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Nonequilibrium protection effect and spatial localization of noise-induced fluctuations: gas flow scattering on partially penetrable obstacle

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The scattering of gas flow on an obstacle can lead to the formation of nonequilibrium steady states (NESS), such as stationary obstacle wakes. These systems may undergo nonequilibrium phase transitions, resulting in the emergence of nonlinear steady-state gas structures under critical conditions. One notable example is the formation of a stratum-like, or two-domain, gas structure ahead of the obstacle due to the blockade effect in the gas [1-5]. This structure can be interpreted as the growth of a dense gas phase nucleus near the obstacle, which acts as a nucleation center.

In our study, we focus on a quasi-one-dimensional driven lattice gas doped with static impurities within a narrow channel with ring topology [1]. The obstacle is modeled as a transverse channel cell partially occupied by impurity particles, and the system is driven by a nonconservative field. We utilize a combination of the local equilibrium approach and mean-field approximation to describe the NESSs and gas fluctuations near them.

Our findings reveal that this nonequilibrium transition is associated with the emergence of a local invariant. Specifically, the state of the obstacle behaves as a local first integral (or adiabatic invariant), becoming insensitive to fluctuations in the gas and the external driving noise.

Below the transition, the gas flow is scattered by the impurity, the structural defect of the lattice. Above the transition, the gas flow is scattered by the gas domain wall, the defect of the gas density distribution. This leads to the protection effect of the obstacle state against gas fluctuations, manifesting as a strong localization of fluctuations near the topological defect (domain wall) and their complete suppression at the obstacle. Additionally, gas fluctuations demonstrate strong anti-correlated behavior at the left and right sides of the impurity. These effects are similar to the skin effect and edge-edge correlation effect in non-Hermitian systems [6].

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