TEMPERATURE DEPENDENCE OF THE MAGNETIC SUSCEPTIBILITY OF SOME *Ag* Mn ALLOYS

J. M. MACHADO DA SILVA *, H. ABE and H. MIYAJIMA
The Institute for Solid State Physics
The University of Tokyo, Roppongi, Minato-ku, Tokyo, Japan

and

J. M. ARAÚJO
Centro de Física (INIC), Faculdade de Ciências
Universidade do Porto, 4000 Porto, Portugal

(Received 9 November 1981)

ABSTRACT — The susceptibility of three alloys of *Ag* Mn (c = 4.96, 6.35 and 13.00 at %) has been investigated around its maximum in terms of a distribution of blocking temperatures.

1 — INTRODUCTION

The nature of the transition of a spin glass has been a point of great controversy. The sharpness of the temperature dependence of the magnetic susceptibility around its maximum depends on the experimental conditions. A.C. susceptibility (χ_a) measurements reveal a sharp cusp at the transition temperature T_0. This maximum of the susceptibility is frequency dependent, although in some cases the shift in T_0 is small and hard to detect [1]. The presence of a D.C. field depresses χ_a and simultaneously rounds up the cusp [2]. D.C. susceptibility measurements as well as A.C. measurements are further complicated by time effects.

A great deal of effort has been concentrated on the theoretical explanation of the spin glass behaviour [3], [4], based on the exchange interaction between the impurity spins. Substantial

(*) On leave of absence from Centro de Física (INIC), Faculdade de Ciências, Universidade do Porto, 4000 Porto, Portugal.

analytical and computational work has been done, but in most cases it does not quite agree with experiments.

Recently Wohlfarth [5] has put forward a phenomenological model based on the original idea of Néel [6], which assumed clustering of the impurity spins in fine particles. Frequency and time effects will be natural consequences, as was discussed by Néel [6] himself.

One of the crucial assumptions in Wohlfarth's model [5] is that the intrinsic Curie temperature of the cluster material is well above the transition temperature T_o (for Mn, $T_C \simeq 95$ K). According to the model, the susceptibility of the clusters is zero below a blocking temperature T_B and given by $\chi = C/T$ for T greater than T_B. If $f(T_B)$ is the distribution function for the blocking temperatures, the susceptibility of the spin glass will be given by

$$\chi(T) = 1/T \int_0^T C\, f(T_B)\, dT_B \quad . \tag{1}$$

In his calculation, Wohlfarth [5] treated C as constant (independent of T_B); however, the analysis may be carried out, to a certain extent, without making any such assumption. In fact, introducing the average

$$\overline{C} = \int_0^\infty C(T_B)\, f(T_B)\, dT_B \quad , \tag{2}$$

and defining a new function

$$g(T) = C(T)\, f(T) / \overline{C} \quad , \tag{3}$$

it is straightforward to check that, as in [5],

$$g(T) = (d(\chi T)/dT) / \lim_{T \to \infty} (\chi T) \quad . \tag{4}$$

The temperature T_o at which the susceptibility has a maximum is given by

$$T_o\, g(T_o) = \int_0^{T_o} g(T)\, dT \quad , \tag{5}$$

which is identical to eq. (8) of ref. [5] after replacing f(T) by g(T). It appears, thus, possible to extract from the experimental data, $\chi(T)$, both the function g(T) and the temperature T_0, *without any assumption about C(T).*

It is also possible to express the second derivative of the susceptibility (eq. (12) of ref. [5]) at T_0 in terms of the function g(T); one gets

$$(d^2\chi / dT^2)_{T_0} = (\bar{C} / T_0)\ (dg / dT)_{T_0} \qquad (6)$$

This expression may be used to verify the consistency of the analysis.

