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Quantum Many-body Physics with Multimode Cavity QED

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Phase transitions, where observable properties of a many-body system change discontinuously, can occur in both open and closed systems. Ultracold atoms have provided an exemplary model system to demonstrate the physics of closed-system phase transitions, confirming many theoretical models and results. Our understanding of dissipative phase transitions in quantum systems is less developed, and experiments that probe this physics even less so. By placing cold atoms in optical cavities, and inducing strong coupling between light and excitations of the atoms, one can experimentally study phase transitions of open quantum systems. We will report our observation of a novel form of nonequilibrium phase transition, the condensation of supermode-density-wave-polaritons. These polaritons are formed from a hybrid "supermode" of cavity photons coupled to atomic density waves of a quantum gas. These results, found in the few-mode-degenerate cavity regime, demonstrate the potential of fully multimode cavities to exhibit physics beyond mean-field theories, possibly in the presence of dynamic synthetic gauge fields. Such systems will provide experimental access to nontrivial phase transitions in driven dissipative quantum systems as well as enabling the studies of novel non-equilibrium spin glasses and neuromorphic computation.