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Critical static measurements of the magnetization in the $Cd_{0.6}Mn_{0.4}Te$ spin glass

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The static nonlinear magnetization M_s of the insulating spin glass $Cd_{0.6}Mn_{0.4}Te$ has been studied in the vicinity of its freezing temperature T_c, in weak magnetic fields H ranging from 0.1 to 55 Oe. The divergence of the nonlinear magnetization above T_c is well described by the scaling function $M_s(t,H)=t^{(\gamma+3\beta)/2}F(H/t^{(\gamma+\beta)/2})$ with critical exponents $\gamma=3.3\pm0.3$ and $\beta=0.9\pm0.2$, as expected for usual three-dimensional (3D) Heisenberg spin glasses. The corresponding value deduced for $T_c=12.37\pm0.05$ K, agrees well with its determination from dynamic measurements. Our result proves that disordered 3D Heisenberg frustrated antiferromagnets exhibit a paramagnetic to spin-glass transition at finite temperature.

I. INTRODUCTION

Does a disordered three-dimensional (3D) Heisenberg frustrated antiferromagnet enter a spin-glass state or a random antiferromagnetic state? As discussed recently,[1,2] this fundamental question cannot be definitively answered without further experimental evidence.

The archetypal compounds for such a study are semimagnetic semiconductors such as $Cd_{1-x}Mn_xTe$, where manganese spins are arranged on a fcc lattice. For $x>0.2$, only the nearest-neighbor (NN) antiferromagnetic interaction between Mn^{2+} ions plays a significant role, since it is an order of magnitude larger than other interactions.[3] Since the fcc lattice is frustrated for NN antiferromagnetic interactions alone, a spin-glass ordering may be inferred at low temperature.[4]

Recent refined experimental data on critical dynamics in these compounds,[1,2,5,6] just above the freezing temperature T_c, lead to two contradictory conclusions. Geschwind *et al.*[2] favor an activated dynamic scaling to interpret their data while Mauger *et al.*[1] and Zhou and coworkers[5,6] are able to fit their results within the usual critical slowing down formalism valid for a phase transition, especially to a spin-glass phase. The latter authors show that the characteristic relaxation time τ diverges at T_c according to a power law $\tau=A(T-T_c)^{-z\nu}$ with a dynamic exponent $z\nu=9\pm1$, in good agreement with calculations.[7] In contrast, Geschwind *et al.*[2] propose an activated dynamic scaling since they claim that the above analysis leads to too large a value for $z\nu$, unrealistic for a spin-glass transition. However, taking into account the difference in composition between samples, the two scaling procedures give a value of T_c smaller than in Ref. 1. Since the dynamic critical exponent is large, it is rather delicate to decide unambiguously between one of the two different scaling approaches, especially when the freezing temperature has not been determined from another independent method. This difficulty was also mentioned recently for another system.[8] In order to justify their scaling procedure, Mauger *et al.*[1] determined T_c independently from other dynamic measurements by looking at the change in the magnetic relaxation regime following small steps in temperature. This method has already been proved to give a reliable determination of T_c.

Within this context we confirm the value of T_c from independent *static* measurements in $Cd_{0.6}Mn_{0.4}Te$. Since the issue is to characterize a phase transition in the limit where τ diverges, the most pertinent physical quantity to be scaled is the nonlinear static magnetization.[9,10] This type of scaling has been achieved successfully on many spin-glass-like compounds.[11–14] In spite of the very weak nonlinear terms in the static magnetization of $Cd_{0.6}Mn_{0.4}Te$ (Ref. 15) our data are precise enough to derive the value of T_c and the critical exponents β and γ from a scaling analysis.

II. EXPERIMENTAL RESULTS AND SCALING ANALYSIS

The nonlinear magnetic susceptibility has already been measured in another $Cd_{0.6}Mn_{0.4}Te$ sample.[15] Although scaling was not attempted in this work, the data indicate the existence of a crossover field $H_c\sim60$ Oe above which the field dependence of the nonlinear susceptibility becomes smaller. Hence, we restricted our investigation to the low-field regime. The present magnetization measurements have been performed in fields ranging from 0.1 to 55 Oe using a highly sensitive superconducting quantum interference device (SQUID), described in Ref. 12.

Since the sample used in the present study has a slightly different composition (x smaller by less than 1%) than that investigated previously,[1] we have again estimated the spin-glass freezing temperature T_c from the change in re-

laxation phenomena of the field-cooled magnetization. Following a step decrease of 0.05 K, the magnetization exhibits a slow relaxation which changes sign suddenly near T_c. With this criterion[13] and a very slow cooling rate (1 mK/s), we found $T_c = 12.40 \pm 0.05$ K.

