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Imaging tunable quantum Hall broken-symmetry orders in graphene

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When electrons populate a flat band their kinetic energy becomes negligible, forcing them to organize in exotic many-body states to minimize their Coulomb energy. The zeroth Landau level of graphene under magnetic field is a particularly interesting strongly interacting flat band because inter-electron interactions are predicted to induce a rich variety of broken-symmetry states with distinct topological and lattice-scale orders. Evidence for these stems mostly from indirect transport experiments that suggest that broken-symmetry states are tunable by boosting the Zeeman energy or by dielectric screening of the Coulomb interaction. However, confirming the existence of these ground states requires a direct visualization of their lattice-scale orders. Here, we image three distinct broken-symmetry phases in graphene using scanning tunneling spectroscopy. We explore the phase diagram by tuning the screening of the Coulomb interaction by a low or high dielectric constant environment, and with a magnetic field. In the unscreened case, we unveil a Kekule bond order, consistent with observations of an insulating state undergoing a magnetic-field driven Kosterlitz-Thouless transition. Under dielectric screening, a sublattice-unpolarized ground state emerges at low magnetic fields, and transits to a charge-density-wave order with partial sublattice polarization at higher magnetic fields. The Kekule and charge-density-wave orders furthermore coexist with additional, secondary lattice-scale orders that enrich the phase diagram beyond current theory predictions. This screening-induced tunability of broken-symmetry orders may prove valuable to uncover correlated phases of matter in other quantum materials.

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