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STATIC AND DYNAMIC PROPERTIES OF THE TWO-DIMENSIONAL ISING SPIN GLASS $Rb_2Cu_{1-x}Co_xF_4$

C. Dekker, A. F. M. Arts and H. W. de Wijn

Fysisch Laboratorium, Rijksuniversiteit Utrecht, P.O. Box 80.000, 3508 TA Utrecht, The Netherlands

Abstract. – From an analysis of the nonlinear part of the dc magnetization and activated dynamic scaling of the ac susceptibility, $Rb_2Cu_{1-x}Co_xF_4$ is established to be an excellent representation of the Edwards-Anderson two-dimensional Ising spin glass model for $x = 0.218$.

Despite the large number of compounds exhibiting spin glass behavior, very few are experimental realizations of the short-range Ising spin glasses as modeled by theory and computer simulations. In particular, experimental work on two-dimensional (2D) Ising spin glasses, for which an extensive literature on simulations is available [1, 2], is virtually absent. In this paper, we focus on the insulating concentrated spin glass $Rb_2Cu_{1-x}Mn_xF_4$ with $x = 0.218$, noting that from the susceptibility spin glass behavior is found for $0.17 < x < 0.40$ [3]. A comparable phase diagram has been discussed for the related mixed 2D system with XY anisotropy $Rb_2Cu_{1-x}Co_xF_4$ [4]. $Rb_2Cu_{1-x}Co_xF_4$ is genuinely 2D with a simple square lattice, has bond rather than site randomness, and exhibits strong Ising anisotropy. Due to the layered K_2NiF_4 crystal structure, the pure constituents are archetypes of 2D ferromagnetism and antiferromagnetism, respectively. We will show from the dc and ac susceptibilities that both the static and dynamic properties establish $Rb_2Cu_{0.782}Co_{0.218}F_4$ to be an experimental realization of the 2D Edwards-Anderson spin glass ordering at $T_c = 0$ K. Recently, from a dynamic study of the susceptibility similar results were obtained for $Fe_{0.3}Mg_{0.7}Cl_2$ [5].

The static magnetization $M(T, H)$ of a single crystal was measured by use of a vibrating-sample magnetometer under field-cooling conditions, and corrected for demagnetization. From the data $M(H)$ isotherms were deduced, which are shown in figure 1 for a selection of temperatures between 4.25 and 2.90 K. To analyze the nonlinearity in the data we expand $M(H)$ in odd powers of the field,

$$M = \chi_0 H - a_3 (\chi_0 H)^3 + a_5 (\chi_0 H)^5 - \cdots, \quad (1)$$

in which a_3 and a_5 are related to the Edwards-Anderson susceptibility according to $a_3 \propto (T - T_c)^{-\gamma}$ and $a_5 \propto (T - T_c)^{-(2\gamma+\beta)}$, with γ and β the usual critical exponents. In the expansion parameter we have included, following Omari *et al.* [6], the linear susceptibility χ_0, which for a symmetric distribution of interactions reduces to a trivial factor $1/T$. In the present compound, χ_0 is enhanced as a result of residual short-range ferromagnetic correlations. The solid lines in figure 1 represent fits of equation (1) to $M(H)$ with χ_0,

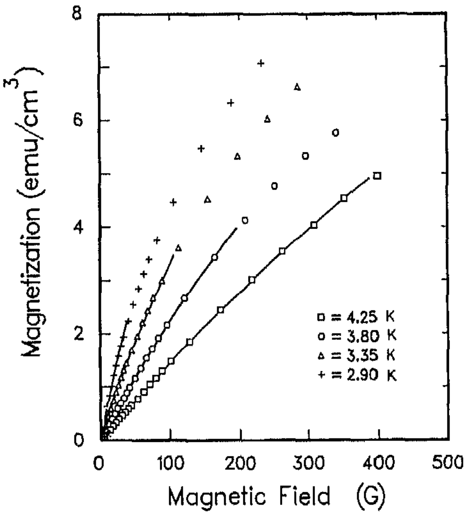

Fig. 1. – Magnetization *vs.* the field at selected temperatures. Solid lines represent fits of equation (1).

a_3, and a_5 as adjustable parameters. The resultant temperature dependences of a_3 and a_5 are depicted in figure 2. The rapid increase of both coefficients levels off at $T \approx 2.9$ K, a temperature somewhat below the freezing temperature T_f [7]. Obviously, below this point the results correspond to nonequilibrium conditions. Above T_f, a power-law divergence to $T_c = 0$ K excellently accounts for the data. From the slopes in figure 2 we derive $\gamma = 4.5 \pm 0.2$ and $2\gamma + \beta = 9.0 \pm 0.5$, and thus $\beta = 0.0 \pm 0.7$, values which are essentially the same as $\gamma = 4.4 \pm 0.4$ and $\beta = 0.0 \pm 0.1$ obtained from a scaling analysis of $M(T, H)$ [7]. To establish more firmly that the divergence of the nonlinear part of $M(H)$ conforms to $T_c = 0$, we have additionally adjusted a divergence at a finite T_c to the results for a_3 and a_5. For values of T_c just below T_f (2.5-2.9 K), the fits turn out to be markedly inferior ($\chi^2 = 5 - 40$, compared with $\chi^2 \approx 1$ at $T_c = 0$ K). The results thus rule out $T_c \approx T_f$, but do not exlude a T_c below, say, 1 K.

