PHYSICS

Emergent complex states in bilayer graphene

Experiments probe a wealth of exotic electronic behavior

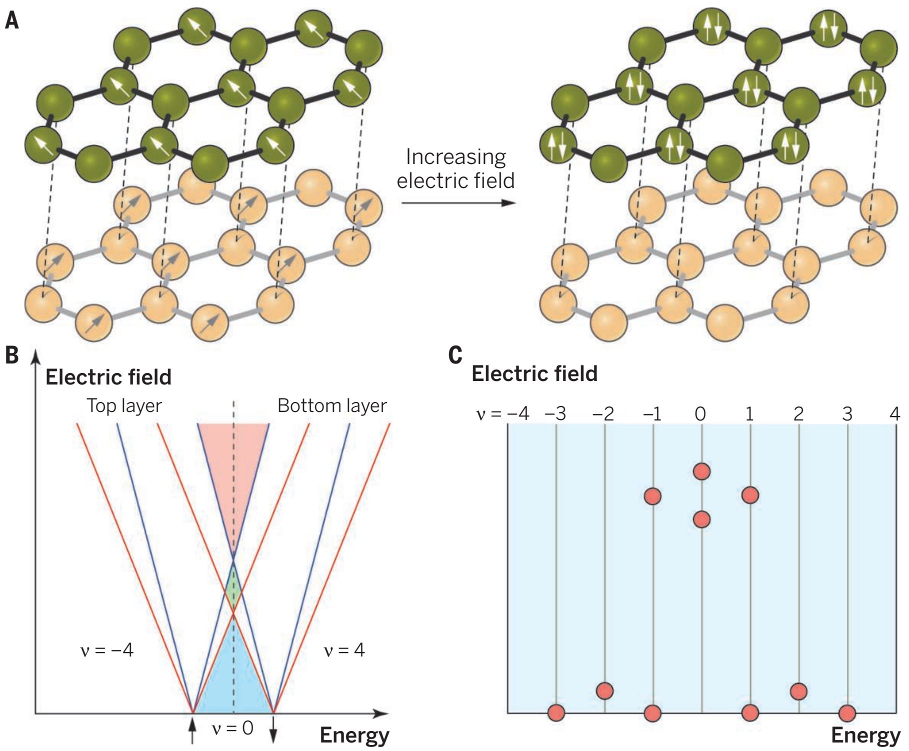
By **Brian J. LeRoy** *and* **Matthew Yankowitz**

Symmetries play a critical role in physical systems. The famous Noether's theorem states that a continuous symmetry of a system has a corresponding conserved physical quantity. For example, a physical system that is invariant in position and time must obey conservation of linear momentum and energy, respectively. The breaking of symmetries has equally important consequences—some examples being the Higgs boson, superconductivity, and ferromagnetism. Electrons in graphene, a monolayer sheet of hexagonally bonded carbon atoms, exhibit an approximate fourfold symmetry due to the two equivalent atoms per unit cell and spin degeneracy. The unusual electronic transport properties that result when a magnetic field is applied reflect these symmetries (*1*–*3*). The two layers of carbon atoms in bilayer graphene provide an extra degree of freedom, making it an even richer system for complex electronic states to emerge. Using different measurement techniques, a trio of studies in this issue—by Kou *et al.* (*4*) on page 55, Lee *et al.* (*5*) on page 58, and Maher *et al.* (*6*) on page 61—have elucidated the nature of these exotic broken-symmetry states.

At small magnetic fields, bilayer graphene exhibits plateaus in Hall conductivity at values $\pm 4N(e^2/h)$ for $N \geq 1$, where N is the (integer) Landau level index, e is the electric charge, and h is Planck's constant. The factor of 4 arises from the spin and layer (also known as valley) degeneracy of bilayer graphene, and the missing plateau at $N = 0$ arises from an extra twofold orbital degeneracy due to the merging of the first two Landau levels at zero energy (*7*). Thus, plateaus occur at Landau level filling factors of $\nu = \pm 4$, 8, 12, etc., with a special eightfold symmetry around zero. The filling factor ν represents the ratio between the number of electrons and magnetic flux quanta. As the magnetic field is increased, the spin and layer degeneracies are broken, causing plateaus to appear at all integer filling factors. In very clean samples and at large magnetic fields, strong Coulomb interactions produce additional quantized Hall states at fractional filling factors. Upon formation of these fractional quantum Hall states (FQHSs), the system is composed of fractionally charged quasiparticles that experience zero magnetic field (*8*). These quasiparticles can inherit the symmetries of their parent electrons, requiring even stronger symmetry-breaking terms before exhibiting broken-symmetry FQHSs. The competition between the strengths of these symmetry-breaking interactions helps determine the specific nature of the electronic ground state. These effects have been fairly well studied in monolayer graphene, but have thus far been largely unexplored in bilayer graphene owing to challenges in sample fabrication. Using various new device structures based on ultraclean bilayer graphene on hexagonal boron nitride (*9*), these three groups have teased out these previously hidden states.

