Nonlinear susceptibility of spin-glass systems in a magnetic field

A. B. Surzhenko
Institute of Metal Physics, Ukrainian Academy of Sciences, 252142 Kiev, The Ukraine

(Submitted 19 April 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **57**, No. 11, 690–694 (10 June 1993)

The behavior of the nonlinear magnetic susceptibilities of spin glasses in a nonzero magnetic field is analyzed by scaling theory. The calculated results are confirmed by experimental results on the amorphous spin glass $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$.

It has now been established that most real spin-glass systems exhibit a critical increase in the nonlinear response of the magnetic susceptibility near the paramagnet–spin-glass transition temperature T_F.[1-5] This circumstance is usually regarded as proof that the transition is of a cooperative nature, so it can serve as a strong argument for invoking the results of scaling theory for a description of the transition.[6] When the scaling-hypothesis approximations are valid for a specific spin glass, its nonlinear susceptibility χ_{NL} is written in the form[1]

$$\chi_{NL}(H,\tau)=\chi_0(0,\tau)-\tau^{\beta}F(H^2/\tau^{\phi}). \tag{1}$$

Here $\chi_0(0, \tau)$ is the nonsingular component of $\chi_{NL}(H, \tau)$, H is the magnetic field, $\tau=|1-T/T_F|$ is the reduced temperature, $F(x)$ is a generalized scaling state function which is uniform with respect to its argument $x=H^2/\tau^{\phi}$, β is the critical exponent of the order parameter of the spin glass, and ϕ is the crossover critical exponent, which is related to β by the scaling relation[6]

$$\phi=\beta\delta=\beta+\gamma. \tag{2}$$

Within the framework of scaling theory, only two of the four exponents written above (ϕ, β, γ, and δ) are thus independent. This circumstance can in principle be utilized to reduce the analysis of the paramagnet–spin-glass phase transitions to an analysis of the particular case $H=0(x=0)$. For this case, we have, according to expression (1),

$$\partial^{(2k)}\chi_{NL}(H=0,\tau)/\partial^{(2k)}H\equiv\chi_{2k}(H=0,\tau)\propto\tau^{\beta-k\phi},\quad k=1,2,\dots . \tag{3}$$

It is for this reason that the singular nature in (3) of the quantities $\chi_{2k}(H=0,\tau)$, $k=1$, 2, . . ., which are usually detected[2-5] by a dynamic method at odd harmonics (the third, the fifth, etc.) of the fundamental frequency of the exciting field, can serve as only indirect confirmation for scaling decomposition (1). The experimental observations of the nonlinear response $\chi_{NL}(H,\tau)$ of the dynamic magnetic susceptibility in a nonzero magnetic field which are presently available are extremely scanty.[4,5] [This case corresponds to an arbitrary value of x and is therefore the only objective criterion for the applicability of scaling theory for description (1) of paramagnet–spin-glass phase transitions.] A theoretical analysis of these observations is exceedingly difficult because the scaling function $F(x)$ is unique for each specific transition of interest. The approach taken in the present letter,[7] involving the introduction of minimal restrictions on the form of $F(x)$, has made it possible, for the first time, to predict certain characteristic features of the nonlinear response of the dynamic magnetic susceptibility of spin-glass systems in a magnetic field.

We first consider the general form of the dependence $\chi_1(H,\tau)$, which can be found from (1) and (2):

$$\partial\chi_{NL}(H,\tau)/\partial H \equiv \chi_1(H,\tau) = -2H\tau^{-\gamma}F'(x). \tag{4}$$

Here and below, $F^{(k)}(x) = d^{(k)}F(x)/dx^{(k)}$. It follows in particular from (4) that in the absence of a magnetic field the signal $\chi_1(H=0,\ \tau\neq 0)$ detected at twice the magnetization-reversal frequency is zero for all $\tau\neq 0$, in accordance with the results of a spectral analysis of the dynamic magnetic susceptibility of spin glasses.[4] In order to determine the quantity $\chi_1(H=0,\ \tau=0)$, on the other hand, or to study the general behavior in (4), the method of Ref. 7 turns out to be extremely convenient. This method involves finding extreme values for a temperature cross section (H=const) and a field cross section (τ=const) of the surface $\chi_1(H,\tau)$ and then extrapolating: $H\to 0$, $\tau\to 0$. Each solution of x_1, for which the partial derivatives