The result of a $T_c = 0$ transition is further corroborated by a study of the dynamic critical behavior. We consider dynamic scaling of the imaginary part of the ac susceptibility $\chi''(\omega, T)$. A full report will appear

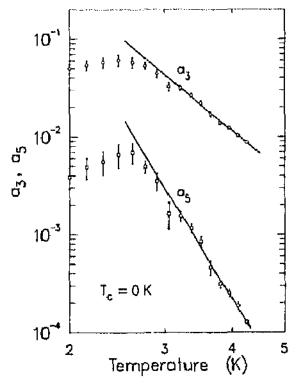

Fig. 2. – Nonlinear susceptibility coefficients a_3 and a_5 (in emu) *vs.* the temperature. Solid lines denote the power-law divergences towards $T_c = 0$ K.

elsewhere [8]. For a 2D spin glass ordering at $T_c = 0$, the dynamics of excitations up to length scales $L \leq \xi$, with $\xi \propto T^{-\nu}$ the correlation length, is anticipated to be governed by thermal activation over energy barriers whose height scales as L^{ψ}, where ψ is a critical exponent with $0 \leq \psi \leq 1$ [9]. Close to the transition, the divergence of ξ implies the presence of divergent barriers and concomitantly an extreme slowing down of the relaxation times. From this, dynamical quantities may be assumed to be functions of the scaling argument $\ln(\omega\tau_0) / \xi^{\psi}$, where τ_0 is a microscopic time [10]. For $\chi''(\omega, T)$ this leads to the activated-dynamic scaling form

$$\chi'' T^{-p} = \mathcal{F}[-\ln(\omega\tau_0) T^q], \qquad (2)$$

in which $\mathcal{F}$ is a scaling function, $p \equiv -1 - \gamma + \psi\nu$, and $q \equiv \psi\nu$. The logarithmic dependence on ω sharply contrasts with conventional critical behavior at a finite T_c, in which case $\omega\xi^{\psi}$ would be the appropriate scaling argument.

To verify activated scaling, $\chi''(\omega, T)$ was measured between 1.6 and 8.0 K for frequencies ranging from 0.3 Hz to 50 kHz. The data were obtained by use of mutual-inductance methods with the driving field along the Ising axis. Figure 3 shows scaling according to equation (2) such as to achieve maximum coincidence of the data for the entire range of frequencies and temperatures considered. Scaling is thus found to be satisfactorily obeyed for $p = -3.0 \pm 0.5$, $q = 2.2 \pm 0.3$, and $\tau_0 = 10^{-13\pm1}$ s, apart from minor deviations near $\omega\tau_c \approx 1$. Combination of p and q yields $\gamma = 4.2 \pm 0.6$, which excellently agrees with the result deduced from the static nonlinear magnetization. The result for γ compares well with estimates of γ for the $\pm J$ 2D Ising spin glass, which range from 4.1 to 5.3 [11]. From the scaling relation $\gamma = \nu(2 - \eta)$ we then deduce $\nu = 2.3 \pm 0.4$ upon adopting $\eta = 0.2 \pm 0.2$ [12]. Further, from $\psi\nu = 2.2 \pm 0.2$, there follows $\psi = 0.9 \pm 0.2$, which is compatible with the upper limit $\psi \leq 1$.

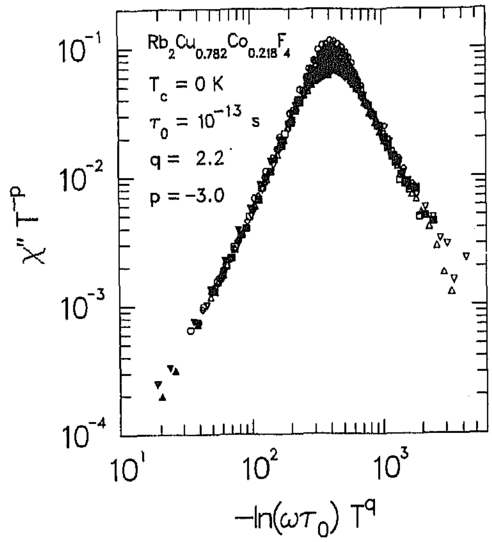

Fig. 3. – Activated-dynamic scaling plot of $\chi''(\omega, T)$.

In conclusion, $Rb_2Cu_{0.782}Co_{0.218}F_4$ appears to be an excellent representation of the 2D Ising spin glass model. Both the static and dynamic properties are consistent with a $T_c = 0$ phase transition. The critical exponents favor the system to belong to the $\pm J$, universality class of 2D spin glasses.

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