Landau Level Spectroscopy of Monolayer and Bilayer Graphene

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We present the first experimental study of cyclotron resonance of electrons and holes in isolated monolayer and bilayer graphene, via infrared transmission measurements in magnetic fields up to B=18 T. For monolayer graphene [1], we directly observe the extraordinary dependence of the Landau lever (LL) transition energy on $\sqrt{B}$ and $\sqrt{n}$, where n is the LL index. This unique relation allows us to distinguish several distinct LL transitions, in striking contrast to the usual two-dimensional case where only one transition- corresponding to the classical cyclotron resonance- is seen. Our detailed observations map out this unusual spectrum near the charge-neutral Dirac point, and strongly suggest that the powerful Kohns theorem does not apply in graphene so that many-particle effects may be seen even in low-mobility samples. For bilayer graphene [2], we study the intraband LL transitions in both the conduction and valence bands, and find that the LL transition energies are roughly linear in B between the lowest LLs, whereas they follow $\sqrt{B}$ for the higher transitions. This highly unusual behavior reflects a change from a parabolic to a linear energy dispersion. The density of states derived from our data generally agrees with the existing lowest order tight binding calculation for bilayer graphene. However, in comparing data to theory, a single set of fitting parameters fails to describe the experimental results. This work has been funded by NSF, DOE, and Microsoft Project Q.

[1] Z. Jiang, E.A. Henriksen, L.-C. Tung, Y.-J. Wang, M.E. Schwartz, M.Y. Han, P. Kim, and H.L. Stormer, Phys. Rev. Lett. **98**, 197403 (2007).

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