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LETTER TO THE EDITOR

Effects of applied transverse field on compensation temperature in a disordered ferrimagnetic binary alloy

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Abstract. The effects of applied transverse field on magnetic properties (transition temperature, compensation temperature and magnetization) of a disordered ferrimagnetic binary alloy which can exhibit two compensation points are examined. It is proposed that the application of a weak transverse field to the sample may be a useful experimental method for finding more than one compensation point as well as the characteristic features in the thermal variation of magnetization not predicted in the Néel theory.

1. Introduction

Ferrimagnetism has been intensively investigated in the past both theoretically and experimentally. Ferrimagnets have several sublattices with a finite resultant moment, comparable with the spontaneous moments of sublattices. In particular, for ferrimagnetic materials there is an interesting possibility of the existence, under certain conditions, of a compensation temperature T_{comp}, at which the resultant magnetization vanishes. The appearance of a compensation point is due to the fact that the magnetic moments of the sublattices compensate each other completely at $T = T_{\mathrm{comp}}$, due to the different temperature dependences of the sublattice magnetizations. In the standard text books of magnetism [1], it is usually written that above this temperature the compensation is no longer obtained, and the resultant moment does not disappear until the Curie point T_{C} is reached.

On the other hand, we have recently found that more than one compensation point can exist in a disordered ferrimagnetic binary alloy of the type $\mathrm{A}_p\mathrm{B}_{1-p}$ consisting of $S_{\mathrm{A}} = \frac{1}{2}$ and $S_{\mathrm{B}} = \frac{3}{2}$ by the use of the two frameworks, namely the standard mean-field theory (MFT) and the effective-field theory with correlations [2]. The purpose of this work is via the MFT to clarify the effects of magnetic field applied perpendicularly to the spontaneous magnetization axis on compensation temperature in the disordered ferrimagnetic binary alloy. As far as we know, such a study has not been carried out. In particular, the results obtained here may clarify the fact that the applied transverse field can control the compensation points.

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2. Formulation

We consider a binary two-sublattice ferrimagnetic Ising spin system (or A_pB_{1-p}) where p is the concentration of A atoms. Let the A and B atoms have different spins ($S_A = \frac{1}{2}$ and $S_B = \frac{3}{2}$) respectively. The Hamiltonian of the system is given by

$$\begin{aligned}\mathcal{H} = \sum_{i<j}\Big[J_A\delta_{iA}\delta_{jA} + J_B\delta_{iB}\delta_{jB} + J_{AB}\big(\delta_{iA}\delta_{jB} + \delta_{iB}\delta_{jA}\big)\Big]S_i^z S_j^z \xi_i\xi_j \\ - H\sum_i\big(\delta_{iA} + \delta_{iB}\big)S_i^x\xi_i\end{aligned} \tag{1}$$

where the $J_{\alpha\beta}$ ($J_{\alpha\alpha} = J_\alpha$) are the exchange interaction between type-α and type-β atoms and the first sum is over all nearest-neighbour pairs. The S_i^z, S_i^x on A atoms are the components of the spin-$\frac{1}{2}$ operator and the S_i^z, S_i^x on B atoms are the components of the spin-$\frac{3}{2}$ operator. H is the magnetic field applied perpendicularly to the spontaneous magnetization axis (or the z axis) and $\delta_{i\alpha}$ (α = A or B) expresses that a site i is occupied by a type-α atom. ξ_i is a random variable which takes the value of unity or zero. Performing the random average (or $\langle\ldots\rangle_r$), the averaged value of ξ_i has a restriction

$$\langle\xi_i\delta_{iA}\rangle_r + \langle\xi_i\delta_{iB}\rangle_r = 1 \tag{2}$$

where $\langle\xi_i\delta_{iA}\rangle_r = p$ is the concentration of A atoms.

