the magnetic field, it further splits into two sets of Landau levels separated by about 0.65meV. Concomitant with this additional Landau level splitting is suppressed tunneling conductance at the Fermi level. These findings strongly suggest that when these four-fold degenerate Landau levels are partially occupied, electron interaction induces an exchange gap and causes the splitting.

Early theory [3] predicted that due to the anisotropic energy dispersion of each valley, Coulomb interaction favors a valley-polarized state at integer filling, where a subset of valleys are fully occupied. Such state spontaneously breaks the point group symmetry. Previous works of the same group [1, 2] indeed observed valley ordering from spatially resolved STM conductance maps near impurities. These maps reveal elliptical Landau orbitals, whose orientation reflects the valley polarization of the broken-symmetry quantum Hall state.

The current work focuses on the interface between two quantum Hall domains of distinct valley polarizations. Remarkably, spatially resolved conductance map (reproduced in Fig.1) show that the exchange gap closes and reopens across the domain wall. Along the domain wall tunneling conductance at Fermi energy is high, establishing the presence of either gapless or low-energy one-dimensional states. A river of electrons flows between quantum Hall valleys!

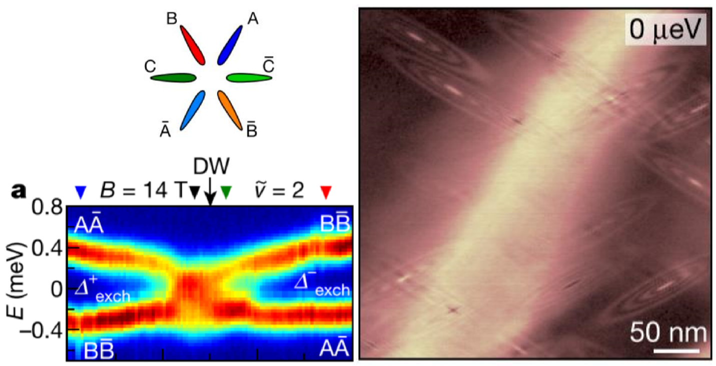

Figure 1: Six degenerate hole pockets on the (111) surface of bismuth under a magnetic field realizes a multi-valley quantum Hall system. Spatially revolved STM spectroscopy shows interaction-induced exchange gap closes and reopens across a domain wall, where valley polarization switches and low-energy topological boundary modes arise. Adapted from the highlighted paper.

To appreciate the significance of this discovery, it is useful to draw a comparison between a valley-polarized quantum Hall state with a ferromagnet insulator. Both are gapped states with spontaneously broken symmetry associated with internal degrees of freedom—valley or spin. In a simple ferromagnetic insulator where a spinful electron is bound to each atom, the charge gap comes from on-site repulsion, while the spin ordering comes from inter-site exchange interaction. The charge gap generally does not close at the magnetic domain wall.

Here, as recognized by the authors, the closing of charge gap at the valley domain wall is a profound manifestation of topology in multi-valley quantum Hall system. Provided that the number of electrons per valley is conserved, a valley-polarized integer quantum Hall state is characterized by a set of topological invariants $\{n_i\}$, where the integer n_i corresponds to the filling of valley i. The two sides of the domain wall, despite having the same total filling, differs in the fillings of individual valleys and hence are topologically distinct quantum Hall states. This topological distinction dictates the existence of gapless boundary modes on the domain wall, which consists of counter-propagating modes from different valleys.

The authors further show that depending on the filling $\tilde{\nu}$ of valley-degenerate Landau levels, the low-energy domain wall modes at the same location on the sample is either gapless within the experimental resolution (for $\tilde{\nu} = 1$), or has a small tunneling gap (for $\tilde{\nu} = 2$). This difference is attributed to an allowed inter-valley scattering process at the domain wall for $\tilde{\nu} = 2$, which breaks the valley symmetry protecting the topological boundary modes [4].

In summary, the highlighted STM spectroscopic study provides a direct visualization of the unifying principle of topology: the closing of gap and the appearance of gapless modes at the interface between topologically distinct states. Numerous intriguing questions await further study. Is it possible to manipulate the valley polarization of quantum Hall states? Are domain wall modes conducting or insulating? Besides domain wall modes, are there other topological excitations present? Can we access fractional quantum Hall regime in bismuth (111) surface? There is no doubt that STM spectroscopy will continue to reveal many more exotic excitations in topological and correlated materials [5].

References

[1] Benjamin E. Feldman, Mallika T. Randeria, Andrs Gyenis, Fengcheng Wu, Huiwen Ji, R. J. Cava, Allan H. MacDonald, Ali Yazdani, Science, 354, 316 (2016).

[2] Mallika T. Randeria, Benjamin E. Feldman, Fengcheng Wu, Hao Ding, Andras Gyenis, Huiwen Ji, R. J. Cava, Allan H. MacDonald, Ali Yazdani, Nature Physics, 14, 796 (2018).

[3] D. A. Abanin, S. A. Parameswaran, S. A. Kivelson, S. L. Sondhi, Phys. Rev. B 82, 035428 (2010).

[4] Kartiek Agarwal, Mallika T. Randeria, A. Yazdani, S. L. Sondhi, S. A. Parameswaran, arXiv:1807.10293

[5] Zhenyu Wang *et al*, arXiv:1903.00515