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Dynamic magnetic hysteresis behavior and dynamic phase transition in the spin-1 Blume–Capel model

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ABSTRACT

The nature (time variation) of response magnetization $m(wt)$ of the spin-1 Blume–Capel model in the presence of a periodically varying external magnetic field $h(wt)$ is studied by employing the effective-field theory (EFT) with correlations as well as the Glauber-type stochastic dynamics. We determine the time variations of $m(wt)$ and $h(wt)$ for various temperatures, and investigate the dynamic magnetic hysteresis behavior. We also investigate the temperature dependence of the dynamic magnetization, hysteresis loop area and correlation near the transition point in order to characterize the nature (first- or second-order) of the dynamic transitions as well as obtain the dynamic phase transition temperatures. The hysteresis loops are obtained for different reduced temperatures and we find that the areas of the loops are decreasing with the increasing of the reduced temperatures. We also present the dynamic phase diagrams and compare the results of the EFT with the results of the dynamic mean-field approximation. The phase diagrams exhibit many dynamic critical points, such as tricritical (●), zero-temperature critical (Z), triple (TP) and multicritical (A) points. According to values of Hamiltonian parameters, besides the paramagnetic (P), ferromagnetic (F) fundamental phases, one coexistence or mixed phase region, (F+P) and the reentrant behavior exist in the system. The results are in good agreement with some experimental and theoretical results.

1. Introduction

The hysteresis properties (hysteresis area, coercivity and remanence) are very important in the magnetic recording media [1]. Real magnetic recording media quality tests and their relationship to the hysteresis based methods can be found in Ref. [2]. Magnetic hysteresis properties have a crucial technological importance for the ferromagnetic thin films. For example, one may control the films' thickness to obtain magnetic hysteresis at a right shape to suit desired technological purpose. Recently, the hysteresis loop of the Ising model [3], the ferromagnetic thin films [4] and the ferromagnetic–antiferromagnetic (Ni/Fe_xMn_{1-x}) bilayers [5] has been studied experimentally and theoretically. There are also some experimental efforts to study the scaling behavior of the hysteresis loop area [6,7]. Other examples of hysteresis include electrochemical adsorbate layers [8], liquid crystalline systems [9], superconducting materials [10], molecular-based magnetic materials [11], soft magnetic nanowires [12], etc.

On the other hand, the dynamic phase transition (DPT) was first found in a study, within a mean-field approach, which is the kinetic spin-1/2 Ising model under a time-dependent oscillating field [13], using a Glauber-type stochastic dynamics [14]. Kinetic spin-1/2 Ising model was also investigated by Monte Carlo simulation [15–18], which allows the microscopic fluctuations, as well as further mean-field studies [19]. Moreover, Tutu and Fujiwara [20] developed the systematic method for getting the phase diagrams in DPTs, and constructed the general theory of DPTs near the transition point based on mean-field description, such as Landau's general treatment of the equilibrium phase transitions. The DPT has also been found in a one-dimensional kinetic spin-1/2 Ising model with boundaries [21]. In the last decade, researches on the DPT are widely extended to more complex systems such as vector type order parameter systems, e.g., the Heisenberg-spin systems [22], XY model [23], Ziff–Gulari–Barshad model for CO oxidation with CO desorption to periodic variation of the CO pressure [24], the two-dimensional Hubbard model subject to bias voltages from the electrodes coupled to the system [25], higher spin systems such as spin-1 [26,27], spin-3/2 [28], etc. mixed-spin Ising systems, e.g., with spins (1/2, 1), with spins (1/2, 3/2), with spins (1, 3/2), with spins (2, 5/2), etc. [29] and metamagnet systems [30]. Finally, we should also mention that experimental evidences for the DPT have been found in many physical systems, such as highly anisotropic (Ising-like) and ultrathin Co/Cu(0.01) ferromagnetic

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films [6], amorphous YBaCuO films [31], ferroic systems (ferromagnets, ferroelectrics and ferroelastics) with pinned domain walls [32], cuprate superconductors [33], polyethylene naphthalate (PEN) nanocomposite [34] and ultrathin $[Co/Pt]_3$ magnetic multilayers [35].

