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Another Spin on Graphene

Antonio H. Castro Neto

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PHYSICS

Another Spin on Graphene

Electrical measurements on graphene reveal further exotic electronic properties of this one-atom-thick material.

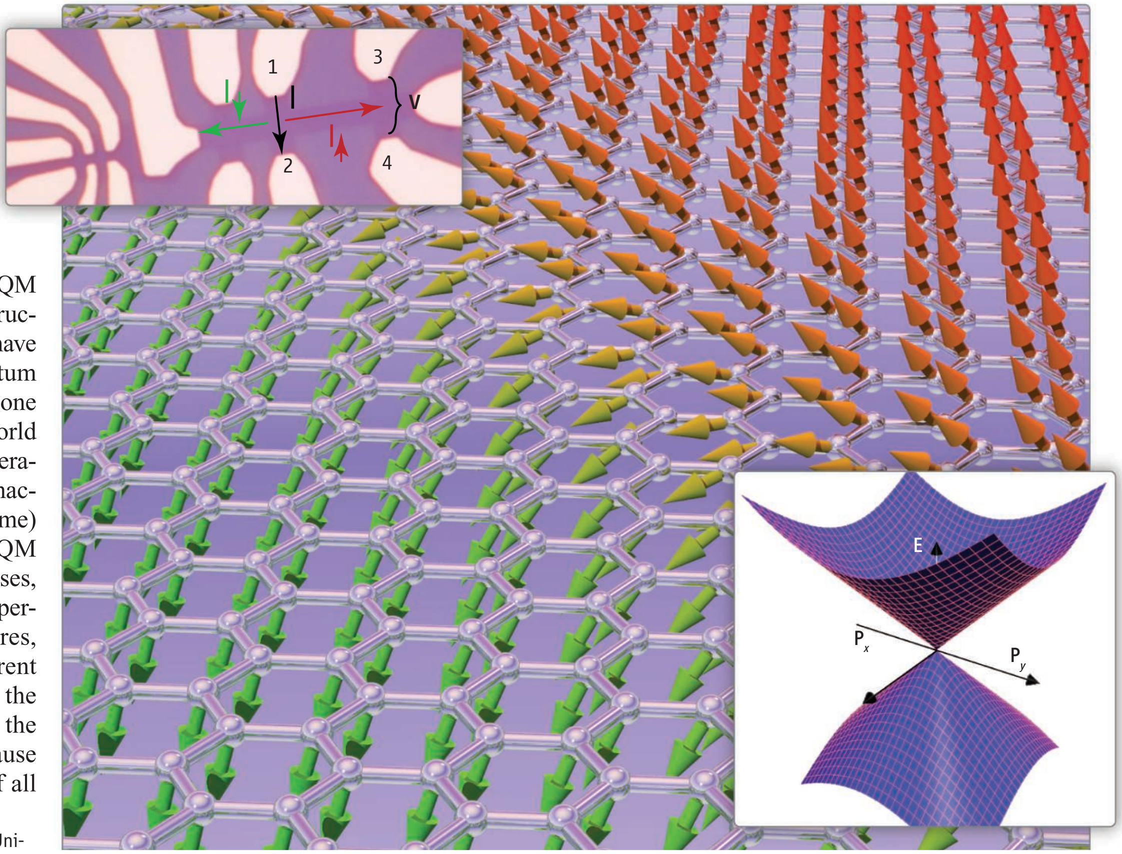
Antonio H. Castro Neto[1,2]

Graphene, the one-atom-thick face of carbon (*1*), startled the condensed matter community from the get-go. It exhibits a large number of new and exotic optical and electronic effects that have not been observed in other materials (*2*, *3*). Most of these effects arise because of two important properties of graphene—the strength of the bonds that keep the carbon atoms together and the peculiar electronic structure of the honeycomb lattice. The electronic excitations in graphene are said to behave like Dirac particles, that is, their energy is proportional to their momentum (*4*). Furthermore, graphene is opening doors for an entirely new technology based on two-dimensional (2D) crystals. On page 328 of this issue Abanin *et al*. (*5*) report another completely unexpected effect that involves nonlocality and quantum mechanics at ambient conditions.