2 — EXPERIMENTAL

We measured the D.C. susceptibility of three *Ag* Mn alloys of atomic compositions 4.96, 6.35 and 13.00 at % respectively. These alloys were zero field cooled, the measuring field being 1.3 kOe. The measurements were performed on a very sensitive magnetic pendulum developed by Matsui et al. [7]. The samples were made by mixing the two components under a vacuum better than 10^{-5} Torr in a high frequency induction furnace. The ingots obtained in this way were remelted in high vacuum in a Bridgeman's furnace and kept at a temperature 30°C above the melting point of Ag (961°C) for two hours, after which they were cooled down at constant rate, reaching room temperature in approximately seven hours.

The homogeneity in the three alloys was checked by chemical analysis. Three bits taken from different points of the sample showed the same Mn concentration c within the accuracy of the method used.

3 — RESULTS AND CONCLUSIONS

The temperature dependence of the magnetic susceptibility for the three different concentrations of Mn is represented in Fig. 1. From these curves we obtained the functions g(T); in fact Fig. 2 gives $d(\chi T)/dT = \bar{C}g(T)$, where $\bar{C} = \lim_{T \to \infty}(\chi T)$ is the Curie

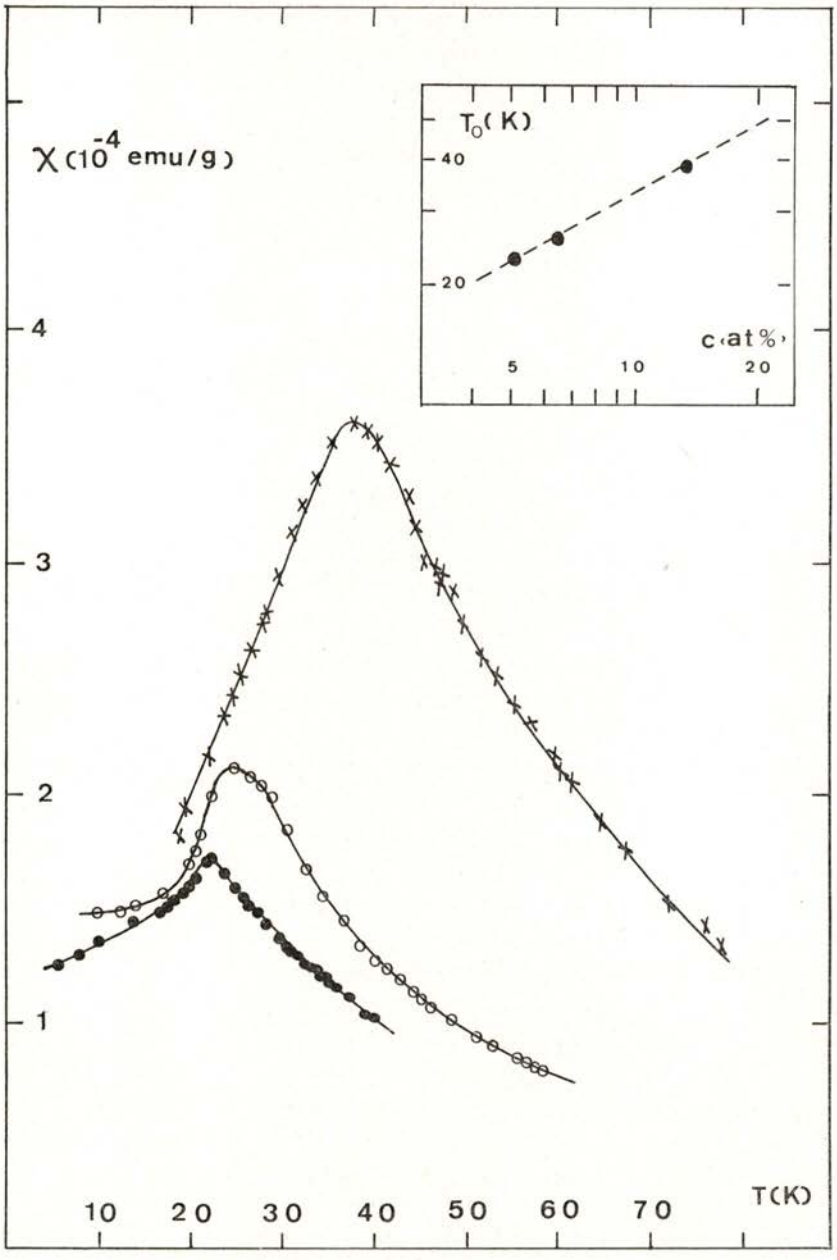

Fig. 1 — Magnetic susceptibility of three *Ag* Mn samples: × — 13.00 at %, o — 6.35 at %, ● — 4.96 at %. The insert shows, in a log-log diagram, the concentration dependence of T_o: 38.1 K (13.00 %), 25.0 K (6.35 %) and 22.4 K (4.96 %).

