Nematic Phase Transitions and Density Modulations in 1D Flat Band Condensates

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We investigate the ground-state properties of one-dimensional Gross-Pitaevskii flat-band lattices. We uncover a geometry-driven phase transition into a macroscopically degenerate nematic state with broken time reversal symmetry. Focusing on all-bands-flat (ABF) models, we demonstrate that even infinitesimal onsite interactions can destabilize a uniform, constant-phase condensate, driving the system into a nematic manifold as the flat-band geometry controlled parameter $\theta > 8/\pi$. At a critical endpoint ($\theta = \pi/4$), where the compact localized states exhibit constant amplitudes, we identify an additional pair of density-modulated ground states characterized by vanishing phase stiffness. Utilizing Bogoliubov-de Gennes excitations and simulated annealing, we show that these density-modulated phases are thermally selected at low temperatures via an order-by-disorder mechanism. Finally, we demonstrate that these non-trivial condensate phases extend beyond ABF models, as exemplified by the sawtooth lattice. Our findings also reveal that the sound velocity in flat-band condensates is a sensitive probe of the underlying geometric phase structure.