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MAGNETIC SUSCEPTIBILITY OF THE TWO-SUBLATTICE FRUSTRATED SYSTEMS IN THE ERGODIC PHASE

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Abstract. *The magnetic susceptibility of the two-sublattice frustrated systems in the ergodic phase is derived in the framework of the mean field theory. The influence of the intrasublattice frustration the behavior of magnetic susceptibility is studied. It is shown that our model can qualitatively explain the experimental data of* $Fe_xMn_{1-x}TiO_3$

I. INTRODUCTION

During the last decade, much attention has been paid to magnetic frustrated systems with multi- sublattice structure [1-8]. In theoretical papers [6-8], the Sherrington-Kirkpatrick model with infinite- ranged interaction[9] has been extended to construct a theory for frustrated antiferromagnets and ferrimagnets. One of the most interesting predictions of this theory is the possibility of increasing the irreversibility temperature T_g (at which system undergoes transition into the spin glass phase) by the external magnetic field h. This behavior of $T_g(h)$ has been observed experimentally in many materials [1-3].

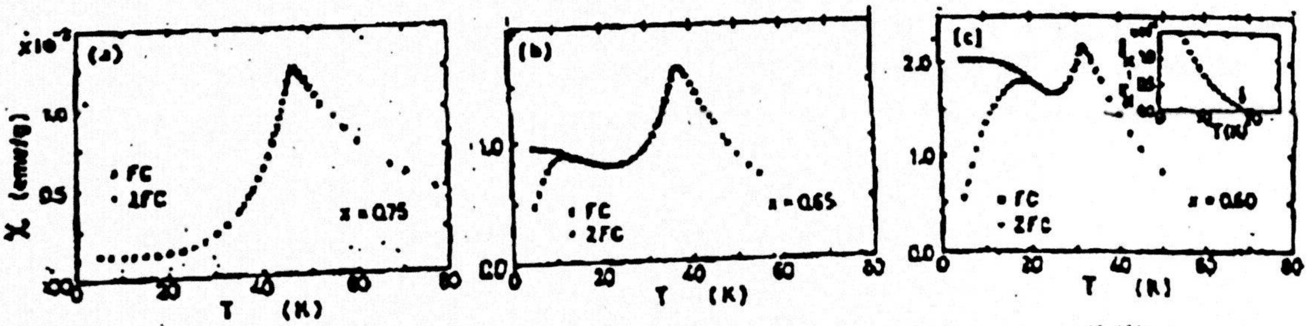

Fig. 1. The temperature dependence on the magnetic susceptibility $\chi(T)$ of $Fe_xMn_{1-x}TiO_3$ for $x = 0.75(a) x = 0.65(b), x = 0.60(c)$. [3]

Recently, Ito, Aruga and coworkers carried out a detailed study of solid solutions $Fe_xMn_{1-x}TiO_3$[2, 3]. The temperature dependence on the magnetic susceptibility $\chi(T)$ of this compound was measured for different Fe concentration x and was presented in Fig.1. Just below T_g, the field cooled susceptibility χ_{FC} and zero field cooled susceptibility χ_{ZFC} start to differ from each other. In the temperature region between T_g and the Nell point T_N (the ergodic phase), the behavior of $\chi(T)$ is quite unusual: *it has a minimum whose depth decreases with* x. In this paper we will show that the behavior of $\chi(T)$ in the ergodic phase could be explained by the two-sublattice Ising model proposed in [7-8].

II. MODEL

In order to model frustrated antiferromagnetic and ferrimagnetic systems, we consider the following Hamiltonian [7-8].

$$H = \sum_{i,j} J_{ij} S_{1i} S_{2j} - \sum_p \sum_{i,j} I_{ij}^{(p)} S_{pi} S_{pj} - h \sum_p \sum_{i=1}^{N_p} S_{pi}, \tag{1}$$

where we consider the simplest two-sublattice situation. The subscript $p = 1, 2$ numbers the spin subsystems, S_{pi} are Ising spin in nature, h is the applied magnetic field, and N_p is the spin number of the $p - th$ subsystem. The inter-and intrasublattice exchange interactions J_{ij} and $I_{ij}^{(p)}$ are supposed to be Gaussian distributed with the average values and dispersion given by

$$\begin{aligned} &< J_{ij} > = J_0, \quad < (J_{ij} - J_0)^2 >^{1/2} = J, \\ &< I_{ij}^{(p)} > = I_{0p}, \quad < (I_{ij}^{(p)} - I_{0p})^2 >^{1/2} = I_p. \end{aligned} \tag{2}$$

Note that the parameters J and I_p serve as measures of inter-and intrasublattice frustrations.

