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Critical dynamics in $Cd_{1-x}Mn_xTe$ spin glasses

B. Leclercq, C. Rigaux, A. Mycielski,* and M. Menant
Groupe de Physique des Solides, Universités Paris VII et Paris VI, 2, place Jussieu, 75251 Paris CEDEX 05, France
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The critical dynamics in $Cd_{1-x}Mn_xTe$ is investigated by accurate Faraday rotation measurements carried out in the vicinity of the freezing temperature on compounds of composition $x=0.38$ and $x=0.50$. The temperature dependence of the average relaxation time is well described by conventional power law, for critical temperatures $T_c=9.9\pm0.1$ K ($x=0.38$) and $T_c=17\pm0.1$ K ($x=0.50$). The validity of the dynamic scaling law for the imaginary part of the complex susceptibility is tested using the $\chi''(T,\omega)$ data obtained in the entire temperature and frequency range. The best scalings performed for the above T_c values yield a dynamic exponent $z\nu=9\pm1$ and an order-parameter exponent $\beta=0.6\pm0.1$ for both investigated compounds. The observation of a unique scaling function in the composition range 0.3–0.5 supports the existence of universality.

Among insulating spin glasses, the semimagnetic semiconductors $Cd_{1-x}Mn_xTe$ provide the best example of Heisenberg systems with short-range magnetic interactions. At concentrations larger than the percolation threshold ($x_p\approx0.2$), the face-centered-cubic lattice is naturally frustrated due to the antiferromagnetic exchange coupling between nearest neighbors. Randomness (due to dilution) and frustration give rise to a spin-glass state at low temperature.

The existence of a phase transition at finite temperature T_c has been well characterized in these compounds by both static and dynamic measurements. In $Cd_{0.6}Mn_{0.4}Te$, the nonlinear static magnetization above T_c is consistently described by the scaling function inferred from the mean-field theory, and the critical exponents β, γ were deduced from the scaling analysis.[1] Dynamic studies of the ac magnetic susceptibility have been carried out for several Mn compositions.[2–6] The critical slowing down of the relaxation time above T_c is well described by the conventional power law whereas the activated dynamic model, initially proposed to describe the spin freezing, does not apply for these compounds.[3,6] The dynamic scaling analysis of the imaginary part χ'' of the complex susceptibility has yielded the determination of the exponents $z\nu$ and β for $Cd_{0.6}Mn_{0.4}Te$ (Ref. 6) and $Cd_{0.7}Mn_{0.3}Te$.[3] The application of generalized in-field scalings to this latter compound has provided an independent determination of T_c and the evaluation of the crossover exponent.[3]

There exists, however, some dispersion among the values of the critical exponents deduced from different scaling analyses, namely for the composition $x=0.40$, which was the most investigated by both static and dynamic measurements. The existence of a class of universality among these spin glasses is not yet settled. This affords a motivation to explore more completely the critical dynamics in $Cd_{1-x}Mn_xTe$ compounds of different Mn concentrations, also including $x\approx0.40$.

We report susceptibility measurements of the dynamic behavior of $Cd_{0.62}Mn_{0.38}Te$ and $Cd_{0.5}Mn_{0.5}Te$. The ac magnetic susceptibility χ_{ac} was obtained from Faraday rotation experiments carried out under an ac magnetic field of weak amplitude (<10 G) to avoid nonlinear effects, at a photon energy E slightly smaller than the band gap ($E/E_g\leq0.8$). In-phase (χ') and out-of-phase (χ'') components of χ_{ac} were measured simultaneously in the vicinity of the spin-glass transition during a slow cooling process (at a rate of 1 mK/s). The temperature is determined within an accuracy of ±0.02 K. The measurements were made over a large number of frequencies of the ac magnetic field (three frequencies per decade) in the range $3\leq f\leq10^5$ Hz. The inclusion of extensive experimental data in the scaling analysis improves the selection of the range of parameters. In the low-frequency range, accurate measurements are made by using a modulation technique.[7] Figure 1 shows the temperature dependence of χ' and χ'' measured at different frequencies for the compound $Cd_{0.62}Mn_{0.38}Te$.

Our analysis of the critical dynamics is based on the conventional slowing down valid for a spin-glass phase transition at finite temperature T_c. The divergence of the relaxation time τ as the transition is approached from above is described by the power law[8]

$$\tau=\tau_0\varepsilon^{-z\nu} \tag{1}$$

where $\varepsilon=T/T_c-1$ is the reduced temperature, z and ν are critical exponents, and τ_0 is the microscopic relaxation time.

