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Nonequilibrium phase transition in the kinetic Ising model on a two-layer square lattice under the presence of an oscillating field

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ABSTRACT

The nonequilibrium or dynamic phase transitions are studied, within a mean-field approach, in the kinetic Ising model on a two-layer square lattice consisting of spin-1/2 ions in the presence of a time varying (sinusoidal) magnetic field has been studied by using Glauber-type stochastic dynamics. The dynamic equations of motion are obtained in terms of the intralayer coupling constants J_1 and J_2 for the first and second layer, respectively, and interlayer coupling constant J_3 between these two layers. The nature (first- or second-order) of the transitions is characterized by investigating the behavior of the thermal variations of the dynamic order parameters. The dynamic phase transitions are obtained and the dynamic phase diagrams are constructed in the plane of the reduced temperature versus the amplitude of the magnetic field and found fourteen fundamental types of phase diagrams. Phase diagrams exhibit one, two or three dynamic tricritical points for various values of $J_2/|J_1|$ and $J_3/|J_1|$. Besides the paramagnetic (p), ferromagnetic (f) and compensated (c) phases, there were the f + c, f + sf, c + sf, af + p, m + p, f + m and c + af, where the af, sf and m are the antiferromagnetic, surface ferromagnetic and mixed phases respectively. Coexistence phase regions also exist in the system.

1. Introduction

Properties of magnetic thin films consisting of various magnetic layered structures or superlattices are of considerable interest both in terms of various aspects of technological applications (mainly in magnetic storage and recording and in synthesis of new magnets for a variety of applications) and as well as fundamental theoretical issues [1]. These materials present interesting novel magnetic properties, such as giant magnetoresistance [2], surface magnetic elastic coupling [3], enhanced surface magnetic moment [4] and surface magnetic anisotropy [5]. Experimentally, several works have been published on the structural and magnetic properties of multilayers, such as Fe/Ni [6], Fe/Ni and Fe/Co [7], Ni/Au [8], and Co/Cu/$Ni_{80}Fe_{20}$ [9]. On the theoretical side, magnetic thin films or the magnetic multilayer systems consisting of spin-1/2 ions have been investigated by a variety of techniques in the equilibrium statistical physics, such as mean-field approximation (MFA) [10], Monte Carlo (MC) simulations [11], renormalization group calculations [12], spin-fluctuation theory [13], effective-field theory [14], two-site cluster approximations [15], the transfer matrix method [16], a linear cluster approximation [17] and the variational cumulant expansion [18]. Further studies have been done by using the effective-field theory and the coupling approximation [19]; the MFA and simplified renormalization group approaches [20]; the MFA and high temperature series expansions [21]; the simple method developed by Jensen and Bennemann [22]; the Green function theory and the quantum MC calculation [23]. The two-layer system (only for ferromagnetic couplings) has been

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studied within different MFA, Migdal–Kadanoff-type renormalization group techniques, scaling theory, as well as numerical MC simulation techniques [24]. It is found that the phase diagrams predicted by special implementations of MFA and Migdal–Kadanoff RG scheme are in good agreement with the phase diagram obtained by the MC simulations. Recently, the phase diagram of a quasi-2D two-layer Ising lattice, with a variable inter-layer interaction parameter, is determined and the critical behavior discussed by phenomenological order–disorder, MFA, simplified renormalization group approach, and Bethe approximation [25]. The behavior of spin-1/2 Ising thin films through the use of layered Bethe lattices [26] and the layered Bethe lattices and Husimi trees (Bethe like lattices) [27] have also been investigated. Finally, we should also mention that the studies on magnetic thin films consisting of spin-1 ions [28] and spin-3/2 ions [29] have also appeared. We should also mention that anisotropic ferro/antiferromagnetic films of classical Heisenberg spins were also studied by using the MC simulations [30].

