Dzyaloshinsky-Moriya anisotropy in reentrant alloys

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(Received 21 October 1985)

We have carried out torque and spin-resonance measurements on a *Au*Fe reentrant alloy. Dzyaloshinsky-Moriya anisotropy effects appear at much higher temperature in the resonance signals than in the static torque results. We propose a physical description which provides a consistent framework for interpreting these and certain other reentrant-alloy effects.

A large number of different alloy systems are now known where the low-temperature magnetic order evolves from spin-glass towards ferromagnetic as the concentration is changed. In each case on the ferromagnetic side of the critical concentration the alloys show behavior which is in various ways uncharacteristic of conventional ferromagnets; these alloys have been dubbed "reentrant," and many phase diagrams have been published showing a low-temperature "ferromagnetic to spin-glass transition" below a ferromagnetic phase. If we believe mean-field-model predictions[1] for these systems, we should expect two characteristic "spin-glass" temperatures—one at which local spin canting takes place, and a lower one at which "strong irreversibility" sets in. There is experimental evidence that two such characteristic temperatures exist,[2–4] but no clear picture has been given for the distinction between weak and strong irreversibility or for the mechanisms leading to various effects which are observed experimentally.

We will present anisotropy measurements on a reentrant alloy which help lead to a physical description providing a phenomenological framework for explaining many of the experimental observations on these systems. We recall that in standard spin glasses a unidirectional anisotropy is observed which arises from Dzyaloshinsky-Moriya (DM) interactions of the form $\mathbf{D}_{ij}\cdot(\mathbf{S}_i\wedge\mathbf{S}_j)$, where $\mathbf{D}_{ij}$ is a vector connected to the lattice.[5] We have studied samples of a $Au-18$ at.% Fe alloy. From earlier work[6–8] this is a canonical reentrant system. Bits of the same ribbon were used for torque and spin-resonance measurements. It was obviously essential for the interpretation to be able to draw on results of other measurements—susceptibility,[6,8] magnetization,[4] Mössbauer,[3,4] and neutron scattering.[9] We will note at this point that our sample has a Curie temperature T_c of 165 K; at around 70 K Mössbauer measurements indicate canting[3,4] and a quasielastic peak appears in the neutron scattering spectra.[9] The coercive field rises strongly below 25 K.[4]

Static torque measurements were performed using a capacity technique.[10] First the sample was cooled to 1.5 K in an applied field of 5 kOe. Observed behavior was identical for any value of the cooling field above about 1 kG. The field was reduced to a value H_t and then was turned by steps through 180° in the sample plane. Signals consistent with a glasslike[5] rigid unidirectional anisotropy were observed for low turning fields, $H_t < 100$ Oe. This shows that as in standard metallic spin glasses the spin system can be turned rigidly against the DM anisotropy. However, this is only true here if the turning field is weak; when higher turning fields were used, high-turn-angle behavior became nonrigid. In other runs the sample was again prepared by cooling to 1.5 K in 5 kOe. Small-turn-angle ($\pm 5°$) torque measurements were made at increasing temperatures for various fixed values of the turning field. The observed torque signal 1 sec after turning is shown in Fig. 1 for two values of the turning field H_t. With $H_t = 3$ kOe the torque signal disappears at $T \simeq 12$ K. At the lowest temperatures there was no observable relaxation, but with increasing T, relaxation effects appeared and became progressively more rapid as 12 K was approached. This is not the behavior observed in CuMn.[10] For $H_t = 45$ Oe, the signal drops much more slowly with T, only becoming lost in the weak parasitic background signal at $T \simeq 60$ K, as already mentioned in Ref. 10. Resonance measurements were made at the X band (9.2 GHz) on a plate sample. If one takes into account, besides the effect of the demagnetizing fields, the presence of a macroscopic unidirectional anisotropy $K\cos\theta$, characterized by the anisotropy field $H_A = K/M$ whose direction is that of the applied field, then one gets for the resonance conditions of the plate

$$(\omega/\gamma)^2 = (H_r + H_A)(H_r + H_A + 4\pi M) \tag{1}$$

for the parallel geometry, and

$$\omega/\gamma = H_r + H_A - 4\pi M \tag{2}$$

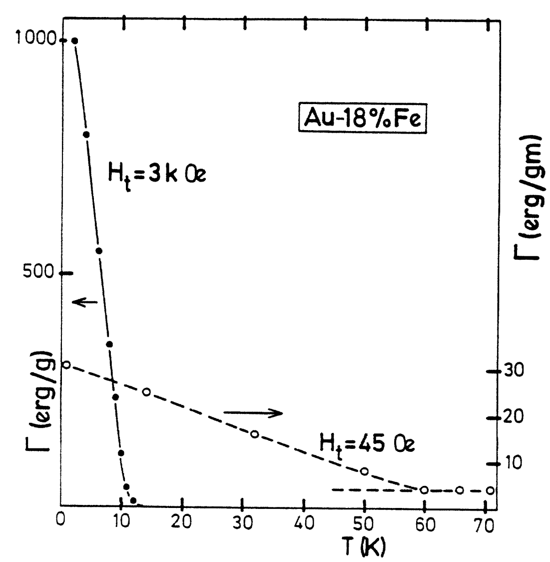

FIG. 1. Torque Γ measured 1 sec after turning magnet through 5° in turning fields H_t of 3 kOe and 45 Oe.

for the perpendicular geometry (static field perpendicular to the plate), where M is the magnetization of the sample in the internal field corresponding to the resonance field H_r, and $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio of the precessing moments.

