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DYNAMIC SCALING IN A SHORT RANGE ISING SPIN GLASS

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Abstract. – Ac susceptibility data on the Ising spin glass \( \text{Fe}_{0.5}\text{Mn}_{0.5}\text{TiO}_3 \) are analysed according to power law scaling and activated dynamic scaling. Both models are found to give a good scaling behaviour. However, the spin glass temperature achieved from activated dynamic scaling is significantly lower than the temperature for the field cooled susceptibility cusp.

Ac susceptibility measurements reveal considerable slowing down of the spin glass dynamics as the spin glass temperature is approached from above. Recent results from such experimental studies have been analysed within two different models for dynamic scaling: power law scaling \([1, 2, 3, 4, 5]\) and activated dynamic scaling \([3, 4, 6]\), using either the in-phase \([4, 5]\) or the out-of-phase \([2, 3, 6]\) component of the ac susceptibility.

In this paper, we present extensive zero field ac susceptibility measurements of the short-range Ising spin glass \( \text{Fe}_{0.5}\text{Mn}_{0.5}\text{TiO}_3 \). The results are used to investigate the applicability of the power law as well as of the activated dynamic scaling form to the spin glass dynamics. In both cases, the quality of the scaling plots can be made exceptionally good. However, in order to obtain good data collapsing using the activated dynamic scaling form, a value of the spin glass temperature significantly lower than the temperature of the field cooled susceptibility cusp is required.

A single crystal of the hexagonal \( \text{Fe}_{0.5}\text{Mn}_{0.5}\text{TiO}_3 \) was used in this experimental study. \( \text{Fe}_{0.5}\text{Mn}_{0.5}\text{TiO}_3 \) is an Ising like spin glass with the spins aligned along the hexagonal \( c \)-axis \([7]\). The ac susceptibility, \( \chi (T, \omega) = \chi' (T, \omega) + i\chi'' (T, \omega) \), along the \( c \)-axis was measured in a SQUID magnetometer. The measurements were performed in the vicinity of the spin glass temperature, \( 0.9 < T / T_g < 1.4 \) with \( T_g \approx 20.9 \) K, and cover an unusually wide range of frequencies of the oscillating magnetic field, \( 5 \times 10^{-4} < \omega / 2 \pi < 5 \times 10^4 \) Hz. The general behaviour of the in-phase \( \chi' (\omega) \) and out-of-phase \( \chi'' (\omega) \) components of the ac susceptibility have been reported elsewhere \([8]\). \( \chi_{eq} (T) = \chi' (T, \omega) \) and \( \chi'' (T, \omega) \) are the scaled quantities in the analyses that follows. \( \chi_{eq} (T) \), the equilibrium susceptibility, has been obtained in a field cooled (FC) susceptibility experiment using a cooling-rate of \( 10^{-4} \) K/sec.

The frequency dependence of the ac susceptibility is according to dynamic scaling governed by a characteristic relaxation time, \( \tau \), which diverges at the spin glass temperature. The divergence of \( \tau \) is in power law scaling written as \([9]\),

\[
\tau = \tau_0 \left( \frac{T}{T_g} - 1 \right)^{-\beta} \quad \text{(Eq. (1))}
\]

where \( t = \frac{T}{T_g} - 1 \), \( \tau_0 \) is the dynamic exponent and \( \beta \) is the correlation length exponent. In the scaling region, \( \omega \to 0 \) and \( T \to T_g \), the ac susceptibility is written as a function of \( \omega t^{-\zeta v} \),

\[
\left( \chi_{eq} (T) - \chi' (T, \omega) \right) / \chi_{eq} (T) = t^\beta \left( \omega t^{-\zeta v} \right) \quad \text{(2)}
\]

where \( \beta \) is the order parameter exponent and \( F (x) \) is a scaling function. \( F (x) \) has a \( x^{\beta / \zeta v} \) dependence at \( T = T_g \) since the scaled quantity has to be independent of the reduced temperature at the transition. This implies that \( \left( \chi_{eq} (T) - \chi' (T, \omega) \right) \propto \omega^{\beta / \zeta v} \) at \( T_g \). Figure 1 shows our data fitted to the scaling law in equation (2). The scaling fit yields \( 2 \beta = 9.5 \pm 0.0 \), \( \beta = 0.7 \pm 0.1 \) and \( T_g = 20.95 \pm 0.1 \). These values of \( \beta \) and \( T_g \) are in good agreement with earlier results of the same spin glass system \([8]\). Furthermore, the ratio \( \beta / \zeta v \) agrees well with the exponent of the power law decay \( (\omega^{0.07}) \) of \( \left( \chi_{eq} (T) - \chi' (T, \omega) \right) / \chi_{eq} (T) \) close to \( T_g \) as determined previously \([8]\).