Using the replica method, in [7,8] we derived the self-consistent system of state equations for our model. The equations for the sublattice magnetizations $m_{1,2}$ and Edwards-Anderson parameters $q_{1,2}$ in the ergodic phase are

$$m_p =< \tanh E_p(z) >_c , \quad q_p =< \tanh^2 E_p(z) >_c , \tag{3}$$

where

$$E_p(z) = T^{-1} \left[h + I_{0p} m_p - \alpha_{p'} J_0 m_{p'} + z \left(I_p^2 q_p + \alpha_{p'} J^2 q_{p'} \right)^{1/2} \right], \tag{4}$$

$$n_p = N_p/(N_1 + N_2), \quad \alpha_p = \sqrt{n_p/n_{p'}}, \quad p \neq p', \tag{5}$$

$$< A(z) >_c = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{-z^2/2} A(z) dz. \tag{6}$$

The irreversibility temperature T_g is defined from the de Almeida-Thouless (A-T) line's equation

$$\frac{J^4 - I_1^2 I_2^2}{T^4} < \cosh^{-4} E_1(z) >_c < \cosh^{-4} E_2(Z) >_c + \sum_p \frac{I_p^2}{T^2} < \cosh^{-4} E_p(z) >_c = 1. \tag{7}$$

It is well known [10] that the replica symmetry equations (3)-(6) are correct only in the region above the A-T line (ergodic phase). Since we shall restrict ourselves to studying $\chi(T)$ in the ergodic phase, these equations are adequate. If we are interested in the behavior of the system below T_g, we have to use much more complicated equations [7,8]. However, both theoretical and experimental investigations show that even in the ergodic phase, properties of disordered magnetic systems quite differ from those of the ordered ones.

III. MAGNETIC SUSCEPTIBILITY

The total susceptibility of our system can be expressed in the following form

$$\chi(T) = n_1\chi_1(T) + n_2\chi_2(T), \tag{8}$$

where χ_p is the susceptibility of the $p-th$ sublattice: $\chi_p = \partial m_p/\partial h$. Differentiating the expression (3) of m_p and q_p with respect to the external field h and introducing the notations $\lambda_p \equiv \partial q_p/\partial h$ and

$$U_p = m_p - < \tanh^3 E_p(z) >_c, \quad V_p = 1 - 4q_p + 3 < \tanh^4 E_p(z) >_c, \tag{9}$$

we obtain the equations for χ_p and λ_p

$$\begin{aligned}
&\left[1 - \frac{I_{01}}{T}(1-q_1)\right]\chi_1 + \alpha_2\frac{J_0}{T}(1-q_1)\chi_2 + \frac{I_1^2U_1}{T^2}\lambda_1 + \alpha_2\frac{J^2U_1}{T^2}\lambda_2 = \frac{1-q_1}{T},\\
&\alpha_1\frac{J_0}{T}(1-q_2)\chi_1 + \left[1 - \frac{I_{02}}{T}(1-q_2)\right]\chi_2 + \alpha_1\frac{J^2U_2}{T^2}\lambda_1 + \frac{I_1^2U_2}{T^2}\lambda_2 = \frac{1-q_2}{T},\\
&-2\frac{I_{01}U_1}{T}\chi_1 + 2\alpha_2\frac{J_0U_2}{T}\chi_2 + \left(1 - \frac{I_1^2V_1}{T^2}\right)\lambda_1 - \alpha_2\frac{J^2V_1}{T^2}\lambda_2 = 2U_1/T,\\
&2\alpha_1\frac{J_0U_1}{T}\chi_1 - 2\frac{I_{02}U_2}{T}\chi_2 - \alpha_1\frac{J^2V_2}{T^2}\lambda_1 + \left(1 - \frac{I_2^2V_2}{T^2}\right)\lambda_2 = 2U_2/T.
\end{aligned} \tag{10}$$

Together with (3)-(9), equations. (10) make it possible to calculate the susceptibility $\chi(T)$ in the ergodic phase.

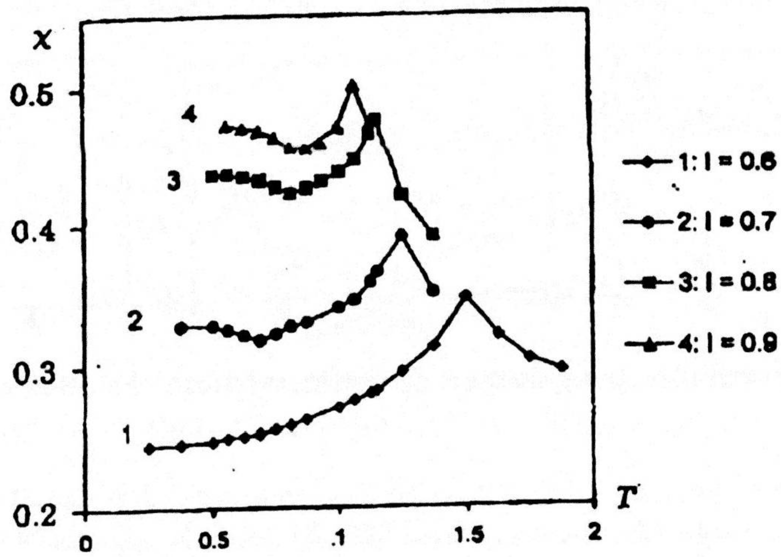

Fig.2: The temperature dependence of the magnetic susceptibility $\chi(T)$ with $J = 0, J_0 = I_0 = 1$ and different values of frustration I: (1) $I = 0.6$, (2) $I = 0.7$,(3) $I = 0.8$ and (4) $I = 0.9$.