Quantum mechanics (QM), the theory of the microscopic universe, associates an amplitude and a phase to an object. Amplitude and phase represent the dual nature of QM; the amplitude is the "particle" aspect and the phase the "wave" aspect. A system is coherent when its phase is well defined (unlike classical mechanics, in QM particles interfere either constructively or destructively if they have a well-defined phase). Quantum effects disappear either when one looks into the macroscopic world or when one goes to high temperatures. This happens because macroscopic objects (like you and me) are all incoherent from the QM point of view. In some rare cases, such as superconductors or superfluids at very low temperatures, it is possible to have a coherent macroscopic state. However, the coherence is destroyed when the temperature is increased because of the uncontrolled motion of all the particles involved. Furthermore, in the great majority of physical systems (micro or macro), the effects are local, that is, an object is only influenced directly by its immediate surroundings. Abanin *et al*. show that graphene exhibits nonlocal quantum effects at room temperature.

In their experiments, an electrical current is passed between two electrodes in close proximity to each other (see the figure, upper inset), and they detect a voltage far away from those electrodes. In an ordinary material under the same conditions (at room temperature and small magnetic fields), this would not happen because the electrons are incoherent and behave classically. After a few collisions with impurities in the system, the electrons would lose their phase information and undergo random walk. To reach nonlocal contacts, this would be a walk too far, and no voltage would be generated. This indicates that graphene is behaving in a quantum mechanical way and creating a nonlocal voltage under unexpected conditions. How is this possible?

There are very few examples of nonlocal transport in electronic systems. A typical example is the quantum Hall effect. In the classical Hall effect, which is observed in any metal, electrons experience a Lorentz force that is perpendicular to applied electrical and magnetic fields, leading to the appearance of a new electric field, or voltage (the Hall voltage), which is perpendicular to the original applied field. When a large magnetic field is applied to a 2D metal, the electronic states become quantized, and the classical Hall effect turns into the quantum Hall effect. The energy gaps associated with these states are large; hence, the bulk of the system is nonconductive. However, there are states at the edge of the sample that carry electric charge.



Probe here, measure there. (**Upper inset**) A graphene device in which a current is applied between electrodes 1 and 2 and a voltage is measured in distant electrodes 3 and 4, due to the splitting of the spin currents (up and down), as shown in the main figure. (**Lower inset**) Graphene electronic dispersion and its Dirac point.

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[1]Graphene Research Centre, National University of Singapore, Singapore 117542. [2]Department of Physics, Boston University, Boston, MA 02215, USA. E-mail: neto@bu.edu

These edge states always propagate in one direction (and for that, they are called "chiral") as a result of combination of the Lorentz force and the confining potential in the edge of the sample. Chirality allows currents to propagate large distances coherently. However, this is not the case in the experiments of Abanin *et al*. because the magnetic fields used are not large enough to produce coherent quantized levels. Nonlocal transport can also occur in systems with long-range order due to electron-electron interactions, such as charge density waves and superconductors. In those cases, the state of the many-body system is coherent over macroscopic scales and the electrons behave cooperatively. However, no such long-range order has ever been detected in graphene.

What Abanin *et al*. advocate as the reason for this anomalous behavior is the unusual physics that occurs at the so-called Dirac point [the point where the cones meet (see the figure, lower inset)] in the presence of a magnetic field. At this particular point, graphene is electrically neutral and its electrical resistance is high. However, small magnetic fields can produce charges with well-defined spin that points either up or down relative to the applied field. As a consequence, the Hall resistance of graphene (the ratio of the Hall voltage to the applied current) close to the Dirac point suffers a large change, and spin-up and spin-down currents are produced in opposite directions (see the figure). Thus, we are faced with a very unusual situation in which the charge of the electron still behaves incoherently (and hence, classically) but its spin behaves coherently (and thus, quantum mechanically). A similar effect occurs in metals and semiconductors with strong coupling between the spin and orbital degrees of freedom of the electrons (*6*). However, in ideal, flat graphene (as the ones supported in boron nitride), the spin-orbit coupling is too weak. In the presence of ferromagnetic contacts (*7*), one would be able to use this effect at room temperature and macroscopic distances for new graphene-based spintronics in 2D, with the electron spin as the quantum degree of freedom. This discovery adds a new chapter to the rich history of graphene.