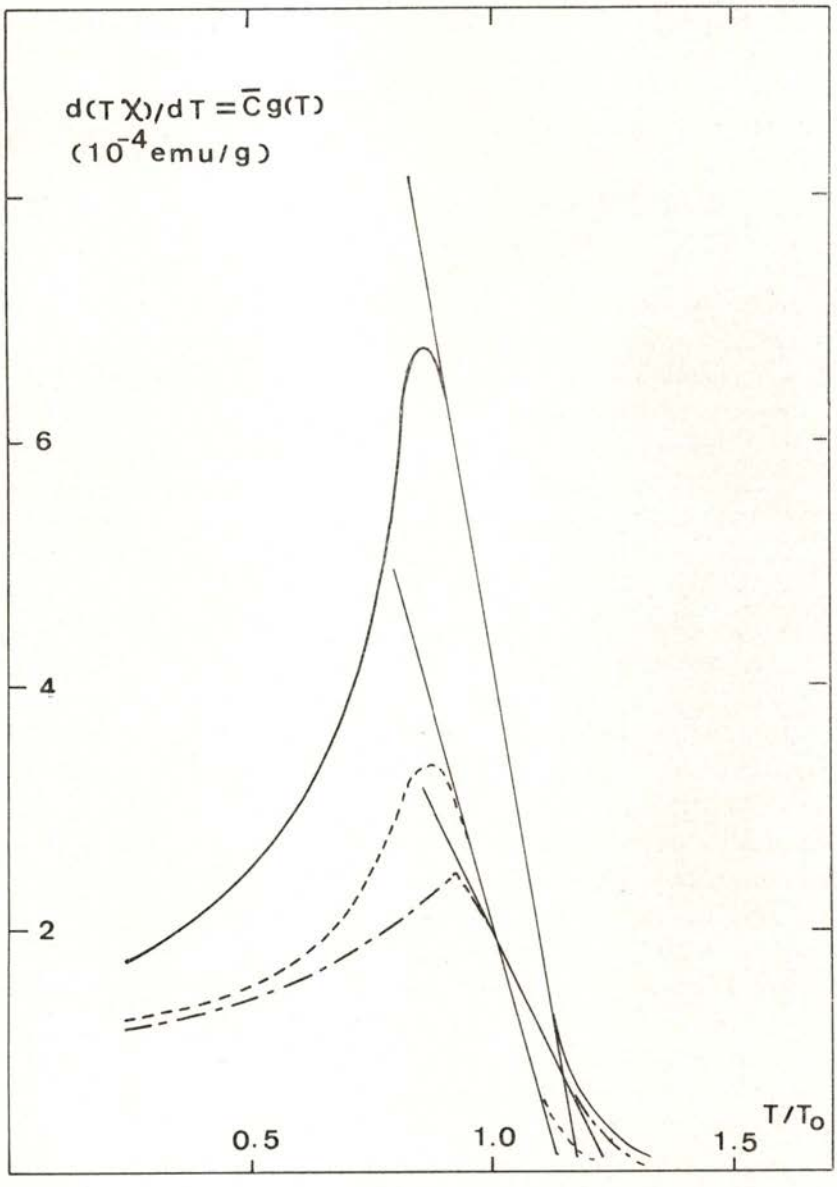

Fig. 2 — The function $\bar{C}g(T)$ as a function of T/T_o: the straight lines represent the derivatives $\bar{C}dg(T)/dT$ at T_o for the three samples: $-\ 6.15\times10^{-5}$ (emu/g. K) for 13.00 %, $-\ 5.08\times10^{-5}$ (emu/g. K) for 6.35 % and $-\ 3.26\times10^{-5}$ (emu/g. K) for 4.96 %.

constant of the alloy, as a function of T/T_0. All three T_0 values. calculated from (5), were consistent with the position of the susceptibility maxima shown in Fig. 1; they are, however, slightly larger than those reported by Korn [8] and Kouvel [9]. Also the second derivatives of χ at T_0 calculated from the experimental values agree, within the experimental accuracy, with those obtained from dg(T)/dT, supporting, therefore, the theoretical model.

Mulder et al. [10] have shown that samples of *Cu* Mn slowly cooled from the melt have wider distributions of T_B than those rapidly quenched. Results from A.C. susceptibility measurements on a quenched sample are almost independent of a superimposed D.C. magnetic field up to values of 2 kOe [10]. However, for the slowly cooled alloys the D.C. magnetic field rounds up the maximum of the susceptibility. This rounding of the maximum in the case of *Ag* Mn alloys is clearly seen in Fig. 1. If one were to accept Wohlfarth's assumption (C independent of T_B) the curves of Fig. 2 would give directly the distribution function $f(T_B)$. If, on the other hand, one were to accept Wohlfarth's expressions for the blocking temperature $T_B = vK/25k_B$, and 'constant' $C = vM_S^2/3k_B$, where v is the effective particle volume, and where both the effective anisotropy coefficient, K, and intrinsic magnetization of the cluster material, M_S, are assumed independent of temperature, one would have $C \propto T_B$ and $g(T) = (T/T_1)\ f(T)$, in which T_1 is the average blocking temperature. This does not coincide with T_c, but, in principle, the sharper the transition the less they will differ. The distribution functions calculated in this way are shown, for the three *Ag* Mn samples, in Fig. 3; they are similar to those given in ref. [10]. Here the higher the concentration, the sharper becomes the distribution function f(T) in the vicinity of T_c, confirming, possibly, that the effect of the D.C. magnetic field is the less pronounced the higher the manganese concentration of the alloy.

One of us (JMMS) is grateful to the Japan Society for the Promotion of Science for a grant awarded him in the year 1979. We would like to thank Mr. M. Aoki and Mrs. F. Sakai for their invaluable assistance in the preparation and chemical analysis of the samples.