In contrast to the previous work [2], the existence of a transverse field H in (1) requires a new formulation for the calculation of $\langle\langle S_i^z\rangle\xi_i\delta_{iA}\rangle_r$ even in the MFT, especially for the magnetization of B atoms, where $\langle\ldots\rangle$ denotes the canonical ensemble average. The formulation is obtained in our recent work [3]. In the MFT, the averaged magnetizations of A and B atoms parallel to the z axis are then given by

$$m_A = \frac{\langle\langle S_i^z\rangle\xi_i\delta_{iA}\rangle_r}{\langle\xi_i\delta_{iA}\rangle_r} = \frac{E_A}{2\Theta_A}\tanh\left(\frac{\beta}{2}\Theta_A\right) \tag{3}$$

and

$$m_B = \frac{\langle\langle S_i^z\rangle\xi_i\delta_{iB}\rangle_r}{\langle\xi_i\delta_{iB}\rangle_r} = \frac{E_B}{2\Theta_B}\frac{3\sinh(3\beta\Theta_B/2) + \sinh(\beta\Theta_B/2)}{\cosh(3\beta\Theta_B/2) + \cosh(\beta\Theta_B/2)} \tag{4}$$

with

$$\begin{aligned}\Theta_A &= \left(H^2 + E_A^2\right)^{1/2} \\ \Theta_B &= \left(H^2 + E_B^2\right)^{1/2}\end{aligned} \tag{5}$$

where $\beta = 1/k_BT$ and the parameters E_A and E_B are defined by

$$\begin{aligned}E_A &= pzJ_Am_A + (1-p)zJ_{AB}m_B \\ E_B &= pzJ_{AB}m_A + (1-p)zJ_Bm_B.\end{aligned} \tag{6}$$

z in (6) is the coordination number. Here, the total magnetization M per site parallel to the z axis is given by

$$M = pm_A + (1-p)m_B. \tag{7}$$

We are interested in studying the T_C and T_{comp} of the disordered ferrimagnetic alloy in the applied transverse field. By linearizing the coupled equations (3) and (4), the critical surface characterizing the ferrimagnetic ($J_{AB} < 0$) phase stability limit is determined from

$$[pa - 1][(1 - p)\gamma b - 1] = p(1 - p)\delta^2 ab \tag{8}$$

with

$$\begin{aligned} 1/t &= zJ_A/k_B T \\ \delta &= J_{AB}/J_B \\ \gamma &= J_B/J_A \\ h &= H/zJ_A \end{aligned} \tag{9}$$

where the parameters a and b are defined by

$$\begin{aligned} a &= \frac{1}{2h}\tanh\left(\frac{h}{2t}\right) \\ b &= \frac{1}{2b}\frac{3\sinh(3h/2t) + \sinh(h/2t)}{\cosh(3h/2t) + \cosh(h/2t)}. \end{aligned} \tag{10}$$

The compensation temperature can be determined by introducing the condition $M = 0$ into the coupled equations (3), (4) and (7). At this point, one should notice the following fact: in a finite transverse field, the $S^z_{i\in A}$ and $S^z_{i\in B}$ components of the system are disordered at high temperatures but below a transition temperature T_C determined from (8) they order and take $m_A \neq 0$ and $m_B \neq 0$, although there is an order with $\langle\langle S^x_i\rangle\xi_i\delta_{iA}\rangle_r \neq 0$ and $\langle\langle S^x_i\rangle\xi_i\delta_{iB}\rangle_r \neq 0$ at all temperatures.

3. Numerical results

In this section, let us examine the phase diagram and total magnetization of the ferrimagnetic binary alloy in an applied transverse field by solving them numerically. However, there exist three coupling constants for the numerical evaluations. In order to relate the present results to those in real ferrimagnetic alloys, let us take $J_A > J_B > 0$ in the following. In real amorphous rare earth (RE)–transition metal (TM) ferrimagnetic alloys, for example [4], J_A, J_{AB} and J_B correspond to TM–TM, RE–TM and RE–RE interactions, respectively.

In figure 3 of [2], we have found that even in the MFT the present system may exhibit two compensation points, when the parameters δ, γ and h are selected as $\delta = -0.3$ (or -0.2, -0.1), $\gamma = 0.5$ and $h = 0.0$. The result indicates that we have to change our concept of only one compensation point in ferrimagnetic materials, as normally written in standard textbooks of magnetism [1]. In this part, therefore, let us clarify how the applied transverse field ($h \neq 0.0$) may change the T_C, T_{comp} and M curves in the ferrimagnetic binary alloy with the fixed parameters δ and γ ($\delta = -0.3$ and $\gamma = 0.5$).