The frequency and temperature dependences of the imaginary component of the magnetic susceptibility are analyzed considering the scaling relations derived from the linear response theory[9,10] or from the fractal cluster model.[11] These relations for $\chi'(T,\omega)$ and $\chi''(T,\omega)$ are

$$\chi'(T,0)-\chi'(T,\omega)\propto(1/T)\omega^{\beta/z\nu}f(\omega\tau)\ , \tag{2a}$$

$$\chi''(T,\omega)\propto(1/T)\omega^{\beta/z\nu}g(\omega\tau)\ , \tag{2b}$$

or similarly

$$\chi'(T,0)-\chi'(T,\omega)\propto(1/T)\varepsilon^{\beta}F(\omega\tau)\ , \tag{3a}$$

$$\chi''(T,\omega)\propto(1/T)\varepsilon^{\beta}G(\omega\tau)\ , \tag{3b}$$

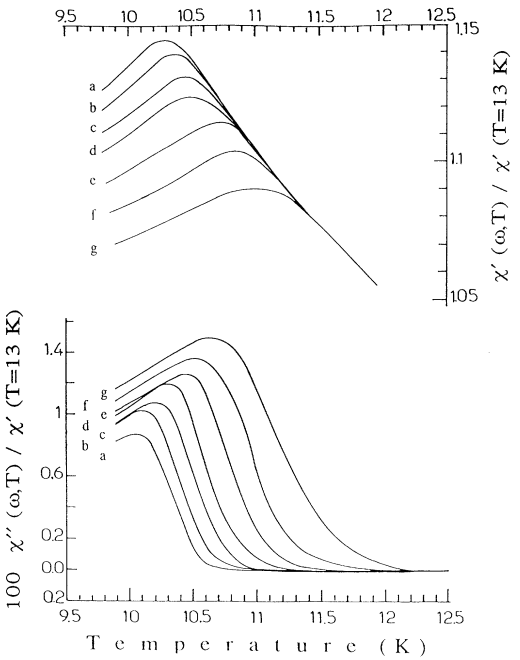

FIG. 1. The in-phase (χ') and out-of-phase (χ'') components of the ac susceptibility vs temperature, measured in $Cd_{0.62}Mn_{0.38}Te$. The different curves correspond to different frequencies of the applied ac field ($\Delta H \approx 10$ G): *a*, 7.5 Hz; *b*, 36 Hz; *c*, 161 Hz; *d*, 754 Hz; *e*, 3.6 kHz; *f*, 16 kHz; *g*, 75 kHz.

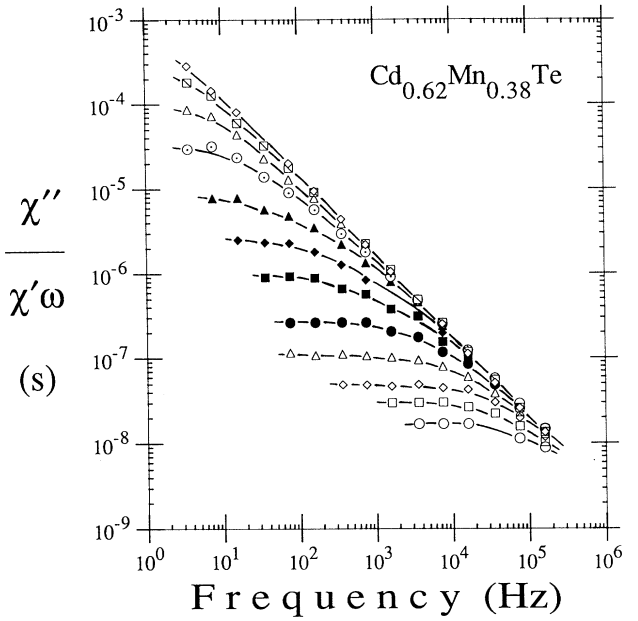

FIG. 2. The logarithm of $\omega^{-1}(\chi''/\chi')$ vs the logarithm of the frequency for $Cd_{0.62}Mn_{0.38}Te$. The different symbols correspond to different temperatures: ○ 11.3 K, □ 11.2 K, ◇ 11.1 K, △ 11 K, ● 10.9 K, ■ 10.8 K, ♦ 10.7 K, ▲ 10.6 K, ⊙ 10.5 K, △ 10.4 K, ☑ 10.3 K, ◇ 10.2 K. In the limit of small frequencies, the curves converge to the average relaxation time $\tau_{av}(T)$.

where $f(x)$, $g(x)$, $F(x)$, and $G(x)$ are universal functions, β is the exponent of the order parameter, and $\omega = 2\pi f$.

