Experimental test of the applicability of a scaling description of ferromagnetic alloys with competing exchange

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A simple experimental test of the applicability of a scaling description of a paramagnet–ferromagnet phase transition has been found. This method has been used to study the paramagnet–ferromagnet phase transition in the frustrated amorphous alloy $(Fe_{70}Cr_{30})_{85}B_{15}$.

Several experimental methods have been developed for studying critical phenomena accompanying second-order paramagnet-ferromagnet (PM–FM) phase transitions.[1] Most are based on a determination of the critical exponents γ, β, and δ describing the power-law behavior of various thermodynamic functions near the critical Curie temperature T_c:

$$\chi(T) \sim \tau^{-\gamma} \qquad (T > T_c), \tag{1}$$

$$M_s(T) \sim \tau^{\beta} \qquad (T < T_c), \tag{2}$$

$$M(H) \sim H^{1/\delta} \qquad (T = T_c). \tag{3}$$

Here χ is the susceptibility, M and M_s are the static and spontaneous magnetizations of the FM, $\tau = |1 - T/T_c|$ is the reduced temperature, and H is the magnetic field.

According to the scaling hypothesis, the values of the critical exponents γ, β, and δ are related by the scaling relation[2]

$$\gamma = \beta(\delta - 1). \quad (4)$$

If the critical exponents found experimentally satisfy relation (4), we have unambiguous evidence in favor of a scaling description of the PM–FM transition.

Conditions (1)–(3) are thus necessary conditions, and relation (4) a sufficient condition, for the applicability of scaling theory for describing the particular entity of interest.

We should also point out that most existing methods for estimating critical exponents suffer from serious disadvantages. In the first place, an error in the determination of T_c unavoidably leads to errors in the values of γ, β, and δ. Second, in the case of frustrated FMs, in which antiferromagnetic exchange interactions operate along with the FM interaction, and the critical region near T_c for these exchange interactions is anomalously wide,[1] there are often experimental difficulties in determining the temperature range in which relations of the type in (1)–(3) are valid. An additional error arises in connection with the determination of the critical exponents. Because of these circumstances, the satisfaction of (for example) relation (4) within an error $\sim 10\%$ is regarded as a completely acceptable criterion for the applicability of a scaling description of the PM–FM phase transition.[1]

In this letter we wish to propose a simple experimental criterion for testing whether the results of scaling theory are applicable to some specific entity of interest. This new method is free of the disadvantages which we just listed.

According to Refs. 1 and 3, the susceptibility of an FM in a nonzero magnetic field can be written

$$\chi(h,\tau) = \tau^{-\gamma}F(h/\tau^{\gamma+\beta}) = h^{(1/\delta)-1}G(h/\tau^{\gamma+\beta}), \quad (5)$$

where $h = \mu_B gH/k_B T_c$ is the reduced magnetic field, and $F(X)$ and $G(X)$ are scaling state functions. Relation (5) was used in Ref. 3 to show that a crossover line described by the equation

$$[d\chi_0'(h,\tau)/d\tau]_{T=T_m} = 0 \quad (6)$$

exists for FMs. Experimentally, this crossover line is manifested in the appearance, at $T_m(h) > T_c$, of peaks on the temperature dependence of the real component χ_0' of the low-frequency dynamic susceptibility. These peaks stem from the existence of critical FM fluctuations at $T > T_c$. From (5) and (6) follow the relations[3]

$$\tau_m \sim h^{1/(\gamma+\beta)}, \quad (7)$$

$$\chi_0'(h,\tau_m) \sim h^{(1/\delta)-1}, \quad (8)$$

where $\tau_m = (T_m - T_c)/T_c$. On the other hand, by combining (4), (7), and (8) we easily find

$$\chi_0'(h,\tau_m) \sim h^{[1/(1+\gamma/\beta)]-1} \sim [h^{1/(\gamma+\beta)}]^{-\gamma} \sim \tau_m^{-\gamma}. \quad (9)$$

The formal similarity between (1) and (9) means that, if the values found for γ from these functional dependences are the same, then we automatically have evidence that (4) holds and evidence that a scaling description of the PM–FM phase transition is valid in the entity of interest. This criterion can be rewritten in the more convenient form

$$d\ln\chi_0'(0,\tau)/d\ln\tau = d\ln\chi_0'(h,\tau_m)/d\ln\tau_m. \quad (10)$$

Whether condition (10) is satisfied does not depend on the choice of T_c, as is easily shown.

The ideas outlined above have been used in the present study to investigate the PM–FM phase transition in the frustrated amorphous ferromagnet $(Fe_{70}Cr_{30})_{85}B_{15}$.

Figure 1a shows the real component χ_0' of the dynamic magnetic susceptibility measured with a standard mutual-induction bridge. We see that this alloy undergoes a reentrant PM–FM-(spin glass) transition at the temperatures $T_c \simeq 32$ K and $T \simeq 6$ K, respectively. Figure 1b shows curves of $\chi_0'(H,T)$ measured in magnetic fields of various strengths. The peaks in $\chi_0'(H,T_m)$ observed at $T_m(H)$ (and marked by the arrows) shrink and shift up the temperature scale with increasing H, in agreement with (7) and (8).