A typical phase diagram for the system with $\delta = -0.3$ and $\gamma = 0.5$ is shown in figure 1, changing the value of p and selecting four values of h. In the figure, the T_C and T_{comp} curves are respectively represented by the broken and full curves. Here, the results of T_C and T_{comp} for $h = 0.01$ are almost equivalent to those in figure 3 of [2] for $h = 0.0$, which clearly shows that two compensation points may exist in the system of $h = 0.01$ (or $h =$

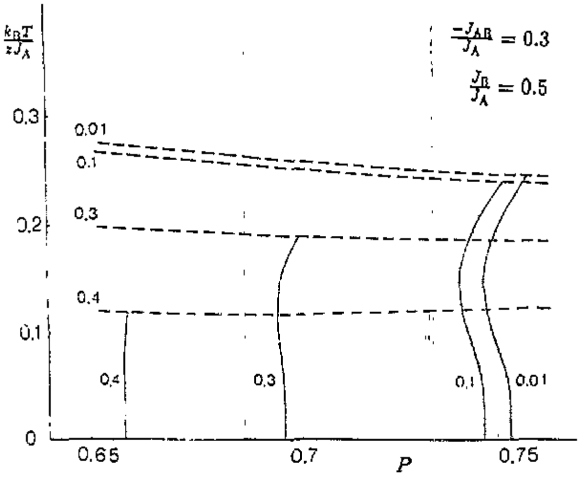

Figure 1. The phase diagram of the disordered ferrimagnetic binary alloy obtained from the MFT, when the parameters J_{AB}/J_A and J_B/J_A are selected as $J_{AB}/J_A = -0.3$ and $J_B/J_A = 0.5$ and the value of H/zJ_A is $H/zJ_A = 0.01$, 0.1, 0.3 and 0.4. The full and broken curves represent respectively the compensation temperature T_{comp} and Curie temperature T_C of the system.

0.0) with a certain concentration very near to $p = 0.75$. In particular, one should notice that, for $h = 0.0$, the spin on B atoms is in the $S_i^z = \pm\frac{3}{2}$ state and hence the compensation point at $T = 0$ K is obtained at $p = 0.75$ due to $\frac{1}{2}p - \frac{3}{2}(1-p) = 0$.

As is seen from figure 1, with the increase of h, the S-shaped curve of T_{comp} for $h = 0.01$ (or $h = 0.0$) changes to a monotonic curve, such as the full curve for $h = 0.4$. It indicates that the two compensation points cannot be observed in the system with $h \geqslant 0.4$. Furthermore, the T_C value decreases with the increase of h. An important fact is that the region in which the T_{comp} can be obtained is moved to a lower concentration when h is increased. As far as we know, such a result has not been reported. It would mean that the compensation point (or points) can be controlled by applying a transverse field to a ferrimagnetic alloy.

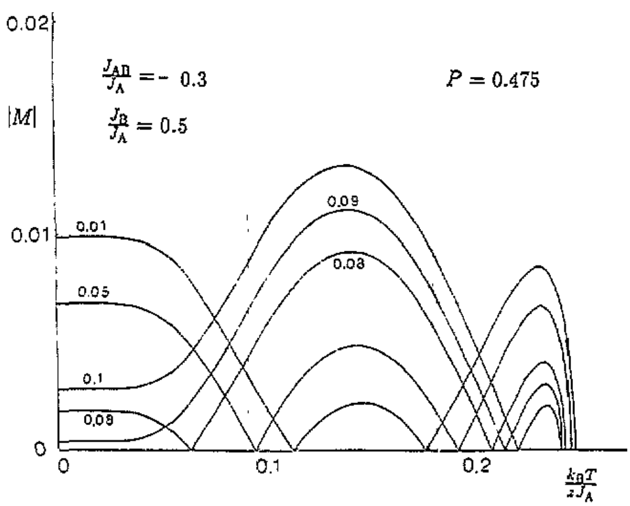

Figure 2. The $|M|$ versus T curves for the system with $p = 0.475$, $J_{AB}/J_A = -0.3$ and $J_B/J_A = 0.5$ in figure 1, when the value of H/zJ_A is selected as $H/zJ_A = 0.01$, 0.05, 0.08, 0.09 and 0.1.

