GRAPHENE

Cracking bilayers

The observation of Hall quantization and complete lifting of the degeneracy in bilayer graphene at magnetic fields an order of magnitude lower than previously reported has important implications for an understanding of the role of many-body interactions in the exotic behaviour of bi- and monolayer graphene.

Kostya S. Novoselov

Ever since isolated graphene was reported for the first time[1] it has continued to impress, and new reasons to be excited about this first two-dimensional atomic crystal appear on a monthly basis. However, for many researchers it is graphene's unusual electronic properties that generate the greatest excitement. Of particular note is the fact that the charge carriers in graphene obey a linear dispersion relation (similar to that of photons), thus mimicking massless relativistic particles. The chiral nature of quasiparticles in graphene (a consequence of electron–hole symmetry) gives rise to a number of unusual effects, including a half-integer quantum Hall effect[2]. Such behaviour was previously considered to be confined to the realm of high-energy particle physics. Graphene has brought such exotic ideas as chiral, massless quasi-relativistic Dirac fermions into the everyday vocabulary of condensed-matter physics. However, for bilayer graphene (two graphene layers in close proximity, resulting in a two-atom-thick material) the situation becomes even more unusual. The charge-carrying quasiparticles in bilayer graphene obey parabolic dispersion, and so have non-zero mass, but retain a chiral nature similar to that in monolayer graphene[3]. Although tremendous progress has been made in characterizing and understanding the behaviour of mono- and bilayer graphene, many questions still remain unanswered. Perhaps one of the most important is the influence of electron–electron interactions on this behaviour, and whether it differs from that in other two-dimensional systems. Most researchers so far have directed this question to monolayer graphene. Now, on page 889 of this issue[4], Feldman and colleagues direct it to the much more challenging (and arguably more interesting) case of bilayer graphene, with intriguing measurements of many-body enhanced splitting of the zero Landau level (which is eight-fold degenerate in this material).

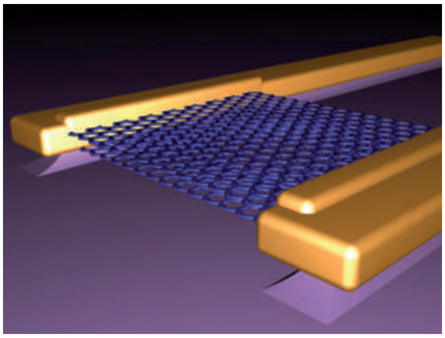

Figure 1 | Free-standing bilayer graphene makes it possible to observe a full lifting of eight-fold degeneracy at the zero Landau level in very modest magnetic fields.

There are two regimes in which electron–electron interactions might be expected to play a measurable part in graphene. The first is in the limit of low energy and low carrier concentration, with the Fermi energy situated near the 'Dirac point' where the valence and conduction bands touch. At this point the density of states is expected to be too small to enable screening of the Coulomb interaction. There have been numerous attempts to identify the signature of electron–electron effects in this regime, but the results of most have been unconvincing. This regime doesn't apply to bilayer graphene because its parabolic dispersion ensures that the density of states is finite even at the zero-energy limit, so there is always something screening electron–electron interactions.

The second regime is in a strong magnetic field, which squeezes carriers close together and shrinks the spatial extent of their wavefunctions. Valley- and spin-splitting effects that are enhanced by electron–electron interactions in this regime have been observed in monolayer graphene, but never in the bilayer form. This has been attributed to the fact that bilayer graphene is usually more disordered and of much lower quality than monolayer graphene, resulting in quasiparticle mobilities that are typically less than half that of those in the monolayer form. Thus, any chance of observing many-body effects in bilayer graphene requires a breakthrough in sample preparation.

Such a breakthrough has been achieved in monolayer graphene by suspending it between two metal contacts, so that it is held well away from the substrate on which it would otherwise sit. Why isolation from the substrate should affect the apparent quality of a graphene sheet is the subject of some debate. But it has been shown to significantly improve its carrier mobility and the uniformity of the samples.

And so Feldman and colleagues apply the same idea to samples of bilayer graphene (Fig. 1). Although this doesn't result in as dramatic an increase in the mobility as has been seen in the monolayer form, it does allow dramatic new phenomena to arise when they are subjected to a magnetic field. Feldman *et al.* detect fully quantized quantum Hall states at magnetic fields more than an order of magnitude lower than previously reported. But more significantly, they observe the emergence of previously unseen quantum states at filling factors 0, ±1, ±2 and ±3, thereby breaking the symmetry of the eight-fold degeneracy of bilayer graphene's zero Landau level.

In principle, there are several mechanisms that could give rise to such symmetry breaking without the need for invoking many-body effects. The authors carefully analyse each of these mechanisms in turn, but find that none provide a sufficiently large level splitting. Rather, the strength of the splitting they observe is about an order of magnitude greater than could be explained by any of the single-particle effects. And so they conclude that the splitting strength is the sought-after signature of many-body interactions at work.

