Zero field fractional Hall states, now in graphene heterostructures

Fractional Quantum Anomalous Hall Effect in Multilayer Graphene
Authors: Z. Lu, T. Han, Y. Yao, Y. Yao, A. P. Reddy, J. Yang, J. Seo, K. Watanabe, T. Taniguchi, L. Fu, Long Ju
arXiv:2309.17436

Recommended with a Commentary by Ashvin Vishwanath, *Harvard University*

The extraordinary physics of the fractional quantum Hall effect is generally associated with a strong magnetic field, that forces electrons to partially fill a Landau level. The featured reference joins other remarkable recent discoveries in moiré systems establishing a fractional quantum Hall state in a relatively weak magnetic field or even zero magnetic field ($B = 0$). The featured reference reports a multitude of quantum Hall plateaus with Hall conductances: $\sigma_{xy} = (1, 2/3, 3/5, 4/7, 4/9, 3/7, 3/5)\,\frac{e^2}{h}$.

The rapid advances in moiré materials in realizing integer and fractional quantum anomalous Hall phases can be traced to a few key advantages. First, the scales associated with the moiré lattice $\approx 5 - 15$nm allows for a significant degree of control, for instance the electron filling of the moiré lattice can be changed electrostatically. In contrast, the equivalent operation in an a solid typically requires chemical doping, which is at best challenging and often infeasible. Additionally, the moiré platforms here all have a valley structure, and if electrons spontaneously polarize in a single valley, they experience time reversal symmetry breaking which generates Berry flux* and can lead to topological bands. This provides a natural mechanism for generating Chern bands. Energetically, the exchange interaction will favor valley polarization, in much the same way that Hund's first rule in atomic structure favors filling atomic orbitals with parallel spin electrons. Here, the valley may be regarded as a type of psuedospin, and exchange promotes the valley polarization.

In a recent Journal Club article Laumann has already reviewed the basics of fractional and integer Chern insulators, in the context of twisted sheets of a transition metal dichalcogenide (TMD), specifically $MoTe_2$. There, optical probes, compressibility measurements and the Streda formula were used to establish integer and fractional quantum Hall states at zero magnetic field. Since that review, notable progress in the form of transport measurements in the twisted $MoTe_2$ system, have appeared, confirming the integer $\sigma_{xy} = 1\,\frac{e^2}{h}$ and fractional $\sigma_{xy} = \left(\frac{2}{3}, \frac{3}{5}\right)\frac{e^2}{h}$ states. This prior experiment serves as a convenient reference point to compare with the findings of the featured reference.

*If however 180 degree rotation (C_2) symmetry is present, the Berry curvature is quenched. The setups we will discuss lack this rotation symmetry.

The most recent progress has been achieved in 5-layer sheets of rhombohedral graphene in the presence of a nearly aligned substrate of boron-nitride (hBN). The substrate gives rise to a moiré pattern from the mismatch of the graphene and the hBN lattices. In addition, one must introduce a large displacement field **D** (vertical electric field) and introduce electrons into the conduction band.

Multilayer (N-layer) rhombohedral graphene consists of graphene stacks that are offset from one another in a staircase fashion. Usually, these are only metastable configurations, so the featured reference had to develop strategies to isolate and create devices from the rhombohedal pentalayer sheets.

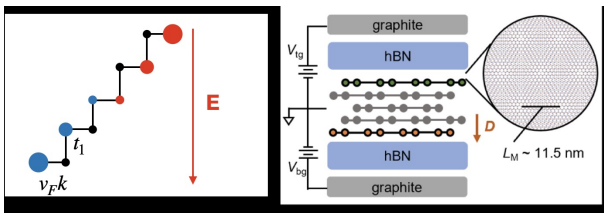

Fig. 0: (Left) Structure of rhombohedral pentalyer graphene. The staggered hoppings lead to near zero modes on opposite surfaces. (Right) Schematic of the device. The hBN substrate on only the top side of the device is aligned with graphene. Added electrons are polarized opposite to the aligned substrate.

