Magnetophonon resonances in graphene

M.T. Greenaway[1,2], P. Kumaravadivel [3,4], J. Wengraf [3,5], L.A. Ponomarenko[3,5], A.I. Berdyugin[3], J. Li[6], J.H. Edgar[6], R. Krishna Kumar[3], A.K. Geim[3,4], and L. Eaves[2]

[1]Department of Physics, Loughborough University,
[2]School of Physics and Astronomy, University of Nottingham,
[3]School of Physics and Astronomy, University of Manchester,
[4]National Graphene Institute, University of Manchester,
[5]Department of Physics, University of Lancaster,
[6]Tim Taylor Department of Chemical Engineering, Kansas State University.

Resonant magnetoresistance measurements on monolayer graphene FETs under "ohmic" low current conditions have been used to study a wealth of novel physics. Recently, we observed magnetophonon resonance (MPR) in graphene, where peaks, periodic in inverse magnetic field, emerge in the magnetoresistance due to inelastic acoustic phonon scattering of electrons between Landau levels [1]. MPR provides a measurement of the transverse (TA) and longitudinal (LA) acoustic phonon velocities and gives insight into the nature of electron-phonon coupling.

At high currents (up to 100 Am^{-1}), electrons are driven far from equilibrium so that their kinetic energy can exceed the thermal energy of the phonons. We observe three non-equilibrium phenomena in monolayer graphene at high currents [2]: (i) a "Doppler-like" shift and splitting of the frequencies of the TA phonons, revealed by shifts of the MPR resonant peaks in the differential resistance, r_y (see Fig. 1a); (ii) an intra-LL Mach effect with the emission of TA phonons when the electrons approach supersonic speed ($\sim$1.4 x 10^4 ms^{-1}), revealed by a broad magnetic field-independent peak in r_y at $I \sim 1$ mA ($\sim$ 70 Am^{-1}) and (iii) the onset of elastic inter-LL transitions and an associated resonance maximum in r_y at a critical carrier drift velocity (see Fig 1b). The third phenomenon is analogous to a "superfluid" Landau velocity and the formation of magneto-excitons involving a quantum jump, h/m, in the electron LL circulation. All three phenomena can be unified in a generic resonance equation. They offer avenues for research on out-of-equilibrium phenomena in other two-dimensional systems.

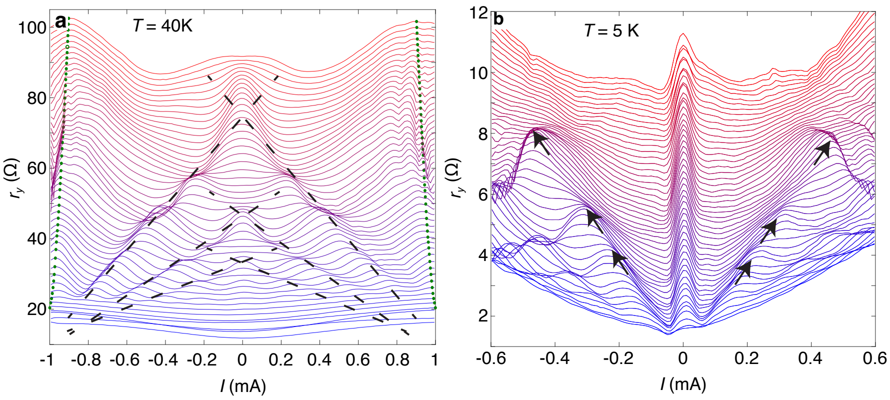

Fig. 1. (a) Plot of the dependence of differential resistance $r_y(I)$ on current for magnetic fields, *B,* between 0 and 2 T in 0.04 T intervals, measured at a carrier density $n = 3.16 \times 10^{12}$ cm^{-2}. Curves are offset by 1.5 Ω and the dashed lines highlight the shift of the positions of the magnetophonon resonance peaks. The green markers close to $I = \pm 1$ mA show the position of the *B*-independent peak in $r_y(I)$ when the electrons approach supersonic speed. (b) Plot of $r_y(I)$ for values of *B* between 0 to 1.2 T. Black arrows highlight the shifts of the resonant peaks in r_y due to elastic inter-LL transitions that arise when the electron velocity approaches the Landau velocity.

[1] P. Kumaravadivel *et al.*, *Nature Communications* **10,** 3334 (2019)
[2] M.T. Greenaway *et al.*, *Nature Communications* **12**, 6392 (2021)