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Study of the critical behavior of the driven lattice gas model with limited nonequilibrium dynamics

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HIGHLIGHTS

- A nonequilibrium model is defined, where the dynamics is regulated by a parameter p.
- Short-time dynamics allows to determine the critical phase transitions as a function of p.
- The critical temperature follows a power law behavior, from a Ising-like to DLG behavior is observed.
- The obtained exponent is consistent with a that estimated analytically of the scalar-field model.
- The critical exponents were calculated and their values range from those of the Ising model's up to the DLG model.

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ABSTRACT

In this paper the nonequilibrium critical behavior is investigated using a variant of the well-known two-dimensional driven lattice gas (DLG) model, called modified driven lattice gas (MDLG). In this model, the application of the external field is regulated by a parameter $p\epsilon[0, 1]$ in such a way that if $p = 0$, the field is not applied, and it becomes the Ising model, while if $p = 1$, the DLG model is recovered.

The behavior of the model is investigated for several values of p by studying the dynamic evolution of the system within the short-time regime in the neighborhood of a phase transition. It is found that the system experiences second-order phase transitions in all the interval of p for the density of particles $\rho = 0.5$. The determined critical temperatures $T_c(p)$ are greater than the critical temperature of the Ising model T_c^I, and increase with p up to the critical temperature of the DLG model in the limit of infinite driving fields. The dependence of $T_c(p)$ on p is compatible with a power-law behavior whose exponent is $\psi = 0.27(3)$.

Furthermore, the complete set of the critical and the anisotropic exponents is estimated. For the smallest value of p, the dynamics and β exponents are close to that calculated for the Ising model, and the anisotropic exponent Δ is near zero. As p is increased, the exponents and Δ change, meaning that the anisotropy effects increase. For the largest value investigated, the set of exponents approaches to that reported by the most recent theoretical framework developed for the DLG model.

1. Introduction

In the last decades, the study of nonequilibrium phenomena has attracted the attention of many branches of science. However, from the point of view of physics, there is not a theoretical framework yet to investigate them systematically.

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In spite of that, several approaches have been proposed, such as the search of exact solutions, mean-field theories, renormalization group techniques, molecular dynamics, and Monte Carlo simulations, among others [1,2]. One of the simplest models that captures many essential features of nonequilibrium behavior is the driven lattice gas (DLG) model, proposed by Katz, Lebowitz and Spohn [3]. It consists of an interacting particle system driven by an external field – applied along one preferential axis of the lattice – that makes the system reach nonequilibrium steady states (NESS) in the long-time limit. In particular, the two-dimensional DLG model exhibits remarkable properties that contrast with those of its equilibrium counterpart, the conservative Ising model, such as its non-Hamiltonian nature, the violation of the fluctuation–dissipation theorem, the occurrence of anisotropic critical behavior [4], the existence of a unique relevant length scale in the anisotropic pattern formation at low temperatures and the consequent self-similarity in the system at different evolution times [5].

At high temperatures, the DLG exhibits a gas-like disordered state, but at low temperatures an anisotropic NESS emerges. This ordered phase is characterized by stripes of high and low particle density, aligned with the field direction. If the particle density is $\rho_0 = 1/2$, the order–disorder phase transition is of second order [4]. Extensive Monte Carlo simulations have shown that the critical temperature depends on the external field E, and it saturates for $E \to \infty$ at a value $T_c^{DLG} \simeq 1.41 T_c^I = 3.20$ ($T_c^I = 2.269\ldots$ is the critical temperature of the two-dimensional Ising model, in units of J/k_B, where J and k_B are the coupling and Boltzmann constants, respectively) [4]. The field generates a strong anisotropy, so a nonzero anisotropic exponent Δ must be defined in such a way that $\xi_\parallel \sim \xi_\perp^{1+\Delta}$, where $\xi_{\parallel(\perp)}$ are spatial correlation lengths in the longitudinal (transverse) direction to the field. Moreover, a double set of critical exponents is needed to take into account both the dynamics and the steady-state behavior of the correlation lengths at the critical point in each direction. These exponents are related by Δ, i.e., $\nu_\parallel = \nu_\perp(1+\Delta)$, $z_\parallel = z_\perp/(1+\Delta)$ [4], where $\nu_i, z_i, i = \parallel, \perp$ are the steady-state and dynamic correlation length exponents, respectively. On the other hand, if $\rho_0 < 1/2$, the transition is of first order with particle–hole invariance [4].

