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Magnetic properties of a ferromagnetic thin film with four spin interaction: A Monte Carlo simulation study

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ABSTRACT

Monte Carlo simulation has been used to study the critical behaviors and the magnetic properties of a ferromagnetic thin Ising film with a plaquette four spin interaction. The effects of the ratio $r_s = J_s/J$ of the surface exchange interaction to the bulk one and the four spin interaction on phase diagrams are investigated. A number of characteristic behaviors have been found, which include the first- and second-order phase transitions, thus also the tricritical points, triple point and isolated critical point.

1. Introduction

The Ising and Heisenberg ferromagnets with higher exchange interaction in spin systems have been extensively investigated both theoretically and experimentally. The theoretical explanation for the origin of multispin interaction terms has been given in the theories of the superexchange interaction, the magnetoelastic effect, the permutation operator, the perturbation expansion and the spin–phonon coupling [1]. Among the magnetic system influenced by the interaction with four spin we cite: solid helium, this system was studied by Roger et al. [2] and within the transverse field, Chunlei et al. [3] have studied the three dimensional Ising system with two and four pseudo spins, in which the numerical results have found a good agreement with the experiment. This models with multispin interaction can be applied to describe the first-order phase transition that is squaric acid crystal ($H_2C_2O_4$) [4–7] and some copolymers [8]. Recently, it has also been shown that four spin cyclic exchange interaction is necessary for quantitative understanding of the experimental results on spin gap [9], Raman peaks [10] and optical conductivity [11], observed in the curate ladder $La_xCa_{14-x}Cu_{24}O_{41}$. In general, models with multispin interaction may exhibit physical peculiarities not observed in the usual spin systems, for example the nonuniversal critical phenomena or deviations from block $T^{3/2}$ law at low temperatures [12]. Theoretically, the influence of multispin interaction on critical properties of various Ising models has been studied using different methods: cluster variational method [13,14], effective field theory [15–20], Monte Carlo simulation [21–23], renormalization group technique [24–27], some more accurate treatments such as series expansions [28], and also exact calculation [29]. Recently Iwashita et al.[23] have applied the Monte Carlo (MC) simulation to study Ising spin system with four spin interaction, they have found that the ground state (GS) and the condition of GS phase transition. Kaneyoshi [19] has studied the phase diagrams of the Ising models with two and four spin interactions on a honeycomb lattice which act only between the nearest neighbor site or the nearest site using correlated approximation. Laaboudi and Kerouad [17] have studied the Blume Emery Griffhte model with four spin interaction [18] using the effective field theory. They have found that the phase diagram of the system may exhibit reentrant and tricritical behaviors. Zaim et al. [30] have applied the MC simulation to study the mixed spin 1/2 and spin 1 Blume Capel ferrimagnetic models with a plaquette four spin interaction on two dimensional square lattice. They have obtained that the phase diagrams of the system may exhibit the reentrant and even the double reentrant behaviors.

The study of ferromagnetic thin film is of intense significance. Not only for its applications in magnetic recording media, a key component of today's information technology industry, but also

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for the fundamental physics it reveals. Finite size effects in thin films arising from both confinement and surface modification give rise to a variety of equilibrium phase behaviors that are not observed in the bulk materials [31].

The aim of this paper is to study the effects of four exchange interaction and bilinear exchange interaction in surface on the critical behavior of a 1/2 spin Ising film with a plaquette four spin interaction using Monte Carlo simulation. The outline of this paper is as follows: In Section 2 we describe the model and detail of Monte Carlo simulation. In Section 3 we present the results and discussions, while Section 4 is devoted to a brief conclusion.

2. Model and Monte Carlo simulation

We consider a spin 1/2 Ising film with a plaquette four spin interaction. In the Monte Carlo simulation [32] based on Metropolis algorithm we apply periodic boundary conditions in the x- and y-directions. Free boundary conditions are applied in the z-direction which is of finite thickness N. The Hamiltonian of the system is given by

$$H = -\sum_{\langle ij\rangle} J_{ij}\sigma_i\sigma_j - J_4 \sum_{\langle ijkl\rangle} \sigma_i\sigma_j\sigma_k\sigma_l, \quad (1)$$

where $\sigma = 1/2$, the symbol $\sum_{\langle ij\rangle}$ indicates summations over all the nearest-neighbors, while $\sum_{\langle ijkl\rangle}$ indicates summations over four sites in every square (plaquette). J_{ij} and J_4 are the bilinear exchange interaction parameters and four exchange interaction parameters, respectively. J_{ij} takes the values J_s in surface (z=1, z=N) and J other wise. The simulations are carried out for simple cubic film containing $L \times L \times N$ spins. $L \times L$ represent the number of sites in each layer of the film and N is the number of layers in the film or its thickness. Our data were generated with 5×10^4 Monte Carlo steps per spin in lattices with L=50 after discarding the first 2×10^4 steps per spin. We define $\beta = 1/k_BT$. When studying the film properties, the quantities of great interest are: The magnetization of the film m,