In this paper, we study the nature (time variation) of response magnetization $m(wt)$ of the spin-1 Blume–Capel model in the presence of a periodically varying external magnetic field $h(wt)$ by employing the effective-field theory (EFT) with correlations under the Glauber-type stochastic dynamics. From these studies, we determine the $m(wt)$–$h(wt)$ or hysteresis loops, and investigate the dynamic magnetic hysteresis behavior. The temperature dependence of the dynamic magnetization, hysteresis loop area and correlation is investigated to characterize the nature of the dynamic transitions as well as obtain the dynamic phase transition temperatures. We also calculate the dynamic phase diagrams and compare the results of the EFT with the results of the dynamic mean-field approximation [26].

The rest of this paper is organized as follows. In next section, we briefly describe the model and obtain the dynamic effective-field equations using the Glauber transition rates in the presence of a time-varying magnetic field. In Section 3 we present the numerical results and discussions. Especially, we investigate and discuss the time variation of response magnetization, dynamic magnetic hysteresis behavior and the thermal variation of dynamic magnetization, hysteresis loop area and correlation, respectively. Finally, the paper ends with a summary and conclusion in Section 4.

2. Model and derivation of dynamic effective-field equation

The spin-1 Ising model with a crystal field interaction or single-ion anisotropy is often called the Blume–Capel (BC) model, was first introduced by Blume [36] and independently by Capel [37]. The model has been the subject of many theoretical studies since its introduction [36,37] more than 40 years ago, because it plays a fundamental role in the multicritical phenomena associated with various physical systems, such as multicomponent fluids, ternary alloys and magnetic systems. It also exhibits variety of critical and tricritical phenomena. These studies were done by the well known methods in equilibrium statistical physics such as the effective-field theory (EFT), the mean-field approximation (MFA), the cluster variation method (CVM), the Monte Carlo (MC) simulation and renormalization group techniques ([38] and references therein). The nonequilibrium properties of the model have also been studied in Ref. [26,39,40].

The Hamiltonian of the BC model is given by

$$\mathrm{H} = -J_{ij}\sum_{\langle ij\rangle} S_i S_j - D\sum_i S_i^2 - h(t)\sum_i S_i, \tag{1}$$

where the S_i takes the value ± 1 or 0 at each site i of a lattice and $\langle ij\rangle$ indicates a summation over all pairs of nearest neighbor sites. J_{ij} is the bilinear exchange interaction parameter, D is the crystal field interaction or single-ion anisotropy, and $h(t)$ is a time-dependent external oscillating magnetic field and is given by

$$h(t) = h_0 \sin(wt), \tag{2}$$

where h_0 and $w = 2\pi\nu$ are the amplitude and the angular frequency of the oscillating field, respectively. The system is in contact with an isothermal heat bath at an absolute temperature T.

Now, we use the EFT with correlations to obtain the dynamic EFT equation for the model. This method was first introduced by Honmura and Kaneyoshi [41] and Kaneyoshi et al. [42], which is a more advanced method dealing with Ising systems than the MFA, because it considers more correlations. Within the framework of the EFT, one finds that

$$\langle S_i^k \rangle = \left\langle \prod_{i=1}^{z} (1 + S_i \sinh(J\,\nabla) + S_i^2[\cosh(J\,\nabla) - 1]) \right\rangle f_k(x+h)\Big|_{x=0}, \tag{3}$$

where $\nabla = \partial/\partial x$ is a differential operator, z denotes the nearest-neighbor sites of the central site i and $z=4$ for the square lattice. The functions $f_k(x+h)$ are defined by

$$f_1(x+h) = \frac{2\sinh[\beta(x+h)]}{2\cosh[\beta(x+h)] + \exp(-\beta \mathrm{D})}, \tag{4}$$

$$f_2(x+h) = \frac{2\cosh[\beta(x+h)]}{2\cosh[\beta(x+h)] + \exp(-\beta \mathrm{D})}, \tag{5}$$

