Thermal Demagnetisation of a Field-Cooled Spin-Glass

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The decay of the field-cooled remanent state in two frustrated alloys has been investigated by magnetisation and neutron depolarisation. The partially frustrated material undergoes domain formation as the remanence decays, while the fully frustrated sample shows only a uniform fading of the magnetisation, consistent with slow paramagnetic dynamics. Domains do not form.

75.50.Lk 75.50.Bb 75.50.Kj 75.60.-d

I. INTRODUCTION

With proper choices of field direction and strength, a single-crystal ferromagnet may easily be magnetised into a single-domain state. If this is done at a sufficiently low temperature, the state will persist once the field is removed. On warming in zero field, the sample will lose its remanent magnetisation, first by breaking up into domains and finally by losing its spontaneous magnetisation at T_c. For frustrated magnetic materials, the situation is more complex.

In many partially− and even fully− frustrated magnetic systems, significant remanent magnetisations can be achieved (∼30% of the total system moment), values that approach the theoretical maximum of M_{rem}/M_{sat} = 50% for an isotropic ferromagnet. On warming such systems, the remanent magnetisation decreases. However, as spin-glasses lack a long-ranged ordered state the domain-formation demagnetisation path is not available. Furthermore, while the partially frustrated materials do exhibit long-ranged FM order and so can form domains, they also exhibit xy−spin-glass behaviour[1]. It is therefore of interest to investigate how the presence of SG order and the absence of FM order affect the decay of the remanent state.

To this end we have combined the global probe of bulk magnetisation with the mesoscopic information provided by neutron depolarisation, to probe the decay of remanence in two frustrated samples on either side of the ferromagnet – spin-glass boundary.

EXPERIMENTAL METHODS

Samples were prepared by arc-melting followed by melt-spinning. Magnetisation and susceptibility measurements were made on a commercial extraction magnetometer equipped with a 9 T superconducting magnet. Bulk magnetisation data were obtained in zero (nulled to better than 0.02 mT) field following cooling to 5 K in 95 mT. The magnetic polarisation J (in Tesla) of a material is related to the magnetisation σ (in $J.T^{-1}kg^{-1}$) through: J = $\sigma\rho\mu_0$ where ρ is the density, and μ_0 is the permitivity of free space. As the reported density of a−$Fe_{90}Zr_{10}$ is consistent with a weighted average of the densities of the two component metals[2], we assumed that this behaviour extends to the alloys studied here.

Neutron depolarisation data were obtained using the C5 beam-line of DUALSPEC, the polarised triple-axis spectrometer, at Chalk River, Ontario. Initial polarisations of ∼96% at λ =0.237 nm were achieved with Cu_2MnAl single crystals as polariser and analyser. Measurements were made between 11 K and 300 K on stacked 15 mm lengths of 20 μm thick ribbons. A set of three orthogonal pairs of 20 cm diameter Helmholtz coils was used to provide 1 mT guide fields oriented along X (parallel to the neutron flight path), Y (horizontal and parallel to the long axis of the sample) and Z (vertical). The sample Y and Z axes were oriented perpendicular to the neutron flight direction (X). Field cooling in 95 mT parallel to Y was carried out using a permanent magnet.

The measurement sequence for the depolarisation data was as follows: The sample was first cooled to ∼10 K with a field of 95 mT applied in the Y direction: parallel to the long axis of the sample (to minimise demagnetisation effects), and perpendicular to the neutron propagation direction. The field was removed and the temperature raised in 5 K steps in zero (<0.02 mT) field. The neutron polarisation at each temperature was obtained with 1 mT guide fields oriented along the X, Y, and Z directions.

When a beam of polarised neutrons of wavelength λ passes through a region containing a uniform magnetic field $\mathbf{B}$, the neutron moments precess about the field and the resulting polarisation, P, of the beam is given by:[3]

$$P = P_o \left(\frac{B_\parallel^2}{B^2} + \frac{B_\perp^2}{B^2} \cos(cBd\lambda) \right) \qquad (1)$$

where P_o is the initial polarisation of the beam, d is the sample thickness, and $< B_{\parallel}^2 >$ and $< B_{\perp}^2 >$ are the mean square domain magnetisations parallel and perpendicular to the beam polarisation. c is a constant with the value $4.633 \times 10^{14}\ m^{-2}T^{-1}$. The oscillation frequency is controlled by the total field, **B**, while the amplitude of the oscillations reflects $B_{\perp}$.

