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Effect of anisotropic Dzyaloshinskii–Moriya interactions on phase diagrams of the Ashkin–Teller model

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HIGHLIGHTS

- Phase diagrams of Ashkin–Teller model with anisotropic Dzyaloshinskii–Moriya interaction.
- The model is focused on the effect of anisotropic DM interaction on the phase diagrams.
- Using mean field theory we have studied this model.
- Different new phase diagrams, including a novel multicritical topology.
- The first and second transitions lines are observed in this model.

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ABSTRACT

In this paper we study, using mean field theory (MFT), the effect of the anisotropic Dzyaloshinskii–Moriya (DM) interaction on the phase diagrams of the spin-half Ashkin–Teller model on hypercubic lattice. Different new phase diagrams are found by varying the anisotropy of DM interaction. The multicritical behavior is studied as a function of four-spin interaction coefficient J_4/J_1 and for two fixed values of spin interaction coefficient J_2/J_1.

1. Introduction

Several years ago, the Ashkin–Teller (AT) model was introduced to study cooperative phenomena of quaternary alloys [1] on a lattice. Some years later, Fan has shown that the AT model could be described in a Hamiltonian form appropriated for localized spin magnetic systems [2] so that it can be considered as two superposed Ising models, which are, respectively, described by the classical spin variables σ and S sitting on each of the sites of a lattice. Within each Ising model there is a two-spin nearest-neighbor interaction and the different Ising models are coupled by a four-spin interaction, indeed there are three components of the Ashkin–Teller model order parameter: $\langle\sigma\rangle$, $\langle S\rangle$ and $\langle\sigma S\rangle$, The last component is the effect of ordering of pairs of spins σ and S. Since this version was introduced, the AT model is one of the most studied systems in statistical mechanics due mainly to the richness of critical phenomena revealed by its phase diagrams both in two and three dimensions [3].

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Furthermore, different methods have been applied to study the critical behavior of this model such as mean field theory [4], Monte Carlo simulations [5,6], renormalization group [7], exact duality [8], series analysis [9] and the mean-field renormalization group approach [10]. However, the phase transitions in the anisotropic Ashkin–Teller model using both the mean field method and Monte Carlo calculations were studied by Bekhechi et al. and they found that the MC simulations reduce the varieties of phase diagrams obtained from MFA to one variety [11,12]. Recently, Santos and SáBarreto [13] have studied the Ashkin–Teller model using new effective field theory, and they have obtained better results from this approximation as compared to others approximations, they have also presented the derivation of correlation identities for the internal energy of this model and they use the same theory to obtain the internal energy and specific heat. More recently, we have studied the phase diagrams of spin 1/2 Ashkin–Teller model with Dzyaloshinskii–Moriya interaction [14], and we have found, using the mean field theory (MFT) on a hypercubic lattice, ten new phase diagrams, including reentrant phenomena in the spin-half Ashkin–Teller model with different isotropic 2Dzyaloshinskii–Moriya (DM) interaction.

A novel anti-symmetric exchange coupling [15,16] called the Dzyaloshinskii–Moriya (DM) interaction has recently attracted great interest. The DM interaction arises from spin–orbit scattering of electrons in an inversion asymmetric crystal field, and it exists in systems with broken inversion symmetry, such as in specific metallic alloys with B20 structure [17–19] and at the surface or interface of magnetic multilayer's [20–22]. The existence of the DM interaction can induce chiral spin structures such as skyrmion [17–22] unconventional transport phenomena [23,24] and exotic dynamic properties [25–27] many of which stimulated interest in fundamental magnetism studies and provided new possibilities for the development of future spintronic devices. However, the effect of this interaction on the ground state and excitation spectrum of the one-dimensional Heisenberg Hamiltonian has been studied in the past for both ferromagnetic and antiferromagnetic cases [28,29].

Moreover, in this paper we are mainly interested in the effect of Dzyaloshinskii–Moriya (DM) interaction where the DM interactions between spins $\sigma - \sigma\,(D_{m1})$ and between spins $S - S\,(D_{m2})$ are not the same. The effect of the anisotropy of DM interaction was analyzed using mean field theory (MFT) of spin-half.

This paper is organized as follows. In Section 2, we define the model and describe the method. Results and discussions are given in Section 3, while Section 4 is reserved to summary and conclusions.

2. Model and method

To further understand the role of the anisotropic DM in Ashkin–Teller model, we consider the Hamiltonian given by:

$$\begin{aligned} H = & -J_1 \sum_{\langle i,j\rangle} \sigma_i^z \sigma_j^z - J_2 \sum_{\langle i,j\rangle} S_i^z S_j^z - J_4 \sum_{\langle i,j\rangle} \sigma_i^z \sigma_j^z S_i^z S_j^z - D_{m1} \left[\sum_{\langle i,j\rangle} (S_i^x S_j^y - S_i^y S_j^x) \right] \\ & - D_{m2} \left[\sum_{\langle i,j\rangle} (\sigma_i^x \sigma_j^y - \sigma_i^y \sigma_j^x) \right] \end{aligned} \tag{1}$$

where the spins $\sigma_i^{x,y,z}$ and $S_i^{x,y,z}$ are the Pauli matrices of a spin-half given by:

$$(\sigma_i, S_i)^x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \qquad (\sigma_i, S_i)^y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \qquad (\sigma_i, S_i)^z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

The matrix conjugate relative to the standard definition is:

$$(\bar{\sigma}_i, \bar{S}_i)^y = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}.$$

Those spins are localized on sites i and j of a hypercubic lattice, whereas $\sum_{\langle i,j\rangle}$ runs over the nearest neighbor interactions. The exchange couplings J_1 and J_2 are the exchange coupling interactions between the spins $\sigma - \sigma$ and $S - S$, respectively, the coefficient J_4 describes the four-spin interaction. D_{m1} and D_{m2} denote the intensity of the Dzyaloshinskii–Moriya interaction, between the spins $\sigma - \sigma$ and between the spins $S - S$, respectively.

In order to write the mean-field equations let H_0 denote the effective Hamiltonian of the system which can be expressed in the standard basis $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$ as:

$$H_0 = \begin{bmatrix} -(h_1 + h_2 + h_4) & -(h_5 - h_6 i) & -(h_7 - h_8 i) & 0 \\ -(h_5 + h_6 i) & -(h_1 - h_2 - h_4) & 0 & -(h_7 - h_8 i) \\ -(h_7 + h_8 i) & 0 & -(-h_1 + h_2 - h_4) & -(h_5 - h_6 i) \\ 0 & -(h_7 + h_8 i) & -(h_5 + h_6 i) & -(-h_1 - h_2 + h_4) \end{bmatrix} \tag{2}$$

where $h_1 = zJ_1 m_\sigma^z$, $h_2 = zJ_2 m_S^z$, $h_4 = zJ_4 m_{\sigma S}^z$, $h_5 = zD_{m1} m_S^y$, $h_6 = zD_{m1} m_S^x$, $h_7 = zD_{m2} m_\sigma^y$, $h_8 = zD_{m2} m_\sigma^x$ being the effective fields, z is the coordination number.