

Nonreciprocal synchronization of active quantum spins

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Active agents are capable of exerting nonreciprocal forces upon one another. For instance, one agent, say A , may attract another agent B while B repels A . These antagonistic nonreciprocal interactions have been extensively studied in classical systems, revealing a wealth of exciting phenomena such as novel phase transitions and traveling-wave states. Whether these phenomena can originate in quantum many-body systems is an open issue, and proposals for their realization are lacking. In [1], we present a model of two species of quantum spins that interact in an antagonistic nonreciprocal way of the attraction-repulsion type. We propose an implementation based on two atomic ensembles coupled via chiral waveguides featuring both braided and non-braided geometries. The spins are active due to the presence of local gain, which allows them to synchronize. In the thermodynamic limit, we show that nonreciprocal interactions result in a nonreciprocal phase transition to time-crystalline traveling-wave states, associated with spontaneous breaking of parity-time symmetry. Remarkably, continuous monitoring of the output field of the waveguides induces a quantum traveling-wave state: a time-crystalline state of a finite-size quantum system, in which parity-time symmetry is spontaneously broken. Our work lays the foundation to explore nonreciprocal interactions in active quantum matter.

In [2], we apply some of these ideas to superradiant lasers, which consist of incoherently driven atoms coupled to a lossy cavity, are a promising source of coherent light due to their stable frequency and superior narrow linewidth. We show that when a fraction of the atoms is not driven, a shift in the lasing frequency and a broadening of the linewidth occur, limiting the performance of a superradiant laser. We explain this behavior by identifying nonreciprocal interactions between driven and undriven atoms, i.e., competing alignment and antialignment of their dipoles. Our results have implications for the realization of superradiant lasers, establishing the relevance of nonreciprocal phenomena for quantum technologies.

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[1] T. Nadolny, C. Bruder, and M. Brunelli, *Phys. Rev. X* **15**, 011010 (2025).

[2] T. Nadolny, M. Brunelli, and C. Bruder, *Phys. Rev. Lett.* **134**, 193603 (2025).