Journal of Magnetism and Magnetic Materials 411 (2016) 55–61

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Compensation temperature of the two-dimension mixed spin-1 and spin-3/2 anisotropic Heisenberg ferrimagnet

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ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form
27 February 2016
Accepted 16 March 2016
Available online 17 March 2016

Keywords:
Ferrimagnetic system
Compensation temperature
Critical temperature
Anisotropy
Thermodynamic function

ABSTRACT

We study a two-dimensional Heisenberg ferrimagnet composed of spin-1 and spin-3/2 sublattices considering both exchange and single-ion anisotropies. The adjoint effects of the two anisotropies on the possible compensation point are investigated. It is concluded that a primary condition for the compensation point to appear is that the single-ion anisotropy of the smaller spins should be nonzero and be greater than a certain value which depends on other parameters. The exchange anisotropy can raise the compensation point slightly. The thermodynamic functions are evaluated. All the thermodynamic functions with various parameter values are smooth no matter whether there is a compensation point or not. Thus, from the thermodynamic functions, one is unable to judge if the compensation occurs.

1. Introduction

A ferrimagnetic material is of populations of atoms with opposing magnetic moments. Explicitly, a ferrimagnet can be partitioned into two sublattices of which the atomic magnetic moments take opposing directions, like an antiferromagnetic material. However, the opposing moments are unequal in magnitudes. Thus, unlike antiferromagnets, a ferrimagnetic material has a measurable net magnetization at low temperature, even in the absence of external magnetic fields, although the magnetization will vanish above a critical temperature T_C. The magnetizations in different sublattices have, in general, different temperature dependence. Therefore, they may cancel each other at a certain temperature T_{com}, known as a compensation point, below T_C. Such compensation points have been observed in a number of real materials, and are of obvious technological interest [1,2].

Theoretical techniques have been employed to understand the magnetic properties of ferrimagnetic systems. Some examples are the mean field theory [3–6], the effective field theory [7–10], the Oguchi approximation [11], the Monte-Carlo simulation [12–14], the Bethe recursion [15], the spin wave theory [16], the Green's function theory [17–20] etc., and even the dynamic equation [21,22].

In studying the ferromagnetic systems, a main topic was the appearance of the compensation point. Usually, in the model investigations of ferrimagnetic systems, the single-ion anisotropy and/or Ising model were used [4,10,13,14,19–22]. The aim was to contain sufficient anisotropy to produce the compensation point. The Ising model is the extreme case that the exchange anisotropy is the strongest. Often, to strengthen the mechanism of the compensation, the next-nearest neighbor exchanges were also included [18–22]. In a recent research [18], only exchange anisotropy was considered without the single-ion anisotropy. It was found that in this case, the next-nearest neighbor exchanges, at least in the sublattice with the lower spin quantum number, was necessary for the compensation to appear. The least necessary condition for the compensation point to appear is still desirable.

In this paper, we intend to investigate the adjoint effects of both the single-ion and exchange anisotropies on the compensation point. We do not consider the next-nearest neighbor exchanges. We will clarify that when there is only the nearest neighbor exchanges the single-ion anisotropy of the sublattice with the lower spin quantum number should be beyond a certain value, which depends on other parameters.

Another point we consider in this paper is the thermodynamic functions of ferrimagnetic systems, calculations of which have not been seen yet. We will evaluate internal energy, free energy and entropy. Our aim is to see if the compensation point can be reflected in the thermodynamic function curves.

The mentioned sublattices in a ferrimagnetic lattice can in fact be different types. One is that all the nearest neighbor sites of each

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http://dx.doi.org/10.1016/j.jmmm.2016.03.060
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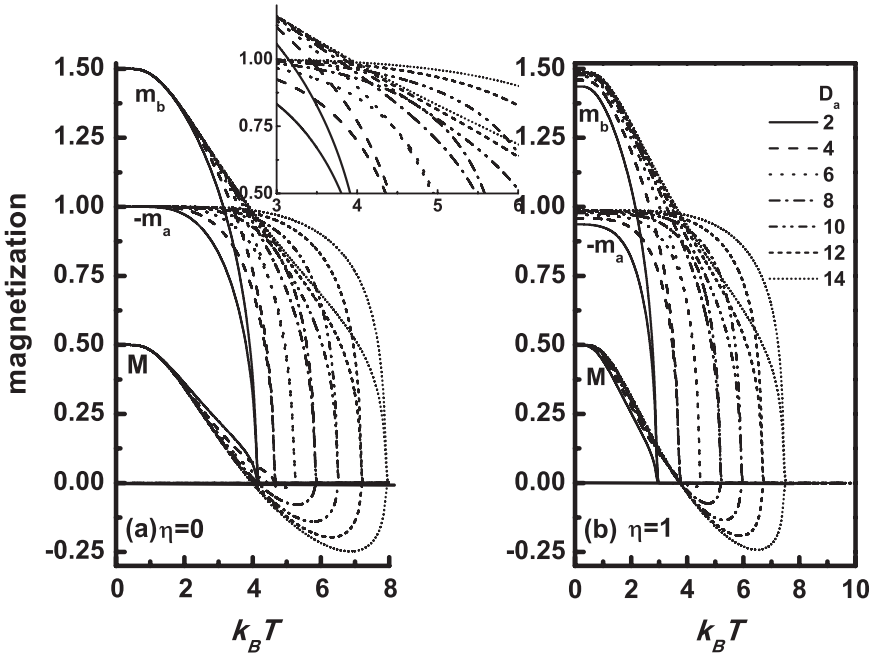

Fig. 1. Temperature dependence of the magnetizations for different D_a values and $D_b = 0$. (a) $\eta = 0$. The inset is the enlargement of the regions around the crosses of the m_a and $-m_b$ to clearly show that the compensation point lowers with rising D_a. (b) $\eta = 1$.

spin in a sublattice belong to the other sublattice. This type of ferrimagnetic structure can roughly be called Néel state. Another one is that for each spin in a sublattice, part of its nearest neighbors belong to the same sublattice and the other part belong to the other sublattice, which can be roughly called collinear state. In this paper, we will investigate the Néel structure.