where $\beta = 1/k_B T$, k_B is the Boltzman factor. Eq. (3) is also exact and is valid for any lattice. If we try to exactly treat all the spin–spin correlations for that equation, the problem quickly becomes intractable. A first obvious attempt to deal with it is to ignore correlations; the decoupling approximation:

$$\langle S_i S_{i'}^2 \ldots S_{i^n}^2 \rangle \cong \langle S_i \rangle \langle S_{i'}^2 \rangle \ldots \langle S_{i^n}^2 \rangle, \tag{6}$$

with $i \neq i' \neq \ldots \neq i^n$ has been introduced within the EFT with correlations [41,43,44]. In fact, the approximation corresponds essentially to the Zernike approximation [45] in the bulk problem, and has been successfully applied to a great number of magnetic systems including the surface problems [42,44,46]. On the other hand, in the mean-field theory, all the correlations, including the self-correlations, are neglected. Based on this approximation, Eq. (3) is reduced to

$$m = \langle S_i \rangle = [1 + \langle S_i \rangle \sinh(J\nabla) + \langle S_i^2 \rangle (\cosh(J\nabla) - 1)]^4 f_1(x+h)\Big|_{x=0}, \tag{7}$$

$$q = \langle S_i^2 \rangle = [1 + \langle S_i \rangle \sinh(J\nabla) + \langle S_i^2 \rangle\, (\cosh(J\,\nabla) - 1)]^4 f_2(x+h)\Big|_{x=0}. \tag{8}$$

As one can see, in our effective-field treatment there naturally appears new order parameter q, which one is able to evaluate. This is not the case of the standard MFA, where all correlations are neglected. This is one of the reasons why the present framework provides better results than the standard MFA.

Expanding the right side of Eq. (7), one can obtain the following equation:

$$m = \begin{bmatrix} 1 + 4\sinh(J\nabla)m + (-7 + 4\cosh(J\nabla) + 3\cosh(2J\nabla))m^2 + \cdots \\ + \frac{1}{16}(70 + 112\cosh(J\nabla) + 56\cosh(2J\nabla) - \sinh(4J\nabla))m^8 \end{bmatrix} f_1(x+h)\Big|_{x=0}, \tag{9}$$

When trigonometric expression is converted to exponential expression, Eq. (9) is reduced to following one:

$$m = \begin{bmatrix} 1 + (-2e^{-J\nabla} + 2e^{J\nabla})m + (-7 + \frac{3}{2}e^{-2J\nabla} + 2e^{-J\nabla} + 2e^{J\nabla} + \frac{3}{2}e^{2J\nabla})m^2 + \cdots \\ + \frac{1}{16}(70 + e^{-4J\nabla} - 8e^{-3J\nabla} + 28e^{-2J\nabla} - 56e^{-J\nabla} - 56e^{J\nabla} + 28e^{2J\nabla} - 8e^{3J\nabla} + e^{4J\nabla})m^8 \end{bmatrix}$$
$$f_1(x+h)\Big|_{x=0}. \tag{10}$$

Now, employing a mathematical relationexp$(\alpha\nabla) f_1(x) = f_1(x+\alpha)$, where $\nabla = \partial/\partial x$ is a differential operator, Eq. (10) obtained as follow,

$$\begin{aligned} m &= f_1(h) + \frac{1}{2}(-f_1(h-J) + f_1(h+J))m \\ &\quad - \left(7f_1(h) + \frac{3}{2}f_1(h-2J) + 2f_1(h-J) + 2f_1(h+J) + \frac{3}{2}f_1(h+2J)\right)m^2 + \\ &\quad \vdots \\ &\quad + \frac{1}{16}\begin{pmatrix} 70f_1(h) + f_1(h-4J) - 8f_1(h-3J) + 28f_1(h-2J) - 56f_1(h-J) \\ -56f_1(h+J) + 28f_1(h+2J) - 8f_1(h+3J) + f_1(h+4J) \end{pmatrix} m^8, \end{aligned} \tag{11}$$

or Eq. (11) is reduced the following form:

$$m = a_0 + a_1 m + a_2 m^2 + a_3 m^3 + a_4 m^4 + a_5 m^5 + a_6 m^6 + a_7 m^7 + a_8 m^8. \tag{12}$$