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Two-Dimensional Dirac Fermions in Graphene at High Magnetic Fields

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Graphene, a single atomic sheet of graphite, is a monolayer of carbon atoms densely packed into a honeycomb structure. It can be viewed as either an unrolled single-wall carbon nanotube or a giant flat fullerene molecule. Advances in micromechanical extraction and fabrication techniques for graphite structures now permit such exotic 2D electron systems to be probed experimentally. It has been discovered that the electrons in graphene are two-dimensional Dirac Fermions, based on the observation of half-integer quantum Hall effect and Berry's phase of π in the magneto-oscillations. We further investigate the transport properties of graphene in extremely strong magnetic fields. Under such condition, we observe new sets of quantum Hall states at filling factors $\nu = 0, \pm 1, \pm 4$, indicating the lifting of the four-fold degeneracy of the previously observed quantum Hall states at $\nu = \pm 4(n + 1/2)$, where $n$is the Landau level index. In particular, the presence of the $\nu = 0, \pm 1$ quantum Hall states indicates that the Landau level at the charge neutral Dirac point splits into four sub-levels, lifting both sublattice and spin degeneracy in graphene. The quantum Hall effect at $\nu = \pm 1, \pm 4$ is studied in tilted magnetic fields at various temperatures. It has been found that $\nu = \pm 4$ are due to the lifting of the spin-degeneracy of the Landau level $n = \pm 1$ while $\nu = \pm 1$ are most likely due to the sublattice degeneracy lifting of $n = 0$. Finally, the availability of large, high quality graphene crystals opens new possibilities for optical and scanning probe studies. A brief discussion of our recent experiments on Raman spectroscopy and STM will be presented.