Electron-electron interactions in bilayer graphene.

1. Broken symmetry states and divergent resistance in suspended bilayer graphene
Benjamin E. Feldman, Jens Martin, Amir Yacoby,
arXiv:0909.2883, Nature Physics **5**, 889 (2009)
2. Local Compressibility Measurements of Correlated States in Suspended Bilayer Graphene
Jens Martin, Benjamin E. Feldman, R. Thomas Weitz, Monica T. Allen, Amir Yacoby,
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3. Interaction-Driven Spectrum Reconstruction in Bilayer Graphene
A. S. Mayorov, D. C. Elias, M. Mucha-Kruczynski, R. V. Gorbachev, T. Tudorovskiy, A. Zhukov, S. V. Morozov, M. I. Katsnelson, V. I. Fal'ko, A. K. Geim, K. S. Novoselov,
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4. Transport Spectroscopy of Symmetry-Broken Insulating States in Bilayer Graphene
J. Velasco Jr., L. Jing, W. Bao, Y. Lee, P. Kratz, V. Aji, M. Bockrath, C.N. Lau, C. Varma, R. Stillwell, D. Smirnov, Fan Zhang, J. Jung,
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Recommended with a Commentary by Paco Guinea, Madrid

The effects of the electron-electron interactions in graphene has recently become a hot and highly debated topic. In the early times of the graphene boom, it was widely assumed that the main features of graphene could be reasonably studied using independent particle models. Theoretical work which did not include interactions where highly successful in explaining the anomalous features observed in the Integer Quantum Hall regime, the dependence on carrier concentration of the electron mobility, transport in p-n junctions (the Klein paradox) or the transparency at optical frequencies. The lack of interaction effects seemed confirmed by careful measurements of the electron compressibility, well explained by independent particle models.

The advent of new samples with greatly enhanced homogeneity, and with carrier mobilities higher by about two orders of magnitude than the graphene

flakes previously used, has changed completely the perception about the role of interactions.

The first hint was the observation of the Fractional Quantum Hall Effect in high mobility suspended samples. This phenomenon proved very elusive, but, when found, the associated energy gaps turned out to be higher than in other 2D electron liquids[1].

New suspended samples allow for the measurement of the electronic properties within a range of $\rho \approx 10^8 \text{cm}^{-2}$ or $\epsilon_F \approx 1\text{meV}$ in single layer graphene. The density dependence of the effective mass and Fermi velocity at low carrier concentrations showed an enhancement of the Fermi velocity of almost a factor of three. This effect is consistent with the expected renormalization of the Fermi velocity in the absence of screening, given a graphene's "fine structure constant" $\alpha = e^2/v_F \approx 2.3 - 2.5$. Similar estimates for α have been used to explain the observation of plasmaron satellites in samples with high carrier concentrations. This value of α puts single layer graphene into the intermediate to strong coupling regime, although its flow towards zero takes the system to the weak coupling regime at low energies.

The situation is much more interesting in bilayer graphene. New experiments in high mobility samples hint to the existence of novel phases at zero carrier concentration and low temperatures. The first indication came from the electron compressibility measurements reported in[2]. These experiments showed a rise in resistivity near the neutrality point, consistent with a tendency towards an insulating state, although the resistivity never went above a value of a few thousand ohms. The existence of a gapped insulating phase was reinforced by extrapolations from measurements made at finite magnetic fields[3], which suggest a gap of about $\Delta \approx 2$ meV.

The experiments reported in[4] present a different picture. The density of states at the Fermi energy is inferred from careful measurements of the carrier density and temperature dependence of the resistivity in a number of high mobility suspended samples. The results show a crossover to a low temperature regime where the density of states is significantly reduced. The band structure of bilayer graphene changes from parabolic to four Dirac cones, due to trigonal warping. The crossover found experimentally occurs at an energy of about 6 meV, which is substantially larger than the crossover energy related to trigonal warping, abou1 1 meV. Hence, the results suggest a spontaneous symmetry breaking associated to interactions. This explanation is supported by measurements performed at finite magnetic fields, which imply that the lowest Landau level is fourfold degenerate, while independent

electron calculations give an eightfold degenerate $n = 0$ Landau level. In any case, the results reported in[4] do not show a finite gap at any concentration.

A last batch of recent experiments with strikingly different results is discussed in[5]. The conductivity of s suspended sample at the neutrality point was measured as function of bias voltage, magnetic field, and perpendicular electric field. The results indicate a gap of for bias voltages between abut -2 and 2 meV at zero magnetic field, zero electric field and zero carrier concentration. The differential conductance shows peaks at voltages above and below this gap, while they tend towards a constant value at larger bias voltages. Conductance peaks adjacent to a gap have the inverse square-root dependence on voltage in their density of state.

All the experiments described above coincide in that a broken symmetry phase due to electron electron interactions seems likely in bilayer graphene near the neutrality point and in the absence of a perpendicular electric field. They differ in many details, however, and the experiments in[4] suggest a gapless phase, while those in[2], and especially those in[5] seem to imply the existence of a gap. The experiments analyze suspended samples with high electron mobility, although the reported mobilities differ, being highest in[4], and lowest in[2, 3], while the samples in[5] show a high intermediate value. The experimental setups also differ: the measurement in[2, 3] give the values of the compressibility in samples with one back gate, while the experiments in[4] and in[5] report the d.c. conductivity in samples with no and with two gates respectively so that one is more sure of the chemical potential being at the charge neutrality point in the last one.

On the theory side, it was soon realized that the combination of parabolic bands and short range, screened interactions lead to logarithmically divergent susceptibilities (see[6] for a summary of early work). The variety of electronic degrees of freedom in bilayer graphene allows for many possible broken symmetry ground states, which, in turn, can be induced by appropriately tuned interactions[7, 8, 9, 10, 11, 12, 13, 14, 15]. There is a gapless, nematic phase consistent with the experiments in[4], and different gapped phases could explain the results in[2], while the interpretation of the experiments in[5] remains less clear. Some of the proposed phases break time reversal symmetry, leading to states with similar properties to a 2D electron gas in the Integer Quantum Hall regime[16]. Recent calculations suggest that many possible phases are almost degenerate, with energy differences per atom below 1 meV[17]. Further complications are introduced by strains, which are probably unavoidable in suspended samples. Disorder can induce, in some

circumstances, local gaps[18]. This situation is reminiscent of other materials with many competing interactions, such as the cuprate superconductors or the manganites, where the interpretation of the low temperature phases is still debated. At least, graphene has a simple, stochiometric composition. so that the reconciliation of the different experiments and a theory explaining the results may be expected soon.

References

[1] Note that this is a phenomenon where the electron kinetic is completely quenched, and the only energy scale is $e^2/(\epsilon \ell_B)$, where e is the electric charge, ϵ is the dielectric constant, and ℓ_B is the magnetic length.

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