Among the mentioned theoretical techniques, the many-body Green's function method has advantages that it is applicable to the whole temperature range [23] and the physical meaning is understandable in the process of deriving formalism. Therefore, we will employ the Green's function method to study the ferrimagnetic lattices.

This paper is arranged as follows. In Section 2, the model and method are presented. In Section 3, results and discussions are given. Finally, Section 4 is our conclusions.

2. Model and method

Our ferromagnetic model is a two-dimensional square lattice composed of mixed spin-1 and spin-3/2 sublattices. Each spin-1 has four nearest spin-3/2 and vice versa, so that it is of a Néel structure. The two sublattices are labeled by subscripts a and b, and the spins are of spin quantum numbers $S_a = 1$ and $S_b = 3/2$, respectively. The Hamiltonian reads

$$H = J\sum_{\langle i,j\rangle}\left[\frac{\eta}{2}(S_{ai}^{+}S_{bj}^{-} + S_{ai}^{-}S_{bj}^{+}) + S_{ai}^{z}S_{bj}^{z}\right] - D_a\sum_i\left(S_{ai}^{z}\right)^2 - D_b\sum_j\left(S_{bj}^{z}\right)^2, \quad (1)$$

where the sums $\langle i, j\rangle$ runs over the nearest neighbor (nn) lattice sites. J is the antiferromagnetic exchange interaction between the nn spins. Throughout this paper, we let $J = 1$. In the Hamiltonian, we have taken into account both the exchange anisotropy and single-ion anisotropy. The parameterη reflects the exchange anisotropy and its value is between 0 and 1. The smaller the η value, the stronger the exchange anisotropy. As $\eta = 0$, we retrieve Ising models. The parameters D_a and D_b reflect the single-ion anisotropy of the two sublattice spins, respectively. In this paper, these two parameters are always assumed positive, meaning the easy-axis anisotropy. The magnetizations of the two sublattices are defined as the quantum statistical average of the spin operators, $m_a = \langle S_a^z\rangle$, and $m_b = \langle S_b^z\rangle$, respectively.

In order to evaluate the sublattice magnetizations, four kinds of Green functions are introduced:

$$G_{aa} = \left\langle\left\langle S_{ai}^{+}; e^{uS_{aj}^{z}}S_{aj}^{-}\right\rangle\right\rangle, \quad (2a)$$

$$G_{ba} = \left\langle\left\langle S_{bi}^{+}; e^{uS_{aj}^{z}}S_{aj}^{-}\right\rangle\right\rangle, \quad (2b)$$

$$G_{bb} = \left\langle\left\langle S_{bi}^{+}; e^{uS_{bj}^{z}}S_{bj}^{-}\right\rangle\right\rangle, \quad (2c)$$

$$G_{ab} = \left\langle\left\langle S_{ai}^{+}; e^{uS_{bj}^{z}}S_{bj}^{-}\right\rangle\right\rangle, \quad (2d)$$

where u is the Callen parameter [24]. We derive the equation of motion of the Green's function via the standard procedure [23]. In the course of derivation, the higher order Green's functions have to be decoupled. For the terms concerning exchange interaction in Eq. (1), we use a Tyablikov or random phase approximation (RPA) decoupling [23,25]

$$\left\langle\left\langle S_{Fl}^{z}S_{Fi}^{+}; e^{uS_{Fj}^{z}}S_{Fj}^{-}\right\rangle\right\rangle = \left\langle S_{Fl}^{z}\right\rangle\left\langle\left\langle S_{Fi}^{+}; e^{uS_{Fj}^{z}}S_{Fj}^{-}\right\rangle\right\rangle;\ l \neq i, \quad (3)$$

where $F = a, b$. For the terms concerning the single-ion anisotropy, we adopt the Anderson-Callen decoupling [26–28],

$$\left\langle\left\langle S_{Fi}^{z}S_{Fi}^{+} + S_{Fi}^{+}S_{Fi}^{z}; e^{uS_{Fj}^{z}}S_{Fj}^{-}\right\rangle\right\rangle = C_F\left\langle\left\langle S_{Fi}^{+}; e^{uS_{Fj}^{z}}S_{Fj}^{-}\right\rangle\right\rangle, \quad (4)$$

where

$$C_F = 2D_F m_F\left\{1 - \frac{1}{2S_F^2}\left[S_F(S_F+1)\right] - \left\langle\left(S_{Fi}^{z}\right)^2\right\rangle\right\}. \quad (5)$$

The Green's functions are Fourier-transformed into wave vector space. Then, by means of the well-known spectral theorem