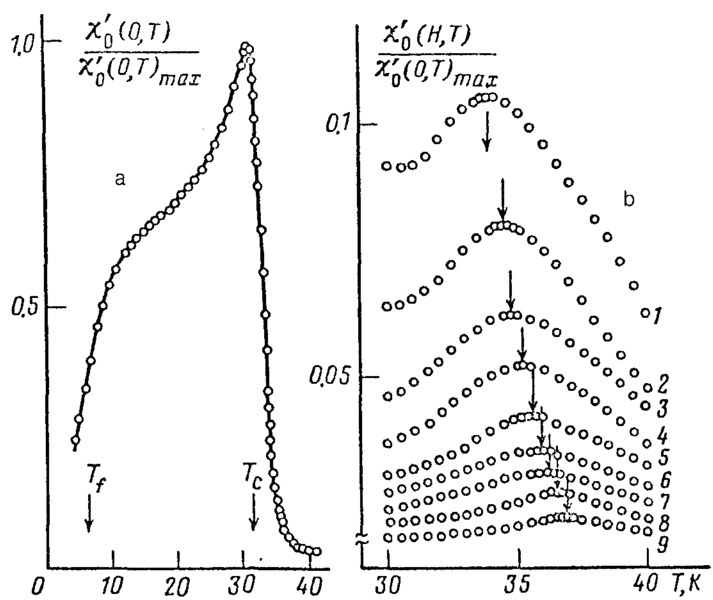

FIG. 1. Temperature dependence of the real component χ_0' of the dynamic magnetic susceptibility of the alloy $(Fe_{70}Cr_{30})_{85}B_{15}$ (a) in a zero magnetic field and (b) in a nonzero magnetic field. 1—$H = 20$ Oe; 2—30; 3—40; 4—50; 5—62; 6—80; 7—100; 8—120; 9—150 Oe.

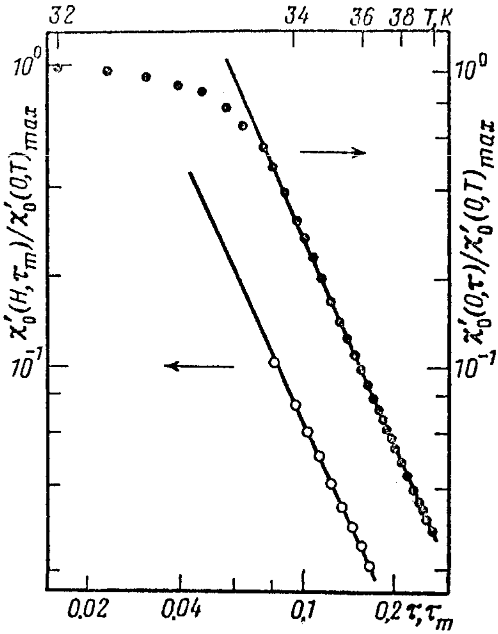

FIG. 2. The normalized susceptibility χ_0' of the alloy $(Fe_{70}Cr_{30})_{85}B_{15}$ versus the reduced temperatures τ and τ_m.

To test criterion (10), we show experimental results on $\chi_0'(0,\tau)$ (the filled points) and $\chi_0'(H,\tau_m)$ (the open points) in full logarithmic scale in Fig. 2. In each case a Curie temperature $T_c = 31.4$ K was selected. Since the plots of $\chi_0'(0,\tau)$ and $\chi_0'(H,\tau_m)$ are linear and parallel in these coordinates, we have evidence for the validity of relations (1) and (9) at reduced temperatures at which the condition $4\pi\chi_0' < 1$ holds. We also have evidence that criterion (10) is satisfied. The latter point is unambiguous evidence that the PM–FM phase transition can be described by the scaling hypothesis near T_c for this alloy.

From these data we can find values for the critical exponents and the critical temperature. Analysis of the temperature dependence $\chi_0'(0,T)$ by the Kouvel–Fisher method[4] for this alloy yields $T_c = 31.5 \pm 0.1$ K and $\gamma = 2.0 \pm 0.1$. The value calculated for δ from the field dependence $\chi_0'(H,\tau_m)$ and (8) is $\delta = 5.0 \pm 0.3$. Using scaling relation (4), we then easily find $\beta = 0.50 \pm 0.05$.

These values of the critical exponents agree well with the theoretical predictions of Ref. 5 for frustrated amorphous FMs and also with the results of Ref. 6, found for the alloy of the same composition by different methods.

We wish to stress that the criterion proposed here is apparently of universal applicability, for all ferromagnets. However, it is most convenient for studying frustrated alloys, since the anomalous broadening of the critical region characteristic of these systems eliminates the experimental difficulties associated with determining the parameters of the crossover line.

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