**Infrared Measurements of Landau Level Transitions in Single and Bilayer Graphene**

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**Introduction**

Graphene, a single atom thick sheet of carbon atoms in a hexagonal lattice, forms the underlying structure of graphite, carbon nanotubes, and buckminsterfullerene. In this role, it has been a theoretical model for 60 years. However the recent isolation of this ultimate two-dimensional material has sparked a much broader range of both theoretical and experimental investigations. This is due in part to the exotic energy dispersions of single and bilayer graphenes, which are linear and hyperbolic, respectively, mimicking massless or massive chiral Dirac particles.

**Experiment and Results**

In the presence of a magnetic field, the energy dispersions of semiconductors become quantized into discrete Landau levels (LL). The phenomenon of cyclotron resonance then results when incident infrared radiation is absorbed by the excitation of carriers between neighboring LLs, with the absorbed frequencies corresponding to the LL energy separation. Since the 1950s, CR has been a fundamental tool for the investigation of semiconductor bandstructures, which generally exhibit resonance energies that are linear in the magnetic field. Recently, we have made the first measurements of LL transitions via infrared transmission measurements in both single (Fig. 1a) and bilayer (Fig. 1b) graphene samples, in magnetic fields up to B = 18 T. We find that both systems present radical departures from the usual CR, exhibiting LL transition energies that are linear in \( \sqrt{B} \) for single layer graphene, and that for bilayers show a shift from a linear-in-B dependence at low energies to linear-in-\( \sqrt{B} \) at higher energies. In further departures from traditional CR, resonance energies in both systems show a dependence on the LL index, while in single layers we have also observed interband in addition to intraband transitions. Departures from the expected ratios of the transition energies are interpreted as indicating physics of interacting Dirac quasiparticles, beyond a simple single particle picture.

![Fig. 1.](image) (a) LL transitions in single layer graphene. Inset shows normalized transmission for three B fields. Dashed lines are best fit to \( \sqrt{B} \). (b) LL transitions among the first nine LLs in bilayer graphene. Dashed lines are fit to theory based on nearest-neighbor tight-binding approximation.

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**References**