In a first approach, we determine the average relaxation time τ_{av} at fixed temperatures. From standard relations including the distribution function $\rho(\tau)$ of correlation times, Ogielski derived[12]

$$\tau_{av} = \int \tau \rho(\tau) d\tau = \lim_{\omega \to 0} \frac{1}{\omega} \frac{\chi''(\omega)}{\chi'(\omega)} . \quad (4)$$

According to Eqs. (1) and (3), $\tau_{av}(T)$ is expected to follow the power law

$$\tau_{av} = \tau_0 \varepsilon^{-(z\nu-\beta)} . \quad (5)$$

We report in Fig. 2 logarithmic plots of $\omega^{-1}(\chi''/\chi')$ vs frequency obtained at fixed temperatures. The extracted values of $\tau_{av}(T)$ are determined every 0.05 K in the temperature range 10.4–12.0 K for $Cd_{0.62}Mn_{0.38}Te$ and 17.7–19.5 K for $Cd_{0.5}Mn_{0.5}Te$. The range of validity of Eq. (5) is tested from the linear fits of $\log\tau_{av}(T)$ vs $\log\varepsilon$ performed for selected values of T_c. The parameters T_c and $z\nu-\beta$, reported in Table I, correspond to the best least-squares fits of the data. The quality of each fit is characterized by a χ^2 value,[13] which does not exceed $2\chi^2_{min}$ for each set of parameters $(T_c, z\nu-\beta)$ reported in Table I. From this analysis we deduce the range of T_c where the power law (5) applies for both investigated compounds:

$$T_c = 9.9 \pm 0.1 \text{ K} \quad \text{for} \quad x = 0.38 ,$$
$$T_c = 17.0 \pm 0.1 \text{ K} \quad \text{for} \quad x = 0.50 . \quad (6)$$

Figure 3 shows the linear fits of $\log\tau_{av}(T)$ vs $\log\varepsilon$ for both compositions.

In a more complete analysis, we test the dynamic scaling relations (2b), and (3b) using the frequency and temperature dependences of the imaginary component $\chi''(T,\omega)$ of the magnetic susceptibility. As shown by Bertrand *et al.*,[14] the applicability of the dynamic scaling relations derived within the linear response approximation imposes a drastic limitation on the temperature range to avoid the inclusion of nonlinear effects in $\chi''(T,\omega)$. Therefore we have restricted the $\chi''(T,\omega)$ data in our scaling analysis to the temperature range $T \geq T_p$, where T_p is the temperature of the $\chi''(T,\omega)$ peak.

For each T_c value selected from the analysis of τ_{av}, the exponents $z\nu$ and β are chosen independently to obtain the best collapse of all experimental data on a unique scaling plot $\chi''(T,\omega)T\varepsilon^{-\beta}$ vs $\omega\varepsilon^{-z\nu}$ performed in a log-log scale. A more accurate approach to the dynamic scaling was also considered taking the form

TABLE I. Transition temperatures and critical exponents determined from the present study for $x = 0.38$ and $x = 0.50$.

Composition	T_c (K)	$z\nu-\beta$ (from τ_{av})	$z\nu$ (according to the scaling law)	β (according to the scaling law)	$z\nu-\beta$ (according to the scaling law)
$x = 0.38$	10.0	7.5±0.3	8	0.6–0.7	7.3–7.4
	9.9	8.3±0.3	9	0.6–0.7	8.3–8.4
	9.8	9.0±0.3	10	0.7	9.3
$x = 0.50$	17.1	7.9±0.3	8–8.5	0.5–0.6	7.5–8.0
	17.0	8.5±0.3	9	0.5–0.6	8.4–8.5
	16.9	9.2±0.3	10	0.6	9.4

