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DYNAMIC SCALING IN SPIN-GLASSES: WHAT TO SCALE?

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Abstract. - We review the various experimental approaches for dynamic scaling in spin-glasses. We establish the relevant linear susceptibilities to be scaled namely $\chi_{eq} - \chi'(\omega)$ and $\chi''(\omega)$. We put emphasis on the assumptions which are necessary for the scaling relations to hold and we discuss their applicability in view of some discrepancies that can be found among the published results.

In this paper we discuss the relevance of the various experimental approaches for dynamic scaling in spin-glasses [1-8]. Whereas everybody agrees on the quantity to be scaled as far as static scaling is concerned (e.g. the non linear susceptibility) the procedure does not seem as precisely defined for dynamic scaling. Also, susceptibility data are now being analysed according to power law scaling and activated dynamic scaling, in order to be able to identify the nature of the transition [7, 8]. It is therefore crucial for the experimentalist to control carefully the scaling procedures.

We shall focus on the analysis of the *linear dynamical susceptibility* according to power law scaling. The non-linear dynamical susceptibility will not be discussed here [4].

We first recall briefly how this analysis has been performed by the various authors. Second, we derive the dynamic scaling relations and we recall that they hold if the interactions J_{ij} are symmetric. Such conditions may not be fulfilled in actual spin-glasses. We argue that depending on the quantity which is scaled, one may end up with different results, even on the same compound and with the same data ([6] vs. [7]).

The first criterion which has been considered in order to define a characteristic time τ was, for sake of simplicity, to pick the temperature T_{max} of the maximum of the ac susceptibility $\chi'(\omega)$. This analysis has no theoretical basis.

A second criterion is to measure the ratio $\chi''(\omega, T) / \chi'(\omega, T)$ [1, 2, 6]. A characteristic time τ_a is defined by:

$$\tau_a = \omega^{-1} (\chi'' / \chi') = (T_f - T_c)^{-z\nu} \quad (1)$$

T_f is the temperature where the ratio χ'' / χ' takes some given value ($\ll 1$).

A third criterion is to measure

$$\Delta\chi = (\chi_{eq} - \chi') / \chi_{eq} = \omega\tau_m \quad (2)$$

and to study the temperature variation of τ_m by selecting a value of $\Delta\chi \ll 1$ [3]. We shall show that the second and third criterion are equivalent.

Recent analysis [5, 7, 8] have investigated the dynamic scaling as follows:

$$\chi'' \quad \text{or} \quad \Delta\chi = \omega^{\beta/z\nu} G(\omega\tau) \quad (3)$$

where $G(x)$ is a universal function of x , β is a standard exponent for the order parameter and τ diverges at T_c as $(T - T_c)^{-z\nu}$.

We describe a straightforward way to derive these dynamic scaling formulae from the linear response theory and a simple scaling argument (it is not entirely obvious why the linear susceptibility should lead to dynamic scaling whereas the corresponding static quantity does not exhibit any singular behaviour).

We write first from linear response theory:

$$i\chi''(t) = -1/kT \, dS(t)/dt \quad (4)$$

$$\chi'(t) = -1/kT \, \Gamma(t) \, dS(t)/dt \quad (5)$$

where $\Gamma(t)$ is a step function and $S(t)$ is the autocorrelation function of the magnetization

$$S(t) = \langle m(0) m(t) \rangle. \quad (6)$$

Dynamic scaling states for the *spin* autocorrelation function [9, 10]:

$$q(t) = \langle S_i(0) S_i(t) \rangle_{av} = t^{-\beta/z\nu} Q(t/\tau). \quad (7)$$

The symbol *av* means that one averages over the distribution of the interactions J_{ij} between sites i and j . $Q(x)$ is a universal function of x . τ diverges as $(T - T_c)^{-z\nu}$.

