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The magnetic properties of the two-dimensional square lattice mixed-spin anisotropic Heisenberg ferromagnet with a transverse magnetic field

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ABSTRACT

The two-dimensional square lattice mixed-spin anisotropic Heisenberg ferromagnet with a transverse magnetic field is studied by means of the double-time Green's function. The analytic expressions of the critical temperature, the high-temperature zero-field susceptibilities, the spin-wave velocity, spin-wave stiffness and spin-wave gap are obtained. The phase diagrams in which the critical temperature, the reorientation temperature and the reorientation magnetic field are shown as a function of single-ion anisotropic parameter are discussed.

1. Introduction

Since the discovery of colossal magnetoresistance (CMR) in hole-doped ferromagnetic manganite materials $La_{1-x}Sr_xMnO_3$, attention has been directed to the study of the magnetic properties of a mixed spin ferromagnet system [1–8]. This is because that, for the high-doped region of $0.15 < x < 0.5$, the dynamics of these systems is mainly governed by the Mn ions, whose average valence changes with x between 4+ and 3+. The Mn^{4+} ions have non-compensated spins in the t_{2g}^3 configuration, which give rise to localized $s = \frac{3}{2}$ spins. On the other hand, the Mn^{3+} ($S = 2$) ions have an extra e_g electron (with $s = \frac{1}{2}$) that couples ferromagnetically to the t_{2g} spins. The e_g electrons tend to be itinerant, and lower their kinetic energy by polarizing with ferromagnetic character the localized t_{2g} spins [9]. Therefore, $La_{1-x}Sr_xMnO_3$ is a very typical mixed-spin ferromagnet in the range of $0.15 < x < 0.5$. The magnetic properties of $La_{1-x}Sr_xMnO_3$ ($0.15 < x < 0.5$) can be described by a mixed spin isotropy Heisenberg ferromagnet model [10–13]. Some theories have been used to study the magnetic properties of $La_{1-x}Sr_xMnO_3$ by means of a mixed-spin isotropy Heisenberg ferromagnet model and give good results compared with experiments [10–13].

However, the crystal lattice structure of epitaxial $La_{0.7}Sr_{0.3}MnO_3/SrTiO_3$ on silicon substrates is not a pseudo-cubic perovskite structure but a two-dimensional thin films [14,15]. Moreover, experiments show that its structure is of a uniaxial anisotropy along the direction normal to the plane and an in-plane anisotropy of thin films. Experimentally, Golosovsky and co-workers measure in detail the spin-wave stiffness and anisotropy field of these thin films [14]. Very recently, Belmeguenai and co-workers study the temperature dependence of magnetic properties of these thin films [15]. However, experimental work is still very scarce. Especially, some parameters values are still not determined, such as the values of perpendicular to plane uniaxial anisotropy and in-plane anisotropy. Therefore, it will lead to a very large difficult to study epitaxial $La_{0.7}Sr_{0.3}MnO_3/SrTiO_3$ thin films in theory. Theoretically, to our knowledge, thus their magnetic properties of has not yet been studied in the literature. However, based on experimental analysis, if one want to study the magnetic properties of $La_{0.7}Sr_{0.3}MnO_3/SrTiO_3$ in theory, he should adopt a two-dimensional mixed-spin anisotropic Heisenberg ferromagnet model [14,15].

It is very important to study the magnetic properties of these thin films. This is because that they are of potential applications that utilize both information processing and data storage in the same device, such as high-density magnetic memories, sensors, and infrared bolometers [14–17]. However, based on above analysis, it is difficult to as a theoretical investigation for these thin films. Therefore, in this Letter, we a mere consider a two-dimensional uniaxial single-ion anisotropic mixed-spin Heisenberg ferromagnet model within a transverse magnetic field by means of double-time Green's function method (DTGFM) in theory.

It is well known that the Green's function method is a powerful tool for calculating the magnetization [18,19]. Although only

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one component of the magnetization was calculated by the DTGFM before the year of 2000, since then method has been developed to calculate all three components of the magnetization in magnetic systems by means of the DTGFM within random phase approximation (RPA) for the terms concerning exchange interaction [20–25] and Anderson–Callen's decoupling (ACD) for the terms concerning the single-ion anisotropy [20,21,26].