References and Notes

1. K. Novoselov *et al*., *Science* **306**, 666 (2004).
2. R. R. Nair *et al*., *Science* **320**, 1308 (2008).
3. N. Levy *et al*., *Science* **329**, 544 (2010).
4. A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, A. K. Geim, *Rev. Mod. Phys.* **81**, 109 (2009).
5. D. A. Abanin *et al*., *Science* **332**, 328 (2011).
6. Y. K. Kato, R. C. Myers, A. C. Gossard, D. D. Awschalom, *Science* **306**, 1910 (2004).
7. N. Tombros, C. Jozsa, M. Popinciuc, H. T. Jonkman, B. J. van Wees, *Nature* **448**, 571 (2007).

8. I thank Tatiana Rappoport for discussions.

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OCEAN SCIENCE

A Frontal Challenge for Climate Models

An unusually detailed portrait of an ocean front off Japan could help improve climate predictions.

Raffaele Ferrari

The ocean surface is filled with a convoluted web of "fronts" that separate waters of different temperatures and salinities (see the figure). Just as thin ducts in the lung called alveoli facilitate the rapid exchange of gases when breathing, fronts are the ducts through which heat, carbon, oxygen, and other climatically important gases enter into the deep ocean. A lack of observations, however, has hampered progress in understanding the dynamics of fronts, which can be as narrow as hundreds of meters and as wide as tens of kilometers. Global satellite measurements of ocean-surface velocities and air-sea fluxes, for instance, are only available at resolutions of a few hundred kilometers. Although shipboard researchers can sample vertical ocean profiles down to centimeter scales, only rarely do they collect profiles that are less than 100 km apart. On page 318 of this issue, D'Asaro *et al*. (*1*) present a breakthrough in observing ocean fronts, providing direct observations of the workings of the Kuroshio front off Japan on scales from kilometers to millimeters. This detailed and wide-ranging portrait was made possible by the development of towed instruments that continuously sample the waters behind a steaming ship, the deployment of freely drifting instruments that follow ocean currents, and the exercising of a great deal of ingenuity in keeping all these tools along the front for a few weeks in 2007.

The convergence of waters at an ocean front can result in water masses sinking rapidly, at rates of 10 to 100 m/day, compared to typical rates of 1 to 10 m/day in the rest of the ocean. These rapid vertical velocities may be key in determining the exchange rate of heat, carbon dioxide, and other gases between the atmosphere and the deep ocean. Fronts, however, are an important element of the ocean-atmosphere coupled climate system, and in efforts to predict the response of climate to anthropogenic activities, such as the burning of fossil fuels. Currently, however, ocean models used for climate studies are based on grids that are coarser than the typical widths of fronts because of computer speed limitations. Although these models can be tuned to reproduce the collective effect of fronts in the present climate, their capability to predict the impact of fronts on future climate is unknown. We are essentially running models of the ocean lungs that do not include alveoli.

Recent work on the stability of fronts seems to indicate that air-sea exchange at fronts is short-lived. The evidence suggests that the exchange is strong when the front first forms, but is suppressed a short time later, when the front becomes unstable. In satellite images, the instability appears as a meander in the front (see the bottom left of the figure); it pushes waters from the light (warm) side of the front over waters on the dense (cold) side (*2*, *3*). The resulting buoyant layer of warmer, lighter water on top of the front is very stable and suppresses any vertical transport, effectively closing the exchange pathway with the atmosphere. This scenario is observed when the atmospheric forces that influence ocean fronts (atmospheric forcing), such as winds, heat loss, or evaporation, are weak. In contrast, D'Asaro *et al*. show that when the atmospheric forces are strong, the exchange pathway remains open. This is because small-scale turbulence develops that mixes heat and gases across the buoyant surface

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. E-mail: rferrari@mit.edu