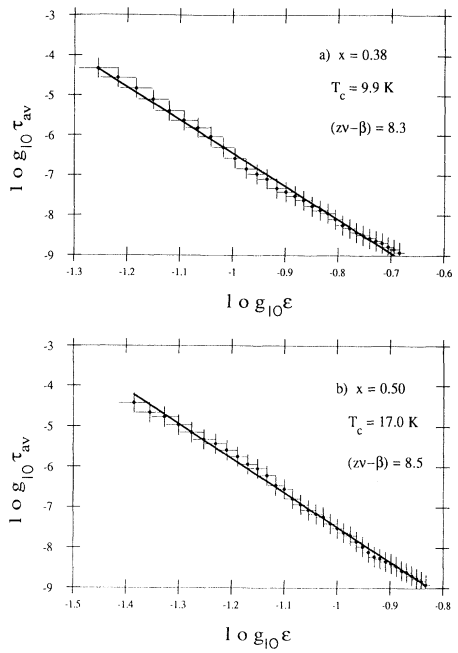

FIG. 3. The logarithm of τ_{av} vs the logarithm of ε. The straight lines represent the least-squares fit of the data. (a) corresponds to $Cd_{0.62}Mn_{0.38}Te$ with $T_c=9.9$ K. (b) corresponds to $Cd_{0.5}Mn_{0.5}Te$ with $T_c=17.0$ K.

$$\chi''(T,\omega)T\omega^{-\beta/z\nu}\approx\bar{g}(\varepsilon\omega^{-1/z\nu}) \quad (7)$$

proposed by Geschwind, Huse, and Devlin[6] to obtain a linear scaling plot. We consider a set of parameters $(T_c,z\nu,\beta)$ as acceptable when the scattering of the scaling plots does not exceed the experimental accuracy. The selected T_c values and the critical exponents $z\nu,\beta$ corresponding to the best scalings are reported in Table I for both investigated compounds. For each T_c within the selected range (6), an excellent agreement is found within the experimental accuracy between the value of $z\nu-\beta$ deduced from the analysis of τ_{av} and the set of parameters $(z\nu,\beta)$ determined from the scaling analysis according to

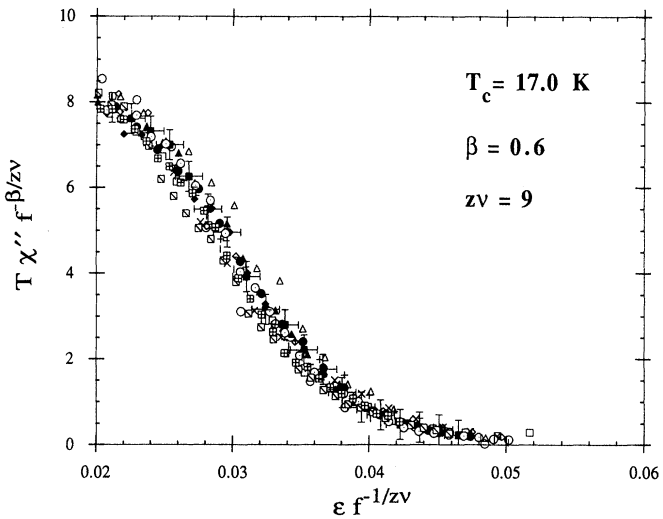

FIG. 4. Scaling of $\chi''(T,\omega)T$ performed according to Eq. (7) for $Cd_{0.5}Mn_{0.5}Te$. The different symbols correspond to different frequencies of the ac field: ○ 3.6 Hz, □ 7.5 Hz, ◇ 16 Hz, × 36 Hz, + 75 Hz, △ 161 Hz, ● 363 Hz, ■ 754 Hz, ◆ 1610 Hz, ▲ 3630 Hz, ⊙ 7540 Hz, | 16 100 Hz, ⊠ 36 300 Hz, ⊞ 75 400 Hz, – 161 000 Hz.

Eq. (7). The exponents $z\nu$ and β obtained from the scaling analysis are quite similar for $x=0.38$ and $x=0.50$: within the range of T_c (6), we obtain $z\nu=9\pm1$, $\beta=0.6\pm0.1$. As previously shown,[3,6] $z\nu$ increases on decreasing T_c. Figure 4 illustrates one of the best scalings performed for $Cd_{0.5}Mn_{0.5}Te$ using the dynamic scaling form (7), with the parameters $T_c=17.0$ K, $z\nu=9$, $\beta=0.6$.