Malozemoff and Pytte \([6]\) have introduced another

\[
\begin{align*}
\text{Fig. 1.} & \quad - \quad \text{Power law scaling of the} \\
& \quad (\chi_{eq} (T) - \chi' (T, \omega)) / \chi_{eq} (T) \text{ data. The symbols 0-11 denote different temperatures in the range 21 K-23.3 K (4 \times 10^{-2} \leq t \leq 1.2 \times 10^{-1}, T_g = 20.95 K).}
\end{align*}
\]
scaling form to describe the spin glass dynamics close to \( T_g \). This scaling form was originally proposed for random field Ising systems [10]. The ac susceptibility is in this model governed by thermally activated dynamics. The divergence of the characteristic relaxation time is written as, \( \tau = \tau_0 \exp \left( \frac{C}{T^Q} \right) \) (Eq. (3)) where \( C \) is a constant and \( Q \) is a critical exponent. In the scaling region, the ac susceptibility is written as a function of \( \ln \left( \frac{\omega \tau_0}{T^Q} \right) \), (Eq. (4))

\[
\frac{\chi_\text{eq}(T) - \chi'(T, \omega)}{\chi_\text{eq}(T)} = t^P G(-\xi^2 \ln(\omega \tau_0))
\]

where \( P \) is a critical exponent, \( G \) is a scaling function and the value of \( \tau_0 \) must be explicitly included. In order to test this scaling form, it is advantageous to first determine \( Q \) and \( T_g \) from the divergence of \( \tau \) according to equation (3). Experimentally, the characteristic relaxation time at a given temperature is often defined by using the cusp temperature of the different \( \chi' \) curves (or equivalently by using the temperature of the inflection point of the \( \chi'' \) curves) and setting \( \tau \) equal to \( \omega^{-1} \). The best fit to equation (3), using a reasonable value of \( \tau_0 = 10^{-13} \) s, yields \( Q = 0.55 \pm 0.10 \) and \( T_g = 20.0 \pm 0.1 \) K. This value of \( Q \) is in good agreement with results from experiments on other systems [4, 6]. However, the value of \( T_g \) is almost 1 K below the value determined from power law scaling and also considerably lower than the cusp temperature (\( \sim 21 \) K) of the low field FC susceptibility curve. Nevertheless, using these values of the scaling parameters, our data have been fitted to the scaling law in equation (4) (see Fig. 2). This fit gives \( P = 0.6 \pm 0.1 \). Our value of \( P \) differs significantly from the value obtained on a \( \text{Eu}_0.4\text{Sr}_{0.6}\text{S} \) spin glass [6] while it is in good agreement with the value obtained on the \( \text{Cd}_{1-x}\text{Mn}_x\text{Te} \) system [4]. In the study of the \( \text{Cd}_{1-x}\text{Mn}_x\text{Te} \) system [4], power law scaling was also shown to yield good scaling behaviour, with the same value of \( T_g \) as in the activated dynamic scaling. However, the extracted value of \( z \nu \) (\( \sim 13 - 15 \)) is uncharacteristically high for a spin glass system. Based on the extracted values of the scaling exponents and the observation of a finite antiferromagnetic correlation length in neutron scattering experiments [11, 12], it was concluded that the transition in the \( \text{Cd}_{1-x}\text{Mn}_x\text{Te} \) system rather resembles a random field transition than a spin glass transition. Our results indicate, in the case of power law scaling, that a decrease of \( T_g \) increases the value of \( z \nu \) while maintaining a reasonable scaling behaviour.

We have also tested the scaling laws in equations (2) and (4) using \( \chi''(T, \omega) \) data. In both cases acceptable data collapsing is obtained, but different values of the scaling exponents are required as compared to those obtained using the \( \chi_\text{eq}(T) - \chi'(T, \omega) / \chi_\text{eq}(T) \). In power law scaling \( \beta \) decreases to 0.4 \pm 0.1 while \( z \nu \) remains unchanged and in activated dynamic scaling \( P \) increases to 0.9 \pm 0.2 while \( Q \) remains unchanged. This discrepancy is surprising and not yet understood.

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**Fig. 2.** Activated dynamic scaling of the \( \frac{\chi_\text{eq}(T) - \chi'(T, \omega)}{\chi_\text{eq}(T)} \) data. The symbols 0-11 denote the same temperatures as in figure 1 \( (5 \times 10^{-2} \leq t \leq 1.7 \times 10^{-1}, T_g = 20.0 \) K).