Nonequilibrium wetting transition in a nonthermal 2D Ising model

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Abstract. Nonequilibrium wetting transitions are observed in Monte Carlo simulations of a kinetic spin system in the absence of a detailed balance condition with respect to an energy functional. A nonthermal model is proposed starting from a two-dimensional Ising spin lattice at zero temperature with two boundaries subject to opposing surface fields. Local spin excitations are only allowed by absorbing an energy quantum (photon) below a cutoff energy $E_c$. Local spin relaxation takes place by emitting a photon which leaves the lattice. Using Monte Carlo simulation nonequilibrium critical wetting transitions are observed as well as nonequilibrium first-order wetting phenomena, respectively in the absence or presence of absorbing states of the spin system. The transitions are identified from the behavior of the probability distribution of a suitably chosen order parameter that was proven useful for studying wetting in the (thermal) Ising model.

1 Introduction and motivation

Nonequilibrium wetting has been the subject of profound investigations in the past few decades\textsuperscript{1,2} \cite{1–8}. In many of the models studied, the growth, or depinning, of an interface is described relative to a (usually one-dimensional) substrate. Temporal and spatial correlations in the interface are examined and dynamical universality classes are identified. In many cases, the nonequilibrium character of the phenomenon can be related to the breaking of detailed balance of configurational moves. In this paper we are concerned with one of the simplest ways in which detailed balance can be broken, leading to an intrinsically nonequilibrium system. In particular, after a move in configuration space the system can get trapped in certain configurations when the probability for the reversed move is identically zero. In thermal equilibrium, at finite temperature $T$, the reversed move always has a nonzero probability, proportional to the Boltzmann factor, which features the (finite) energy difference of the initial and final configurations. However, if we leave thermal equilibrium, by imposing constraints on the local absorption or emission of energy, detailed balance may be broken. We can go one step further along this line and leave the thermal context altogether by considering a classical system, say, at zero temperature, and providing a nonthermal mechanism for local energy exchange.

To concretize our proposal, consider a (quasi-)two-dimensional lattice spin system at $T = 0$ which is exposed to a photon bombardment from some external source. The photon energies $h\nu$ are limited by a cutoff $h\nu_{\text{max}} = E_c$. We assume that a spin hit by a photon may absorb an energy $E \leq h\nu$, so that in all cases $E < E_c$. Conversely, a spin may (always) relax by emitting a photon of arbitrary energy and we assume that photon leaves the plane so that the probability for absorption of emitted photons is negligible. The origin of the energy cutoff in this model is quantum mechanical. Although it is not necessary to invoke quantum mechanics explicitly to provide nonthermal energy fluctuations (random-field or random-bond disorder, electromagnetic fields, mechanical or chemical oscillators being alternative sources), it is a convenient framework for obtaining a sharp energy cutoff. In this manner we arrive at a model in which excitations of energy superior to $E_c$ are excluded, which implies that certain configurations can be trapping or “absorbing”.

In the following we develop this model further and investigate how the character of a wetting transition is modified when thermal fluctuations are replaced by constrained nonthermal ones. We do so using Monte Carlo simulation and start within the context of the exactly solved wetting transition of a system in thermal equilibrium. Our paper is structured as follows. In Section 2 we test our simulation approach on the critical wetting transition in the two-dimensional Ising model \cite{9}. Section 3 is devoted

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\textsuperscript{1} For a recent review of nonequilibrium wetting, see \cite{1}.

\textsuperscript{2} For a tutorial review of nonequilibrium phase transitions see \cite{2}.
to the definition of the nonthermal model, the analysis of the bulk phases and the observation and characterization of nonequilibrium wetting transitions of various nature. Conclusions are drawn in Section 4.

2 Wetting transition in the 2D thermal Ising model

Consider the two-dimensional square lattice Ising model with ferromagnetic nearest-neighbor interaction \( J > 0 \), at a temperature \( T \) below the bulk critical temperature \( T_c \) and in zero bulk magnetic field. In this situation the bulk consists of large coexisting regions of positive and negative magnetization. In the thermodynamic limit, the behavior of the bulk is independent of the boundary conditions, but this is not the case for the interface between the coexisting phases. In the case of a wetting transition, the surface excess free energy depends in a singular way on a surface parameter is approximated by a normalized histogram.

In Figure 2 the resulting histograms are shown for \( T/T_c = 0.5 \). For \( H_1 \) significantly smaller than 0.89\( J \) the distributions are centered around a value close to unity, while for substantially larger surface fields, it is very unlikely to measure a \( \Delta \) close to 1. Around \( H_1 = 0.89J \) one observes a transition region where the distributions are broad, indicating the presence of large fluctuations consistently with a second-order interfacial phase transition. If we identify the wetting transition in the Ising model heuristically with the point where the distribution of \( \Delta \) has a maximal variance, the result is in quite satisfactory agreement with the exact location. Note that in the limit \( T \downarrow 0 \) the wetting transition, at \( H_1 = J \), is, exceptionally, of first order and purely determined by minimum energy considerations. In Figure 3 our estimates for the transition point for several temperatures are compared with the exact result of Abraham for the critical wetting phase boundary [9],

\[
e^{2J/kT} = (\cosh(2J/kT) - \cosh(2H_1/kT)) \sinh(2J/kT),
\]

For temperatures not too close to \( T_c \) we are able to determine the wetting transition fairly accurately. Closer to the critical temperature the interface is more fuzzy and it becomes increasingly difficult to differentiate between partial and complete wetting in a small system as we used. The method appears to be useful in principle for locating the wetting transition qualitatively. This is corroborated by the fact that the shape of the histogram provides an indication of the order of the transition. If, like in the thermal Ising case, one only observes distributions with one maximum and notices an increase of the variance in between the two sets of sharper shapes corresponding to the partial wetting (P) or complete wetting (C) states, one is in all likelihood dealing with a second-order phase transition. Close to a first-order transition, on the other hand, one rather expects distributions with two maxima that exchange dominance on crossing the transition point [17]. Further, the valley between the maxima is an expression of the hysteresis effect, the strength of which is proportional.