Physics: Viewpoint

Going their eight separate ways

Shaffique Adam
Center for Nanoscale Science and Technology
National Institute of Standards and Technology
100 Bureau Drive, mailstop 6202
Gaithersburg, MD 20899-6202

Subject Areas: Bilayer Graphene, Quantum Hall Effects

Symmetry is at the heart of all physics. Predicting the behavior of a material by studying its underlying symmetries is one of the oldest and most powerful theoretical techniques with quite impressive consequences: the symmetry of time invariance gives rise to energy conservation and rotational symmetry underlies the conservation of angular momentum. What then if a symmetry is broken? It often hints at exciting new phenomena such as the emergence of the Higgs boson in particle physics or ferromagnetism in condensed matter physics.

Very recently, two experimental groups, one led by Philip Kim at Colombia reporting in the current issue of Physical Review Letters [1] and one led by Harvard's Amir Yacoby publishing in Nature Physics [2], have reported on the 8-fold symmetry breaking of the zero energy Landau level in bilayer graphene systems. The Columbia experiment used the typical set-up of bilayer graphene on a SiO_2 substrate [3] and found that the unusual zero energy Quantum Hall octet, while intact at lower magnetic fields, split up completely into 8 separate Landau levels when exposed to 35 Telsa (generated at the National High Magnetic Field Laboratory, and close to the limit of what is currently possible for manmade static magnetic fields). The Harvard group used "suspended graphene", an otherwise identical system, but where additional processing is used to remove the supporting SiO_2 substrate [4]. They report that the same symmetry breaking occurred at the more moderate magnetic field of about 3 Telsa.

Before we can piece together what might be going on, we should first discuss what is "bilayer graphene" and understand why one expects a quantum Hall octet state to occur at zero energy.

Graphite is a well-known allotrope of carbon. And unlike diamond, its wealthier cousin whose unit cell is an octahedron living in three spatial dimensions, graphite comprises a weakly coupled stack of two dimensional (2D) carbon, with each layer being just one atom thick. The 2D carbon sheet is called graphene. In the plane, carbon naturally arranges itself into a honeycomb structure with single carbon atoms at the vertices and strong sp^2 bonds along the edges.

In a strong magnetic field, the orbital motion of graphene electrons that are confined to 2D-plane, get quantized into Landau levels and exhibit the quantum Hall effect [5]. Because the honeycomb is actually two identical interpenetrating triangular lattices, called A and B, the graphene Landau levels come in a degenerate pair – with wavefunctions localized on the carbon atoms of either the A or B sublattice. This is commonly known as "valley degeneracy" because in momentum space these wavefuntions are also localized around two distinct points (or valleys) in the hexagonal Brillioin zone. And since carbon is a light element, the electron spin and orbital motion in graphene are essentially decoupled, implying that electron spin is an additional quantum degeneracy (with a small Zeeman coupling), and thus resulting in spin and valley giving rise to the four-fold degeneracy of the monolayer graphene Landau levels.

Bilayer graphene is two electronically coupled graphene sheets, where the coupling is such that one can still describe the system with two interpenetrating triangular lattices, except that one lattice is on the top layer and the other on the bottom layer [6]. Therefore, in bilayer graphene, "layer degeneracy" is the same as "valley degeneracy". However, quite unlike any other quantum Hall system, there is an additional degeneracy – the n = 0 and n = 1 Landau level both have zero energy arising from the fact that the wavefunctions for both these states are localized on either the top or bottom layer. The zero energy Landau level in graphene is therefore 8-fold degenerate (spin, valley, Landau level), and called a quantum Hall octet [3,6-7].

One could think of several mechanisms to break each of the individual degeneracies: For spin, just like for free electrons, the magnetic field distinguishes between spins that are parallel and anti-parallel with the direction of the field; For layers, the top and bottom layers are not identical e.g. in suspended graphene, any applied gate voltage V_g (both for positive V_g that induces electron carriers and $-V_g$ for holes) bends the layers towards the gate so that the curvature is always larger on the bottom layer, (while for non-suspended graphene, the substrate itself obviously breaks the inversion symmetry); And finally, the (weak) hopping between carbon atoms that form the triangular lattice in the bottom layer and the atom in the top layer that lies in the center of this triangle breaks the Landau level degeneracy. But all of these mechanisms are expected to be very weak for non-interacting electrons, and cannot by themselves explain the splitting of the quantum Hall octet.

