Fractional quantum Hall effect and insulating phase of Dirac electrons in graphene
by Xu Du, Ivan Skachko, Fabian Duerr, Adina Luican, Eva Y. Andrei
arXiv:0910.2532, Nature **462**, 192 (2009)
and
Observation of the Fractional Quantum Hall Effect in Graphene
by Kirill I. Bolotin, Fereshte Ghahari, Michael D. Shulman, Horst L. Stormer, Philip Kim
arXiv: arXiv:0910.2518, Nature **462**, 196 (2009)

Recommended and a Commentary by Francisco Guinea, Madrid

The papers commented here demonstrate the existence of the Fractional Quantum Hall in graphene. They represent the culmination of a long and arduous search, despite the relative ease needed to observe its non interacting counterpart, the Integer Quantum Hall effect.

Research in graphene had an enormous boost when the Integer Quantum Hall Effect was observed in 2006 in samples produced by mechanical cleavage and deposited on SiO_2. The unusual succession of plateaus, $\sigma_{xy} = 2(2n + 1)e^2/h$ with n an integer, were an unambiguous proof of the the massless nature of the carriers. This highlighted the difference between graphene and other systems which exhibit the IQHE. The quick confirmation that a graphene bilayer also showed anomalous behavior came shortly afterwards. For the first time in any material, the IQHE was also observed at room temperature in graphene. Recent experiments have showed the IQHE at fields as low as 0.1T in bilayer graphene[1]. The IQHE has been recently observed in single layer graphene grown on SiC with great accuracy.

The vanishing effective mass of graphene leads to gaps between Landau levels of order $\Delta \sim \hbar v_F/\ell_B$, where $v_F \approx 10^6$ m/s is the Fermi velocity, and $\ell_B = \sqrt{\Phi_0/B}$ is the magnetic length, Φ_0 being the quantum unit of magnetic flux. In a doped semiconductor with a parabolic band, the gap is $\Delta \sim \hbar^2/(m_{eff}\ell_B^2)$, where m_{eff} is the effective mass of the carriers. As typically $m_{eff} \sim 10^{-1}m_e$, the gaps are significantly larger in graphene. In the Fractional Quantum Hall Effect, the expected gaps are due to the electron electron interaction, and the relevant energy scale is $e^2/(\kappa\ell_B)$, where e is the electric charge, and κ is the dielectric constant. For graphene on SiO_2, $\kappa \sim 4$, so that the gaps can be larger than in materials such as GaAs, where $\kappa \sim 10$.

Theoretical arguments suggested that the vanishing effective mass of the carriers was no obstacle to the formation of a correlated Laughlin state at fractional fillings. It has been generally believed that the reason for the lack of observations was the relatively low mobilities of graphene on SiO_2 substrates, $\mu \lesssim 10^4 \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$, as compared with those in doped semiconductor samples where the FQHE had been observed, where $\mu \approx 10^6 \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ has been achieved.

The problem of sample disorder was overcome by suspending the graphene layer above the substrate and annealing it, achieving a gain of more than one order of magnitude in mobility. The mobilities in the papers commented here are of order $10^5\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ at low temperatures, and mobilities exceeding $10^6\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$ have recently been reported in suspended samples (A. K. Geim, private communication). Another disorder related effect, the fluctuation in carrier density at the neutrality point was reduced to less than $\pm 10^9 \text{cm}^{-2}$. Contrary to expectations, suspended graphene samples failed to show even the IQHE, using the standard four terminal setup for the measurement.

The paper from A. Yacoby's group showing the IQHE in a graphene bilayer mentioned earlier[1] opened new perspectives, as the measurement was done using a two terminal setup. This geometry allows only measurement of the conductance of the device, and it mixes the components of the conductivity tensor, σ_{xx} and σ_{xy}. In the two papers commented here, and in unpublished results from A. K. Geim's group in Manchester University, the conductance shows unambiguous steps at $\nu = 1/3$. The measurements done at Columbia and Manchester indicate a second plateau at $\nu = 2/3$, and the paper by Bolotin *et al.* also suggests a third plateau at $\nu = 1/2$. All experiments show that the plateau at $\nu = 1/3$ survives at a temperature of 10K, which makes the FQHE state in graphene more stable than in any doped semiconductor.

A suspended two terminal setup is mechanically more stable than a four terminal one. Calculations show that the mixing of σ_{xx} and σ_{xy} in devices of small dimensions, $L \lesssim 1\mu\text{m}$, can suppress the expected steps in the IQHE and FQHE regimes[2]. The mechanical strains in the samples may also induce effective magnetic fields which interfere with the IQHE and the FQHE even in very clean ballistic samples[3]. A third explanation is the formation of scrolls at the edges of long suspended samples, which lead to parallel conductance channels between the contacts, independent of the magnetic field (A. K. Geim, private communication). It would be interesting to disentangle the contribution from these effects, by observing the change in the plateaus with the mobility of the carriers, or by inducing externally strain, or by ironing the edges.

References

[1] Broken symmetry states and divergent resistance in suspended bilayer graphene, B. E. Feldman, J. Martin, and A. Yacoby, arXiv:0909.2883, Nature Phys. **5**, 889 (2009).

[2] Integer and Fractional Quantum Hall Effect in Two-Terminal Measurements on Suspended Graphene, by I. Skachko, X. Du, F. Duerr, A. Luican, D. A. Abanin, L. S. Levitov, E.Y.Andrei, arXiv:0910.2518. Fractional Quantum Hall Effect in Suspended Graphene: Transport Coefficients and Electron Interaction Strength, by D. A. Abanin, I. Skachko, X. Du, E. Y. Andrei, L. S. Levitov, arXiv:0912.1134.

[3] Singular elastic strains and magnetoconductance of suspended graphene, by E. Prada, P. San-Jose, G. León, M. M. Fogler, and F. Guinea, arXiv:0906.5267 (2009).