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Long-range interactions in magnetic bilayer above the critical temperature

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ABSTRACT

In this paper we have studied the stabilization of the long-range order in $(z;x)$-plane of two isotropic Heisenberg ferromagnetic monolayers coupled by a short-range exchange interaction ($J_\perp$), by a long range dipole-dipole interactions and a magnetic field. We have applied a magnetic field along of the z-direction to study the thermodynamic properties above the critical temperature. The dispersion relation ω and the magnetization are given as function of dipolar anisotropy parameter defined as $E_d = (g\mu)^2 S/a^3 J_\parallel$ and for other Hamiltonian parameters, and they are calculated by the double-time Zubarev-Tyablikov Green's functions in the random-phase approximation (RPA). The results show that the system is unstable for values of $E_d \geq 0.012$ with external magnetic field ranging between $H/J_\parallel = 0$ and 10^{-3}. The instability appears for E_d larger then $E_d^c = 0.0158$ with $H/J_\parallel = 10^{-5}$, $E_d^c = 0.02885$ with $H/J_\parallel = 10^{-4}$, and $E_d^c = 0.115$ with $H/J_\parallel = 10^{-3}$, i.e., a small magnetic field is sufficient to maintain the magnetic order in a greater range of the dipolar interaction.

1. Introduction

In the last three decades it has been of great interest to know the magnetic properties of thin films [1–3]. These systems are interesting because they are linked to technological applications which moves the advancement of condensed matter physics [4]. There are also academic interests that considers interesting the highly non-linear response to small disturbances, and also because they present new physical phenomena, such as, giant magnetoresistance [5] and oscillating interlayer exchange coupling [6]. They also are interesting due to exist contradictions between theoretical and experimental predictions, for example, Bloch [7] indicated that a 2D magnetic system, whose spins are coupled by isotropic short-range exchange interactions, cannot display any long-range magnetic order at finite temperature, this result was proved by Mermin and Wagner [8]. From an experimental point of view, the literature results show that 2D magnetic systems exhibit phase transitions at finite temperature [9–15,17]. Naturally this fact occurs because a real system is composed by particles coupled by various interactions (short, long, isotropic and anisotropic, and so on). Besides this fact and considering that, strictly speaking, there are not experimental realizations easy of magnetic systems in two dimensional, and then in many practical cases, the quasi-two-dimensional systems are used as a good approximation [16]. Therefore, it does not violate Mermin-Wagner theorem.

The classical and quantum Heisenberg model is the most appropriate theoretical model to describe static magnetism in a 2D lattice. For this reason, it is very important to increase the knowledges about the Heisenberg model once this theoretical description can give us the overall thermodynamic properties in magnetic systems. On the other hand, in its simplest case, this model incorporates only a short-range isotropic exchange coupling, and for this reason, the isotropic Heisenberg model in 2D does not explain the long-range order. There are several others studies that generalize the Heisenberg model, for example the introduction of interactions like magnetocrystalline anisotropy [18–20] and dipole-dipole interactions [21–23], that give rise relevant results and more realistic. These interactions completely change the properties of the magnetic system, giving an explanation about the long-range order to the theoretical model. Regarding the dipole-dipole interaction, it is very interesting to observe that this interaction give a weaker contribution than the exchange interaction, but it is a long-range and isotropic interaction in the spin space. Therefore, due to both properties the dipole-dipole interaction is essential for stabilizing long-range magnetic order, as have been shown at long time ago [21,22], and recently [24].

A further interesting question accounts for the competition between the exchange interaction and the magnetic anisotropy. In thin films, as in transition metal, the isotropic exchange interaction is much larger than the anisotropy, but experimental results shows that such anisotropies affect the magnetic properties of the ferromagnetic and paramagnetic phases. This magnetic anisotropy ranges, besides the Curie temperature (T_c) is one important difference between magnetism in 2D and 3D lattices.

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In addition, ferromagnetic systems such as $(CH_3NH_3)_2$-$CuCl_4$, which has a quasi-two-dimensional ordination, presents anisotropy of magnetic susceptibility preserved until $T \approx 1.2T_c$ [25], although several experimental technique has been used to investigate the existence of an isotropic magnetic susceptibility in epitaxial Fe/W(110) films [26] and in Co-films grown on a vicinal *Cu*-substrate [27], both with paramagnetic phase.

Moreover, a great attention has been given to understand the competition between interactions of short- and long-ranges [28–30]. In particular, the elementary excitation spectrum of a system, only with ferromagnetic isotropic exchange interaction, presents in 2D and 3D lattices an excitation mode proportional to k^2, i.e., ($\omega \sim k^2$) in the region of $k \to 0$. When the dipolar interaction is taken into account, the shape of the dispersion relation changes dramatically. The 3D case presents $\omega \sim k$ and the 2D case presents $\omega \sim \sqrt{k}$.

In the present paper, we applied the Green's functions technique to extend the previously work by Arruda and co-workers [23], in which the problem of competition between exchange interaction, with short-range order, and the dipole-dipole interaction shows that the dipole-dipole interaction leads from a ferromagnetic order to an instability at a critical value $E_d^c = 0029$, in a system composed by a bilayer of cubic (001) lattice. In our calculation, we applied a magnetic field H along of z direction and show that a field with low intensity is enough to give rise stability to the long-range order interaction.

The remainder of the paper is organized as follows. The Hamiltonian model and theoretical method are introduced in Sec. 2. In Sec. 3, we present an discuss the results obtained for the dispersion relation, the thermal behavior of the magnetization and finally some conclusions are given.

