The $n = 0$ Landau level in graphene: Unusual properties in recent experiments

The zero-energy state in graphene in a high magnetic field
Joseph G. Checkelsky, Lu Li, N. P. Ong
http://www.arxiv.org/abs/0708.1959
Phys. Rev. Lett. **100**, 206801 (2008)

Divergent resistance at the Dirac point in graphene: Evidence for a transition in a high magnetic field
Joseph G. Checkelsky, Lu Li, N. P. Ong
http://www.arxiv.org/abs/0808.0906
Phys. Rev. B **79**, 115434 (2008)

Scanning Tunneling Spectroscopy of Graphene
Guohong Li, Adina Luican, Eva Y. Andrei
http://www.arxiv.org/abs/0803.4016
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Interest in graphene really took off after it was found that it presented unusual Integer Quantum Hall features. The results showed unambiguously that the electronic states in graphene are fundamentally different from those in the better understood two dimensional electron gases (2DEG). The effective mass is zero, and there is no gap between the valence and conduction band.

The main difference in the Quantum Hall regime between graphene and the other 2DEG lies in the existence of a new Landau level formed by electronic states originating both in the valence and conduction bands. This $n = 0$ Landau level shows electron and hole features, leading to two sets of edge currents. The well known quantization of the Hall current in graphene can be written as:

$$\sigma_{xy} = \frac{\nu e^2}{h} = \frac{2e^2}{h} \left(\pm 2n + 1 \right) \tag{1}$$

The $n = 0$ Landau level is responsible for the n independent term in the above expression.

There are four $n = 0$ bulk Landau bands, arising from spin and valley degeneracy. To a first approximation, they lie at the Dirac energy. Calculations using the continuum Dirac equation show that the wavefunctions are fully localized in one of the two sublattices in which the honeycomb lattice can be divided. Similar states are expected in corrugated graphene, even in the absence of a magnetic field.

The experimental study of the $n = 0$ Landau level has attracted a great deal of attention, and has evolved rapidly, as better quality (higher mobility) samples become available, and higher magnetic fields and lower temperatures were studied. Early experiments, reported in Abanin et al., http://www.arxiv.org/0702125, Phys. Rev. Lett. 98, 196806 (2007), showed a peak in the longitudinal resistivity at the neutrality point, and a plateau in the Hall conductivity. A metallic like longitudinal resistivity can be explained by electron and hole edge modes, even when the Zeeman energy or interaction effects induce a spin gap in the bulk (see: H. A. Fertig and L. Brey, http://arxiv.org/0604260, Phys. Rev. Lett. 97, 116805 (2006)). These electron and hole edge states lead to counter-circulating currents at each edge, with opposite spins. Backscattering can occur due to magnetic impurities. The analysis of the current and voltage distributions require the inclusion of leakage into the bulk, and, as a result, the Hall resistivity is not quantized.

The next set of experiments, presented in Z. Jiang, et al., http://www.arxiv.org/0705.1102, Phys. Rev. Lett. **99**, 106802 (2007), studied the dependence of the longitudinal and transverse resistivity on magnetic field orientation and temperature (see also the earlier work reported in Z. Jiang, et al., http://arxiv.org/0703822, Phys. Rev. Lett. **98**, 197403 (2007)). Tilting the applied field with respect to the normal to the graphene layer, orbital and spin effects can be distinguished. The paper found that the longitudinal resistivity followed an activated behavior for fillings $\nu = \pm 1$, which correspond to one or three of the four Landau bands with $n = 0$ occupied. The gaps obtained from the temperature dependence were only dependent on the component of the field normal to the layer. This suggested that these gaps were not due to spin effects (the value of the gaps was also larger than the Zeeman splitting). The experiments also showed a gap between the $n = 0 (\nu = 1)$ and $n = 1 (\nu = 2)$ significantly lower than that expected in the absence of interaction effects.

Checkelsky *et al*, in the papers mentioned at the beginning, have investigated further the dependence of the resistivity on temperature and disorder. They found an abrupt rise, by more than three orders of magnitude, from $\sim 10^3$ ohms to $\sim 10^6$ ohms, in a narrow field range. This rise occurred at lower fields as the quality of the samples increased (the quality was estimated from the offset of the Dirac energy with respect to zero gate voltage, which is a measure of the number of charged dopants in the sample). The dependence of the resistivity on applied field is well fitted by assuming a Kosterlitz-Thouless transition at a critical field, H_c, $R \propto e^{c/\sqrt{1-H/H_c}}$, where c is a constant. The dependence on gate voltage suggests that the transition is limited to low carrier concentrations, $\nu \approx 0$.

The fact that the transition is better defined in the cleanest samples, and the possible existence of an activation gap above the critical phase imply that the insulating phase does not arise from the localization of the electronic orbitals by disorder.

Li *et al* have studied the lowest Landau level, among other properties, in graphene by scanning tunneling measurements. By applying a voltage between the tip and a graphene layer on top of graphite (but decoupled from it) they identify filled and empty Landau levels. The $n = 0$ Landau level splits into two peaks, while the $n \neq 0$ levels do not. The observed splitting is weakly field dependent, and it is of the same order of magnitude as the gap observed by the same technique at the Dirac energy in the absence of a magnetic field. The physical mechanism leading to ths gap is, at present, unknown.

As mentioned above, the splitting of the bulk $n = 0$ Landau level does not imply automatically insulating behavior, because counter-circulating edge modes can exist at all energies, this being one of the unusual properties of graphene. Moreover, these modes have opposite spins, in a similar way to those in topological insulators, making impossible backscattering processes due to non magnetic impurities. Interaction effects can open gaps at the edges, as shown recently in Efrat Shimshoni, H. A. Fertig, G. Venketeswara Pai, http://arxiv.org/0807.2867. Experimentally, the existence, or lack thereof, of gapped edge states can only be addressed by careful non local measurements.