This finding is important as it might lead to a better understanding of the mechanisms that do and do not lift the degeneracy inherent in the electronic structure of mono- and bilayer graphene. Of particular interest is the state at filling factor zero, where the level splitting in conjunction with the electron–hole symmetry in bilayer graphene might lead to some particularly unusual effects (such as, for instance, counter-propagating spin-polarized edge states in monolayer graphene[5]). Splitting enhanced by many-body effects has previously been observed in monolayer graphene[5–7] (also at filling factor zero) but we are still in the dark about the exact mechanism and the nature of the resulting electronic states.

Eight-fold degeneracy of the lowest Landau level provides us with an exciting puzzle: which one of those degeneracies will be lifted first, or can we actually even change an order of it by altering some external parameters (such as in-plane magnetic field, for instance). Depending on the circumstances, it might repeat the situation that is most probably realized in monolayer graphene (most probably it is the spin-splitting that is the dominant effect there) or, it might be something much more exotic. The authors claim that the insulating state at the compensation point behaves differently when compared with the similar state in monolayer graphene. In addition, it has some peculiar dependence on in-plane magnetic field, which is generally not expected at all. One is thing obvious: we can expect very exciting new physics to occur in this regime. ❐

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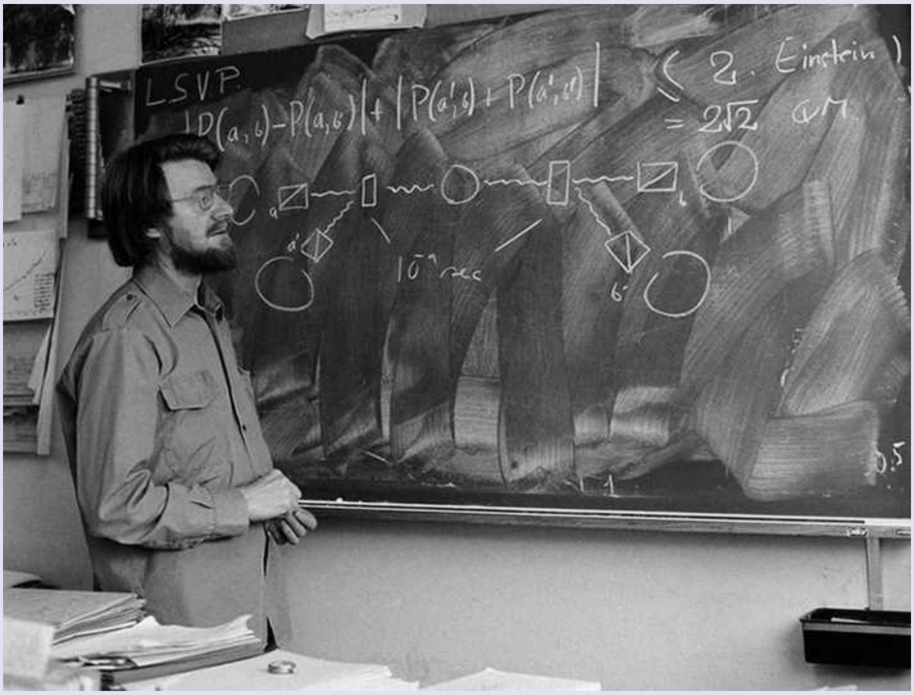
QUANTUM MECHANICS

Shaken foundations



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In 1975, Alain Aspect presented John Bell (pictured) with a proposal: he would perform a set of new experiments to check whether or not the inequalities that Bell had derived a decade earlier were violated. Legend has it that Bell first asked the young Frenchman if he had a permanent job; only when Aspect answered in the affirmative did Bell encourage him to publish his ideas.

By 1982, Aspect and his co-workers had produced experimental data that showed clear violation of Bell's inequalities. The data could therefore be explained within the framework of quantum mechanics, but not so within so-called realistic local theories. Aspect's work now stands as a cornerstone of our understanding of the foundations of quantum theory, and proved to be a seminal contribution to quantum information science. Moreover, it is only as a consequence of his experiments that the now-famous Einstein–Podolsky–Rosen paper of 1935 was noticed, and cited, by a wider audience. Nevertheless, in 1975 Bell was worried that Aspect's career might be compromised by engaging in research considered to be, at best, on the margins of physics.

This episode is just one example given by Olival Freire in his "collective biographical profile" of nine physicists, including Bell, who around 1970 were researching the foundations of quantum theory (*Studies in History and Philosophy of Modern Physics* doi:10.1016/j.shpsb.2009.09.002; 2009). Freire calls them "quantum dissidents" (with the exception of one — Léon Rosenfeld). These dissidents were fighting the prevailing attitude of the time that all of quantum physics' foundational issues had essentially been put to rest by its founding fathers, and proved that there were important unsolved questions, not only with regard to quantum non-locality, but also concerning decoherence, the quantum measurement problem and the quantization of gravitation.

United as the dissidents were in agreeing that much remained to be done, the scope of their work and the approaches they took were distinctly different. The protagonists of Freire's study were critical of each other's contribution, but the goal wasn't to develop one particular alternative interpretation. Many avenues were explored, and not without sacrifice: certainly the professional careers of H. Dieter Zeh and John Clauser were severely hampered. But the efforts of these nine helped to establish the foundations of modern physics as a 'proper' and important field of research. Quantum theory has grown stronger through their successes — even if it was at the risk of being toppled from its very foundations.

ANDREAS TRABESINGER