The resonance-field data (Fig. 2) show the usual demagnetizing field effects associated with the buildup of magnetization and then, starting below 70 K, a drop in resonant field for *both* parallel and perpendicular geometries, characteristic of the onset of *unidirectional* anisotropy.[11] Earlier results by Sarkissian[7] on *Au*Fe show similar behavior. The resonant-field[12] curves (Fig. 2) were analyzed with the help of magnetization results taken[13] on a similar sample. In the temperature range 80–150 K comparison of the data obtained in the parallel and perpendicular geometries with Eqs. (1) and (2), where $H_A = 0$, leads to the absolute value of the magnetization and a nearly temperature-independent ω/γ value, corresponding to a g factor of ~ 2.01. At lower temperatures, assuming the same temperature-independent value for ω/γ, the value of the macroscopic induced anisotropy field H_A is extracted using Eq. (2) for the perpendicular geometry and is shown in Fig. 3. H_A is seen to increase regularly as the temperature is lowered below $T \sim 70$ K. A consistent value of $H_A(T)$ is obtained using the data for the parallel geometry and Eq. (1). The parallel geometry linewidth shown in Fig. 3 (the one for the perpendicular being nearly the same) reveals a strong increase above the plateau value corresponding to the ferromagnetic temperature range when T is lowered. This extra linewidth is concomitant with the presence of the macroscopic anisotropy field H_A. Similar behavior for the linewidth with the occurrence of a maximum at low temperatures has been observed on *Au*Fe and other systems.[6,7,11]

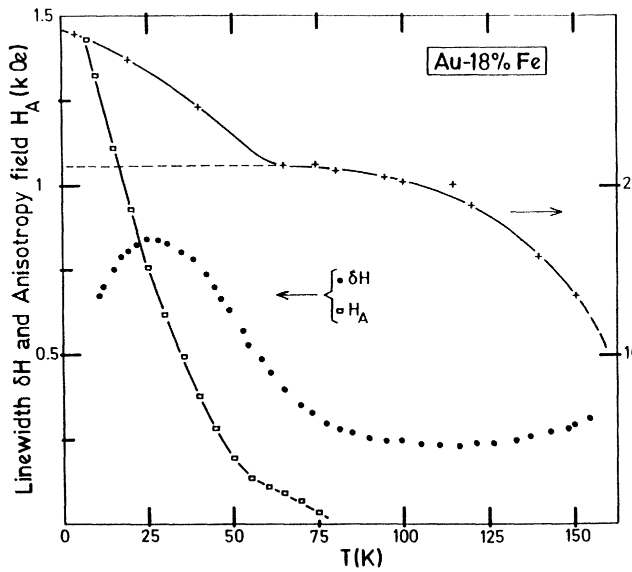

FIG. 3. Temperature variation of the resonance linewidth δH (●) and of the deduced anisotropy field H_A (□) compared with ^{57}Fe average hyperfine field taken from Ref. 4.

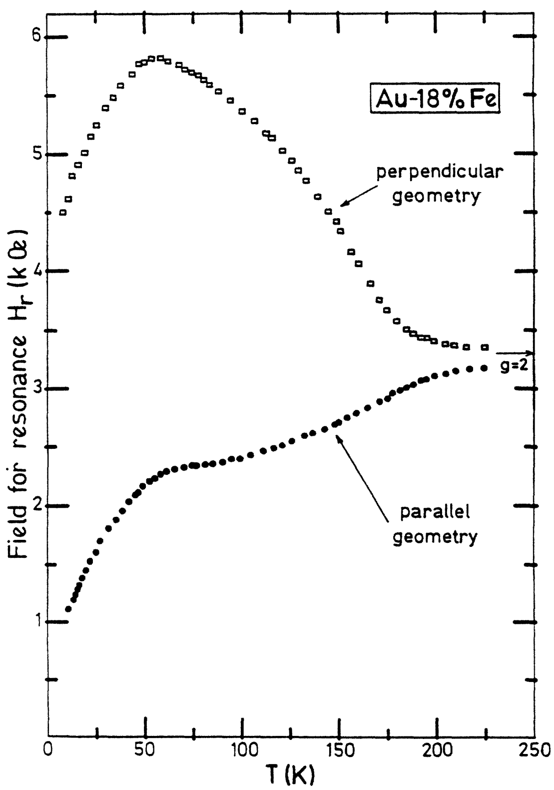

FIG. 2. X-band resonance field H_r as a function of temperature for plate-shaped sample in parallel and perpendicular field geometry.