$$m = \frac{1}{N}\sum_{Z=1}^{N} m_z. \quad (2)$$

The magnetization per layer m_z where $1 < z < N$

$$m_z = \frac{1}{L \times L}\sum_{j=1}^{L\times L} \sigma_j. \quad (3)$$

The magnetic susceptibility of the film χ,

$$\chi = \frac{1}{N}\sum_{z=1}^{N} \chi_z. \quad (4)$$

The magnetic susceptibility per layer χ_z,

$$\chi_z = \beta(L \times L)(\langle m_z^2\rangle - \langle m_z\rangle^2). \quad (5)$$

The Binder cumulant of the film

$$BC = 1 - \frac{\langle m^4\rangle}{3\langle m^2\rangle^2}. \quad (6)$$

The critical temperatures are determined from the maxima of susceptibility curves and the first-order phase transitions are obtained by locating the discontinuities of the magnetization curves.

3. Results and discussions

In this section, we study the effect of the four spin exchange interaction J_4 and the surface bilinear exchange interaction J_s on the phase diagrams of a spin 1/2 Ising model with a plaquette four spin interaction. We take J as the unit of energy, we introduce the reduced bilinear exchange interaction in surface $r_s = J_s/J$ and the reduced four spin exchange interaction $r_4 = J_4/J$. Before illustrating the phase diagrams, we investigate the finite size effect on the critical temperature. Therefore, we plotted the susceptibility χ (Fig. 1a) and fourth-order Binder cumulant BC (Fig. 1b) versus the temperature for fixed values N=4, $r_s = 1.5$, and $r_4 = 1.0$, and for different system sizes (L=40, 60 and 70). In these figures, we can see that the value of the critical temperature is independent of the system size when $L \geq 40$ and the curves for the Binder cumulant intersect at the same value ($k_BT_c/J \simeq 4.6$).

In Fig. 2 we give the phase diagrams in the (k_BT_c/J, r_s) plane for different values of the film thickness (N=3, 4 and 6) and for two

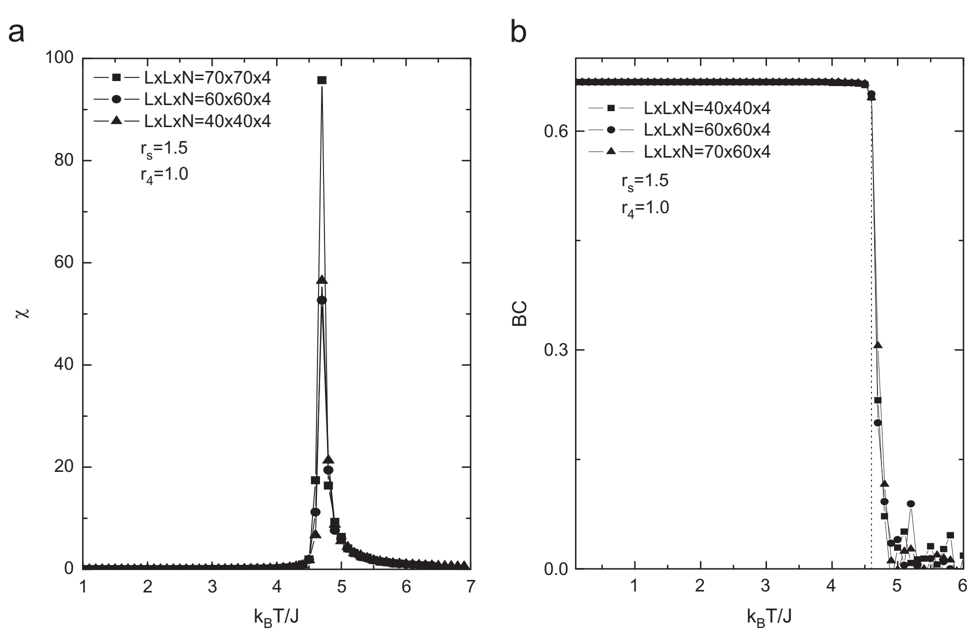

Fig. 1. (a) The dependence of the total susceptibility on the temperature for $r_s = 1.5$, $r_4 = 1.0$ and for different system sizes. (b) The dependence of fourth-order Binder cumulant BC on the temperature k_BT/J for $r_s = 1.5$, $r_4 = 1.0$ and for different system sizes.