Journal of Magnetism and Magnetic Materials 368 (2014) 36–43

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Random field distributed Heisenberg model on a thin film geometry

Ümit Akıncı

Department of Physics, Dokuz Eylül University, Tr-35160 İzmir, Turkey

ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form
11 May 2014
Available online 20 May 2014

Keywords:
Heisenberg thin film
Special point
Random magnetic field
Tricritical behavior

ABSTRACT

The effects of the bimodal random field distribution on the thermal and magnetic properties of the Heisenberg thin film have been investigated by making use of a two spin cluster with the decoupling approximation. Particular attention has been devoted to the obtaining of phase diagrams and magnetization behaviors. The physical behaviors of special as well as tricritical points are discussed for a wide range of selected Hamiltonian parameters. For example, it is found that when the strength of a magnetic field increases, the locations of the special point (which is the ratio of the surface exchange interaction and the exchange interaction of the inner layers that makes the critical temperature of the film independent of the thickness) in the related plane decrease. Moreover, tricritical behavior has been obtained for higher values of the magnetic field, and influences of the varying Hamiltonian parameters on its behavior have been elucidated in detail in order to have a better understanding of the mechanism underlying the considered system.

1. Introduction

Recently, there has been growing interest both theoretically and experimentally in the finite magnetic materials especially in semi-infinite systems and thin films. The magnetic properties of the materials in the presence of free surfaces are drastically different from the bulk counterparts. This is because of the fact that the free surface breaks the translational symmetry, i.e. surface atoms are embedded in an environment of lower symmetry than that of the inner atoms [1,2]. If the strength of the surface exchange interaction is greater than a critical value, the surface region can exhibit an ordered phase even if the bulk is paramagnetic and it has a higher transition temperature than the bulk one. The aforementioned situation has been observed experimentally in Refs. [3–5]. A rigorous review of the surface magnetism can be found in Ref. [6].

In a thin film geometry, it was experimentally found that the Curie temperature and the average magnetic moment per atom increase with the increasing thickness of the film [7,8]. The thickness dependence on the Curie temperature has also been measured in Co [9], Fe [10] and Ni [11] films. One class of films which exhibit a strong uniaxial anisotropy [12] can be modeled using the Ising model. These systems have been widely studied in the literature by means of several theoretical methods such as Monte Carlo (MC) simulations [13], mean field approximation (MFA) [14] and effective field theory (EFT) [15]. Indeed Ising thin films keep wide space in the literature (e.g. see references in Ref. [16]). Thin films which do not exhibit a strong uniaxial anisotropy require to solve the Heisenberg model in the thin film geometry. But in contrast to the Ising counterpart, the Heisenberg model in a thin film geometry has been solved in limited cases. The Heisenberg model on a thin film geometry with Green function method [17–19], renormalization group technique [20], MFA [21], EFT [22,23] and MC [24,25], are among them. Besides, critical and thermodynamic properties of the bilayer [26,27] and multilayer [28] systems have been investigated within the cluster variational method in the pair approximation.

Working on the random field distributed magnetic systems is important. Although it is difficult to realize these systems experimentally, certain mappings between these systems and some other systems make these models valuable. The most obvious one is the similarity between the diluted antiferromagnets in a homogenous magnetic field and the ferromagnetic systems in the presence of random fields [29,30]. Besides, a rich class of experimentally accessible disordered systems can be described by the random field Ising model (RFIM) such as structural phase transitions in random alloys, commensurate charge-density-wave systems with impurity pinning, binary fluid mixtures in random porous media, and the melting of intercalates in layered compounds such as TiS_2 [31]. Also, RFIM has been applied in order to describe the critical surface behavior of amorphous semi-infinite systems [32,33] and the magnetization process of a garnet film [34]. Because of these motivations, the Ising model in a quenched random field has been studied over three decades. The model which is actually based on the local fields acting on the lattice sites, which are

E-mail address: umit.akinci@deu.edu.tr

http://dx.doi.org/10.1016/j.jmmm.2014.05.018
0304-8853/

taken to be random according to a given probability distribution, was introduced for the first time by Larkin [35] for superconductors and later generalized by Imry and Ma [36].