In order to test the universality of the scaling function, the scaling analysis is performed using the relation (3b) for three compositions: $x=0.30$, from the $\chi''(T,\omega)$ data previously obtained,[3,10] $x=0.38$, and $x=0.50$, taking $T_c=6.4$ K, 9.9 K, and 17.0 K, respectively, with identical critical exponents ($z\nu=9$, $\beta=0.6$). Figure 5 shows in the same plot the scaling performed for the three compositions. We obtain the same $G(x)$ function as expected from universality. The initial slope of the scaling curve

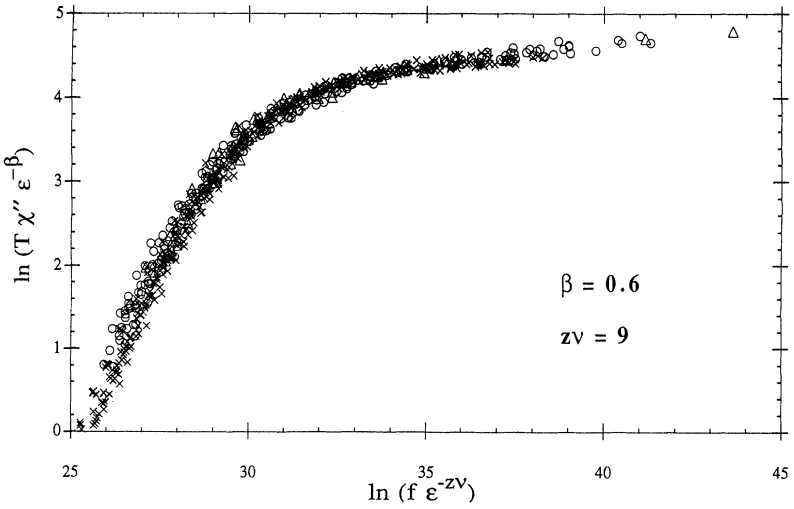

FIG. 5. Scaling of $\chi''(T,\omega)T$ performed according to the relation (3b) for $Cd_{1-x}Mn_xTe$ using the parameters $z\nu=9$ and $\beta=0.6$. The symbols refer to different Mn concentrations: △: $x=0.30$, $T_c=6.4$ K; ○: $x=0.38$, $T_c=9.9$ K; ×: $x=0.50$, $T_c=17.0$ K. The scaling plots corresponding to each composition are shifted with respect to each other along the horizontal and vertical axes to account for the different normalization factors.

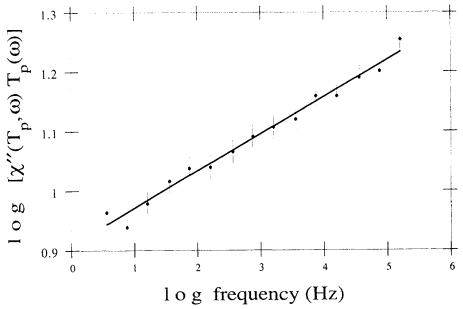

FIG. 6. The logarithm of $\chi''(T_p,\omega)T_p$ vs the logarithm of the frequency for $Cd_{0.62}Mn_{0.38}Te$. The straight line corresponds to the least-squares fit of the data. The slope indicates the value of $\beta/z\nu$.

reported in Fig. 5 corresponds to the asymptotic limit of the $G(x)$ function, namely $G(x)\sim x$ (small x).

To complete our determination of the critical exponents we have examined the frequency dependence of the $\chi''(T,\omega)$ peak. As pointed out in Ref. 6, the amplitude and the temperature T_p of the $\chi''(T,\omega)$ peak should satisfy the relation

$$\chi''(T_p,\omega)T_p(\omega)\propto\omega^{\beta/z\nu}\ . \tag{8}$$

Figure 6 shows the linear dependence of $\log[\chi''(T_p,\omega)T_p]$ as a function of $\log\omega$. The least-squares fit of the data yields

$$\beta/z\nu=0.063\pm0.006 \quad \text{for } x=0.38\ ,$$
$$\beta/z\nu=0.060\pm0.006 \quad \text{for } x=0.50\ ,$$

which are quite consistent with the exponents $z\nu$ and β determined from the complete scaling analysis (Table I).

For comparison with previous works, we report in Table II the values of the critical exponents deduced from different scaling analyses in $Cd_{1-x}Mn_xTe$ compounds. The values of $z\nu-\beta$ obtained for $x=0.30$ (Ref. 3) and $x=0.40$ (Ref. 2) from the analysis of the onset of χ''/χ' are quite coherent with our results deduced from τ_{av}. The dynamic exponent $z\nu=9\pm1$ obtained from our present data is similar to our previous determination for $x=0.30$,[3] but the large value $z\nu=11.3\pm1$ reported by Geschwind, Huse, and Devlin[6] for $Cd_{0.6}Mn_{0.4}Te$ is not compatible with our results. We have checked carefully that whatever the choice of T_c, our $\chi''(T,\omega)$ data cannot be well fitted with $z\nu=11.3$.

TABLE II. Critical exponents in $Cd_{1-x}Mn_xTe$ spin glasses.

