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The effects of next nearest-neighbor exchange interaction on the magnetic properties in the one-dimensional Ising system

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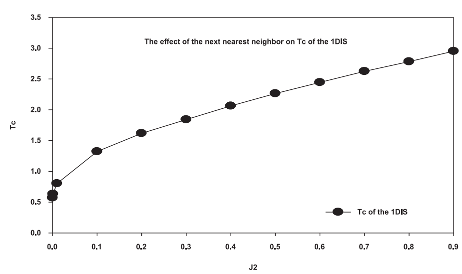
HIGHLIGHTS

- Magnetic properties of the one-dimensional Ising system (1DIS) were studied by EFT.
- Effect of next nearest-neighbor exchange interaction (J_2) in the 1DIS was studied.
- Magnetic properties of FM and AFM 1DIS strongly depend on the J_2.
- AFM 1DIS has two hysteresis loops similar to the glasses for the small J_2.
- If $J_2=0$, 1DIS has a phase transition but its susceptibility can't be calculated.

GRAPHICAL ABSTRACT

The figure shows the effects of next nearest-neighbor on the critical temperature of the 1DIS.



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ABSTRACT

In this work, we investigate the effects of next nearest-neighbor exchange interaction (J_2) on the magnetic properties in the one-dimensional Ising system (1DIS) by using Kaneyoshi approach within the effective field theory for both ferromagnetic and antiferromagnetic case. It is found that the magnetic properties strongly depend on the J_2 in the 1DIS. The critical temperature of the 1DIS decreases as the J_2 decreases and it has almost a stable value ($T_c=0.571$) when the J_2 approaches to zero (but not zero). The coercive field point, remanence magnetization and the area of the hysteresis loop of the 1DIS decrease and the hysteresis curves of the 1DIS exhibit paramagnetic behaviors as the J_2 decreases. The susceptibility of the 1DIS has a distinct peak at T_c. The magnetizations of the 1DIS are $m_1=m_2=M_T=1$ in the ferromagnetic case, but they are $m_1=-1$, $m_2=1$ and $M_T=0$ in the antiferromagnetic case at $T=0$. Moreover, the hysteresis curves of the m_1 and m_2 of the AFM 1DIS exhibit elliptical hysteresis behaviors with two distinct loops similar to the glasses for small next nearest-neighbor exchange interaction values ($J_2=0.0001$, 0.001 and 0.01) and they have two different coercive field points far away from $H=0.000$.

1. Introduction

One-dimensional systems have attracted a great deal of interest in theoretical and experimental physics. Because, their analytical calculations are generally much more amenable and easier than higher-dimensional ones [1,2]. The researchers especially focus on whether the one-dimensional systems have phase transition or not. Many models have been carried out to understand this main query in the one-dimensional systems. Examples of one-dimensional models with phase transitions; the one-dimensional system of the KH_2PO_4 (KPD) is first proposed by Kittel and he found that one-dimensional system of the KPD undergoes a first-order phase transition at $T\neq 0$ [3]. Chui–Week's model with the infinite size transfer matrix which indicates the existence of phase transition in the one-dimensional systems [4]. Burkhardt's model with a transfer operator [5]. Dauxois–Peyrard's model proposed for DNA denaturation which has evidences for phase transition in the one-dimensional systems [6,7] and the results of which are in

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good agreement with the experimental results of short chains obtained by Campa and Giansanti [8]. However, many works reported in the literature suggested that the one-dimensional models have no phase transitions. Such as, Van Hove's theorem for homogeneous fluid-like models by Van Hove [9]. Generalized Van Hove's theorem for lattice models by Ruelle [10] and Dyson [11], and the most famous argument is given by Landau and Lifshitz which reinforces that there is no phase transition in one-dimension for $T \neq 0$ [12].