On the other hand, there has been less attention paid to the random field effects on the Heisenberg model. The spin-1/2 isotropic classical Heisenberg model with bimodal random magnetic field distribution is studied within the EFT for a two spin cluster (which is abbreviated as EFT-2) [37,38] and within the EFT with the probability distribution technique [39]. Similar results have been obtained such as tricritical behavior. Besides, the amorphization effect for the bimodal random magnetic field distributed isotropic Heisenberg model has been studied [40]. Recently, the spin-1/2 anisotropic quantum Heisenberg model with trimodal random magnetic field distribution has been investigated within the EFT-2 [41]. All of these works are related to the bulk systems. Thus, some questions are open for the Heisenberg model in a thin film geometry such as whether tricritical behavior exists or not and the behavior of the special point with the random field distribution.

Thus, the aim of this work is to determine the effect of the bimodal random magnetic field distribution on the phase diagrams and magnetization behavior of the isotropic Heisenberg thin film. For this aim, the paper is organized as follows: in Section 2 we briefly present the model and formulation. The results and discussion are presented in Section 3, and finally Section 4 contains our conclusions.

2. Model and formulation

A thin film in the simple cubic geometry is treated in this work. The schematic representation of the thin film can be seen in Fig. 1. The system is infinitely long in the x and y directions, while finite in the z direction. The thin film can be treated as a layered structure which consists of interacting L parallel layers. Each layer (in the xy plane) is defined as a regular lattice with coordination number 4, i.e. each layer of the thin film has a square lattice. The Hamiltonian of the isotropic Heisenberg model is given by

$$\mathcal{H} = -\sum_{\langle i,j\rangle} J_{ij}(s_i^x s_j^x + s_i^y s_j^y + s_i^z s_j^z) - \sum_i H_i s_i^z \tag{1}$$

where s_i^x, s_i^y and s_i^z denote the Pauli spin operators at a site i. J_{ij} stands for the exchange interactions between the nearest neighbor spins located at sites i and j and H_i is the longitudinal magnetic field at a site i. The first sum is carried over the nearest neighbors of the thin film, while the second one is over all the sites. The exchange interaction (J_{ij}) between the spins on the sites i and j takes values according to the positions of the nearest neighbor spins. Let us denote the intralayer exchange interactions in the surfaces of the film as J_1 and all other exchange interactions as J_2. This means that all nearest neighbor spins which belong to the surfaces of the film interacted J_1 with each other, while all other nearest neighbor spins have exchange interaction J_2.

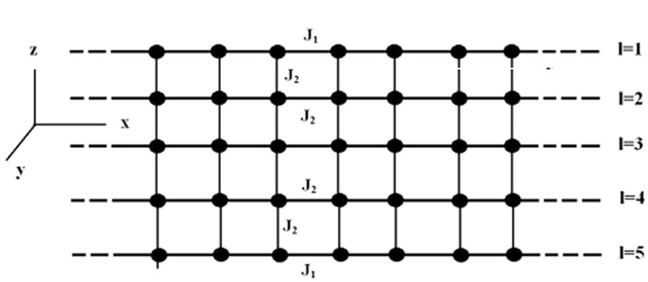

Fig. 1. Schematic representation of the thin film which has thickness L=5.

Magnetic fields are distributed according to a bimodal distribution function to a lattice site which is given by

$$P(H_i) = \frac{1}{2}[\delta(H_i - H_0) + \delta(H_i + H_0)] \tag{2}$$

where δ stands for the delta function. This distribution distributes to magnetic field H_0 half of the lattice sites and $-H_0$ the remaining half of the lattice sites randomly.