Compounds	$z\nu-\beta$	$z\nu$	β	Ref.
$Cd_{0.7}Mn_{0.3}Te$	8.85±0.45	9.25±0.75	0.8±0.1	3
$Cd_{0.6}Mn_{0.4}Te$	8.8±0.9			2
		11.3±1	0.59±0.05	6
			0.9±0.2	1
			0.7±0.2	14

The best scalings can be achieved only over a limited range of the critical exponents β whatever the choice of T_c for each Mn composition (Table I). The inclusion in our scaling analysis of $\chi''(T,\omega)$ data obtained over a large number of frequencies improves the selection of the parameter β. We found β values quite consistent with the determination of Geschwind, Huse, and Devlin[6] for $Cd_{0.6}Mn_{0.4}Te$, while slightly larger values (although compatible) were deduced from the scaling of the nonlinear static magnetization in $Cd_{0.6}Mn_{0.4}Te$,[1] and from the dynamic scaling analysis in $Cd_{0.7}Mn_{0.3}Te$.[3]

In conclusion, the critical dynamic behavior in the vicinity of the spin-glass transition is investigated in $Cd_{1-x}Mn_xTe$ vs Mn composition. The existence of a phase transition at finite T_c in these insulating Heisenberg systems with short-range interactions is well confirmed. The $\chi''(T,\omega)$ data are well fitted by the dynamic scaling law, for the critical temperatures $T_c=9.9\pm0.1$ K ($x=0.38$) and $T_c=17.0\pm0.1$ K ($x=0.50$). In-field dynamic measurements, which are in study, are required to determine more accurately T_c, and thus $z\nu$. The same scaling function is found in the composition range $0.30\le x\le0.50$ with identical values of the critical exponents $z\nu,\beta$, inferring the existence of universality among these spin glasses. Very comparable values of $z\nu$ and β are found in short-range insulating Ising spin glasses,[15] reinforcing the argument that the Heisenberg systems can be described in an Ising picture.[16]

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*Permanent address: Institute of Physics, Polish Academy of Sciences, Al. Lotnikow 32, 02-668 Warsaw, Poland.

[1] A. Mauger, J. Ferré, and P. Beauvillain, Phys. Rev. B **40**, 862 (1989).

[2] A. Mauger, J. Ferré, M. Ayadi, and P. Nordblad, Phys. Rev. B **37**, 9022 (1988).

[3] Y. Zhou, C. Rigaux, A. Mycielski, M. Menant, and N. Bontemps, Phys. Rev. B **40**, 8111 (1989).

[4] M. Saint Paul, J. L. Tholence, and W. Giriat, Solid State Commun. **60**, 621 (1986).

[5] S. Geschwind, A. T. Ogielski, G. E. Devlin, J. Hegarty, and P. Bridenbaugh, J. Appl. Phys. **63**, 3291 (1988).

[6] S. Geschwind, D. A. Huse, and G. E. Devlin, Phys. Rev. B **41**, 4854 (1990).

[7] J. Ferré, J. Rajchenbach, and H. Maletta, J. Appl. Phys. **52**, Suppl. (3), 1967 (1981).

[8] P. C. Hohenberg and B. I. Halperin, Rev. Mod. Phys. **49**, 435 (1977).

[9] N. Bontemps, J. Ferré, and A. Mauger, J. Phys. (Paris) Colloq. **49**, C8-1063 (1989).

[10] Y. Zhou, Ph.D. thesis, Université Paris VI, 1990 (unpublished).

[11] M. Continentino and A. P. Malozemoff, Phys. Rev. B **34**, 471 (1986).

[12] A. T. Ogielski, Phys. Rev. B **32**, 784 (1985).

[13] P. Beauvillain, C. Dupas, J. P. Renard, and P. Veillet, Phys. Rev. B **29**, 4086 (1984).

[14] D. Bertrand, A. Mauger, J. Ferré, and P. Beauvillain, Phys. Rev. B **45**, 507 (1992).

[15] P. Nordblad, L. Lundgren, P. Svedlindh, K. Gunnarsson, H. Aruga, and A. Ito, J. Phys. (Paris) Colloq. **49**, C8-1069 (1989); K. Gunnarsson, P. Svedlindh, P. Nordblad, and L. Lundgren, Phys. Rev. Lett. **61**, 754 (1988).

[16] A. Mauger, J. Villain, Y. Zhou, C. Rigaux, N. Bontemps, and J. Ferré, Phys. Rev. B **41**, 4587 (1990).