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LETTER TO THE EDITOR

Nonlinear susceptibility of Au–Fe spin-glass-based multilayers

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Abstract. We show that the high-magnetic-field, nonlinear magnetic susceptibility, χ_{nl}, of 2 and 4 nm thick Au–Fe films can be fitted with critical exponents very similar to those previously found for equivalent Cu–Mn films. We infer from this agreement that anisotropic interactions can play only a minor role in determining the quasi-static critical behaviours of these two spin glasses.

We have previously shown [1, 2] that both the low- and high-magnetic-field nonlinear magnetic susceptibilities, χ_{nl}, of 2 nm thick layers of the spin glass (SG) Cu–Mn were best described by critical behaviour appropriate to a two-dimensional (2D) system. Specifically, the high-field nonlinear susceptibility

$$\chi_{nl}(H) = \chi_0 - M/H \tag{1}$$

could be fitted by the static scaling equation given by Geschwind *et al* [3]:

$$\chi_{nl} = t^{\beta} F\left[t/H^{2(\gamma+\beta)}\right] \tag{2}$$

using 2D parameters. Here χ_0 is the linear susceptibility, F is the scaling function, β and γ are scaling parameters and t is the reduced temperature, $t = (T - T_g)/T_g$, where T_g is the (non-zero) spin-freezing temperature in the limit of infinite measuring time. In 2D, $T_g = 0$ K, t is replaced by T and β and γ take 2D values.

It is of interest to determine whether such behaviour depends upon the detailed nature of the SG. In particular, it has been predicted theoretically that the lower critical dimension of SGs can be affected by the magnitude of anisotropic interactions [4]. Anisotropic interactions could then modify the approach to 2D behaviour and, thereby, either the functional dependence of the quasi-static spin-freezing temperature, T_f, on the thickness of the SG layers or the critical exponents of equation (2). We previously showed that finite-size effects on T_f were very similar for the low-anisotropy SG Cu–Mn, the high-anisotropy SG Au–Fe [5] and the short-range SG Ni–Mn [6]. In this letter we examine the critical behaviour of the high-anisotropy SG Au–Fe [7].

To obtain enough SG material for quantitative studies, our samples consist of sputtered multilayers with 50–100 SG layers separated from each other by non-magnetic Cu interlayers thick enough ($t_1 = 30$ nm) that the SG layers are magnetically de-coupled. The sputtering system and sputtering procedures have been described elsewhere [8–10]. The system has been shown to give multilayers that are well layered and with interfaces only a few atoms thick. Because Au–Fe can change its properties with ageing at room temperature [11], the samples were stored in liquid nitrogen until they were measured.

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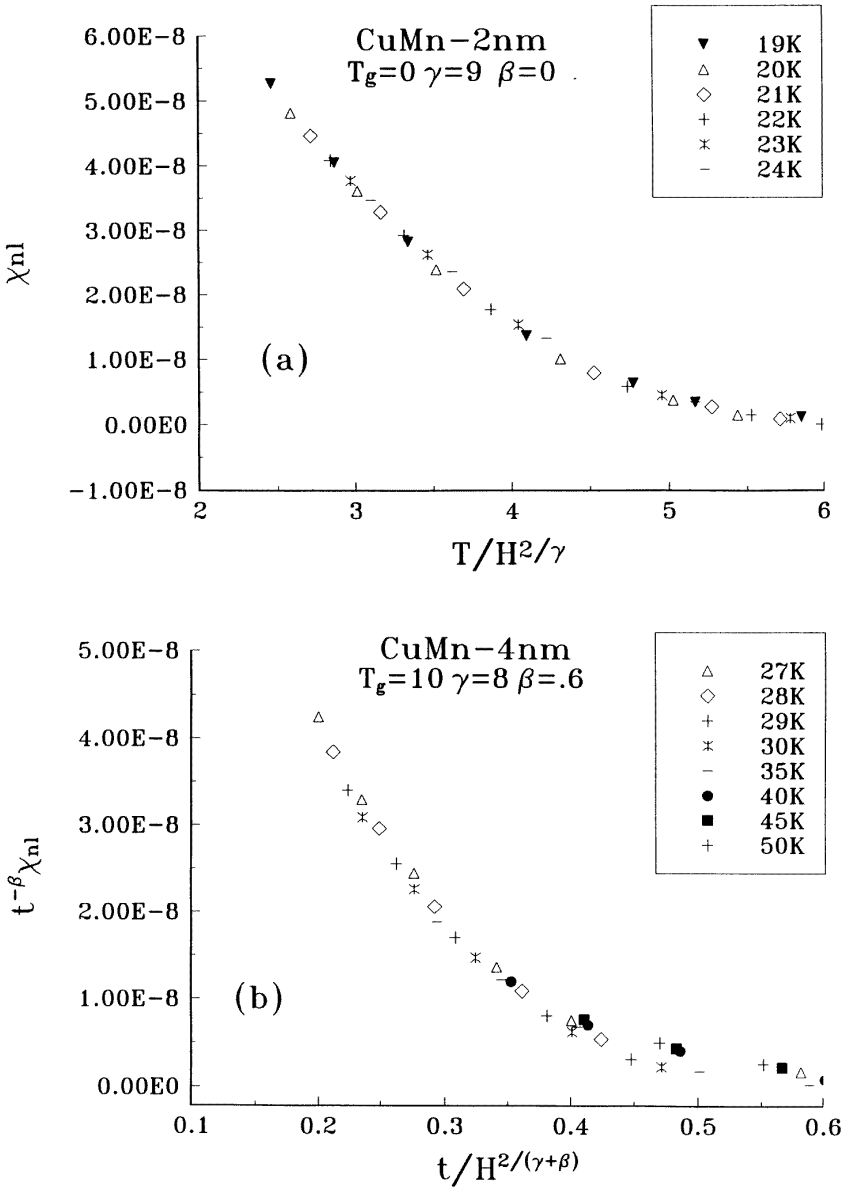