In figure 2, the temperature dependences of M in the system are examined by selecting $p = 0.475$ in figure 1 and applying weak transverse fields. For $h = 0.01$, as predicted in figure 1, the system shows two compensation points ($T^1_{\mathrm{comp}} < T^2_{\mathrm{comp}}$) in the M–T curve. By increasing h from $h = 0.01$ to $h = 0.08$, the two compensation temperatures T^1_{comp} and T^2_{comp} for $h = 0.01$ move in opposite directions; the T^1_{comp} decreases and the T^2_{comp} increases. For $h = 0.09$, however, the T^1_{comp} may disappear and only the T^2_{comp} can be observed in the system. When $h = 0.1$, the same behaviour is also obtained. Thus, by changing h one may observe the variation of T_{comp}, as shown in figure 2.

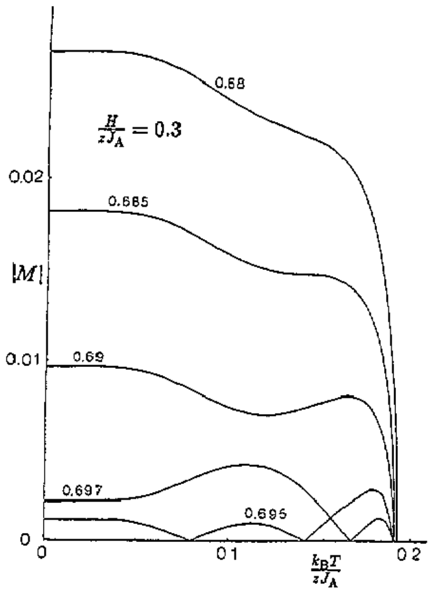

Figure 3. The $|M|$ versus T curves for the system with $J_{AB}/J_A = -0.3$, $J_B/J_A = 0.3$ in figure 1, when the value of p is changed from $p = 0.68$ to $p = 0.697$.

On the other hand, we can also get some characteristic behaviours of M by fixing the value of h and changing the value of p. In figure 3, typical results are depicted for the system with $h = 0.3$, $\delta = -0.3$ and $\gamma = 0.5$, when the value of p is changed from $p = 0.68$ to $p = 0.697$. That is to say, they are obtained by changing p from the left-hand side to the right-hand side in figure 1 and crossing the S-shaped curve of T_{comp} for $h = 0.3$. As depicted in the figure, the M–T curves may exhibit some outstanding features; for $p = 0.69$, the magnetization curve shows a minimum and a maximum in the temperature region below T_C. For $h = 0.695$, as predicted in figure 1, two compensation points are found. When $h = 0.697$, only one compensation point is obtained.

4. Conclusions

In this work, we have examined the effects of applied transverse field on magnetic properties of a disordered ferrimagnetic binary alloy consisting of $S_A = \frac{1}{2}$ and $S_B = \frac{3}{2}$ by the use of the standard mean-field theory. As discussed in section 3, the disordered ferrimagnetic alloy may show two compensation points as well as characteristic behaviours in the thermal variation of the resultant magnetization, such as the M–T curves in figures 2 and 3. Some of these phenomena were also obtained in the previous work [2] for $h = 0.0$, which have not been predicted in the Néel theory of ferrimagnetism [5]. Here, an important point is that the applied transverse field can control the positions of T_C and T_{comp} as well as the thermal variation of M in an appropriate way, as shown in figures 1–3. Thus, the application of a weak transverse field to a ferrimagnetic alloy may be a useful experimental method for finding more than one compensation point as well as the characteristic behaviours in the thermal variation of M.

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