We note that $T \simeq 70$ K is very close to the canting temperature observed by Mössbauer[3,4] as can be seen by direct comparison with the hyperfine-field behavior as shown in Fig. 3. Neutron scattering results[9] show the onset of a quasielastic peak at almost the same temperature on a sample of similar concentration. We underline the fact that the ESR line position and the small-angle torque experiments both provide information on the same macroscopic anisotropy induced by DM anisotropy but *in different time windows.* Remarkably, the temperature at which the anisotropy appears in the ESR measurement is a factor of 5 higher than the temperature at which the small-angle torque signal becomes observable in the same applied field. We obtain similar results when comparing torque and ESR in other reentrant systems $(Fe_{77}Mn_{23})_{75}P_{16}B_6Al_3$ and *Ni*–21 at.% Mn. In standard metallic spin glasses torque signals[14] and ESR lineshifts[15] go to zero at temperatures which differ by about a factor of 1.4. The results for the reentrant systems can be seen to be more dramatic.

We will outline a physical picture for reentrant systems based on the Heisenberg mean-field model[1] but including DM anisotropy. Below T_c, there is a ferromagnetic state with each time-averaged local moment parallel to the local domain magnetization direction. As all spins are parallel, we expect no DM anisotropy. Then, below a canting temperature T_K, the spins acquire nonzero static components perpendicular to the magnetization direction z.[3] $\langle m_z \rangle$ remains almost unchanged,[4] and in zero applied field the domain structure is conserved.[16,17] There are strong ferromagnetic correlations among the static x,y components; hence the quasielastic neutron signal peaked at $q = 0$, which appears below T_K.[9,18] As the local spins are no longer parallel, DM anisotropy should appear below T_K.

Experimentally, the DM anisotropy shift indeed appears in the resonance experiments nearly at the same temperature as the canting and the neutron quasielastic peak. One can note that the characteristic time scale of these experiments corresponds to a similar range of very short times ($\sim 10^{-10}$ sec). DM anisotropy effects are also likely to be responsible for the extra linewidth observed when entering the canted state: We suggest that its temperature behavior reveals an exchange-narrowing process of the distribution of local anisotropy fields, whose degree is expected to be temperature dependent in the canted state. It is to be realized that, if the Mössbauer and neutron experiments are directly sensitive to the modification of the local spin orientations, it is through the DM-induced anisotropy that the canting of the spins shows up in the ESR experiments.

Why is it that for applied fields of the order of 1 kG, anisotropy is only seen in the static torque measurements below a much lower temperature T_F? The obvious explanation is that for T between T_K and T_F, when the applied field is turned, the system can adjust itself on a time scale much shorter than the 1-sec time scale of the measurement. Using spin-glass terminology, when $T < T_K$ and the magnetization is rotated at ESR frequencies, the system remains within one well during the effective observation time of 10^{-10} sec. However, under slowly turning applied fields the system can escape from the well and choose a more suitable one, minimizing both exchange and anisotropy interactions, on a time scale shorter than 1 sec. There will then be no "static" torque signal. Only below T_F does the system remain blocked in one well for long times after the field has been turned. Indeed, the effective value of T_F is strongly dependent on H_t, θ, and the time scale chosen in the torque experiments.

As has already been demonstrated by Senoussi,[16,19] once we have a static DM anisotropy, domains and domain walls will become pinned because turning spins with respect to the lattice costs DM anisotropy energy. We consider that the drop in the ac χ' susceptibility[6] and the increase in the coercive field[4,19] which occur near T_F are due to domain-wall pinning arising from quasistatic DM anisotropy. We also ascribe the maximum observed[20] in $\chi''(T)$, concomitant with the drop of $\chi'(T)$, to a resonance effect occurring when the relaxation rate of the anisotropy is equal to the measuring frequency.

We conclude that in reentrant systems, the ESR line shift and the neutron quasielastic peak are manifestations of homogeneous Gabay-Toulouse canting below T_K. Torque signals arising from quasistatic DM anisotropy only appear at a lower temperature which is strongly dependent on the strength of the applied field. The temperature dependence of the susceptibility and the magnetization also reflects the onset of quasistatic DM anisotropy pinning. Much further work is needed on these reentrant systems, particularly on the dynamics of their complex ordering process.

We have profited from discussions with S. Senoussi, M. Hennion, I. Mirebeau, and B. Hennion. We are grateful to F. Varret and A. Hamzić for making experimental data available. The Laboratoire de Physique des Solides at the Université Paris-Sud is a "laboratoire associé au Centre National de la Recherche Scientifique."

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