$$\partial\chi_1(H,\tau)/\partial\tau = 2H\tau^{-\gamma-1}[\gamma F'(x) + \phi x F''(x)], \tag{5a}$$

$$\partial\chi_1(H,\tau)/\partial H = -2\tau^{-\gamma}[F'(x) + 2xF''(x)] \tag{5b}$$

vanish, correspond to the crossover line at the indicated surface:

$$H_1^2 = x_1\tau_1^{\phi}. \tag{6}$$

This line is manifested experimentally by the appearance of maxima (minima) on the plots of $\chi_1(H=\text{const},\ \tau)$ and $\chi_1(H,\ \tau=\text{const})$. An estimate of the amplitude of these maxima, $\chi_1(H_1,\ \tau_1)$, with the help of (2), (4), and (6), leads to the simple relation

$$\chi_1(H_1,\tau_1) \propto H_1^{-1+2/\delta} \propto \tau_1^{\beta-\phi/2}. \tag{7}$$

From this relation we find, in particular, the necessary condition for the validity of the results derived by our approach: $\beta<\gamma$ ($\delta>2$). This inequality holds for the overwhelming majority of real spin glasses.[2-5] In the limit $H_1 \to 0$, $\tau_1 \to 0$ we thus have $\chi_1(H_1,\ \tau_1)\to -\infty$, so the temperature dependence of $\chi_1(H=0,\tau)$ has the typical Kronecker-delta shape in the absence of a magnetic field. Clearly, the peak observed in $\chi_1(H=0,\tau)\to -\infty$ in this case becomes finite for any nonzero value $H=H_m>0$, shifting in the temperature τ and decreasing in absolute value [see (7)] as the field increases further ($H>H_m$).

These arguments can undoubtedly also be used to analyze the signals $\chi_k(H,\ \tau)$ of higher harmonics of the nonlinear response of the dynamic magnetic susceptibility of a spin glass. However, a generalization of (7) to the case of arbitrary k indicates a significant strengthening (with increasing value of k) of the field dependence

$$\chi_k(H_k,\tau_k) \propto H_k^{-k+2/\delta} \propto \tau_k^{\beta-k\phi/2},\quad k=1,2,..., \tag{7*}$$

so corresponding experimental studies, even in relatively weak magnetic fields, would be extremely problematical.

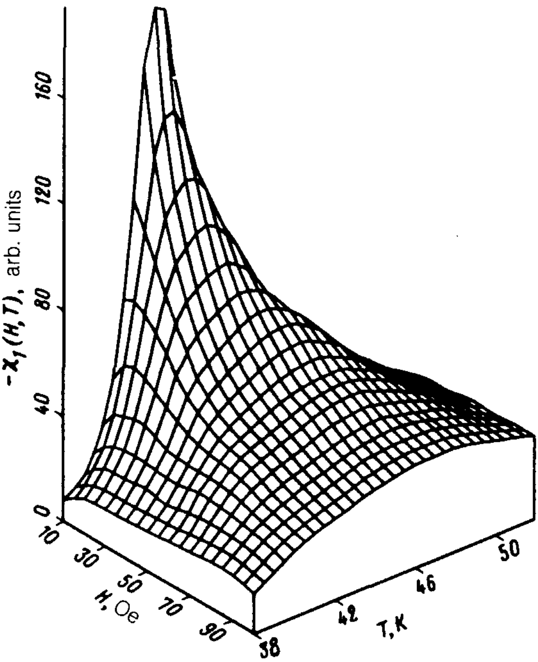

FIG. 1. Nonlinear susceptibility χ_1 (H,T) of the amorphous spin glass $(Fe_{0.65}Mn_{035})_{75}P_{16}B_6Al_3$ plotted as a function of the temperature T and the static magnetic field H. The amplitude and frequency of the magnetization reversal are, respectively, h_0=Oe, and $f=\omega/2\pi=$ 75 Hz.