Here lies an important assumption: if the bond distribution is symmetric, then one can identify the spin autocorrelation function to the magnetization autocorrelation function [9, 10].

$$S(t) = q(t). \quad (8)$$

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It is then a matter of simple algebra to derive the scaling relations, provided the system is ergodic.

$$\chi'(\omega) = \chi_{eq} + \omega^{\beta/z\nu} H(\omega\tau) \quad (9)$$

$$\chi''(\omega) = \omega^{+\beta/z\nu} F(\omega\tau) \quad (10)$$

$H(x)$ and $F(x)$ are other universal functions of x . If one develops the $F(\omega\tau)$ and $H(\omega\tau)$ functions in the vicinity of zero, one finds:

$$\delta\chi \quad \text{or} \quad \chi'' = \omega(T - T_c)^{\beta - z\nu}. \quad (11)$$

Equation (11) shows now explicitly that the second and third criteria, i.e. equation (1) or (2), are equivalent (taking the ratio χ''/χ' or $\delta\chi/\chi_{eq}$ hardly changes the result close to T_c). This derivation yields however $z\nu - \beta$ instead of $z\nu$ and therefore corrects equation (1) (usually $\beta \leq 1$). This was already found in the framework of a specific model for spin-glasses (the fractal cluster model) [11]; we have just shown that it is in fact a general result.

One would expect, from this derivation, that it should not matter whether one uses equations (9), (10), (11) or alternatively (1) or (2).

Indeed, in [5], the values derived from equation (3) for $z\nu$ and T_c are found in good agreement with previous work on the same system [2] where equation (1) was used. In contrast, there is a definite disagreement on these quantities in reference [6], where equation (1) is used, and [7], where equation (13) is used, though the sample ($\text{Cd}_{0.6}\text{Mn}_{0.4}\text{Te}$) and the data are similar, leading eventually to entirely different conclusions: spin-glass transition in [6], dynamically inhibited transition to a type III antiferromagnet in [7].

A possible explanation for these discrepancies is as follows: in real spin-glasses, the bond distribution is seldom symmetric. For instance, systems like $\text{CdIn}_{0.3}\text{Cr}_{1.7}\text{S}_4$ [2, 5] and $\text{Eu}_{0.4}\text{Sr}_{0.6}\text{S}$ [12] are well known to exhibit an average ferromagnetic interaction, whereas $\text{Cd}_{0.6}\text{Mn}_{0.4}\text{Te}$ exhibits rather an antiferromagnetic trend. Therefore the identity (8) may not be verified. Equations (9) and (10) then comprise non critical terms which may modify the fitting parameters T_c and $z\nu$.

We suggest what seems to us a reasonable approach of this problem, namely to measure χ'' or $\chi_{eq} - \chi'$ very close to their onset. Such small irreversibilities are mainly due to the longest time constants and we expect the diverging (i.e. critical) times to slow down first (this was the implicit assumption performed in

[1-3, 6]. We believe that this analysis minimizes the weight of the regular terms. We have performed a tentative analysis of the χ' results published in [7]. We do find, although with a somewhat poor accuracy, that using as a criterion $\delta\chi = 0.5\%$, the best fit is obtained for $T_c = 12.6 - 13$ K and $z\nu = 6 - 8$.

We emphasize that, as a practical matter, one should rather use χ'' than $\Delta\chi$. The former determination relies on a null method and it is fairly easy to check that there is no "base line" shift. If any shift occurs during the measurement of χ' , possibly of the order of $\Delta\chi$, it may be very difficult to detect.

In conclusion, though the use of the most general scaling formulae (9) or (10) is certainly appealing, we have argued that because actual spin-glasses do not necessarily follow the assumptions which underly such relations, one should be very careful when applying them. We have suggested a more restrictive approach: measuring the onset of irreversibilities in χ'' or $\Delta\chi$. Drawing conclusions on the mere basis of dynamic scaling may however remain difficult and we believe that joined static and dynamic scalings are necessary.

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