Macroscopic Fluctuations: an approach to nonequilibrium physics

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Understanding the statistics of macroscopic fluctuations in nonequilibrium systems remains as one of the major challenges of theoretical physics. This interest is rooted in the prominent role that fluctuations play in equilibrium, where their statistics is directly linked to the relevant thermodynamic potentials via the Einstein formula. Similarly, it is nowadays expected that a deeper understanding of nonequilibrium fluctuations will pave the way to a sound definition of nonequilibrium potentials, though we already know that these functions do typically have some striking features peculiar to nonequilibrium behavior (as e.g. non-local behavior leading to long-range correlations). Among all possible observables that can be defined, the currents of locally-conserved quantities play a key role as tokens of nonequilibrium physics, appearing in response to any driving mechanism (as e.g. a boundary gradient or external field) pushing the system out of equilibrium. In this way, the distribution of current fluctuations is a central object of investigation, with the associated current large deviation function (LDF) acting as a marginal of the nonequilibrium analog of thermodynamic potential.

In recent years, a macroscopic fluctuation theory (MFT) has been formulated to study dynamic fluctuations in systems far from equilibrium, starting from a mesoscopic description of the system of interest in terms of fluctuating hydrodynamics. In this way, MFT offers detailed predictions for the large deviation functions in terms of a complex spatio-temporal variational problem for the locally-conserved fields and the associated currents. As an interesting by-product, MFT also determines the optimal path to a fluctuation from the solution of the Euler-Lagrange equations for this variational problem. The optimal path encodes key information on this problem, shedding light on e.g. the reasons behind the enhanced probability of rare events out of equilibrium, the possibility of dynamic phase transitions and new symmetries.

In this work, we derive a fundamental relation which strongly constraints the architecture of these optimal paths for general d-dimensional nonequilibrium diffusive systems, implying a non-trivial structure for the dominant current vector fields. Interestingly, this general relation makes manifest the spatio-temporal non-locality of the current statistics and the associated optimal trajectories [1]. Moreover, we validate its predictions against both numerical simulations of rare events and microscopic exact calculations of three paradigmatic models of diffusive transport in $d = 2$ [2]. Finally, we focus on dynamic phase transitions (DPTs) at the fluctuating level, with a special relevance in nonequilibrium physics, and we observe for the first time a DPT in the current statistics of an archetypal two-dimensional (2d) driven diffusive system, the weakly asymmetric simple exclusion process (WASEP), characterizing its properties using macroscopic flucuation theory. The complex interplay among the external field, anisotropy and currents in 2d leads to a rich phase diagram, with different symmetry-broken fluctuation phases separated by lines of 1st - and 2nd-order DPTs. Order in the form of coherent jammed states emerges to hinder transport for low-current fluctuations, revealing a deep connection between rare events and self-organized structures which enhance their probability, an observation of broad implications [3].

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