The features of the nonlinear response of the dynamic magnetic susceptibility of a spin glass predicted above have been tested in the particular case of the amorphous alloy $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$, which undergoes a paramagnet–spin-glass transition at $T_F \approx 42$ K (Ref. 3). The quantities $\chi_k(H,\tau)$, $k=1, 2$, were measured with a standard mutual-induction bridge. When this method is used with a weak $(h_0 \rightarrow 0)$ exciting magnetic field $h=h_0 \sin \omega t$, it is possible to observe the nonlinear susceptibility $\partial^{(k)}\chi_{NL}(H,\tau)/\partial H^{(k)}$ directly in the $(k+1)$st harmonics of the fundamental magnetization-reversal frequency.[2-5] A nonzero amplitude ($h_0 \approx 6$ Oe), on the other hand, unavoidably leads to a differentiation error. This error is particularly noticeable in studies in weak magnetic fields $H \leqslant h_0$. The surface $\chi_1(H > h_0, T)$ found in view of the latter comment (Fig. 1) indicates a complete qualitative agreement between theoretical results (6) and (7) and the experimental data. Significantly, three crossover lines of the type in (7) are observed at the same time on this surface. They correspond to the temperature maximum [see (5a)] and two field maxima [see (5b)] $(T>T_F$ and $T<T_F)$, of the nonlinear susceptibility $\chi_1(H, T)$. The presence of extrema on the field dependence $\chi_1(H, T=\text{const})$ is apparently characteristic of only paramagnet–spin-glass phase transitions. It is generally not observed in corresponding studies of ferromagnetic systems.[7] Furthermore, specifically this circumstance leads to a simple explanation for the sign variation of the nonlinear susceptibility $\chi_2(H,T)$ which occurs in a study in a nonzero magnetic field $H>h_0$ of the nonlinear $(k=2)$ response of the dynamic magnetic susceptibility of both the "classical" spin glass Au-(1.5 at. % Fe)[5] and the amorphous alloy $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$ which we are discussing in the present letter (Fig. 2). It is quite sufficient to note that $\chi_2(H,T)$ is

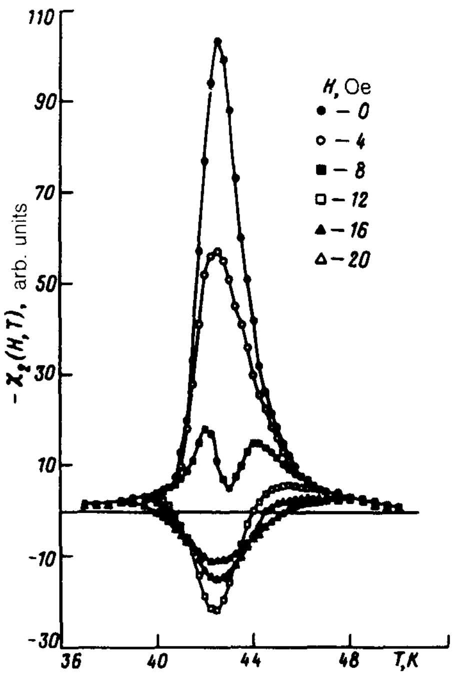

FIG. 2. Temperature dependence of the nonlinear susceptibility, $\chi_2(H, T)$, of the amorphous spin glass $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$, measured at various values of the static magnetic field H ($h_0=6$ Oe, $f=\omega/2\pi=75$ Hz. Filled circles—0 Oe; open circles—4; filled squares—8; open squares—12; filled triangles—16; open triangles—20 Oe.

precisely the same as the expression on the right side of (5b). For each fixed temperature $T_m \neq T_F$ we can thus work from Fig. 1 to determine the value H_m corresponding to the maximum value of $\chi_1(H, T_m)$ and thus to the switch of χ_2 from a negative sign ($H<H_m, T_m$) to a positive sign ($H>H_m$). On the temperature dependence ($H_m=\text{const}$), on the other hand, these features of the paramagnet–spin-glass phase transitions are manifested in the appearance of an interval ($\tau < \tau_m$) of temperatures, $T_1<T < T_2$, for which we have $\chi_1(H_m, T)>0$ (Fig. 2). With decreasing magnetic field H_m, this interval narrows [see (6)], and in the limit $H_m \rightarrow 0$ ($\tau_m \rightarrow 0$) the quantity $\chi_2(H,T)$ becomes negative throughout the temperature range studied.[2-5]

