論文内容の要旨

論文題目

Universal behavior of macroscopic out-of-equilibrium systems
examined in the electrohydrodynamic turbulence of liquid crystals
（訳：液晶電気対流の乱流状態に見る巨視的非平衡系の普遍挙動）

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Finding and understanding universal rules and concepts in nature have been arguably the central mission of the physics. In this respect statistical physics reached a milestone in the mid 20th century, when scale invariance turned out to smooth out the dependence on most microscopic ingredients of the systems and lead to universal macroscopic behavior. Such a situation typically arises for phase transitions, and indeed, universality in critical phenomena at equilibrium has been well established with many convincing experiments and powerful theoretical tools like renormalization group. Theoretical and numerical studies have evidenced that, even for systems driven far from equilibrium, the scale invariance does lead to universality, which is rendered even richer and more nontrivial due to dynamics. However, unfortunately, such out-of-equilibrium universality has been surprisingly elusive in experiments, and therefore it has been unclear to what extent such universal macroscopic behavior is relevant in actual phenomena.

This series of works is devoted to overcome this frustrating situation. Focusing on turbulent regimes of electrically driven nematic liquid crystals, we experimentally investigate the so-called absorbing phase transitions and growth of rough interfaces, both known from the theoretical side for the existence of outstanding, truly out-of-equilibrium universality classes. Mainly due to fairly large effective system sizes and short microscopic time scales, the electroconvection of liquid crystals allows us to precisely determine statistical properties of macroscopic phenomena in hand and to make critical comparisons with the wealth of theoretical predictions.

Large part of the thesis concerns a phase transition into an absorbing state, i.e., a state from which the system can never escape once it entered. It is found between two topologically different turbulent states of the electroconvection, called dynamic scattering modes 1 and 2

(DSM1 and DSM2). The statistical properties of the observed spatiotemporal intermittency of DSM2 patches are carefully determined to characterize both static and dynamic critical behavior of this phase transition, measuring a total of 12 critical exponents, 5 scaling functions, and 8 scaling relations, all in full agreement with those for the directed percolation universality class. This provides the first clear experimental realization of this outstanding, truly out-of-equilibrium universality class, dominating most phase transitions into an absorbing state.

As is usually the case for critical behavior, universal scaling laws for absorbing phase transitions do reflect a few basic, global properties of the system such as symmetry. The effect of the Ising-like, Z_2 symmetry is investigated for the DSM1-DSM2 transition with the twist alignment of liquid crystals, which now has two distinct, left-handed and right-handed DSM1 domains, separated by interfaces of topological defects, DSM2. Macroscopic dynamics is then governed by coarsening of these domains, which is not driven by curvature and shows logarithmic decay of the interface length at criticality, characteristic of the generalized voter universality class in 2 dimensions which comprises phase transitions into two symmetric absorbing states.

Understanding scaling laws governing critical behavior also serves to explain past experimental observations. The DSM1-DSM2 transition is known to exhibit hysteresis loops, whose width depends algebraically on the ramp rate of the applied voltage. It is shown here that this is in fact an aspect of the directed percolation critical behavior, weakly broken by the existence of very rare spontaneous nucleations. Analytical arguments and numerical simulations show that systems undergoing a phase transition into such a quasi-absorbing state universally exhibit this peculiar hysteresis, and that the exponent characterizing the power law of the hysteresis is directly linked to the order parameter exponent of absorbing phase transitions. This phenomenon is conjectured to occur in a variety of experimental systems, providing a possibly useful tool to access critical behavior experimentally.

For voltages higher than that for the spatiotemporal intermittency regime, DSM2 patches grow with rough interfaces. Measuring this roughening process with controlled initial conditions, it is shown that both spatial and temporal scalings agree well with those from the Kardar-Parisi-Zhang theory, which constitutes the most fundamental class for such surface growth processes. Moreover, exhaustive experiments reveal that the interface fluctuations are governed by the largest eigenvalue of random matrices, whose ensemble is determined by the geometry of the growth process, confirming recent theoretical predictions.

It is hoped that those comprehensive experimental realizations of truly out-of-equilibrium universal behavior, mostly found for the first time in experiments, will trigger further studies and understanding on such scale-invariant phenomena, and hopefully, on more general universal structures in systems driven far from equilibrium.