Figure 1. Scaling plots for (*a*) 2 nm of $Cu_{0.90}Mn_{0.10}$ with $T_g = 0$ K, $\gamma = 9$ and $\beta = 0$, and (*b*) 4 nm of $Cu_{0.90}Mn_{0.10}$ with $T_g = 10$ K, $\gamma = 8$ and $\beta = 0.6$.

A Quantum Design MPMS SQUID magnetometer [12] with low-field capability was used to measure the magnetization M as a function of the magnetic field H, from which the total susceptibility $\chi_t = M/H$ was calculated. Before beginning a series of runs, the magnetic field was calibrated at 298 K for fields up to 2000 G using a Pd reference sample. The system was degaussed to approximately 0.5 G at the start of each run to minimize any residual field. To reduce the effects of any such field further, M was measured alternately in positive and negative fields at a series of fixed steps from 5 G to 10 kG. The process was

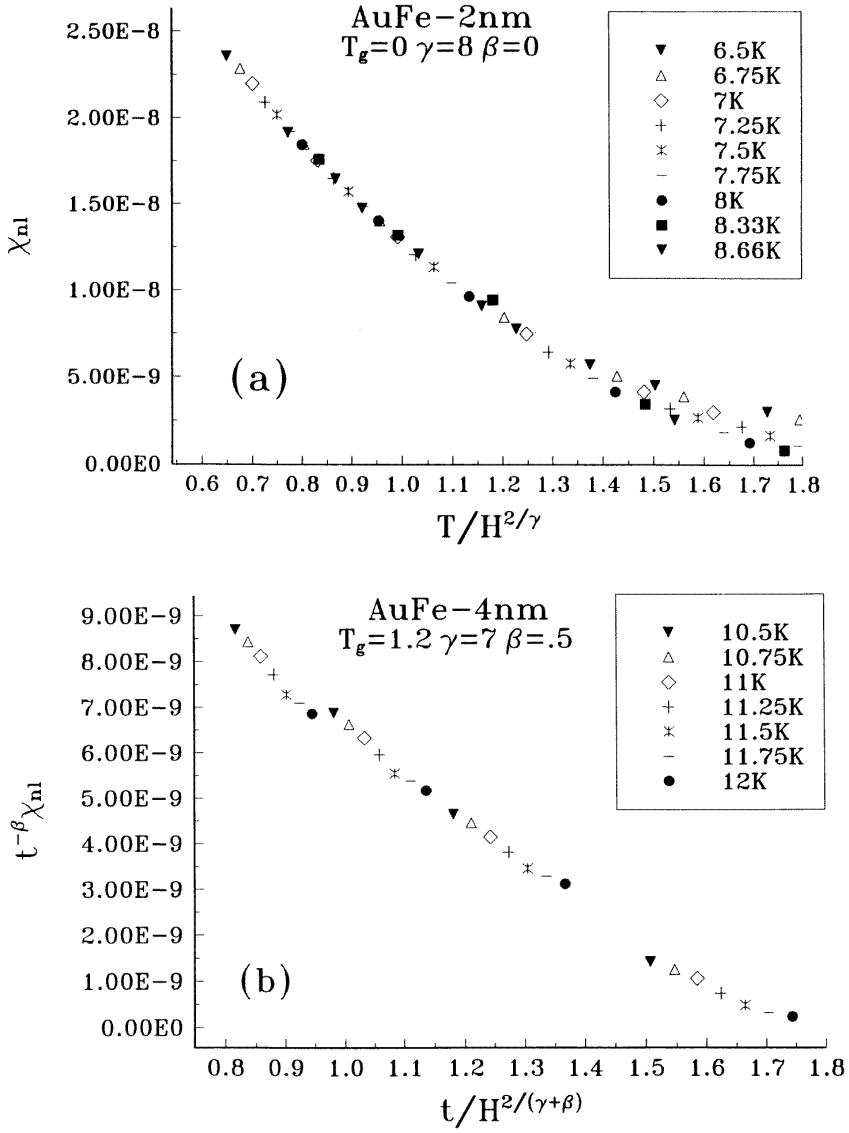

Figure 2. Scaling plots for (*a*) 2 nm of $Au_{0.97}Fe_{0.03}$ with $T_g = 0$ K, $\gamma = 8$ and $\beta = 0$, and (*b*) 4 nm of $Au_{0.97}Fe_{0.03}$ with $T_g = 1.2$ K, $\gamma = 7$ and $\beta = 0.5$.

then repeated with the order of positive and negative fields reversed, and the average of all four measurements at each H was used to define $M(H)$. χ_0 in equation (1) was obtained from the slope of a straight line fit to ten data points ranging from -50 G to $+50$ G. Calculations of χ_{nl} from measurements of the same sample on different days, varying the order of positive and negative field measurements, established the reproducibility of the data, which was approximately one part in 10^2. The fitting parameters also agreed within mutual uncertainties across multiple runs, as indicated in the results.

We tested our measuring system and procedures by comparing results for $Cu_{0.9}Mn_{0.1}$