By performing scanning single-electron transistor measurements on an extremely clean bilayer graphene sample, Kou *et al.* observed a rich sequence of symmetry-broken quantum Hall states (QHSs) and FQHSs. Surprisingly, the sequence of FQHSs is not symmetric about filling factor $\nu = 0$, as is observed in monolayer graphene, but rather exhibits a $\nu \rightarrow \nu + 2$ pattern that is attributed to the extra twofold orbital degeneracy specific to bilayer graphene. Electron-electron interaction strength is expected to vary depending on the orbital polarization, weakening the strength of some of the typically observed FQHSs and resulting in an unusual sequence of states that is not electron-hole symmetric.

Lee *et al.* and Maher *et al.* add an additional ingredient to the mix: the ability to tune phase transitions in the QHSs and FQHSs with an external transverse electric field, which provides an independent symmetry-breaking term for the layer and orbital degeneracies. Lee *et al.* find particularly surprising behavior at $\nu = 0$, where four of the eight degenerate states in the



Bilayer graphene phase diagram. (**A**) Schematic of the bilayer graphene lattice indicating spin and layer configurations for the $\nu = 0$ state. At a small electric field, the system is in a canted antiferromagnetic phase (left); at a high field, it is in a layer-polarized phase (right); and at intermediate fields, it is in a coherent superposition of the two. (**B**) Schematic of the Landau level (LL) energies of bilayer graphene in an electric field. The LLs are initially spin-split because of a magnetic field, and become layer-polarized under an electric field. The orbital degree of freedom, indicated by color (red or blue), also evolves with electric field. For the $\nu = 0$ state, the canted antiferromagnetic (blue), spin-layer coherent (green), and layer-polarized (red) phases are color coded. (**C**) Experimentally observed phase transitions in the lowest LLs of bilayer graphene as a function of electric field. In general, phase transitions occur at crossings or splittings of LL lines shown in (B).

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lowest Landau level are filled. At small electric fields, the ground state is spin polarized (canted antiferromagnetic), and above a critical field the ground state transitions to become layer polarized (see the figure, panel A). What is new is that the lifted orbital degeneracy due to the electric field induces a spin-layer coherent phase (coherent superpositions of Landau levels with the same orbital index but different spin and valley indices) separating the fully spin and fully layer polarized phases (see the figure, panels B and C). Maher *et al.* additionally track the electric field–induced phase transitions of FQHSs, observing weak electron-hole asymmetry reminiscent of the Kou *et al.* findings. The phase transitions in the FQHSs tend to match those observed in the parent QHSs, indicating that the fractionally charged quasiparticles inherit the same symmetries as their parent electrons and couple to symmetry-breaking terms with similar strength. The $\nu = 4/3$ and $5/3$ states are exceptions, exhibiting a phase transition at zero electric field where their parent $\nu = 2$ state does not, suggesting that the competition between ground state phases in the QHSs and FQHSs may be exceedingly complex.

It is remarkable that these three studies, using independent measurement and sample fabrication techniques, draw consistent conclusions about the nature of a system with so many degrees of freedom. Another recent study (*10*) examined FQHSs in high-quality suspended bilayer graphene and found rather different results, observing only two fully developed states at $\nu = -1/2$ and $-4/3$. The $\nu = -1/2$ state is especially intriguing, as it is expected to be non-Abelian (behaving as neither a boson nor fermion) and is not of the same origin as any of the FQHSs observed on the substrate-supported devices of Kou *et al.* or Maher *et al.* This result further demonstrates the wide variability of FQHSs in bilayer graphene, in contrast to monolayer graphene, in which the FQHS sequence is similar across all experiments. Though considerable work is necessary to fully understand the rich phase diagram of bilayer graphene, these studies open exciting pathways toward realizing and controlling the exotic emergent states. ■