On the other hand, effective field theory is a very successful method for investigations of the magnetic properties of the nanostructures. Such as, magnetic properties of the Ising nanotube, Ising nanowire, Ising nanoparticle and Ising thin film were first studied by Kaneyoshi [13–30], magnetic properties of the cubic nanowire were studied by Jiang et al. [31,32], dynamic behaviors of Ising nanowire were studied by Ertaş and Kocakaplan [33], magnetic properties of the core/shell Ising nanostructures were studied by Kantar et al. [34–36], magnetic properties of Ising nanotube were studied by Magoussi et al. [37], magnetic properties of cylindrical transverse Ising nanowire were studied by Kocakaplan et al. [38], phase transitions of honeycomb-structured ferroelectric thin film were studied by Wang and Ma [39], phase diagrams of transverse Ising nanowire were studied by Bouhou et al. [40], magnetic behavior of nanowires was studied by Zaim et al. [41], band structures of the magnetic properties in a mixed Ising nanotube were studied by Şarlı [42], magnetic susceptibility and magnetic reversal events of Ising nanowire were studied by Şarlı and Keskin [43], hysteresis behaviors of Ising nanowire were studied by Keskin et al. [44], magnetic properties of Ising nanowire and core/shell nanoparticles were studied by Yüksel et al. [45,46] and phase diagrams of Ising nanowire were studied by Akıncı [47,48].

However, to the best of our knowledge, the effects of next nearest-neighbor exchange interaction (J_2) on the magnetic properties (magnetization, susceptibility, phase transition, hysteresis curves, critical temperature and coercive field point) in the one-dimensional Ising system (1DIS) have not been investigated yet. Therefore, the purpose of this paper is to investigate the effects of next nearest-neighbor exchange interaction (J_2) on the magnetic properties in the 1DIS by using Kaneyoshi approach within the effective field theory for both ferromagnetic and antiferromagnetic case.

The outline of this paper is as follows: In Section 2, we give the theoretical method. In Section 3, we present the theoretical results and discussion, followed by a brief summary.

2. Theoretical method

We investigate the magnetic properties of the ferromagnetic ($J_1>0$) and the antiferromagnetic ($J_1<0$) 1DIS shown in Fig. 1 within the effective field theory. Each site in Fig. 1 is occupied by the spin-1/2 Ising particle. By using Kaneyoshi approach [13–30], the Hamiltonian of the 1DIS is given by,

$$\mathcal{H} = -J_1\sum_{\langle ij\rangle} S_i^z S_j^z - J_2\sum_{\langle ii\rangle} S_i^z S_i^z - H\left(\sum_i S_i^z + \sum_j S_j^z\right). \tag{1}$$

where, J_1 is the exchange interaction between two nearest-neighbor magnetic atoms (m_1 and m_2) of the 1DIS. J_2 is the exchange interaction between two next nearest-neighbor magnetic atoms (m_1 and m_1 or m_2 and m_2) of the 1DIS. $S^z = \pm 1$ is the Pauli spin operator. H is the external magnetic field. The 1DIS shown in Fig. 1 has two different magnetizations; m_1 and m_2 are the magnetization of the 1DIS. m_1 and m_2 are the nearest-neighbor atoms and they interact with the nearest-neighbor exchange interaction J_1. m_1 and m_1 or m_2 and m_2 interact with the next nearest-neighbor exchange interaction J_2. One notes the next nearest-neighbor exchange interaction (J_2) should be small than the nearest-neighbor exchange interaction ($J_2<J_1$). The magnetizations of the 1DIS are given by,

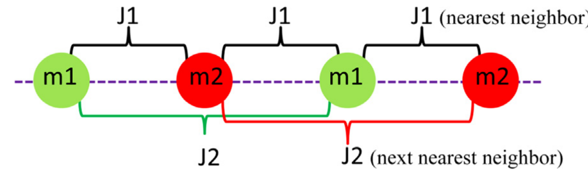

Fig. 1. Schematic representation of the one-dimensional Ising system (1DIS). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$\begin{aligned} m_1 &= [\cosh(J_1\nabla)+m_2\sinh(J_1\nabla)]^2[\cosh(J_2\nabla)+m_1\sinh(J_2\nabla)]^2 F_{S-1/2}(x)|_{x=0},\\ m_2 &= [\cosh(J_1\nabla)+m_1\sinh(J_1\nabla)]^2[\cosh(J_2\nabla)+m_2\sinh(J_2\nabla)]^2 F_{S-1/2}(x)|_{x=0}. \end{aligned} \tag{2}$$

where, $\nabla = \partial/\partial x$ is the differential operator and the function of $F_{S\text{-}1/2}(x)$ is defined by as follows for the spin-1/2 Ising particles.