There have been mainly two kinds of methods used to calculate all three components of the magnetization. One method is to calculate the statistical averages of spin operators simultaneously [20-23], and the other is to use the frame rotation method (FRM) [24,25]. The former needs to construct the three-component Green's functions. Thus calculation is very tedious. And the latter only needs to construct the one-component Green's function. Its theoretical deduction is analogy to deduce one component of the magnetization case. The calculation is simple relatively and saves the computation time.

In this Letter, we use FRM by means of DTGFM to study the magnetic properties of the two-dimensional mixed-spin anisotropic Heisenberg ferromagnet within a transverse magnetic field. The Letter is organized as follows. In Section 2, we set up the Hamiltonian and derive the basic self-consistent equations by use of the formulism of the Green's function. In Section 3, we discuss our results. In the last section, we present some concluding remarks.

2. Model and formulism

In this Letter, we study the magnetic properties of the mixed-spin anisotropic Heisenberg ferromagnet within a transverse magnetic field on two-dimensional square lattice (TDSL). Its Hamiltonian is given by:

$$H=-2J\sum_{\langle i,j\rangle}\left[s_i^xS_j^x+s_i^yS_j^y+s_i^zS_j^z\right]-D\sum_i\left(s_i^z\right)^2-D\sum_j\left(S_j^z\right)^2-h^x\left(\sum_i s_i^x+\sum_j S_j^x\right),\tag{1}$$

where the summation is over the nearest neighbor spins. $J>0$ is the ferromagnetic exchange integral. s_i^x, s_i^y, s_i^z and S_j^x, S_j^y, S_j^z are the spin(s,S) operators at sites i, j, with $s=\frac{3}{2}$ and $S=2$, respectively. The parameter D represents the single-ion anisotropy. h^x is the external magnetic field along x axis (i.e. the transverse magnetic field).

In this Letter, we use the same theoretical method described in Refs. [24,25]. This method is based on a transformation of the fixed coordinate system (x,y,z) into a local coordinate system (x',y',z'), where the new z' axis is parallel to the magnetization. We confine the rotation in the xz plane of a single square layer and only consider in-plane magnetization. Hence no demagnetization field needs to be taken into account. This means $y=y'$. Note that the magnitude of spin s is less than S. Therefore the spins s_i and S_j deviated from the z axis angles are different. Based on above analysis, this gives:

$$\langle s_i^{x'}\rangle=\langle s_i^{y'}\rangle=\langle S_j^{x'}\rangle=\langle S_j^{y'}\rangle=0.\tag{2}$$

The magnetizations in the fixed system (x,y,z) can be read as:

$$\langle s_i^x\rangle=\langle s_i^{z'}\rangle\sin\theta_s,\qquad \langle s_i^z\rangle=\langle s_i^{z'}\rangle\cos\theta_s,$$
$$\langle S_j^x\rangle=\langle S_j^{z'}\rangle\sin\theta_S,\qquad \langle S_j^z\rangle=\langle S_j^{z'}\rangle\cos\theta_S,\tag{3}$$

where $\langle s_i^{z'}\rangle$ and $\langle S_j^{z'}\rangle$ are the total magnetizations of spins s and S, respectively. $\langle s_i^z\rangle$ and $\langle S_j^z\rangle$ are the magnetization components normal to the film plane while $\langle s_i^x\rangle$ and $\langle S_j^x\rangle$ denote the components parallel to the film plane. θ_s and θ_S are the spins s and S deviated from the z axis angles, respectively. Of course, the angles θ_s and θ_S are *a priori* unknown.

We introduce the spin raising and lowering operators $B_i^{\pm\prime}=B_i^{x\prime}\pm iB_i^{y\prime}$, which satisfies the commutation relations $[B_i^{+\prime},B_j^{-\prime}]=2B_i^{z\prime}\delta_{ij}$ and $[B_i^{\pm\prime},B_j^{z\prime}]=\mp B_i^{\pm\prime}\delta_{ij}$. Where $B=s$ or S. Eq. (1) can be rewritten as

