PHYSICAL REVIEW B VOLUME 41, NUMBER 13 1 MAY 1990

Giant transverse hysteresis in an asperomagnet

J. M. D. Coey,* P. P. Freitas,† and T. S. Plaskett
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 20 February 1990)

Comparison of the magnetoresistance of amorphous thin films of $Tb_{80}U_{20}$ and the nonmagnetic analog $Y_{80}U_{20}$ reveals hysteresis for the terbium alloy, which extends to fields in excess of 8 T at 4.2 K. Hysteresis is found in the magnetization curve only in fields below 4 T at the same temperature. The magnetoresistance effect, attributed to scattering of electrons by the frozen transverse spin components, which have spatial fluctuations on the scale of the interatomic spacing, is interpreted in terms of the magnetization process of the amorphous alloy. Evidence of weak localization is observed in both films below 1 K.

Asperomagnets are a class of magnetic glasses where the spins are frozen in random directions following a (locally) anisotropic probability distribution.[1] The longitudinal spin-correlation length ξ_z greatly exceeds the transverse spin-correlation length ξ_{xy}. Although the ferromagnetic component of the magnetic order may be quite short ranged in zero applied field (i.e., ξ_z may be only a few interatomic distances), a modest field will induce approximately half of the collinear saturation magnetization M_s. In other words, spin configurations with a large net magnetic moment are only marginally higher in energy than those with no net moment. At low temperatures, asperomagnets typically exhibit ferromagnetic hysteresis with a large remanence M_r such that $M_r/M_s \approx 0.1$–0.5.

A group of materials with these characteristics are amorphous rare-earth alloys with random uniaxial anisotropy and ferromagnetic exchange. Many such alloys have been investigated.[1] Thin films of *a*-DyCu, for example, show magnetic hysteresis loops well below the spin freezing temperature that consist of a few large Barkhausen jumps, due to collective reversal of the spins in a macroscopic domain[2] which produces a sudden change in the longitudinal magnetization (i.e., that measured in the direction of the applied field). Some information about the transverse spin components in *a*-$ErCo_2$ has been inferred from neutron diffraction, where it was found that the transverse components of the rare-earth spins tend to be antiparallel on nearest-neighbor sites.[3]

Here we report on the magnetoresistance of *a*-$Tb_{80}U_{20}$, which shows hysteresis of a quite different character to that of the magnetization. The measurements probe the transverse spin correlations directly, and the new effect is interpreted in terms of the magnetization process of the random magnet.

Amorphous alloys of $Tb_{80}U_{20}$ and $Y_{80}U_{20}$ (a nonmagnetic analog) were prepared by sputtering from 99.9%-pure targets of the elements. Films approximately 150 nm thick were deposited on glass substrates, and then covered with a 20-nm overlayer of SiO_2. The magnetic properties of the *a*-Tb-U alloys have been described elsewhere;[4] *a*-$Tb_{80}U_{20}$ shows a spin freezing transition at 160 K. Conductivity measurements were made using the four-point van der Pauw method in a ^{3}He cryostat equipped with an 8-T superconducting magnet. Resistivities are approximately 250 $\mu\Omega$ cm for both samples; the corresponding free-electron mean free path λ is 3 Å.

The magnetization hysteresis loop of an *a*-$Tb_{80}U_{20}$ film measured at 4.2 K in a SQUID magnetometer is shown in Fig. 1. The magnetization cannot be saturated because of the strong random single-ion anisotropy of the terbium, but there is nonetheless a ferromagnetic type of hysteresis with a remanent magnetization which is some 20% of the saturation value of the terbium sublattice. The low remanence and the fact that $M/M_s < 0.5$ throughout the range of applied field suggest that some of the Tb-Tb interactions are antiferromagnetic.[1] The loop is traced reversibly in fields greater than 4 T.

The magnetoresistance of *a*-$Y_{80}U_{20}$ at 4.2 K is negative, reversible, and isotropic, but negligibly small in the present context [$< 0.1\%$ in 7 T; Fig. 2(a)], whereas the transverse or longitudinal magnetoresistance of *a*-$Tb_{80}U_{20}$ can exceed 2% at the same temperature, and it depends on the thermal and magnetic history of the sample. (Note that "transverse" and "longitudinal" as applied to magnetoresistance refer to the orientation of the current with respect to the applied magnetic field, whereas in the context of the spin components they refer to their orientation with respect to the local ferromagnetic axis *z*.) The transverse virgin curve [Fig. 3(a)] shows no effect at all up to 2.5 T; the resistance then decreases sharply and exhibits the symmetric "butterfly" hysteresis curve on cycling from +8 to −8 T, shown in Fig. 4.

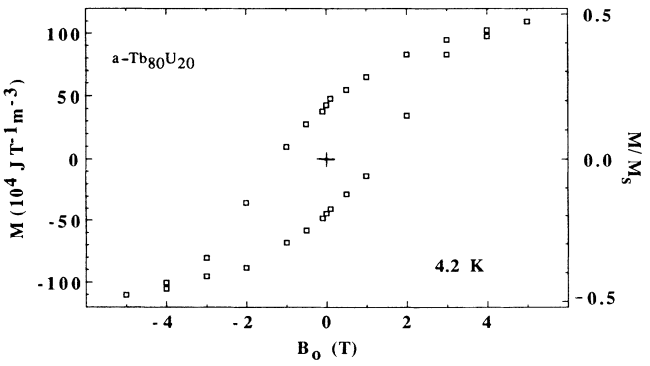

FIG. 1. Magnetization hysteresis loop of $Tb_{80}U_{20}$ at 4.2 K.

