

Simultaneous symmetry breaking in spontaneous Floquet states: Floquet-Nambu-Goldstone modes, Floquet thermodynamics, and the time operator

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We study simultaneous symmetry-breaking in a spontaneous Floquet state, focusing on the specific case of an atomic condensate. We first describe the quantization of the Nambu-Goldstone (NG) modes for a stationary state simultaneously breaking several symmetries of the Hamiltonian by invoking the generalized Gibbs ensemble, which enables a thermodynamical description of the problem. The quantization procedure involves a Berry-Gibbs connection, which depends on the macroscopic conserved charges associated to each broken symmetry and whose curvature is not invariant under generalized gauge transformations. We extend the formalism to Floquet states simultaneously breaking several symmetries, where Goldstone theorem translates into the emergence of Floquet-Nambu-Goldstone (FNG) modes with zero quasi-energy. In the case of a spontaneous Floquet state, there is a genuine temporal FNG mode arising from the continuous time-translation symmetry breaking, whose quantum amplitude provides a rare realization of a time operator in Quantum Mechanics. Furthermore, since they conserve energy, spontaneous Floquet states can be shown to possess a conserved Floquet charge. Both the temporal FNG mode and the Floquet charge are distinctive features of a spontaneous Floquet state, absent in conventional, driven systems. Nevertheless, these also admit a thermodynamic description in terms of the Floquet enthalpy, the Legendre transform of the energy with respect to the Floquet charge. We apply our formalism to a particular realization of spontaneous Floquet state, the CES state, which breaks $U(1)$ and time-translation symmetries, representing a time supersolid. Using the Truncated Wigner method, we numerically compute its quantum fluctuations, which are theoretically predicted to be dominated by the temporal FNG mode at long times, observing a remarkable agreement between simulation and theory. Based on these results, we propose a feasible experimental scheme to observe the temporal FNG mode of the CES state.

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