By contrast, in a sample containing many small domains of thickness $\delta \ll d$, with random magnetisation directions, the neutrons will undergo a series of brief precessions about randomly oriented fields. These scramble the polarisation, and if the precession angle within each domain is small (*i.e.* $c\delta\lambda B \ll 2\pi$), the final polarisation is given by:

$$P = \exp(-\alpha\lambda^2) \tag{2}$$

with $\alpha = \frac{1}{2}c^2 < B_{\perp}^2 > d\delta$ (other symbols have the meaning given above). For this case, the polarisation simply decays to zero with increasing thickness or magnetisation, and no oscillations are observed.

RESULTS

Fig. 1 shows depolarisation data for an 80 μm thick sample of a$-Fe_{88}Ru_2Zr_{10}$ field cooled in $B_y = 95$ mT. This material contains significant exchange frustration, but is well below x_c and has T_{xy}/T_c=0.5[4,5]. On warming, the polarisation decreases from ∼0.55 to −0.9, before rising back towards 1. This behaviour is seen only when the neutron polarisation is along X and Z, i.e. perpendicular to the original cooling field. The Y data show very little (∼1%) variation indicating that the initial magnetisation lies along Y and that no component develops perpendicular to Y as the magnetisation decays. If we attribute the rotation at 10 K to a uniform magnetisation, we deduce an internal field of ∼0.5 T, that decays to zero around 100 K. Beyond this temperature there is a clear pedestal that persists to ∼160 K, and this feature is again only present in the X and Z data. Since the end-point corresponds to T_c, we attribute the pedestal to the presence of domains with magnetisation directions that lie preferentially along the Y axis as a result of demagnetising fields.

The internal field causing the neutrons to precess was assumed to decay on warming as: $B(T) = B_0 \exp(-T/\sigma)^{\alpha}$. This form was chosen as it is smooth and monotonic and was able to reproduce most of the data extremely well with $\alpha \sim 2$. The bottom panel of Fig. 1 shows a comparison between the polarisation (J) derived from bulk magnetisation data, and the internal field deduced from the X and Z channels of the depolarisation measurements using Eqn. 1. The two, independent determinations of the magnetisation are in perfect agreement below 60 K. The failure above this point is associated with a very rapid collapse of the neutron polarisation signal that reflects the development of a domain structure. As domains form, the coherent rotation of the neutron polarisation is no longer possible and the signal collapses. Neither of the models used here (Eqns. 1 and 2) are valid in this region. Above ∼100 K, the signal is clearly dominated by the presence of domains. The solid line above 80 K in the central panel of Fig. 1 is a fit assuming depolarisation by small domains (Eqn. 2). Examination of the 3-axis depolarisation data shows that the domains are oriented almost exclusively parallel to Y. Fitting the data above 80 K yields $T_c = 162 \pm 1$ K, and a domain thickness of 0.67±0.01 μm, consistent with previous estimates of T_c in this alloy[4] and domain sizes in similarly frustrated a$-Fe-Zr$ alloys[6].

The a$-Fe_{88}Ru_2Zr_{10}$ sample serves as an almost ferromagnetic reference. It is easy to field-cool a large remanent magnetisation, and that remanent state readily breaks up into domains on warming. The resulting domains are magnetised parallel to the long axis of the ribbons (Y) by demagnetising fields. Bulk magnetisation and neutron depolarisation yield identical remanent magnetisations in the field-cooled state.

a$-Fe_{90}Sc_{10}$ is fully frustrated and therefore lies on the SG side of the FM–SG boundary[7,8]. Fig. 2 shows that this leads to two obvious changes: (i) the remanent magnetisation is greatly reduced, and (ii) there is no domain plateau. Both changes are expected. The increase in frustration will reduce the degree of spin alignment that can be achieved by the 95 mT cooling field, and since we are now in the spin glass phase, there is no long-range order and so domain formation is not possible. As with the previous sample, we obtain good agreement between B and J. The feature in the Y data has precisely the same shape as those seen in the X and Z data, and can be fitted by assuming a 4° mis-alignment between the sample magnetisation and our $Y-$axis. There is no domain feature in any channel below T_{sg}=100 K.

With no long-range ordered state available, the decay of the remanent magnetisation in a$-Fe_{90}Sc_{10}$ takes a particularly simple form. The field-cooled magnetisation starts out parallel to Y so that the X and Z channels show the same polarisation and the Y channel is unaffected. As the temperature is raised, the internal polarisation of the sample decays. The neutron polarisation signals show that X and Z channels track together while the Y channel remains constant (apart from the mis-alignment signal), therefore the sample never develops a magnetisation perpendicular to the $Y-$axis (B_y < 1 mT compared with a maximum magnetisation of 200 mT). In principle, the depolarisation signals cannot be used to distinguish a samples magnetised along $+Y$ from one magnetised along $-Y$, so that domains that formed parallel to $\pm Y$ and extend through the thickness of the entire sample (240μm in 12 layers) would not affect the Y channel depolarisation signal. However, such domain formation would lead to a loss of bulk magnetisation without a change in either the X or Z channels of the depolarisation data. The close consistency between the bulk magnetisation and the internal field derived from

X or Z depolarisation allows us to rule out even this unlikely decay mechanism.