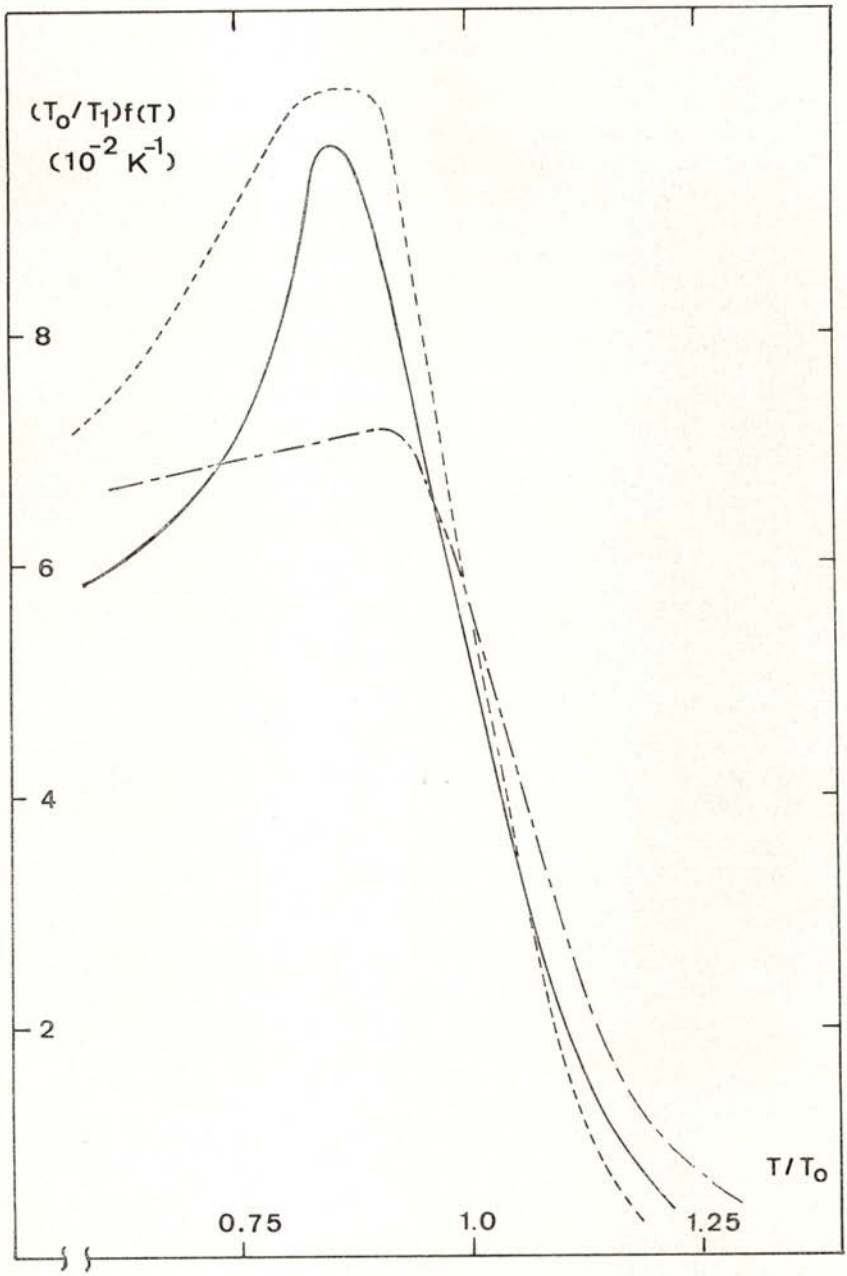

Fig. 3 — The distribution function f(T) multiplied by T_o/T_1 for the three samples of *Ag* Mn: —— (13.00 %), - - - (6.35 %), — · — (4.96 %).

REFERENCES

[1] THOLENCE, J. L., *J. Appl. Phys.*, **50** (1979), 7310.
[2] CANNELLA, V. and MYDOSH, J. A., *Phys. Rev.*, **B6** (1972), 4220.
[3] HEBER, G., *Appl. Phys.*, **10** (1976), 101.
[4] ANDERSON, P. W., *Amorphous Magnetism*, 2, (1977), 1.
[5] WOHLFARTH, E. P., *Physics Letters*, **70A** (1979), 489.
[6] NÉEL, L., *Ann. Géophys.*, **5** (1949), 99.
[7] MATSUI, M., HIROAKI, N. and CHIKAZUMI, S., *Japan. J. Appl. Phys.*, **15** (1976), 299.
[8] KORN, D., *Z. Phys.*, **214** (1968), 136.
[9] KOUVEL, J. S., *J. Phys. Chem. Solids*, **24** (1963), 795.
[10] MULDER, C. A. M., von DUYNEVELDT, A. J. and MYDOSH, J. A., *Journal Magn. and Mag. Materials*, **15-18** (1980), 141.