In addition to leading to a qualitative description of these effects, the approach which we are taking in this letter allows us to carry out an exact quantitative analysis of the conversion and to determine the critical temperature T_F and the values of the critical exponents. While the most common approach in studies of phase transitions is to reconstruct the general form of the scaling function $F(x)$,[6] in our case the corresponding problem was solved for the first derivative of this function, $F'(x)$ [see (4)]. It turns out that the experimental $\chi_1(H, T)$ curves (Fig. 1) used here conform best to a common $F'(x)$ curve (Fig. 3) under the conditions $T_F=41.61\pm0.03$ K, $\beta=0.48\pm0.02$, and $\gamma=2.40\pm0.10$. The existence of a single scaling function $F'(x)$ for the transition discussed above is unambiguous confirmation that the description of this transition in (1) in the framework of scaling theory is correct. We can thus use Eq. (2); we find $\delta=6.0\pm0.3$ and $\phi=2.90\pm0.15$.

The critical exponents calculated in this letter differ from the results of Ref. 3

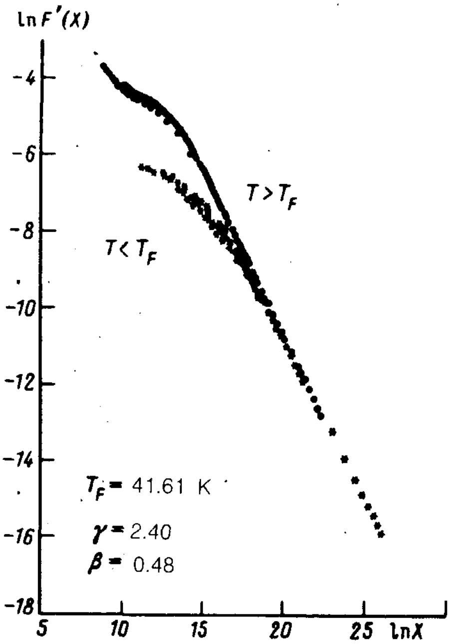

FIG. 3. The derivative of the scaling function, $F'(x)$, for the paramagnet–spin-glass phase transition in the amorphous alloy $(Fe_{0.65}Mn_{0.35})_{75}P_{16}B_6Al_3$ (T_F=41.61 K, γ=2.40, β=0.48).

(β =0.76±0.04, γ=2.05±0.05, and δ=3.8±0.3), found for an alloy of the same composition. However, this circumstance can be fully explained, since critical fluctuations of a ferromagnetic nature which stem from the proximity of the composition of this alloy to the concentration corresponding to the onset of a long-range ferromagnetic order significantly influence the paramagnet–spin-glass transition of interest here.[3] Since the second-harmonic signal is definitely nonzero for a ferromagnet (even in the absence of a magnetic field),[6,7] the method proposed above for determining the critical exponents is evidently more sensitive than the methods used in Ref. 3 to the presence of ferromagnetic fluctuations.

This work was carried out with financial support from the Ukrainian State Committee on Science and Technologies.

[1] M. Suzuki, Progr. Theor. Phys. **58**, 1151 (1977); J. Chalupa, Solid State Commun. **22**, 315 (1977).
[2] H. Bouchiat, J. Phys. (Paris) **47**, 71 (1986).
[3] V. G. Bar'yakhtar, A. B. Surzhenko, and G. A. Takzeĭ, Zh. Eksp. Teor. Fiz. **102**, 1674 (1992) [Sov. Phys. JETP **75**, 905 (1992)].
[4] L. P. Levy and A. Ogielski, Phys. Rev. Lett. **57**, 3288 (1986); L. P. Levy, Phys. Rev. B **38**, 4963 (1988).
[5] T. Taniguchi, H. Matsuyama, S. Chikazawa, and Y. Miyako, J. Phys. Soc. Jpn. **52**, 4323 (1983).
[6] H. E. Stanley, *Introduction to Phase Transitions and Critical Phenomena* (Clarendon Press, Oxford, 1971).
[7] S. C. Ho, I. Maartense, and G. Williams, J. Phys. F **11**, 1107 (1981).

Translated by D. Parsons