The observed decay of the field-cooled polarisation on warming is consistent with the spin-glass being a paramagnet with extremely slow dynamics. Field cooling partially orients most of the moments so that there is a net magnetisation, but large mis-alignments persist between the moments and the remanence is low. The random differences from moment to moment are too rapid for the neutron moment to follow and so it sees only the average background polarisation. On warming, the moments relax back to an isotropic state, but unlike the sample on the FM side of the FM–SG boundary, a$-Fe_{90}Sc_{10}$ never passes through a domain state on the way to T_{sg}: The field-cooled magnetisation simply fades. It does not change direction, and no domains form.

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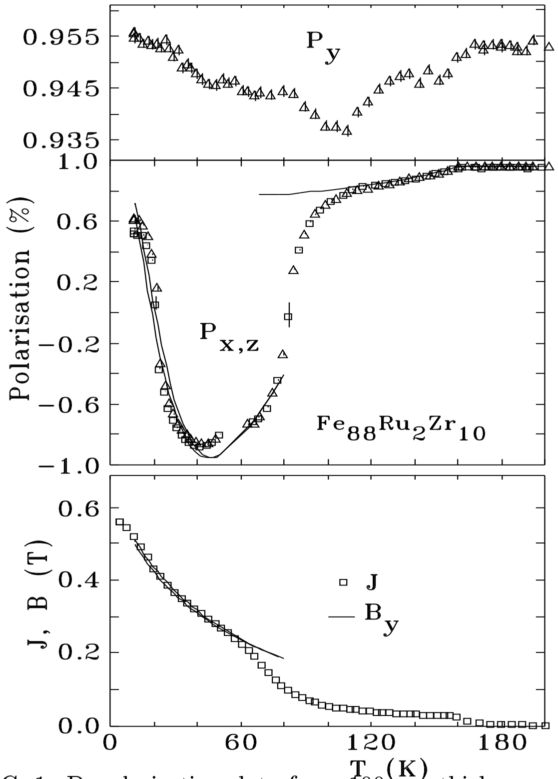

FIG. 1. Depolarisation data for a 100 μm thick sample of a$-Fe_{88}Ru_2Zr_{10}$ field cooled in 95 mT parallel to Y. Observed signals are shown for neutrons polarised parallel to Y (Top), X and Z (Centre). Solid lines are fits described in the text. A comparison of internal fields derived from magnetisation (J) and depolarisation data (B_y) assuming a uniformly magnetised material is shown at the bottom.

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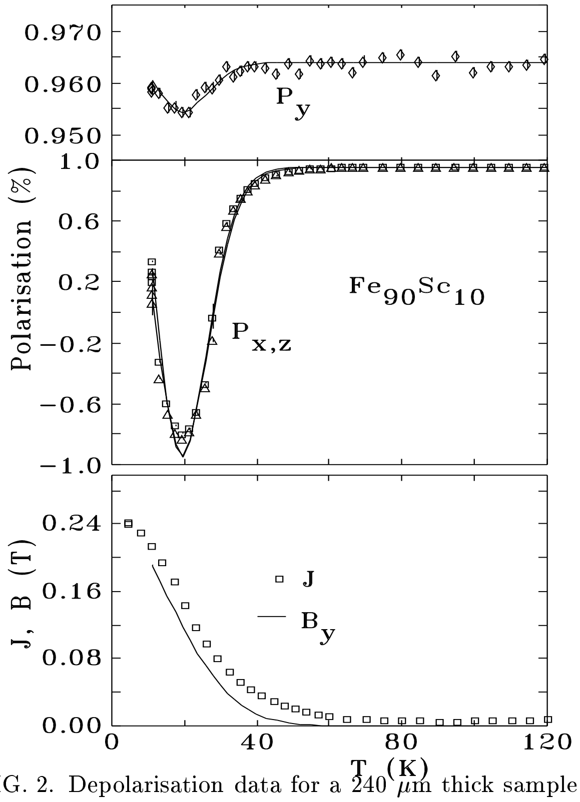

FIG. 2. Depolarisation data for a 240 μm thick sample of a$-$Fe$_{90}$Sc$_{10}$ field cooled in 95 mT parallel to Y. Observed signals are shown for neutrons polarised parallel to Y (Top), X and Z (Centre). Solid lines are fits described in the text. A comparison of internal fields derived from magnetisation (J) and depolarisation data (B$_y$) is shown at the bottom. This sample is a spin glass and so lacks the domain formation feature.