Strong suppression of weak (anti)localization in graphene
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http://www.arxiv.org/abs/cond-mat/0603826
Phys. Rev. Lett. **97**, 016801 (2006)

Bipolar supercurrent in graphene
Authors: H. B. Heersche, P. Jarillo-Herrero, J. B. Oostinga, L. M. K. Vandersypen, A. F. Morpurgo
http://www.arxiv.org/abs/cond-mat/0612121
Nature **446**, 56 (2007)

Recommended with a Commentary by Francisco Guinea, Instituto de Ciencia de Materiales de Madrid.

Graphene, i. e., a graphite monolayer, is attracting researchers in droves. Graphene is interesting both for its fundamental properties and potential applications. The current activity started when it was shown that samples made up of a single or a few graphene layers could be isolated, observed, and measured with ease and reproducibility, see **Electric Field Effect in Atomically Thin Carbon Films** by K.S. Novoselov, A.K. Geim, S.V. Morozov, D. Jiang, Y. Zhang, S.V. Dubonos, I.V. Grigorieva, and A.A. Firsov, cond-mat/0410550, and Science **306**, 666 (2004).

Graphene is a two dimensional system in its most extreme form. The samples being currently studied have lateral dimensions of a few microns, while their thickness is a few angstroms. The electrons move through an underlying honeycomb lattice, with a basis of two sites per unit cell. This structure leads to a band structure unusual in condensed matter: the bands show a linear dependence on momentum near the Fermi level, and the effective mass is zero. The material is a semimetal, with a vanishing density of states at the Fermi level, as in an insulator, but no gap between the conduction and valence bands either. The number of carriers can be tuned by means of an external gate, and hole-like and electron-like behavior can be induced, with typical carrier densities of $\pm 10^{22} - 10^{23}\mathrm{cm}^{-2}$. Graphene combines features of metals and insulators, leading to a rich variety of novel phenomena.

A large fraction of the articles posted in the cond-mat archives are theoretical, although the number of experimental papers is slowly picking up.

There are at least two obvious reasons for it: i) There is a clear consensus on what the theoretical model for the electronic properties of graphene is, and many novel features can be extracted from it by means of back of an envelope calculations, and ii) Experimentalists have a tendency towards submitting their results to journals which do not encourage prior posting of the manuscripts. The papers mentioned here report solid experimental facts about the electronic coherence in single layer graphene, and have sparked a great deal of theoretical activity, which will not be addressed here.

S. V. Morozov *et al* performed, the standard experiment used to probe the quantum coherence of electrons in a two-dimensional metal: they studied the magentoresistance at low magnetic fields and temperatures. It is well known that a magnetic field modifies the phase of the electronic wavefunctions, changing their interference patterns. In particular, it suppresses the enhancement of backscattering in the presence of disorder experienced by wavepackets with respect to that for classical point particles. Because of that, the resistance drops by a small fraction when a magnetic field is applied (weak localization effect).

The situation in graphene is more subtle, as there are two electron valleys, and, within each valley, electrons have a quantum number associated with the existence of two atoms in the unit cell. This quantum number is coupled to the momentum of the particle, and it modifies the interference of waves around closed loops, responsible for the weak localization effects. Using quasiclassical arguments, it can be said that electrons acquire an additional Berry's phase. Alternatively, it can be argued that the orbital degree of freedom makes graphene similar to materials with a strong spin-orbit coupling, where the spin orientation is determined by the direction of motion of the electron The change in the interference properties makes possible a positive magnetoresistance (weak antilocalization) if the intervalley scattering can be neglected.

The results by S. V. Morozov *et al* show an even more intriguing behavior: they found an almost negligible magnetoresistance in single layer samples, while systems with more than one layer had more conventional properties, consistent with ordinary weak localization. Finally, the article also shows that the electronic decoherence processes, extracted from the samples where some magnetoresistance was observed, has the features expected in a two dimensional metal.

H. B. Heersche *et al* have studied the proximity effect, that is, the propagation of Cooper pairs in a normal metal induced by its coupling to superconducting electrodes. Cooper pairs can propagate in normal metals in the absence of defects which break time reversal symmetry, such as magnetic impurities, provided that the electron wavefunctions remain coherent. In that case, an effective coupling between superconducting electrodes is induced, leading to the Josephson effect and supercurrents, and Andreev steps associated to multiple scattering at finite voltages. The hallmark of the Josephson effect is that it depends on the coupling between the electrodes in the same manner as ordinary transport in the normal state, and the maximum superconducting current is related to the gap and the normal state resistance.

The formation of Cooper pairs in graphene is slightly more complicated than in ordinary metals. The band structure has two inequivalent valleys, related by time reversal symmetry, $\vec{\mathbf{p}} \leftrightarrow -\vec{\mathbf{p}}$. Hence, a Cooper pair is made up from electrons from the two different valleys. The valley degree of freedom would also allow for states with unusual pairing symmetries, if graphene had an intrinsic tendency towards superconductivity.

The experiments reported by H. B. Heersche *et al* show all the features expected for a superconductor-normal metal-superconductor junction: A supercurrent which can be transmitted by either electron or holes in the graphene layer, Andreev features at finite voltages, Shapiro steps in the presence of radiation, a proportionality between the critical current and the normal state resistance of the junction, and interference patterns when a magnetic field is applied. The critical current between the electrodes follows reasonably well the expected dependence on the normal state resistance. The authors are able to probe graphene at the neutrality point, where the chemical potential is such that carriers change from electrons to holes. In this situation, a finite critical current is observed. A signal of the quick pace of developments in the field is that the authors use the anomalous features of single layer graphene in the Integer Quantum Hall regime in order to characterize the samples.

It is finally worth remarking that these experiments are complementary, in the sense that weak localization properties are sensitive to the coherence of electrons within each valley, while the proximity effect measures the coherence (entanglement) of the two electrons in different valleys.