The evaluation of the nonlinear magnetization $M_s(H,T) = \chi_0(T)H - M(H,T)$ requires the knowledge of the linear susceptibility term $\chi_0(T)$. Within experimental uncertainties we found the same magnetic susceptibility curves at 0.1 and 1 Oe, for temperatures above 12.6 K, so that they can be identified with $\chi_0(T)$ in this range. To get enough accuracy in the analysis of $M_s(H,T)$ from our data, we performed field-cooled magnetization measurements for four fields below H_c (Fig. 1). We checked that no time effects occur in the field-cooled magnetization curves at least for cooling rates smaller than 2 mK/s, for fields higher than 0.1 Oe and for measurements done far enough above T_c ($T > 12.6$ K). Under these conditions the system is assumed to be in thermodynamic equilibrium. The nonlinear magnetization associated with phase transitions in magnetic systems can be analyzed from the universal scaling expression

$$M_s(t,H) = t^{(\gamma+3\beta)/2} F(H/t^{(\gamma+\beta)/2}) ; \quad (1)$$

t stands for the reduced temperature, $t = (T - T_c)/T_c$.

This expression (1) must remain valid for spin glasses and we followed the same procedure as that described in Ref. 13 to analyze our data. The best fit (Fig. 2) is realized taking $T_c = 12.37 \pm 0.05$ K, a value very close to our previous dynamic determination, and critical exponents $\gamma = 3.3 \pm 0.3$ and $\beta = 0.9 \pm 0.2$. In the region of small nonlinearities, i.e., far above T_c, the expansion of expression (1)

$$M_s = b_1 t^{-\gamma} H^3 + b_2 t^{-(2\gamma+\beta)} H^5 - b_3 t^{-(3\gamma+2\beta)} H^7 + \cdots \quad (2)$$

reduces to the first term in H^3, giving asymptotically a straight line with slope 3 in the lower part of the log-log plot shown in Fig. 2, i.e., for $H/t^{(\gamma+\beta)/2} < 10^4$ Oe. As expected the slope of the experimental curve is close to 3 in this range. Its significant decrease for higher fields, or when approaching T_c, is directly related to the increasing importance of higher-order terms in the expansion of M_s [expression (2)] which makes possible the determination of the exponent β. The upper part of the scaling curve tends towards the predicted asymptotic form,

$$M_s/t^{(\gamma+3\beta)/2} \sim (H/t^{(\gamma+\beta)/2})^{(\gamma+3\beta)/(\gamma+\beta)} , \quad (3)$$

implied by the nondivergence of M_s at T_c.

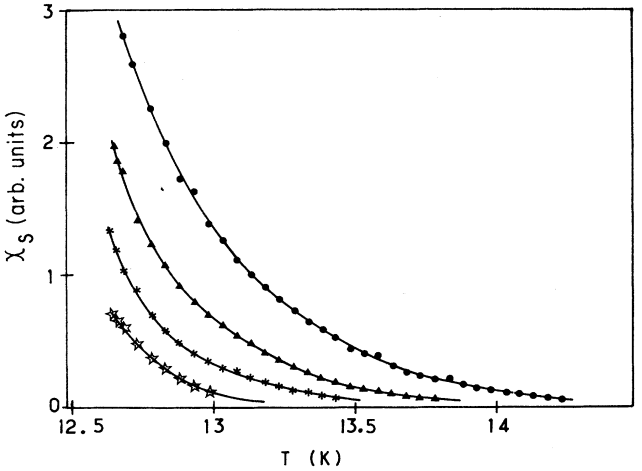

FIG. 1. Nonlinear magnetic susceptibility as a function of temperature, for magnetic fields $H = 10$ Oe (☆), 18 Oe (✱), 30 Oe (▲), 55 Oe (●). The experimental uncertainty is about the size of the symbols used for the data point.