To explain the temperature dependence of $\chi(T)$ for $Fe_xMn_{1-x}TiO_3$ we shall consider the case when two sublattices are equivalent: $n_1 = n_2 = 0.5$, $\alpha_1 = \alpha_2 = 1$, $I_{01} = I_{02} \equiv I_0$, $I_1 = I_2 \equiv I$. In addition, we are especially interested in the situation when frustrations of the intrasublattice interactions are much stronger than those of the inter-sublattice interactions: $J/I \sim 0$. To determine the behavior of $\chi(T)$ it is necessary to solve equations (3) - (10). The results of our calculations for some values of the intrasub-lattice frustration I with $J_0 = 1, I_0 = 1, J = 0$ are presented in Fig.2. One can see that for the chosen parameters of the model, $\chi(T)$ has a minimum which smear out at $I = 0,6$.

IV. COMPARISON WITH EXPERIMENT

According to experiments [11,12], $Fe_xMn_{1-x}TiO_3$ is a typical Ising antiferromagnet with easy-axis anisotropy along the hexagonal c-axis. In $FeTiO_3$, spins within a c-layer are ferromagnetically coupled, and the ferromagnetic sheets stack up antiferromagnetically along the c-axis (see Fig.3). In $MnTiO_3$, on the other hand, the intralayer and the interlayer spin couplings are both antiferromagnetic. Therefore, in mixed compound $Fe_xMn_{1-x}TiO_3$ the competition between ferromagnetic and antiferromagnetic interactions creates frustrations among spins. In addition, the interlayer antiferromagnetic coupling is much weaker than the intralayer one [12] so we can expect that the frustrations of the intralayer interactions must be dominant. This is the reason for $Fe_xMn_{1-x}TiO_3$ being described by our model with chosen parameters in Section 3.

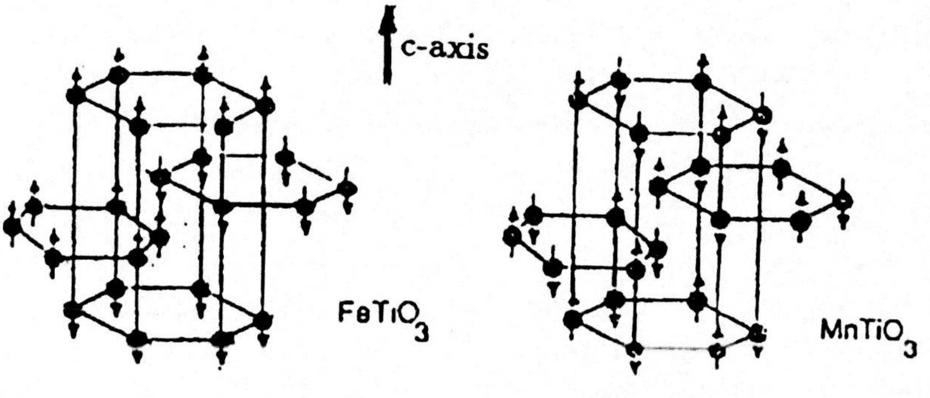

Fig.3: Schematic magnetic structure of $FeTiO_3$ (a) and $MnTiO_3$ (b) [2].

Let us compare the results obtained in Section 3 with the experimental data for $Fe_xMn_{1-x}TiO_3$ [3]. The agreement between our calculation (Fig. 2) and experiment (Fig.1) is qualitatively obvious: (1) At the same temperature the stronger is the frustration I (or the higher is Mn- concentration) the higher is the value of χ; and (2) In the temperature region $T_g \leq T \leq T_N$ function $\chi(T)$ has a minimum. Its depth increases with the degree of the intrasublattice frustration.

V. CONCLUSIONS

The foregoing analysis and the agreement between theory [6,8] and experiment [1-3] show that the two- sublattice model with infinite-ranged interaction quite satisfactorily describes the static properties of real frustrated magnetic systems like $Fe_xMn_{1-x}TiO_3$, at least in the ergodic phase. The limit of this model is that it can describe these systems only qualitatively but not quantitatively. This is the general feature of the models based on the mean field theory of spin glasses [10].

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ĐỘ CẢM TỪ CỦA HỆ TỪ MẤT TRẬT TỰ HAI PHÂN MẠNG TRONG PHA ERGODIC

Hoàng Dũng

Đại học KH Tự Nhiên - ĐHQG TP. HCM

Trong khuôn khổ lý thuyết trường trung bình, đã tính độ cảm từ của hệ từ mất trật tự gồm hai phân mạng trong pha ergodic. Nghiên cứu ảnh hưởng của thăng giáng tương tác trao đổi trong phân mạng lên độ cảm từ. Chứng tỏ rằng mô hình trên có thể giải thích định tính kết quả khảo sát thực nghiệm đối với hợp kim $Fe_xMn_{1-x}TiO_3$.