$$\begin{aligned}
H={}&-2J\sum_{\langle i,j\rangle}\Big[\frac{1}{4}\left(s_i^{+\prime}S_j^{+\prime}+s_i^{-\prime}S_j^{-\prime}\right)(\sin\theta_S\sin\theta_s+\cos\theta_S\cos\theta_s+1)\\
&+\frac{1}{4}\left(s_i^{+\prime}S_j^{-\prime}+s_i^{-\prime}S_j^{+\prime}\right)(\sin\theta_S\sin\theta_s+\cos\theta_S\cos\theta_s+1)\\
&+s_i^{z\prime}S_j^{z\prime}(\sin\theta_S\sin\theta_s+\cos\theta_S\cos\theta_s)\\
&+\frac{1}{2}s_i^{z\prime}\left(S_j^{+\prime}+S_j^{-\prime}\right)(\cos\theta_S\sin\theta_s-\sin\theta_S\cos\theta_s)\\
&-\frac{1}{2}\left(s_i^{+\prime}+s_i^{-\prime}\right)S_j^{z\prime}(\cos\theta_S\sin\theta_s-\sin\theta_S\cos\theta_s)\Big]\\
&-D\sum_i\Big[\frac{1}{4}\left(s_i^{+\prime}s_i^{+\prime}+s_i^{-\prime}s_i^{-\prime}+s_i^{+\prime}s_i^{-\prime}+s_i^{-\prime}s_i^{+\prime}\right)\sin^2\theta_s\\
&+s_i^{z\prime}s_i^{z\prime}\cos^2\theta_s-\frac{1}{4}\left(s_i^{z\prime}s_i^{+\prime}+s_i^{z\prime}s_i^{-\prime}+s_i^{+\prime}s_i^{z\prime}+s_i^{-\prime}s_i^{z\prime}\right)\sin 2\theta_s\Big]\\
&-D\sum_j\Big[\frac{1}{4}\left(S_j^{+\prime}S_j^{+\prime}+S_j^{-\prime}S_j^{-\prime}+S_j^{+\prime}S_j^{-\prime}+S_j^{-\prime}S_j^{+\prime}\right)\sin^2\theta_S\\
&+S_j^{z\prime}S_j^{z\prime}\cos^2\theta_S-\frac{1}{4}\left(S_j^{z\prime}S_j^{+\prime}+S_j^{z\prime}S_j^{-\prime}\right.\\
&\left.+S_j^{+\prime}S_j^{z\prime}+S_j^{-\prime}S_j^{z\prime}\right)\sin 2\theta_S\Big]\\
&-h^x\Big\{\sum_i\left[\left(s_i^{+\prime}+s_i^{-\prime}\right)\cos\theta_s+s_i^{z\prime}\sin\theta_s\right]\\
&+\sum_j\left[\left(S_j^{+\prime}+S_j^{-\prime}\right)\cos\theta_S+S_j^{z\prime}\sin\theta_S\right]\Big\}.
\end{aligned}\tag{4}$$

In order to obtain the magnetizations and the energy of the magnetic excitations, we consider the Green's function:

$$G_{AA}^{\pm\prime}=\langle\langle A_i^{\pm\prime};e^{uA_j^{z\prime}}A_j^{-\prime}\rangle\rangle\tag{5}$$

where $A=s,S$, and u is the Callen parameter [26]. The FRM was used by two different groups [24,25]. They gave different formulas for the energy spectrum. However, these formulas did not give a visible difference for magnetization in the numerical results. Hence, in this Letter, we will follow Schwieger [24] consideration. Ultimately, we choose the Green's function:

$$G_{AA}^{+\prime}=\langle\langle A_i^{+\prime};e^{uA_j^{z\prime}}A_j^{-\prime}\rangle\rangle.\tag{6}$$

We derive the equation of motion of the Green's function by a standard procedure [18,19]. In the course of this, the higher order Green functions have to be decoupled. For the terms concerning exchange interaction in Eq. (4), we use a RPA decoupling [18,19]:

$$\langle\langle A_l^{z\prime}A_i^{+\prime};e^{uA_j^{z\prime}}A_j^{-\prime}\rangle\rangle=\langle A_l^{z\prime}\rangle\langle\langle A_i^{+\prime};e^{uA_j^{z\prime}}A_j^{-\prime}\rangle\rangle,\quad l\neq i.\tag{7}$$

For the terms concerning the single-ion anisotropy, we adopt the ACD [20,21,26]:

$$\langle\langle A_l^{+\prime}A_l^{z\prime}+A_l^{z\prime}A_l^{+\prime};e^{uA_j^{z\prime}}A_j^{-\prime}\rangle\rangle=C_A\langle\langle A_l^{+\prime};e^{uA_j^{z\prime}}A_j^{-\prime}\rangle\rangle,\tag{8}$$

where

$$C_A=2\langle A_l^{z\prime}\rangle\left\{1-\frac{1}{2A^2}\left[A(A+1)-\langle\left(A_l^{z\prime}\right)^2\rangle\right]\right\}.\tag{9}$$