The experiments [1-2] also suggest that the energy splitting of the 8 new Landau levels is not directly related to any of these individual symmetry-breaking mechanisms, and that the splittings suddenly emerge at particular values of magnetic field, rather than a gradual transition. Moreover, just like in monolayer graphene, after a critical sample-dependent magnetic field, the new zero energy quantum Hall plateau shows a diverging resistance as a function of both magnetic field and temperature [8]. All this hints that much richer physics is at play [6-10].

While it is fair to say that the nature of this symmetry breaking in bilayer graphene is still unknown, and indeed, other than the observation of the 8-fold splitting, the two experiments themselves disagree in many important details, one could still speculate on its origin. Suspended graphene is different in two important respects from graphene on a substrate. The substrate, being a dielectric material, effectively screens the Coulomb repulsion between electrons, implying that suspended graphene has much stronger many-body interactions. Secondly, the disorder scale in suspended graphene is an order of magnitude smaller since many of the trapped charges reside in the substrate.

One telling fact is that in both experiments, the emergent Landau level energy splittings are quite comparable to the energy scale that characterizes the disorder in the sample, estimated from zero-field transport studies [11]. The octet Landau level consists of both electron-like and hole-like states, which would be broadened by this disorder energy scale (which gives a finite width to the levels shown in Fig. 1). In addition, disorder changes the local charge neutrality point breaking the sample up into a spatially inhomogeneous landscape of electon-like and hole-like regions. One would then have local islands of quantum Hall metals (that are in different Landau level states) surrounded by insulating regions. Only when a percolating metallic path connects a single Landau level state from the source to the drain contacts, would one then observe the transition from one quantum Hall plateau to another. The role of the (relatively large) Coulomb interaction between electrons in this inhomogeneous medium is an open problem and likely to be the key to understanding both the symmetry breaking of the zero energy Landau level and the emergence of the highly resistive phase that was observed in both the monolayer and bilayer graphene experiments. As illustrated by these recent experiments, graphene research continues to deliver exciting new puzzles keeping the field alive and vibrant.

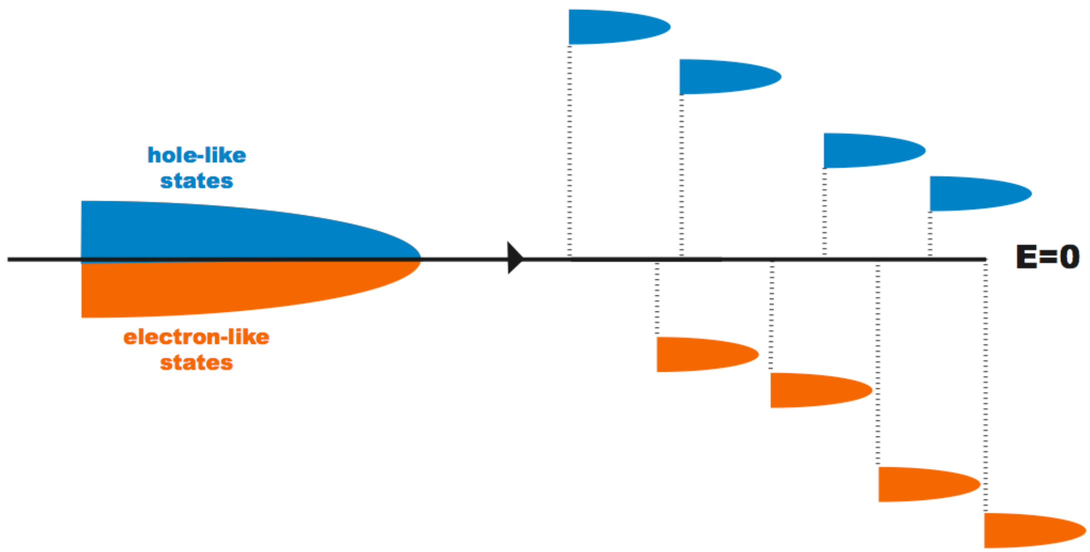

Figure 1: Schematic of the eight-fold symmetry breaking of the zero energy Landau level in graphene bilayers. Vertical axis is energy, while offsets in the horizontal axis are done for visual clarity.

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