The simplest way for solving this system within the EFT method is using the EFT-2 method [42] which is a two spin cluster approximation within the EFT method. This method is a generalized form of the earlier formulation for the Ising model [43]. By following the same procedure given in Ref. [23] we can arrive at the magnetization expressions of each layer of the film as

$$\begin{aligned} m_1 &= \langle \Theta_{1,1}^3 \Theta_{2,2} \rangle F_1(x,y,H_0)|_{x=0,y=0} \\ m_k &= \langle \Theta_{2,k-1} \Theta_{2,k}^3 \Theta_{2,k+1} \rangle F_2(x,y,H_0)|_{x=0,y=0}, k=2,3,\ldots,L-1 \\ m_L &= \langle \Theta_{2,L-1} \Theta_{1,L}^3 \rangle F_1(x,y,H_0)|_{x=0,y=0}. \end{aligned} \tag{3}$$

Here m_i $(i=1,2,\ldots,L)$ denotes the magnetization of the ith layer. The operators in Eq. (3) are defined via

$$\Theta_{k,l} = [A_{kx} + m_l B_{kx}][A_{ky} + m_l B_{ky}] \tag{4}$$

where $l=1,2,\ldots,L$ and

$$\begin{aligned} A_{km} &= \cosh(J_k \nabla_m) \\ B_{km} &= \sinh(J_k \nabla_m), \quad k=1,2; \; m=x,y. \end{aligned} \tag{5}$$

The functions in Eq. (3) are given by

$$F_n(x,y,H_0) = \int dH_1 dH_2 P(H_1) P(H_2) f_n(x,y,H_1,H_2) \tag{6}$$

where

$$f_n(x,y,H_1,H_2) = \frac{\sinh(\beta X_0)}{\cosh(\beta X_0) + \exp(-2\beta J_n)\cosh(\beta Y_0^{(n)})} \tag{7}$$

and where

$$\begin{aligned} X_0 &= x + y + H_1 + H_2 \\ Y_0^{(n)} &= [4J_n^2 + (x - y + H_1 - H_2)^2]^{1/2} \end{aligned} \tag{8}$$

with the values n=1,2. In Eq. (7), $\beta = 1/(k_B T)$ where k_B is the Boltzmann constant and T is the temperature.

Magnetization expressions given in the closed form in Eq. (3) can be constructed via acting differential operators on related functions. The effect of the exponential differential operator on an arbitrary function $G(x)$ is given by

$$\exp(a\nabla)G(x) = G(x+a) \tag{9}$$

with any constant a.

With the help of the Binomial expansion, Eq. (3) can be written in the form

$$\begin{aligned} m_1 &= \sum_{p=0}^{6} \sum_{q=0}^{2} K_1(p,q) m_1^p m_2^q \\ m_k &= \sum_{p=0}^{2} \sum_{q=0}^{6} \sum_{r=0}^{2} K_2(p,q,r) m_{k-1}^p m_k^q m_{k+1}^r \\ m_L &= \sum_{p=0}^{6} \sum_{q=0}^{2} K_1(p,q) m_L^p m_{L-1}^q \end{aligned} \tag{10}$$

where k is not equal to 1 or L and

$$\begin{aligned} K_1(p,q) &= \sum_{i=0}^{3} \sum_{j=0}^{3} \sum_{k=0}^{1} \sum_{l=0}^{1} k_1(i,j,k,l) \delta_{p,i+j} \delta_{q,k+l} \\ K_2(p,q,r) &= \sum_{i=0}^{1} \sum_{j=0}^{1} \sum_{k=0}^{3} \sum_{l=0}^{3} \sum_{m=0}^{1} \sum_{n=0}^{1} k_2(i,j,k,l,m,n) \delta_{p,i+j} \delta_{q,k+l} \delta_{r,m+n} \end{aligned} \tag{11}$$

and

$$k_1(p,q,r,s) = \binom{3}{p}\binom{3}{q} A_{1x}^{3-p} A_{1y}^{3-q} A_{2x}^{1-r} A_{2y}^{1-s} B_{1x}^p B_{1y}^q B_{2x}^r B_{2y}^s$$