Thermal demagnetization 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 magnetization and neutron depolarization. The partially frustrated material undergoes domain formation as the remanence decays, while the fully frustrated sample shows only a uniform fading of the magnetization, consistent with slow paramagnetic dynamics. Domains do not form. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1450822]

I. INTRODUCTION

With proper choices of field direction and strength, a single-crystal ferromagnet may easily be magnetized 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 magnetization, first by breaking up into domains and finally by losing its spontaneous magnetization at T_c. For frustrated magnetic materials, the situation is more complex.

In many partially and even fully frustrated magnetic systems, significant remanent magnetizations can be achieved (~30% of the total system moment), values that approach the theoretical maximum of $M_{\mathrm{rem}}/M_{\mathrm{sat}}=50\%$ for an isotropic ferromagnet. On warming such systems, the remanent magnetization decreases. However, as spin glasses (SGs) lack a long-ranged ordered state the domain-formation demagnetization path is not available. Furthermore, while the partially frustrated materials do exhibit long-ranged ferromagnetic (FM) order and so can form domains, they also exhibit *xy*–spin-glass behavior.[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 magnetization with the mesoscopic information provided by neutron depolarization, to probe the decay of remanence in two frustrated samples on either side of the ferromagnet–spin-glass boundary.

II. EXPERIMENTAL METHODS

Samples were prepared by arc melting followed by melt spinning. Magnetization and susceptibility measurements were made on a commercial extraction magnetometer equipped with a 9 T superconducting magnet. Bulk magnetization data were obtained in zero (nulled to better than 0.02 mT) field following cooling to 5 K in 95 mT. The magnetic polarization J (in Tesla) of a material is related to the magnetization σ (in $J.\mathrm{T}^{-1}\ \mathrm{kg}^{-1}$) through: $J=\sigma\rho\mu_0$ where ρ is the density, and μ_0 is the permittivity 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 behavior extends to the alloys studied here.

Neutron depolarization data were obtained using the C5 beam-line of DUALSPEC, the polarized triple-axis spectrometer, at Chalk River, Ontario. Initial polarizations of ~96% at $\lambda=0.237$ nm were achieved with Cu_2MnAl single crystals as polarizer and analyzer. Measurements were made between 11 and 300 K on stacked 15 mm lengths of 20-μm-thick ribbons. A set of three orthogonal pairs of 20-cm-diam 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 depolarization 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 minimize demagnetization 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 polarization at each temperature was obtained with 1 mT guide fields oriented along the X, Y, and Z directions.

When a beam of polarized neutrons of wavelength λ passes through a region containing a uniform magnetic field **B**, the neutron moments precess about the field and the resulting polarization, P, of the beam is given by[3]

$$P=P_0\left(\frac{B_\parallel^2}{B^2}+\frac{B_\perp^2}{B^2}\cos(cBd\lambda)\right), \tag{1}$$

where P_0 is the initial polarization of the beam, d is the sample thickness, and $\langle B_\parallel^2\rangle$ and $\langle B_\perp^2\rangle$ are the mean square domain magnetizations parallel and perpendicular to the beam polarization; c is a constant with the value $4.633\times10^{14}\ \mathrm{m}^{-2}\,\mathrm{T}^{-1}$. 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 magnetization directions, the neutrons will undergo a series of brief precessions about randomly oriented fields. These scramble the polarization,

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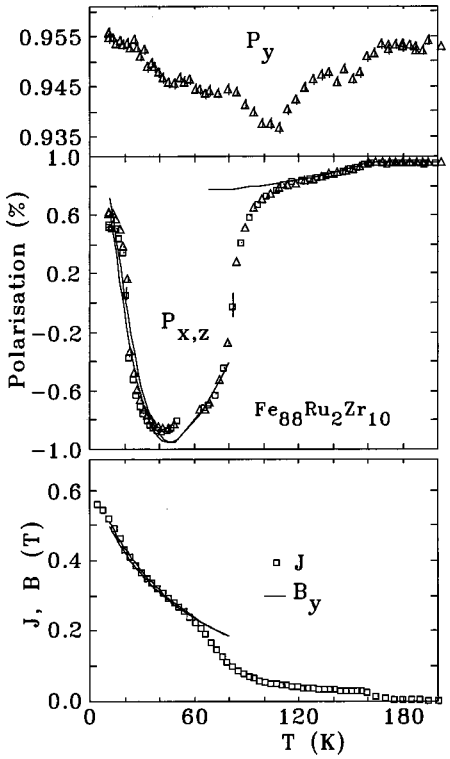