Although a great amount has been known about the equilibrium properties of magnetic thin films or the magnetic multilayer systems consisting of spin-1/2 ions, as far as we know, only a few works have been done about the nonequilibrium aspects of the magnetic thin films consisting of spin-1/2 ions by Jang et al. [31–34]. They studied the dynamic behavior of a classical Heisenberg spin system with bilinear exchange anisotropy in planar thin film geometry by using the dynamic MC simulation. Especially, they investigated the hysteresis, and studied the dynamic phase transition (DPT) and found a continuous DPT, but they did not present the dynamic phase diagrams. The MC simulations of critical dynamics have been used to study the short-time process and scaling behavior of a two-layer Ising model [35]. It has been shown that there are critical points even when the coupling between the two layers is not equal to zero. Some interesting problems in nonequilibrium systems are the nonequilibrium phase transition or the DPT in which the mechanism behind it has not yet been explored rigorously and the basic phenomenology is still undeveloped. Hence, further efforts on these challenging time-dependent problems, especially calculating the DPT points and constructing the dynamic phase diagram, should promise to be rewarding in the future. For these reasons, the DPT has attracted much attention in recent years, theoretically, in different systems, such as Ising systems [36], the anisotropic XY spin system [37], Bose–Einstein condensates with topological modes [38], and Bose–Hubbard model [39]. Experimental evidence for the DPT has been found in ultrathin Co films on a Cu (001) surface [40], amorphous YBaCuO films [41], ferroic systems (ferromagnets, ferroelectrics and ferroelastics) with pinned domain walls [42], cuprate superconductor [43], and polyethylene naphthalate (PEN) nanocomposites [44]. Besides the scientific interest, the study of DPT can inspire new methods in materials manufacturing and processing, and rather interesting methods in nanotechnology, such as pattern formation [45], monomolecular organic films [46], beam-induced transformation and many others [47]. Recently, Berkolaiko and Grinfeld [48] have developed a simple theory to detect the type of DPT and the existence of the tricritical point, seen in the kinetic spin-1/2 Ising system placed in an oscillating field. They also stated that their theory can be extended to cover the dynamic mean-field theory derived for the Blume–Capel model by Keskin et al. [49]. Moreover, the DPT may play a role in the evolution of the early universe [50].

The purpose of the present paper is to study the DPT in the bilayer square lattice consisting of spin-1/2 ions under the presence of a time-dependent oscillating external magnetic field, and calculate the DPT temperature and to construct the phase diagrams in the plane of the reduced temperature versus the amplitude of the magnetic field, and also the reduced temperature versus the ratio of J_3/J_1. The time evolution of the system is described by Glauber-type stochastic dynamics [51]. The nature (first- or second-order) of the transitions is characterized by investigating the behaviors of the thermal variations of the dynamic order parameters.

The rest of the paper is organized as follows. In Section 2, the bilayer square lattice consisting of spin-1/2 ions is introduced and the derivation of the mean-field (MF) dynamic equations of motion is given by using Glauber-type stochastic dynamics in the presence of a time-dependent oscillating external magnetic field. In Section 3, the stationary solutions of the coupled dynamic equations are solved and the thermal behaviors of the dynamic order parameters are investigated; hence the DPT points are calculated. Section 4 contains the presentation and the discussion of the dynamic phase diagrams. Finally, the summary and conclusion are given in Section 5.

2. Bilayer square lattice consisting of spin-1/2 ions

The bilayer square lattice is an extension of its one-layer version; hence one considers two identical layers of square lattices G_1 and G_2 that are placed parallel to each other forming the bilayer square lattice, illustrated in Fig. 1. Each layer has N sites and every spin, namely spin-1/2 ion, interacts with its nearest-neighbor (NN) and the corresponding adjacent spins in the other layer whose sites are labeled by i, i', j and j', as seen in Fig. 1. The Ising Hamiltonian of such a bilayer square lattice system can be written as

$$\mathcal{H} = -J_1 \sum_{\langle ij \rangle} S_i S_j - J_2 \sum_{\langle i'j' \rangle} \sigma_{i'}\sigma_{j'} - J_3 \sum_{\langle ii' \rangle} S_i \sigma_{i'} - H \sum_i S_i - H \sum_{i'} \sigma_{i'} \tag{1}$$

where S_i and $\sigma_{i'}$ correspond to the spin of each layer and take values ± 1 at each site; $\langle ij \rangle$ and $\langle i'j' \rangle$ indicate a summation over all pairs of nearest-neighboring sites of each layer. J_1 and J_2 are exchange constants for the first and second layer, respectively, which is also called intralayer coupling constants, and J_3 is the interlayer coupling constant over all the adjacent neighboring sites of layers. H is a time-dependent oscillating external magnetic field: $H(t) = H_0 \cos(wt)$, where H_0 and $w = 2\pi\nu$ are