

Forbidden Landau-Level Transitions and Mode Hybridization via Phonon-Polariton Nanocavities

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The field of cavity QED with correlated materials is rapidly expanding. A key challenge is realizing cavity modes with sufficiently large wavevectors to access many-body excitations beyond the dipole limit. Thin flakes of hexagonal boron nitride (hBN) provide an ideal platform, as they support deeply subwavelength mid-infrared confinement through hyperbolic phonon-polaritons with extreme field compression. Here, we use hBN-encapsulated graphene to investigate the impact of nonlocal strong light-matter coupling on quantum Hall systems. By engineering nanoscale hBN cavities, we tailor the polaritonic dispersion to hybridize with graphene inter-Landau-level electronic transitions, forming Landau-phonon-polaritons [3].

Combining scattering-type scanning near-field optical microscopy (s-SNOM) with phototransport spectroscopy, we observe the breakdown of dipole selection rules induced by large-wavevector cavity modes, along with signatures of nonlocal strong coupling in both allowed and nominally forbidden inter-Landau-level transitions (Fig. 1). The interaction strengths approach the ultrastrong-coupling regime [4], where the many-body electronic ground state is modified by the electromagnetic environment even in the absence of real photons. This platform enables direct probing and control of electronic correlations through cavity engineering, opening new pathways toward light-tunable correlated phases.

Figures

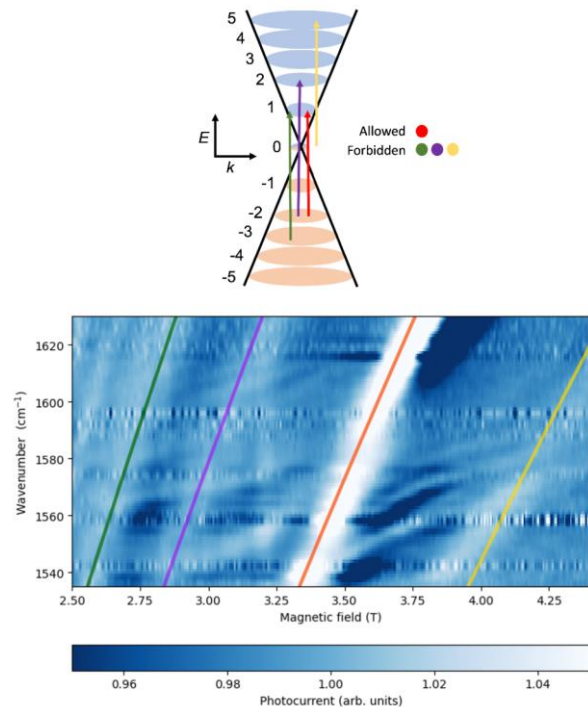


Figure 1: (Top panel) Schematic of graphene Landau levels in a quantizing magnetic field. Colored arrow indicates inter-Landau level transitions: the dipole-allowed transition (in red: -2 to 1), and several forbidden transitions (in yellow: 0 to 5, in purple: -2 to 2; in green: -3 to 1). (Bottom panel) Photocurrent spectroscopy map as a function of magnetic field and excitation wavenumber. Solid colored lines trace the calculated inter-Landau level transition dispersions, using the same colors coding as the top panel.

References

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- [2] E. Yoxall *et al.*, Nature Photon 9, 674–678 (2015).
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- [4] G. Andolina *et al.*, arXiv:2501.04133 (2025).