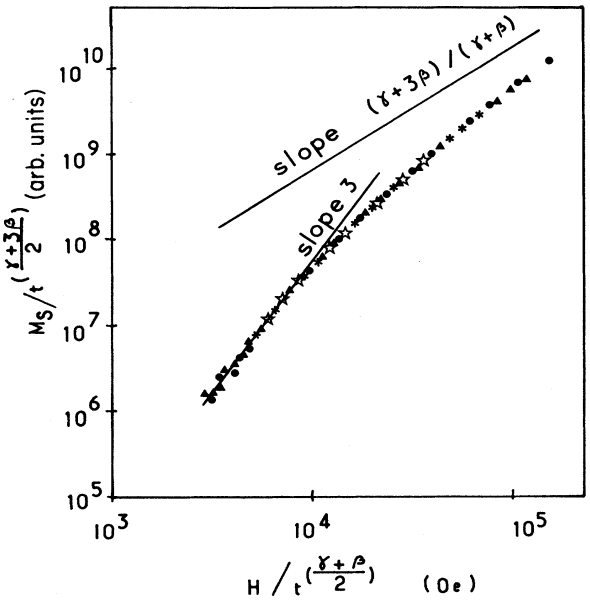

FIG. 2. Scaling of the nonlinear magnetization M_s vs magnetic field H. The reduced temperature is $t = (T - T_c)/T_c$. The scaling procedure leads to $T_c = 12.37$ K, $\gamma = 3.3$, and $\beta = 0.9$. The symbols used for the various magnetic fields are the same as in Fig. 1.

III. DISCUSSION

The value of $T_c = 12.37 \pm 0.05$ K, obtained from the scaling analysis of the nonlinear static magnetization, where T_c is taken as a fitting parameter, agrees well with its determination from the relaxation of the field-cooled magnetization: $T_c = 12.40 \pm 0.05$ K. Therefore, our two independent determinations of T_c are reliable. Considering our previous dynamic studies on another sample having a similar composition,[1] we stress that static and dynamic scaling analyses lead to exactly the same value of T_c, a fact which strongly supports the spin-glass transition hypothesis.[14]

This conclusion does not support the dynamic scaling analysis of the real part of the ac magnetic susceptibility,[2] in which the spin freezing was interpreted as a dynamic activated process in a random antiferromagnet. If one compares the two sets of temperature corresponding to the cusps of the ac susceptibility curves measured at several

frequencies for the two studied samples,[1,2] the data appear similar if one shifts the temperature for the sample studied in Ref. 2 by -0.3 K with respect to that considered in Ref. 1. Following the critical analysis given in Ref. 1 we are inclined to define $T_c = 12.6$ K for the sample studied in Ref. 2, which lies far above the estimation of Geschwind *et al.* ($T_c = 12.2$ K). In a critical scaling analysis, a too low value of T_c leads to an overestimation of the critical exponent $z\nu = 13$,[2] as compared to the most probable value of $z\nu = 9$, obtained using a consistent value for T_c.[1,5,6] The difference between the two analyses reported in Refs. 1 and 2 could arise for reasons we have already discussed elsewhere.[16]

Let us now discuss the universality of the exponents γ and β determined in the present work for $Cd_{0.6}Mn_{0.4}Te$. The result $\beta = 0.9 \pm 0.2$ is very close to the value $\beta = 0.8 \pm 0.1$, deduced from the dynamic scaling in applied magnetic fields[5,6] in other frustrated systems: $Cd_{0.7}Mn_{0.3}Te$ and $Hg_{0.7}Mn_{0.3}Te$. The universality of this exponent is now well established for insulating[13] or metallic[10,11,17] spin glasses. It has been noticed already[18] that this value of β, close to its mean-field determination, indicates a stiff ordering which contrasts with the soft ordering ($\beta = 0.5$) deduced from simulations in short-range Ising systems.[18]

The present work gives the first direct determination of γ in semimagnetic semiconductors. However, since the crossover exponent ϕ has been estimated to be between 3 and 4,[5,6] the value of γ can be deduced from the knowledge of β taking into account the scaling relation $\phi = \beta + \gamma$. Our determination of $\gamma = 3.3 \pm 0.3$ is consistent with the above experimental value of ϕ.

In many previous studies the scaling of the nonlinear magnetization used magnetic fields larger than the crossover field H_c or took into account temperatures too far from T_c, so that the analysis led to erroneously small values of γ. Restricting the comparison to experiments performed in conditions similar to ours, the value of γ we deduced is in good agreement with those reported earlier for insulating[13] or metallic[10,11,17,19] spin glasses.

We return to the fundamental question, does $Cd_{0.6}Mn_{0.4}Te$ behave like a canonical spin glass? Our static and dynamic scaling studies give a positive answer since they lead to the same value of the freezing temperature T_c. Moreover, the static nonlinear magnetization scales with values of the critical exponents $\beta = 0.9 \pm 0.2$ and $\gamma = 3.3 \pm 0.3$, already reported for other spin glasses. The same holds for the dynamic exponent value $z\nu = 9 \pm 1$.

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