Competing Ordered Filling Factor Two States in Bilayer Graphene

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Introduction

The quantum Hall (QH) effect, in which a two-dimensional sample's Hall conductivities become quantized, is a remarkable transport anomaly commonly observed at strong magnetic fields. However, it may also appear at zero magnetic field if time reversal symmetry is broken. Charge-neutral bilayer graphene is unstable to a variety of competing and closely related broken symmetry states, such as those with non-zero Hall conductivities (quantum anomalous Hall and quantum spin Hall states), zero Hall conductivities (quantum valley Hall and layer antiferromagnetic states) or spontaneous intervalley coherence (Kekulé order). So far only the LAF state (which appear to be the thermodynamic ground state) and the layer polarized state (at finite interlayer electric field $\mathbf{E}_\perp$), have been observed experimentally. Other spontaneous QH states, and competing states with Kekulé order, have eluded experimental observation.

Experimental Results and Discussion

Here we explore these spontaneous Hall states by taking advantage of their adiabatic connection to QH states at integer filling factors within bilayer graphene's eightfold degenerate lowest Landau levels (LLs). Our results reveal two distinct states: (1). Phase I is fully resolved only near $\mathbf{E}_\perp$ and large **B**, and has a relatively small gap that extrapolates to 0 at **B**=0. This phase is spontaneously spin-polarized and has coherence between valleys (layers), *i.e.* with Kekulé valley order. (2). Phase II appears only at finite $\mathbf{E}_\perp$, but can be stabilized at a much smaller **B** and has a much larger gap with a finite **B**=0 intercept, suggesting that this state survives to anomalously weak **B**. Because finite **B** couples to the spin and orbital moments and finite $\mathbf{E}_\perp$ favors layer (valley) polarization, this state is expected to form a majority-spin QAH state but minority-spin QVH state, where majority (minority) spins refer to those that occupy all four (half) of the orbital-degenerate LLs. It follows that its charge, spin, and valley Hall conductivities are all quantized to $2e^2/h$. The anomalous stability of phase II at small **B** is consistent with the stability of QVH (QAH) state at large $\mathbf{E}_\perp$ (finite **B**). The data are acquired on SCM2 and resistive 31T magnet Cell 9. Our results represent the first spectroscopic mapping of the exotic behavior hosted in BLG at filling factor =2. By shedding light on the competition between ordered states in BLG, we provide a roadmap for studying the spontaneous symmetry breaking in BLG and its thicker chiral cousins.

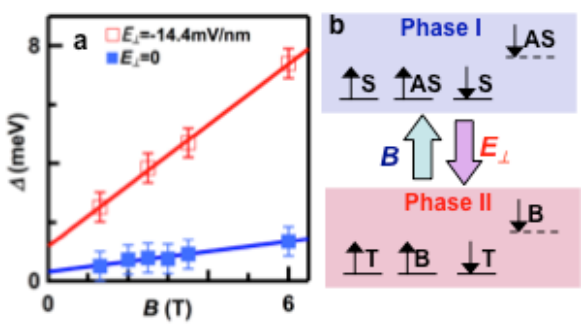

Fig.1. (a). Measured LL gap $\Delta(\mathbf{B})$ at ν=2 and $\mathbf{E}_\perp$=0 and -14.4 mV nm^{-1}, respectively. (b). Schematics of transitions between Phase I and Phase II at ν=2. (T/B: top/bottom layer; S: symmetric state |S>=|T>+|B>; |AS>: antisymmetric state |T>-|B>).

Conclusions

Our results represent the first spectroscopic mapping of the exotic behavior hosted in BLG at filling factor ν=2. By shedding light on the competition between ordered states in BLG, we provide a roadmap for studying the spontaneous symmetry breaking in BLG and its thicker chiral cousins.

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References

[1] J. Velasco Jr, Y. Lee, F. Zhang, K. Myhro, D. Tran, M. Deo, D. Smirnov, A. H. MacDonald, and C. N. Lau, Competing ordered states with filling factor two in bilayer graphene, *Nature Communications* **5**, 4550 (2014).