Reproducible, quantum anomalous Hall effect in a TMD moiré bilayer

Quantum anomalous Hall effect from intertwined moiré bands
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Nature 600, 641 (2021)

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New vistas in condensed matter physics have been opened by the realization that moiré systems of various sorts can be constructed from bilayers (or more layers) of electronically active materials, and that this can be used as a tunable, and readily oiré probed laboratory for the study of highly correlated electronic matter. As is inevitable – and even reasonable in a new field – many of the ideas being explored will prove, in the end, to have been overly exuberant. While it is worth exploring the possibility of exotic phases, in the final analysis there will likely prove to be fewer exotic phases and more familiar phases manifesting in unusual ways derived from new quantitative relations. In particular, while "Mott insulators" have been invoked as the explanation of many observed insulating phases, in the end a consensus seems to be emerging that at least many of these are instead broken symmetry states – flat band analogues of quantum Hall ferromagnets as well as other more complicated density-wave states. That is not to say that broken symmetry states – especially when the broken symmetries are unusual – are not exciting in their own right!

In the highlighted paper, Li *et al* have identified a quantum anomalous Hall insulating phase in a transition metal dichalcogenide (TMD) hetero-bilayer consisting of one layer of $MoTe_2$ and another of WSe_2 arranged in what is called AB stacking with a twist angle of 60^o. (Because each monolayer breaks inversion symmetry, there are a variety of possible orientations even with commensurate twist angles.) The hole density per moiré unit cell, ν, and the relative weight of states originating from the two layers can be separately controlled through the use of upper and lower gates. Specifically, the displacement field, D, can be tuned to change the electronic structure at fixed ν. In the relevant range of D, on the basis of band-structure considerations, the authors have concluded that the bands at the Fermi energy for $0 < \nu < 2$ are two-fold degenerate, corresponding to a pseudo-spin degree of freedom that (due to spin-valley locking) simultaneously specifies the polarization of the electron spin, and an orbital degree of freedom such that one band has Chern-number $c = 1$, and the other has $c = -1$.

The quantum anomalous Hall phase occurs at $\nu = 1$, and is characterized by a Hall resistance in the absence of any applied magnetic field with value $R_{xy} = h/e^2$ and a value of R_{xx} (in Ohms per square) that is much smaller and which appears to be tending to 0 as the temperature, $T \to 0$. The nature of this phase has been confirmed in several ways. 1) A study of the low T evolution of R_{xy} as a function of magnetic field, B, applied perpendicular to the bilayer, shows a "plateau" value $R_{xy} = h/e^2$ as B is decreased from a starting value somewhat above 0.1 T, continuing as B is made slightly negative, until it suddenly switches to $R_{xy} = -h/e^2$ when $B = -B_c \sim -0.01T$. Conversely, starting with a negative B, R_{xy} switches from $-h/e^2$ to $+h/e^2$ when $B = +B_c$. 2) The value of R_{xy} is approximately T independent as well, from a base temperature of 0.3K up to around 2K. 3) In a broader range of B, the preferred value of ν at which the quantized Hall response is strongest shifts linearly with B as $\nu_c = 1 - c^\star(B/B_0)$ where B_0 is the field corresponding to one magnetic flux quantum per moiré unit cell ($B_0 = \phi_0/A$, where A is the unit cell area and ϕ_0 is the magnetic flux quantum) and $c* = 0.95 \pm 0.05$ is the effective Chern-number of the state.

No numbers are given either for the accuracy or the precision of the quantized values of R_{xy}. By eye it looks as if the reported values are a few percent larger than the expected value of h/e^2. The constancy of R_{xy} as a function of field in the low field range appears to be quite a bit better than this, suggesting that the precision of the effect is considerably better. It is also worth noting that the results are "reproducible." The authors mention that they have studied five similarly prepared devices, three of which exhibit the quantum anomalous Hall effect, and while the other two do not, they do exhibit a quantized Hall response in the presence of a "moderate" B. The lack of perfect reproducibility is attributed by the authors – probably correctly – to different levels of sample inhomogeneity, which is likely an important issue in all such moiré systems.

Together, the evidence of a quantum anomalous Hall phase in this system seems entirely convincing. Note that this is necessarily a phase with a spontaneously broken symmetry – at the very least time-reversal symmetry must be broken to permit a Hall response. The most straightforward interpretation of this phase – which was the initial proposal in the recommended paper – is that it is a pseudo-spin ferromagnet, in which the exchange interaction favors a fully pseudo-spin aligned state which therefore has $c = 1$ or $c = -1$. While such a state is not "exotic" in the sense that it can be approximately understood at the level of Hartree-Fock theory, it is nontheless unusual. It is a state with equilibrium circulating current order, as well as net spin ferromagnetism.

However, in contrast to the case in magic-angle twisted bilayer graphene (TBG), the TMD bilayer is not fine-tuned to a flat band condition. (This is good news of a sort in that it means that small inhomogeneities – which can have outsized effects in a fine-tuned situation – are less likely to be amplified in the present case.) While correlation effects are manifestly essential, the analogy with quantum Hall ferromagnets is not obviously compelling in conditions in which the band dispersion is also significant. Indeed, other theoretical proposals concerning the origin the state have been made[1, 2], each of which involve distinct sets of (additional) ingredients. Probably the most original and conceptually interesting of these[2] involves a *weak coupling* instability of a parent coplanar (three-sublattice) antiferromagnetic phase. While for some range of D, this state corresponds to a familiar antiferromagnetic insulator, at a critical value of D a quadratic band-touching arises that – in the absence of further symmetry breaking — would mark the point of an insulator to metal transition.

However, such a critical point is known to be perturbatively unstable[4], and indeed in this case it is shown in Ref. [2] to lead to an instability to a non-coplanar anti-ferromagnetic insulating phase with the requisite Chern bands to account for a quantum anomalous Hall effect.

Direct testing of exactly what broken symmetries arise in this phase remains a work in progress.

It must be noted that this is not the first experimental observation of a quantum anomalous Hall state. 1) As has been justly celebrated, such a phase was first seen experimentally in magnetically doped semiconductor heterstructures[3]. However, in this case the requisite symmetry breaking came from ferromagnetic ordering of the embedded (large S) spins; while by symmetry this state must also have equilibrium circulating current order, this is a secondary effect and probably relatively weak. Moreover, disorder plays a significant role in these systems. 2) Such a state was first seen in the moiré universe in twisted bilayer graphene.[5, 6, 7, 8] This was also a spectacular discovery, and is very similar in character to the one reported in the present paper. However, in the graphene case, the state appears to be much more delicate – dependent on some still not completely understood details of the alignment between the graphene bilayer and the underlying BN substrate. The robustness of the present results, and their justly touted reproducibility, make the present results a clear and important further step in the study of this interesting physics.

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[8] This list of previous observations of quantum anomalous Hall states in graphene-based systems is incomplete.