The critical behavior of the DLG model, in the limit $E \to \infty$, has become the subject of a long-standing debate. The first theoretical approach was carried out by Janssen et al. [6]. They considered that the anisotropic behavior in the Langevin equation was mainly originated by the particle current. Based on this, the set of critical exponents was calculated, and a new universality class was found [6–8]. Their results were confirmed by several numerical simulations [9]. This subject was later revisited from a different theoretical approach by Garrido et al. [10]. In this case, the Langevin equation was obtained from a coarse-grain process of the master equation and considering the external field as the main source of the anisotropic behavior. A different set of values for the critical exponents was obtained [10–12]; it corresponded to the previously found universality class of the random DLG model (RDLG), where the field direction changes randomly on each Monte Carlo trial [13]. These results were supported numerically by the simulations of Achahbar et al. [14] and Albano and Saracco [15,16]. In this last case, the critical behavior was analyzed by studying the critical short-time dynamics (STD) of the order parameter.

In all of the briefly commented works above, the field magnitude was fixed at a large value, which for practical purposes is equivalent to studying the model in the $E \to \infty$ limit. This means that the jumps of the particles to an empty nearest-neighbor site in the direction of E are always accepted, while jumps against it are forbidden. In addition, the dynamics imposed on this model makes it difficult to study it in the limit of small drives, i.e., in the $E \to 0$ limit. In order to describe the behavior in this regime, new models have been proposed. As an example, the nonconservative Ising model where an external driving field mimicking a shear profile is applied [17]. Here, this field has a magnitude $\dot{\gamma}$, and is decoupled from the Ising dynamics, making the study at any value of $\dot{\gamma}$ easier. It has been found that this model exhibits second-order phase transitions between stripe-ordered configurations and paramagnetic disordered ones. Furthermore, the critical temperature depends on $\dot{\gamma}$, in such a way that it decreases to T_c^I in the limit of $\dot{\gamma} \to 0$, while it saturates at large values. The set of critical exponents for each $\dot{\gamma}$ was estimated for the first time, and was later confirmed by the work using a similar model with friction by Hutch et al. [18].

In this work, a new model based on the DLG is proposed, and its critical behavior is studied by means of Monte Carlo simulations by using the STD technique [19]. In this case, the magnitude of the external field is fixed at a large value, but its application is controlled by a parameter $p\epsilon[0, 1]$, with the following conditions: (a) if $p = 0$ the drive is not applied, so the model becomes the Ising model, and (b) if $p = 1$ the standard DLG model is recovered. In this way the influence of the external field grows as p increases.

The paper is organized as follows: in Section 2 the proposed model is described; in Section 3 a brief description of STD is given. The obtained results are presented and discussed in Section 4, and finally, in Section 5 conclusions are stated.

2. The model

The DLG model [3] is defined on the square lattice of size $L_x \times L_y$ with periodic boundary conditions along both directions, and contained in a thermal bath at a temperature T. The driving field, E, is applied along the L_x-direction. Each lattice site can be empty or occupied by a particle. If the coordinates of the site are (i, j), then the label (or occupation number) of that site is $\eta_{ij} = \{0, 1\}$, where 0 (1) means that the site is empty (occupied). The set of all occupation numbers specifies a particular configuration of the lattice. The particles interact among themselves through a nearest-neighbor attraction with positive coupling constant ($J > 0$). So, in the absence of any field, the Hamiltonian is given by

$$H = -4J \sum_{\langle ij;i'j' \rangle} \eta_{ij}\eta_{i'j'}, \tag{1}$$