$$F_{S-1/2}(x) = \tanh[\beta(x+H)]. \tag{3}$$

By using Kaneyoshi approach (KA) [13–30] for the magnetic properties of the nanostructure within the effective field theory, the magnetizations and susceptibility of the 1DIS are obtained as in Eq. (2). By using Eq. (2) and mathematical relation Eq. (4) [49], the magnetizations of the 1DIS are obtained as follows,

$$e^{a\nabla} = f(x+a). \tag{4}$$

$$\begin{aligned} m_1 &= (A_0+A_1m_1+A_2m_1^2+A_3m_1^3+\cdots)F_{\text{Spin}-1/2}(x)|_{x=0},\\ m_2 &= (B_0+B_1m_2+B_2m_2^2+B_3m_2^3+\cdots)F_{\text{Spin}-1/2}(x)|_{x=0}. \end{aligned} \tag{5}$$

By differentiating each side of Eq. (5) with H, we get the χ as follows,

$$\begin{aligned} \chi_1 &= \lim_{H\to 0}\frac{\partial m_1}{\partial H},\\ \chi_2 &= \lim_{H\to 0}\frac{\partial m_2}{\partial H},\\ \chi_1 &= (A_1+2A_2m_1+3A_3m_1^2)\chi_1 F_{\text{Spin}-1/2}(x)|_{x=0}\\ &\quad +(A_{11}+2A_{12}m_2+3A_{13}m_2^2)\chi_2 F_{\text{Spin}-1/2}(x)|_{x=0}\\ &\quad +(A_0+A_1m_1+A_2m_1^2+A_3m_1^3+\cdots)\frac{\partial}{\partial H}F_{\text{Spin}-1/2}(x)|_{x=0},\\ \chi_2 &= (B_1+2B_2m_2+3B_3m_2^2)\chi_2 F_{\text{Spin}-1/2}(x)|_{x=0}\\ &\quad +(B_{11}+2B_{12}m_1+3B_{13}m_1^2)\chi_1 F_{\text{Spin}-1/2}(x)|_{x=0}\\ &\quad +(B_0+B_1m_2+B_2m_2^2+B_3m_2^3+\cdots)\frac{\partial}{\partial H}F_{\text{Spin}-1/2}(x)|_{x=0}, \end{aligned} \tag{6}$$

by arranging Eq. (6), we obtain the χ_1 and χ_2 as follows,

$$\begin{aligned} \chi_1 &= a_1\chi_1+a_2\chi_2+a_0\frac{\partial}{\partial H}F_{\text{Spin}-1/2}(x)|_{x=0},\\ \chi_2 &= b_1\chi_1+b_2\chi_2+b_0\frac{\partial}{\partial H}F_{\text{Spin}-1/2}(x)|_{x=0}, \end{aligned} \tag{7}$$

The coefficients a_0-a_2 and b_0-b_2, are given by,

$$\begin{aligned} a_1 &= (A_1+2A_2m_1+3A_3m_1^2+\cdots)F_{\text{Spin}-1/2}(x)|_{x=0},\\ a_2 &= (A_{11}+2A_{12}m_2+3A_{13}m_2^2+\cdots)F_{\text{Spin}-1/2}(x)|_{x=0},\\ a_0 &= (A_0+A_1m_1+A_2m_1^2+A_3m_1^3+\cdots),\\ b_1 &= (B_1+2B_2m_2+3B_3m_2^2+\cdots)F_{\text{Spin}-1/2}(x)|_{x=0},\\ b_2 &= (B_{11}+2B_{12}m_1+3B_{13}m_1^2+\cdots)F_{\text{Spin}-1/2}(x)|_{x=0},\\ b_0 &= (B_0+B_1m_1+B_2m_1^2+B_3m_1^3+\cdots). \end{aligned} \tag{8}$$