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Electric Field Effect in Atomically Thin Carbon Films

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Two-dimensional gas of massless Dirac fermions in graphene

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and

Experimental Observation of Quantum Hall Effect and Berry's Phase in Graphene

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Recommended with a Commentary by Rafael De Picciotto, Bell Laboratories.

Graphene, the planar arrangement of Carbon atoms on a honeycomb lattice, is a unique realization of a two dimensional electronic system. The conduction and valence bands of Graphene meet at six points in the Brillouin zone, where Dirac like dispersion relations occur. Recent experimental strides allow fabrication and transport measurements of thin Graphite sheets that are a few and even one monolayer thick – with the results pointing directly to this distinctive Dirac spectrum.

The 2004 work by Novoselov *et al.*, has demonstrated that repeated peeling of a highly oriented graphite crystal can be used to leave ultra thin carbon sheets on the surface of a Silicon substrate. They then proceeded to fabricate field effect devices, where a planar gate is used to vary the charge density and Ohmic reservoirs are attached to facilitate transport measurements.

Amazingly, the mobility of charge carriers in these devices was found to exceed 10,000 cm^2/Vs despite the crudeness of the methods used. With other techniques used to fabricate high mobility two-dimensional electron gases (e.g. in AlGaAs heterostructures) – great care is taken to provide for a pristine environment in the immediate vicinity of the active layer - to promote high carrier mobility. Thus, typical 2D gases are inconveniently buried a few hundred nanometers bellow a solid surface – limiting the smallness of the devices that can be made. These new Graphene sheets, on the other hand, are not buried at all. They can therefore be manipulated on a very small scale and have the potential of supporting ultra small devices, perhaps containing only a few Carbon atoms, embedded in a highly conductive 2D sheet.

The recent works by Zhang *et al.* and Novoselov *et al.*, utilizes these techniques to investigate the magneto-transport properties of a high-mobility single layer of Graphene. With a truly 2D layer, and such a high mobility, the Quantum Hall effect is readily observed. However, the Dirac points of Graphene lead to a twist in the quantization of the Hall conductance. Instead of the usual quantization rule (for a spin degenerate system), $R_{xy}^{-1} = n \times 2e^2/h$ with n the number of occupied Landau levels, in Graphene the finding is: $R_{xy}^{-1} = 2(n + \frac{1}{2}) \times 2e^2/h$. This shift of the integer n by 1/2 is also manifested in the observation of a half period phase shift in the magneto-oscillations of the longitudinal resistance at lower magnetic field and can be traced back to the existence of a Berry's phase - arising from bands degeneracy at the Dirac points. The resulting "relativistic" spectrum in a strong magnetic field includes an unusual lowest Landau level of mixed electron-hole character whose energy is magnetic field independent. The contribution of this level to the overall Hall conductance is half the usual one.

Still, a two-fold degeneracy resulting from the two equivalent triangular sub-lattices of Graphene ensures that the measured Hall conductance is an integral multiple of the quantum value – as required from the quantization of charge in a non-interacting electron system. It remains to be seen whether charge fractionalization, expected in the fractional Quantum Hall regime, will be any different in Graphene as compared to the findings in AlGaAs heterostructures.