99

Quantum Simulation of Correlated Exciton Phases via Ultrafast Optical Microscopy

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Abstract

Moiré superlattices formed from transition metal dichalcogenide (TMDC) heterostructures have emerged as a compelling platform for exploring quantum many-body physics. These systems are viewed as a solid-state counterpart to ultracold atomic gases in optical lattices for quantum simulation. A central open question concerns the coherence and dynamics of quantum phases arising from photoexcited moiré excitons, especially under dissipative conditions.

To address this, we employed transient photoluminescence and ultrafast reflectance microscopy to directly image non-equilibrium exciton phase transitions in twisted WS_2/WSe_2 heterobilayers. Surprisingly, both experimental data and theoretical modeling reveal that strong long-range dipolar repulsion between moiré excitons leads to a *freezing* of exciton motion in the Mott insulator phase, persisting for over 80 ns. This result defies the conventional expectation that repulsive interactions delocalize particles, while attractive ones promote binding. The observed phenomenon of frozen dynamics due to strong repulsive interactions is characteristic of highly coherent systems, a feature previously realized exclusively in ultracold gases.

We further investigated the interplay between exciton and charge orders in Bose-Fermi mixture, as well as the quantum melting of generalized Wigner crystals, revealing rich and tunable excitonic correlations in moiré systems.