Rhombohedral multilayers are attractive platforms for realizing correlation driven physics. The valley structure of single layer graphene is inherited by the multi-layers. Restricted to a valley, the low energy Hamiltonian takes a 2×2 form, due to a hidden Su-Schriffer-Heeger structure of the Hamiltonian that only involves 'zero modes' at the opposite ends of the rhombohedral graphene stacks. In its simplest form:

$$H = \begin{pmatrix} V/2 & t_1(p_x + ip_y)^N \\ t_1(p_x - ip_y)^N & -V/2 \end{pmatrix}$$

Here the voltage V is applied by the displacement field, and, if it is small enough, only splits the energy of the zero modes on opposites sides of the sample. Finally p is the momentum deviation from one of the nodes, properly scaled, so that $p = v_F k/t_1$, where $t_1 \approx 350meV$ is the interlayer hopping. The high order in momentum in the off diagonal terms that grows with increasing the number of layers N, arises from mixing between zero modes on opposite sides of the sample.

Clearly this gives rise to a very flat band structure with Berry curvature, whose flatness is enhanced for larger N. Indeed, previous theory has highlighted this setting, along with a substrate induced moire potential, as a promising platform to realizing Chern bands from spontaneous valley polarization. However, the previous theory considered only moderate displacement fields, which typically leads to bands with large Chern number. In contrast, the featured experimental reference considers a different regime, with much larger displacement fields.

In the device studied in the featured reference, only one of the hBN substrates is expected to be oriented with the the graphene. The sign of the displacement field is chosen so that the added electrons are on the opposite sides of the 5-layer sandwich than the interface with

