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Investigation of critical phenomena and magnetism in amorphous Ising nanowire in the presence of transverse fields

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ABSTRACT

A cylindrical magnetic nanowire system composed of ferromagnetic core and shell layers has been investigated by using effective field theory (EFT) with correlations in the presence of transverse fields and surface shell amorphization. Both weak and strong exchange couplings at the core–shell interface have been considered. The main attention has been focused on the former situation where the system exhibits similar characteristic features with that observed in thin film and semi-infinite systems in which the surface effects are prominent. A complete picture of the phase diagrams and magnetization profiles has been represented and the effect of the surface shell amorphization on these properties has been discussed. Furthermore, we have investigated the ground state behavior of total magnetization m_T curves and we have observed that m_T curves exhibit highly non-monotonous and exotic ground states in the presence of frustration in the surface shell. We have also analyzed the necessary conditions for the occurrence of reentrant behavior in the system.

1. Introduction

The research on magnetic small particles is currently one of the most actively studied topics in statistical mechanics and condensed matter physics. The reason is due to the fact that these fine particles are considered as promising candidates in a wide variety of technological applications [1–7]. In particular, magnetic nanowires and nanotubes such as ZnO [8], FePt, and Fe_3O_4 [9] can be synthesized by various experimental techniques and they have many applications in nanotechnology [10,11], and they are also utilized as raw materials in fabrication of ultra-high density magnetic recording media [12–14]. Due to their reduced size, surface effects may become dominant, hence these nanoscaled small magnetic particles may exhibit several size dependent properties. For instance, it has been experimentally shown that the $La_{0.67}Ca_{0.33}MnO_3$ (LCMN) nanoparticle exhibits a negative core–shell coupling, although the bulk LCMN is a ferromagnet [15,16].

From the theoretical point of view, these systems have been studied by a wide variety of techniques such as mean field theory (MFT) [17,18], effective field theory (EFT) [19–21], Green functions (GF) formalism [22], variational cumulant expansion (VCE) [23,24], and Monte Carlo (MC) simulations [25–31]. We learned from those studies that the core–shell concept can be successfully applied in nanomagnetism, since the aforementioned methods are capable of explaining various characteristic behaviors observed in nanoparticle magnetism. The MC simulation technique [32] is regarded as a powerful numerical approach for simulating the behavior of many complex systems, including magnetic nanoparticle systems. Nevertheless, the only disadvantage of this method is the need for a large amount of computer facilities due to

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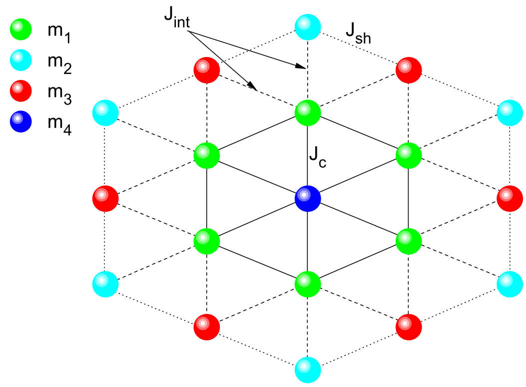

Fig. 1. Schematic representation of an infinitely long cylindrical Ising nanowire (top view). Sublattice magnetizations of the core layer are denoted by m_1 and m_4 whereas m_2 and m_3 define the sublattice magnetizations of the shell layer with the coordination numbers $z = 5$ and 6, respectively. Solid, dotted and dashed lines respectively represent the exchange interactions of the core, shell and interface.

the long calculation times originating from the exhausting sampling averaging procedures. On the other hand, despite its mathematical simplicity, EFT is considered to be quite superior to conventional MFT since the former method exactly takes into account the single-site correlations and neglects the multi-site correlations whereas the latter technique ignores the whole correlations in the calculations. Therefore the results obtained by EFT are expected to be qualitatively more precise than those obtained by MFT. EFT formalism of ferroelectric nanoparticles has been introduced for the first time by Kaneyoshi [19]. In a series of consecutive studies, he extended the theory for the investigation of thermal and magnetic properties of the nanoscaled transverse Ising thin films [33], and also for cylindrical nanowire and nanotube systems [20,34].

Despite the growing technological advances, it is still hard to fabricate pure nanomaterials. The existence of disorder, such as site and bond disorder or the presence of random fields in magnetic nanoparticle systems constitutes an important role in material science, since it may induce some important macroscopic effects on the thermal and magnetic properties of real materials [35,36]. For instance, magnetic properties of $CoFe_2O_4$ particles with a magnetically disordered surface layer, and the surface spin disorder in $NiFe_2O_4$ nanoparticles have been investigated previously [37,38]. In addition, spin-glass surface disorder in antiferromagnetic small particles [17] has been examined. Based on EFT, the phase diagrams and thermal variation of the magnetization curves of a cylindrical nanowire with diluted surface sites have been investigated, and a number of characteristic phenomena have been found [39,40]. Besides, effects of the quenched disordered shell bonds, as well as interface bonds on the magnetic properties of the same model have been considered, and it has been found that a compensation point can be induced by a bond dilution process in the surface when the antiferromagnetic interface interactions are considered [41]. Very recently, the effect of the random magnetic field distribution on the phase diagrams and ground state magnetizations of the Ising nanowire has been investigated for discrete [42] and continuous random fields [43]. It has been found in these recent works that the system may exhibit reentrant behavior and first order phase transitions for discrete distribution of random fields which disappear for continuous random fields.

Apart from these, investigation of the effect of the structural disorder on the magnetism of nanoscaled particle systems with core–shell structure would be an interesting discussion, since the problem has not yet been examined in detail for nanoscaled magnetic particles, and the situation deserves particular attention. In discrete lattice models, the structural disorder is generally characterized by a random distribution of the nearest-neighbor interactions. In surface magnetism, in order to simulate an amorphous surface, the Handrich–Kaneyoshi model of amorphous ferromagnets [44] has been widely applied in the literature for thin films and semi-infinite ferromagnets within the framework of EFT. For amorphous Ising films [45–48] it has been found that the system may exhibit reentrant behavior, as well as first order transitions depending on the thickness of the film due to the presence of structural disorder and transverse fields whereas for semi-infinite ferromagnets [49,50], in addition to the observation of reentrant behavior on the surface originating from the existence of amorphization and transverse fields, it has also been observed that the reduced magnetization curve falls below those of the corresponding crystalline ferromagnets.

The purpose of the present work is to clarify within the framework of EFT, how the magnetism in a nanoparticle system is affected in the presence of an amorphous surface shell in the presence of transverse fields. In order to simulate a realistic system, we consider different transverse fields in the core and shell layers. The outline of the paper is organized as follows: in Section 2, we briefly present our model and the related formulation. The results and discussions are presented in Section 3, and finally Section 4 is devoted to our conclusions.

2. Formulation

We consider an infinitely long nanowire system composed of the usual Ising spins which are located on each lattice site (Fig. 1). The system is composed of a ferromagnetic core which is surrounded by a ferromagnetic shell layer. At the interface, we also define an exchange interaction between core and shell spins which can be of ferromagnetic type. The Hamiltonian