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# Effects of the randomly distributed magnetic field on the phase diagrams of the Ising Nanowire II: Continuous distributions

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The effect of the random magnetic field distribution on the phase diagrams and ground state magnetizations of the Ising nanowire has been investigated with effective field theory with correlations. Gaussian distribution has been chosen as a random magnetic field distribution. The variation of the phase diagrams with that distribution parameters has been obtained and some interesting results have been found such as disappearance of the reentrant behavior and first order transitions which appear in the case of discrete distributions. Also for single and double Gaussian distributions, ground state magnetizations for different distribution parameters have been determined which can be regarded as separate partially ordered phases of the system.



## 1. Introduction

Recently there has been growing interest both theoretically and experimentally in the magnetic nanomaterials such as nanoparticles, nanorods, nanotubes and nanowires. Nowadays, fabrication of these nanomaterials is no longer difficult, since development of the experimental techniques permits us making materials with a few atoms. For instance, acicular magnetic nanoelements were already fabricated [1–3] and magnetization of the nanomaterial has been measured [4]. Nanoparticle systems have growing application areas, e.g. they can be used as sensors [5], permanent magnets [6], beside some medical applications [7]. In particular, magnetic nanowires and nanotubes have many applications in nanotechnology [8,9]. Nanowires can be used as an ultrahigh density magnetic recording media [10–12] and they have potential applications in biotechnology [13,14], such as Ni nanowires can be used for bio-separation [15,16].

In the nanometer scale, physical properties of these finite materials are different from those of their bulk counterparts. Some properties of these materials, which highly depend on the size and the dimensionality, can be used for fabrication of materials for various purposes. From this point of view, it is important to determine the properties of these materials theoretically. Most common used theoretical methods for determining the magnetic properties of these materials are mean field approximation (MFA), effective field theory (EFT) and Monte Carlo (MC) simulation as in bulk systems. For instance, nanoparticles investigated by EFT with correlations [17], MFA and MC [18]. The phase diagrams and the magnetizations of the nanoparticle described by the transverse Ising model have been investigated by using MFA and EFT [19,20]. Moreover, investigation of compensation temperature of the nanoparticle [21] and magnetic properties of the nanocube with MC [22] are among these studies.

Another method, namely variational cumulant expansion (VCE) based on expanding the free energy in terms of the action up to *m*th order, has been applied to the magnetic superlattices [23] and ferromagnetic nanoparticles [24,25]. The first order expansion within this method gives the results of the MFA.

Various nanostructures can be modeled by core–shell models and these models can be solved also by MFA, EFT and MC such as FePt and $Fe_3O_4$ nanotubes [26]. The phase diagrams and magnetizations of the transverse Ising nanowire has been treated within MFA and EFT [27,28], the effect of the surface dilution on the magnetic properties of the cylindrical Ising nanowire and nanotube has been studied [29,30], the magnetic properties of nanotubes of different diameters, using armchair or zigzag edges has been investigated with MC [31], initial susceptibility of the Ising nanotube and nanowire have been calculated within the EFT with correlations [32,33] and the compensation temperature which appears for negative core–shell coupling has been investigated by EFT for nanowire and nanotube [34]. There are also some works dealing with hysteresis characteristics of the cylindrical Ising nanowire [35,36]. Beside these, higher spin nanowire or nanotube systems have also been investigated, such as spin-1 nanotube [37], mixed spin-3/2,1 core shell structured nanoparticle [38], mixed spin-1/2,1 nanotube [39] systems.

On the other hand, as far as we know, there have less attention paid on quenched randomness effects on these systems, except the site dilution. However, including quenched randomness or disorder effects in these systems may induce some beneficial

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results. For this purpose we investigate the effects of the random magnetic field distributions on the phase diagrams of the Ising nanowire within this work. As stated in [29] the phase diagrams of the nanotube and nanowire are qualitatively similar, then investigation of the effect of the random magnetic field distribution on the nanowire will give hints about the effect of the same distribution on the phase diagrams of the nanotube.

The Ising model in a quenched random field (RFIM) has been studied over three decades. The model which is actually based on the local fields acting on the lattice sites which are taken to be random according to a given probability distribution was introduced for the first time by Larkin [40] for superconductors and later generalized by Imry and Ma [41]. Beside the similarities between diluted antiferromagnets in a homogenous magnetic field and ferromagnetic systems in the presence of random fields [42,43], the importance of the random field distributions on these systems comes from the fact that, random distribution of the magnetic field drastically affects the phase diagrams of the system, and hence the magnetic properties. This situation has been investigated widely in the literature for the bulk Ising systems. For example, using a Gaussian probability distribution, Schneider and Pytte [44] have shown that phase diagrams of the model exhibit only second order phase transition properties. On the other hand, Aharony [45] and Mattis [46] have introduced bimodal and trimodal distributions, respectively, and they have reported the observation of tricritical behavior. With the same distributions and using EFT with correlations, Borges and Silva [47–49] showed that three dimensional lattices show tricritical behavior while two dimensional lattices do not exhibit this behavior. On the other hand, by using two site EFT instead of one site EFT, tricritical behavior can be observed on a square lattice [50]. Similarly, Sarmento and Kaneyoshi [51] investigated the phase diagrams of RFIM by means of EFT with correlations for a bimodal field distribution, and they concluded that reentrant behavior of second order is possible for a system with ($q \geq 6$). Recently, Fytas et al. [52] applied MC simulations on a simple cubic lattice. They found that the transition is continuous for a bimodal field distribution, while Hadjiagapiou [53] observed reentrant behavior and confirmed the existence of a tricritical point for an asymmetric bimodal probability distribution within the MFA based on a Landau expansion.