multilayers with SG layer thicknesses $W_{SG} = 2$ and 4 nm with those previously obtained by Mattsson *et al* using different samples and a different measuring system [2]. For these SG layer thicknesses we measured values of $T_f = 15.5 \pm 0.5$ and 21.5 ± 0.5 K, respectively, from the peaks in χ versus T in the zero-field cooled (ZFC) state using a measuring time of about 5 min per data point. Figures 1(a) and (b) give our results together with the best fits of equation (2). Our best-fit parameters for $W_{SG} = 2$ nm, $T_g = 0$ K, $\gamma = 9 \pm 1.5$ and $\beta = 0$ correspond to 2D behaviour, whereas those for $W_{SG} = 4$ nm, $T_g = 10 \pm 1$ K, $\gamma = 8 \pm 1.5$ and $\beta = 0.6 \pm 0.2$ do not. Both sets of parameters agree, to within mutual uncertainties, with those found in the previous study [2].

The data and fits for our $Au_{0.97}Fe_{0.03}$-based samples with similar layer thicknesses are shown in figures 2(a) and (b). Note that the magnitude of the non-linear term is 2–5 times smaller than that for Cu–Mn, which gives rise to the larger fluctuations in the data and to greater uncertainties in the exponents. Here our respective values for T_f are 5.8 ± 0.2 and 8.5 ± 0.5 K. The best-fit parameters for these samples are $T_g = 0$ K, $\gamma = 8 \pm 1.5$ and $\beta = 0$ for $W_{SG} = 2$ nm, and $T_g = 1.2 \pm 0.5$ K, $\gamma = 7 \pm 1.5$ and $\beta = 0.5 \pm 0.2$ for $W_{SG} = 4$ nm. To within the mutual uncertainties, $T_g = 0$ obtained for $W_{SG} = 2$ nm and the exponents for both samples all agree with the values obtained for the Cu–Mn spin glass.

These results, combined with our earlier measurements of the dependence of T_f on the SG layer thickness, indicate that any differences between the anisotropies of Cu–Mn and Au–Fe have little effect on finite-size effects either on T_f or on critical behaviour in these metallic SGs. Although at the beginning of this work we expected that the quasi-static critical behaviour would be a sensitive probe for effects of anisotropy, these measurements provided no evidence to support this expectation.

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