2. Theoretical model and Green's functions formalism

In this paper, we calculate the effects of a dipolar interaction on the magnetic properties of ferromagnetic bilayer above the critical temperature due to application of an external magnetic field. The system is composed by two superposed layers, namely *l*- and *m*-layer, of a square lattice sorted out by a distance y, corresponding to a 3D tetragonal structure, and in particular to a (010) simple cubic one for $y = a$, as show the schematic representation in Fig. 1. Each layer is composed by $N/2$ magnetic moments and each magnetic moment interact ferromagnetically with the nearest neighbor spins through short-range exchange interaction ($J > 0$). Here $J = (J_\parallel, J_\perp)$, where $J_\parallel$ couples only the nearest neighbor spins located within each layer and $J_\perp$ couples the nearest neighbor spins located in the different layers. The interaction of a magnetic moment with all others is considered through the dipolar long-range interaction. An external magnetic field is applied in the direction of easy z-axis at all lattice points. We have considered the bilayer immersed in a non-magnetic medium, i.e., diamagnetic material, represented by a 2D quantum Heisenberg model of spin-1/2 with short-range interactions, long-range interactions and a Zeeman term, which is described by the total Hamiltonian.

$$\mathcal{H} = \mathcal{H}_{ex} + \mathcal{H}_{ze} + \mathcal{H}_{dd}, \tag{2.1}$$

where, $\mathcal{H}_{ex}$ is the exchange interaction Hamiltonian, $\mathcal{H}_{ze}$ is the Zeeman effect Hamiltonian and $\mathcal{H}_{dd}$ is the dipole-dipole interaction Hamiltonian. We consider the spins S localized on the sites of two infinite square lattices parallel to the (z, x)-plane. Moreover, we are assuming that the nearest neighbor spins interact ferromagnetically in the plane and between planes. Now, introducing the relation $S_i^\pm = S_i^x \pm iS_i^y$, and the commutation relations between the spin operators $[\mathbf{S}_i^-, \mathbf{S}_j^+] = 2\mathbf{S}_i^z\delta_{ij}$ and $[\mathbf{S}_i^\pm, \mathbf{S}_j^z] = \mp\mathbf{S}_i^\pm\delta_{ij}$, the exchange interaction Hamiltonian $\mathcal{H}_{ex}$ (short-range) can be written as

$$\mathcal{H}_{ex} = -\sum_{i\neq j}\sum_{j} J_{ij}\left[\frac{1}{2}(S_i^+S_j^- + S_i^-S_j^+) + S_i^zS_j^z\right]. \tag{2.2}$$

where the summations run over all distinct pairs of nearest neighbor spins on the lattice. The J_{ij} is equal to $J_\parallel$ in plane and $J_\perp$ in inter-plane. The term of Zeeman effect in Eq. (2.1), due to external magnetic field applied along the z-axis, is given by

$$\mathcal{H}_{ze} = -h\sum_i S_i^z. \tag{2.3}$$

This term ensures that in the ground state ($T = 0$), the magnetic dipole moments are aligned in the direction of the z-axis. In this equation, we have $h = g\mu_B H_0$, where μ_B is the Bohr magneton, H_0 is the external magnetic field and g is the Landé factor.

The dipole-dipole interaction Hamiltonian (long-range), in Eq. (2.1), is given by Refs. [23,30].

$$H_{dd} = \frac{1}{2}g^2\mu_B^2\sum_{i\neq j}\sum_{j}\frac{1}{R_{ij}^3}\left\{\mathbf{S}_i\cdot\mathbf{S}_j - \frac{3}{R_{ij}^2}(\mathbf{S}_i\cdot\mathbf{R}_{ij})\,(\mathbf{S}_j\cdot\mathbf{R}_{ij})\right\}, \tag{2.4}$$

where $\mathbf{R}_{ij} = \mathbf{R}_i - \mathbf{R}_j$ is the relative position of sites *i*-*j*, which can be written in terms of circular coordinates. Now, introducing $\gamma = g\mu_B$, $R_{ij}^\pm = R_{ij}^x \pm iR_{ij}^y$ and using the commutation relations between the spin operators above defined, we obtain

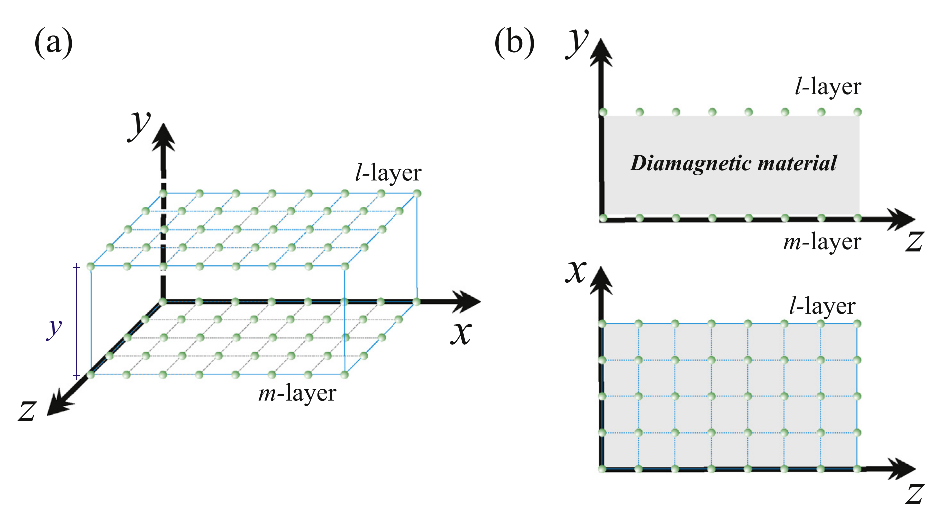

Fig. 1. (a) 3D Schematic representation of a magnetic bilayer geometry. Two points of view are shown in (b) with a diamagnetic material between the layers: (*y*,*z*) plane on top and (*x*,*z*) plane on bottom.