FIG. 1. Depolarization data for a-$Fe_{88}Ru_2Zr_{10}$ field cooled in 95 mT parallel to Y. Observed signals are shown for neutrons polarized parallel to Y (top), X, and Z (center). Solid lines are fits. A comparison of internal fields derived from magnetization (J) and depolarization data (B_y) assuming a uniformly magnetized material is shown at the bottom.

and if the precession angle within each domain is small (i.e., $c\delta\lambda B \ll 2\pi$), the final polarization is given by

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

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

III. RESULTS

Figure 1 shows depolarization 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 polarization decreases from ~ 0.55 to -0.9, before rising back towards 1. This behavior is seen only when the neutron polarization is along X and Z, i.e., perpendicular to the original cooling field. The Y data show very little ($\sim$1%) variation indicating that the initial magnetization lies along Y and that no component develops perpendicular to Y as the magnetization decays. If we attribute the rotation at 10 K to a uniform magnetization, 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 magnetization directions that lie preferentially along the Y axis as a result of demagnetizing 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 polarization (J) derived from bulk magnetization data, and the internal field deduced from the X and Z channels of the depolarization measurements using Eq. (1). The two, independent determinations of the magnetization are in perfect agreement below 60 K. The failure above this point is associated with a very rapid collapse of the neutron polarization signal that reflects the development of a domain structure. As domains form, the coherent rotation of the neutron polarization is no longer possible and the signal collapses. Neither of the models used here [Eqs. (1) and (2)] are valid in this region. Above $\sim$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 depolarization by small domains [Eq. (2)]. Examination of the three-axis depolarization 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 magnetization, and that remanent state readily breaks up into domains on warming. The resulting domains are magnetized parallel to the long axis of the ribbons (Y) by demagnetizing fields. Bulk magnetization and neutron depolarization yield identical remanent magnetizations 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] Figure 2 shows that this leads to two obvious changes: (i) the remanent magnetization 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° misalignment between the sample magnetization 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 magnetization in a-$Fe_{90}Sc_{10}$ takes a particularly simple form. The field-cooled magnetization starts out parallel to Y so that the X and Z channels show the same polarization and the Y channel is unaffected. As the temperature is raised, the internal polarization of the sample decays. The neutron polarization signals show that X and Z channels track together while the Y channel remains constant (apart from the misalignment signal), therefore the sample never develops a magnetization perpendicular to the Y axis ($B_y < 1$ mT compared with a maximum magnetization of 200 mT). In principle, the depolarization signals cannot be used to distinguish a sample magnetized along $+Y$ from one magnetized along $-Y$, so that domains that formed parallel to

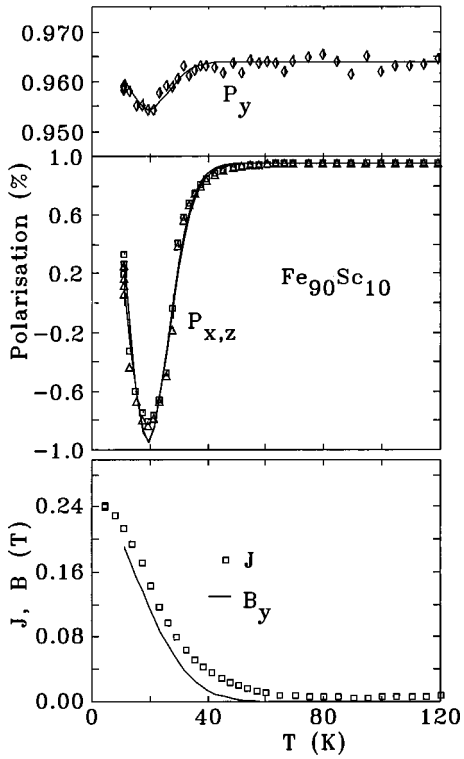

FIG. 2. Depolarization data for a-$Fe_{90}Zr_{10}$ field cooled in 95 mT parallel to Y. Observed signals are shown for neutrons polarized parallel to Y (top), X, and Z (center). Solid lines are fits. A comparison of internal fields derived from magnetization (J) and depolarization data (B_y) is shown at the bottom. This sample is a spin glass and so lacks the domain formation feature.

$\pm Y$ and extend through the thickness of the entire sample (240 μm in 12 layers) would not affect the Y channel depolarization signal. However, such domain formation would lead to a loss of bulk magnetization without a change in either the X or Z channels of the depolarization data. The close consistency between the bulk magnetization and the internal field derived from X or Z depolarization allows us to rule out even this unlikely decay mechanism.

The observed decay of the field-cooled polarization 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 magnetization, but large misalignments 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 polarization. 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 magnetization simply fades. It does not change direction, and no domains form.

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