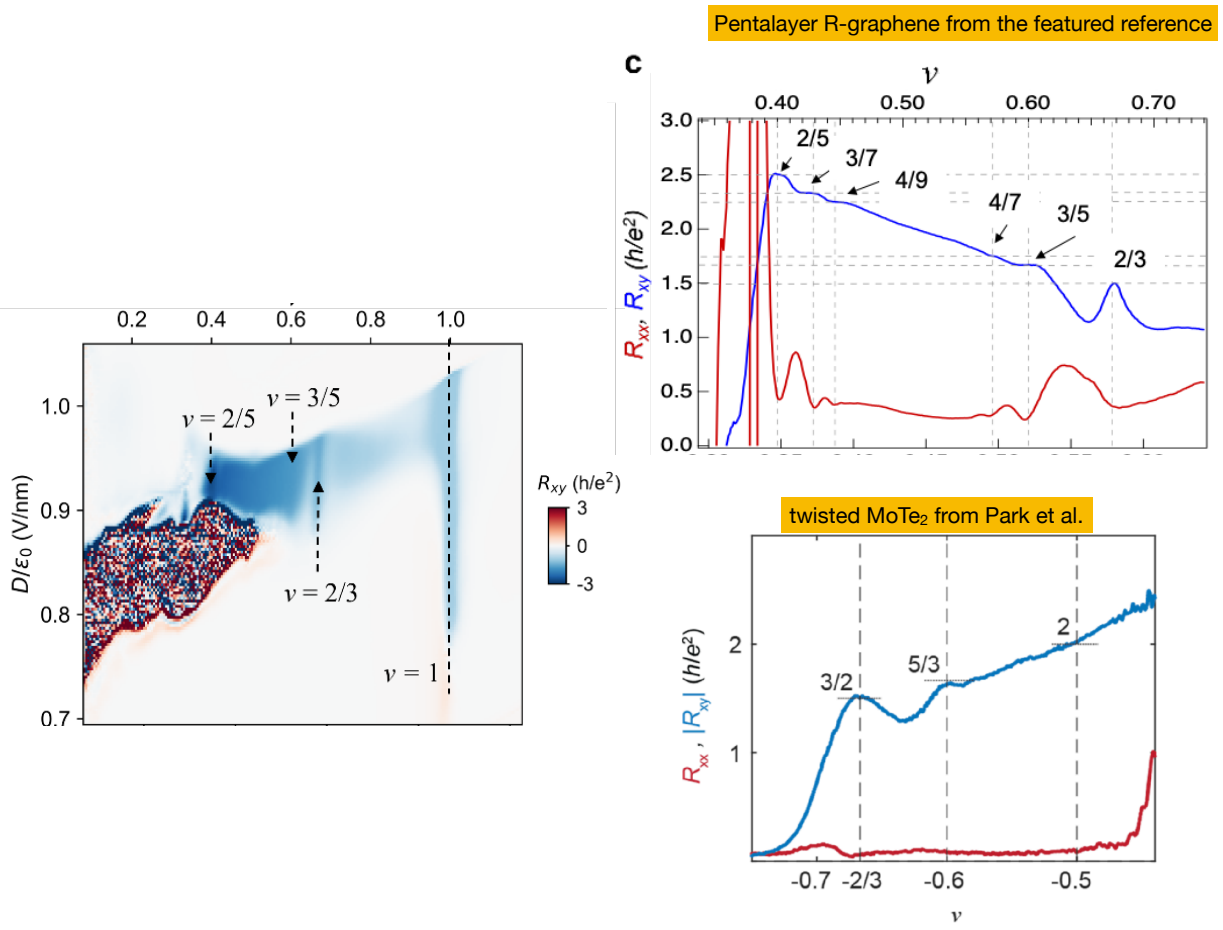

Figure 1: (Left) Measured R_{xy} from the featured reference as a function of filling (horizontal axis) and displacement field (vertical axis). Integer and fractionally quantized Hall states are marked, and a highly resistive state shown as a speckled band appears at lower densities. The electron temperature is $T \approx 0.1K$. (Top Right) From the featured reference, six Jain sequence fractions are observed as Hall plateaus on varying density, and as dips in R_{xx}. (Bottom Right) Comparison with transport measurements on twisted $MoTe_2$ from Park et al..

the moiré pattern. This makes for a relatively weak moiré potential. A curious fact is that it is still able to open gaps and lead to insulating topological states. This hints at additional interaction physics at work in organizing electrons into the observed topological phases.

The phase diagram from the featured reference on changing electric field and density is shown in Figure 1. At unit filling of the moiré, over a wide range of displacement fields, a Chern insulator with well quantized Hall conductance is observed even at $B = 0$. A natural conclusion is that interactions polarize spin and valley, leading to a Chern insulator at $\nu = 1$.

At partial filling of the Chern bands, both fractional quantum Hall states and a highly resistive Wigner crystal like phase are observed. The high resistivity state emerges at smaller fillings, $\nu < 1/2$, occupying a band in the displacement field/filling phase diagram. This is consistent with a topologically trivial Wigner crystal, whose period adjusts as the density is changed. At higher densities, very strikingly, several fractions are observed - $\nu = 2/3$, $3/5$, $4/7$, $4/9$, $3/7$, $2/5$ as quantized plateaus in R_{xy} on changing the density, and as dips in R_{xx} (Figure 1 top right). These are corroborated by their trajectories in a magnetic field which obey the Streda relation. At densities below $\nu = 2/5$, the high resistance state takes over and covers $\nu = 1/3$, so no fractional state is observed at this filling.

It is instructive to compare these results with the fractional Chern insulators in $MoTe_2$ (Park et al.) shown in bottom right panel of Figure 1. In general, transport measurements are generally believed to give cleaner results in the graphene devices. For the *integer* Chern insulators the multilayer graphene device's R_{xx} in the integer plateau is a fraction of that in twisted $MoTe_2$. Also, fewer fractions are seen in the TMD platform, consistent with these expectations. However, surprisingly, the values of R_{xx} in the plateaus (which ideally should be zero) are smaller in the TMDs than in the graphene platform. A point of commonality is that all of the observed fractions are part of the Jain sequence, $\nu = \frac{p}{2p+1}, \frac{p+1}{2p+1}$, pointing to the underlying stability of the composite fermions in these fractionally filled Chern bands.

Various future directions seem promising: (i) comparing the twisted TMD and multilayer graphene platforms, to better understand the origin of their differences. Some of these distinctions could arise from the fact that in contrast to graphene, where the spin and valley degrees of freedom are decoupled, in the TMDs they are strongly locked together. Also, given the difference in moiré periods, the twisted TMDs are expected to be governed by larger energy scales than the graphene devices (ii) In both platforms there is a dip in R_{xy} between $\nu = 2/3$and$3/5$. Could these be explained by competing neighboring phases? (iii) The rhombohedral graphene physics is expected also in structures with different number of layers $N = 4$, 6 etc. with different ranges of displacement fields. Understanding the evolution of the phase diagram with the number of layers would give valuable information on the underlying mechanism. (iv) Other studies of graphene bilayers and trilayers have reported superconductivity and flavor polarization, and were discussed in an earlier Journal Club Commentary by Guinea. Interfacing integer and fractional Hall states with superconductivity is a long standing quest. The zero field stability of the quantum Hall states along with these observations of superconductivity makes this a promising single platform to combine these disparate phases.

The rapid progress in the development of topological moiré platforms will, we feel, spark a wave of new discoveries in quantum matter and open a door into unexplored territory.