In a recent series of papers, phase transition properties of infinite dimensional RFIM with symmetric double [54] and triple [55] Gaussian random fields have also been studied by means of a replica method and a rich variety of phase diagrams have been presented. The situation has also been handled on 3D lattices with nearest-neighbor interactions by a variety of theoretical works such as EFT [56,57], EFT with multi site spin correlations [58], MC simulations [59–61], pair approximation [62], and the series expansion method [63].

As seen in the short literature in bulk Ising systems, random field distributions keep up to date in the literature. Thus the aim of this work is to inspect the effects of random field distributions on the phase diagrams of the nanowire system as a nanostructure. The paper is organized as follows: In Section 2 we briefly present the model and formulation. The results and discussions are presented in Section 3, and finally Section 4 contains our conclusions.

## 2. Model and formulation

We consider a nanowire which has geometry shown in Fig. 1. The Hamiltonian of the nanowire is given by

$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle} s_i s_j - J_2 \sum_{\langle m,n \rangle} s_m s_n - J_3 \sum_{\langle i,m \rangle} s_i s_m - \sum_i H_i s_i - \sum_m H_m s_m \quad (1)$$

where $s_i$ is the $z$ component of the spin at a lattice site $i$ and it takes the values $s_i = \pm 1$ for the spin-1/2 system. $J_1$ and $J_2$ are the exchange interactions between spins which are located at the core and shell, respectively, and $J_3$ is the exchange interaction between the core and shell spins which are nearest neighbor to each other. $H_i$ and $H_m$ are the external longitudinal magnetic fields at the lattice sites $i$ and $m$ respectively. Magnetic fields are distributed on the lattice sites according to a given probability distribution. The first three summations in Eq. (1) are over the nearest-neighbor pairs of spins, and the other summations are over all the lattice sites.

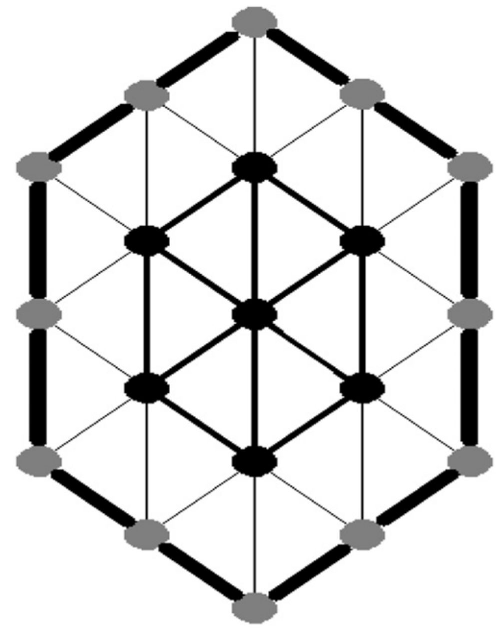

Fig. 1. Schematic representation of a cylindrical nanowire (top view). The gray/black circles represent the surface/shell magnetic atoms, respectively.

This work – as a continuation of the earlier work [68] – deals with the following continuous magnetic field distribution,

$$P(H_i) = pG(0,\sigma) + \frac{1-p}{2}[G(H_0,\sigma) + G(-H_0,\sigma)] \quad (2)$$

where $G(H_0,\sigma)$ is the Gaussian distribution centered at $H_0$ with a width $\sigma$ and it is given by

$$G(H_0,\sigma) = \left(\frac{1}{2\pi\sigma^2}\right)^{1/2} \exp\left[-\frac{(H_i - H_0)^2}{2\sigma^2}\right] \quad (3)$$

Distribution given in Eq. (2) reduces to the system with zero magnetic field (pure system) for $p = 1, \sigma = 0$. According to the distribution given in Eq. (2), $p$ percentage of the lattice sites are subjected to a magnetic field chosen from the Gaussian distribution which has $\sigma$ width and $H_0 = 0$ as a center. Half of the remaining sites are under the influence of a field $H_i$ which is randomly chosen from the magnetic field distribution $G(H_0,\sigma)$, whereas the distribution $G(-H_0,\sigma)$ used as distribution function on the remaining sites.

Four different representative magnetizations ($m_i, i = 1,2,3,4$) for the system can be given by usual EFT equations which are obtained by differential operator technique and decoupling approximation (DA) [64,65],

$$\begin{aligned}
m_1 &= t[A_1 + m_1 B_1]^4 [A_3 + m_2 B_3][A_3 + m_3 B_3]^2 [A_1 + m_4 B_1] \\
m_2 &= [A_3 + m_1 B_3][A_2 + m_2 B_2]^2 [A_2 + m_3 B_2]^2 \\
m_3 &= [A_3 + m_1 B_3]^2 [A_2 + m_2 B_2]^2 [A_2 + m_3 B_2]^2 \\
m_4 &= [A_1 + m_1 B_1]^6 [A_1 + m_4 B_1]^2
\end{aligned} \quad (4)$$

Here $m_1, m_4$ are the magnetizations of the two different representative sites in the core and $m_2, m_3$ are the magnetizations of the two different representative sites in the shell. The coefficients