REFERENCES

1. K. S. Novoselov *et al.*, *Nature* **438**, 197 (2005).
2. Y. Zhang *et al.*, *Nature* **438**, 201 (2005).
3. C. R. Dean *et al.*, *Nat. Phys.* **7**, 693 (2011).
4. A. Kou *et al.*, *Science* **345**, 55 (2014).
5. K. Lee *et al.*, *Science* **345**, 58 (2014).
6. P. Maher *et al.*, *Science* **345**, 61 (2014).
7. E. McCann, V. I. Fal'ko, *Phys. Rev. Lett.* **96**, 086805 (2006).
8. J. K. Jain, *Phys. Rev. Lett.* **63**, 199 (1989).
9. M. Yankowitz *et al.*, http://arxiv.org/abs/1401.5145 (2014).
10. D.-K. Ki *et al.*, *Nano Lett.* **14**, 2135 (2014).

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NEUROSCIENCE

Following the same nerve track toward different cell fates

Schwann cell precursors can become either neurons or glia

By **Chaya Kalcheim**[1] *and* **Hermann Rohrer**[2]

The autonomic nervous system controls the activity of internal organs such as the heart, lung, and gut, maintaining homeostasis of body functions in response to changing external conditions (*1*). It is composed of two antagonistic branches, sympathetic and parasympathetic. The former is essential for adapting to activity (i.e., fight-and-flight), whereas the latter is important at rest. Sympathetic neurons form ganglia along the body axis; parasympathetic ganglia are distributed all over the body. On page 87 and page 82 in this issue, Espinosa-Medina *et al.* (*2*) and Dyachuk *et al.* (*3*) challenge current views on how the parasympathetic nervous system is formed. These ganglia arise from progenitor cells that migrate along nerve fibers to peripheral targets. Known as Schwann cell precursors, these cells had previously been thought to give rise only to non-neuronal cells. Moreover, the nerve tracks include the very nerve fibers that ultimately innervate the parasympathetic neurons once they reach their destination and mature.

Both sympathetic and parasympathetic neurons derive from neural crest cells that emigrate from the neural tube (precursor to the brain and spinal cord) during early vertebrate development (*4*, *5*). This migration to sites of ganglion formation and the molecular control of neuron differentiation have been well delineated for sympathetic ganglia, but the formation of parasympathetic ganglia has remained unclear (*6*, *7*). Espinosa-Medina *et al.* and Dyachuk *et al.* demonstrate that parasympathetic ganglia are formed not by the aggregation of migrating neural crest cells but rather from Schwann cell precursors derived from neural crest cells. The Schwann cell precursors track along outgrowing axons from neurons in the developing hindbrain and transiently display a dual identity—part Schwann cell precursor and part parasympathetic neuron progenitor.

During mouse embryonic development, two parasympathetic ganglia (sphenopalatine and lingual) in the head are absent when a facial nerve that emanates from the hindbrain is partially eliminated (*8*). This pointed to a role for cranial nerves in parasympathetic neuron development. Extending these findings to additional parasympathetic ganglia in the mouse head and trunk, Espinosa-Medina *et al.* used genetic methods to delete other cranial nerves—the glossopharyngeal nerve and/or the vagus nerve. The authors observed that the generation of parasympathetic neurons that constitute the otic ganglion—which stimulates a salivary gland—depends on the presence of the glossopharyngeal cranial nerve.

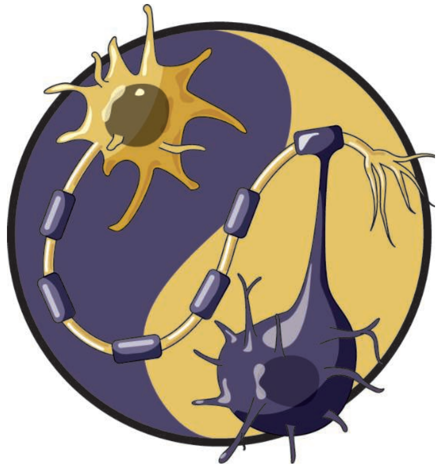

ILLUSTRATION: V. ALTOUNIAN/*SCIENCE*

Formation of the cardiac ganglion—which innervates the heart—depends on the presence of the vagus nerve. Detailed analysis revealed that both parasympathetic ganglia arise from cells that accompany the cranial nerve fibers as they grow toward the site of parasympathetic ganglion formation. These migrating cells express the transcription factor SOX10, which indicates their crest cell origin and is a marker for future Schwann cells. During their migration, however, they also turn on the expression of another transcription factor, PHOX2B, which is a marker for autonomic neurons. They therefore assume a bi-fated precur-

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