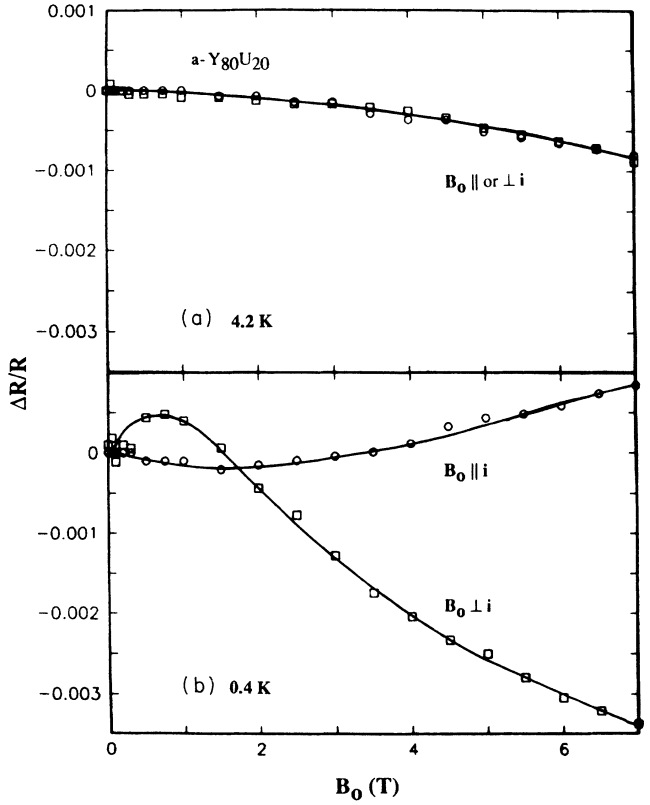

FIG. 2. Transverse and longitudinal magnetoresistance of a-$Y_{80}U_{20}$ (a) at 4.2 K and (b) at 0.4 K. The curves are reversible on increasing and decreasing field.

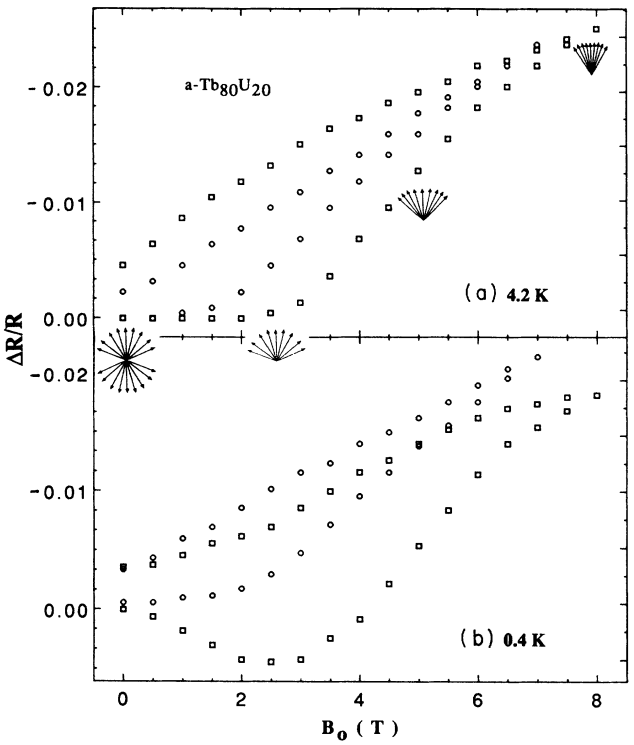

FIG. 3. Transverse (□) and longitudinal (○) magnetoresistance of a-$Tb_{80}U_{20}$ (a) at 4.2 K and (b) at 0.4 K. The sketches indicate the magnetic structures at various points along the curves. Both the virgin curves and the return to zero field are shown.

At 0.4 K, a-$Y_{80}U_{20}$ shows anisotropic magnetoresistance curves which are quite different from the isotropic behavior seen at higher temperatures. In the transverse direction, there is a maximum at 0.8 T [Fig. 2(b)], which is typical of weak localization in two dimensions.[5,6] The maximum is absent if the field is applied parallel to the current direction, when the longitudinal magnetoresistance is weakly positive, due perhaps to the electron-electron interaction which gives a weak isotropic positive magnetoresistance at very low temperatures.[6] From the shape of the curve in the transverse direction, we estimate the spin-orbit scattering time and the inelastic scattering time to be $\tau_{so}=4.8\times10^{-12}$ s and $\tau_{in}=9.6\times10^{-12}$ s, respectively, taking a diffusion constant $D=1.7\times10^{-4}$ m^2s^{-1}, given by the free-electron model. The behavior of a-$Tb_{80}U_{20}$ is a little more complex; it appears to be the superposition of the butterfly hysteresis and weak-localization effects. The virgin magnetoresistance curve of a-$Tb_{80}U_{20}$, may be attributed to stronger spin-orbit antilocalization ($\tau_{so}=2.3\times10^{-12}$ s). The data suggest that weak localization is possible in the presence of magnetic scattering from a magnetically concentrated amorphous alloy,[7] but they are also open to the interpretation that a different magnetization process operates below 1 K. The butterfly-hysteresis curve obtained on cycling the field from +8 to −8 T is otherwise quite similar to the one obtained at 4.2 K.

The giant hysteresis of the magnetoresistance may be understood in terms of the magnetization process of the asperomagnetic alloy. The mean free path is similar to the Tb-Tb nearest-neighbor distance (~3.6 Å), so the electrons will be scattered from local fluctuations in the frozen magnetization. The magnetoresistance associated with ordered magnetic moments is generally of the form[8]

$$\rho_m=\rho_o-\alpha m^2-\beta m_\perp^2,$$

where ρ_o is the spin disorder resistance (e.g., in the

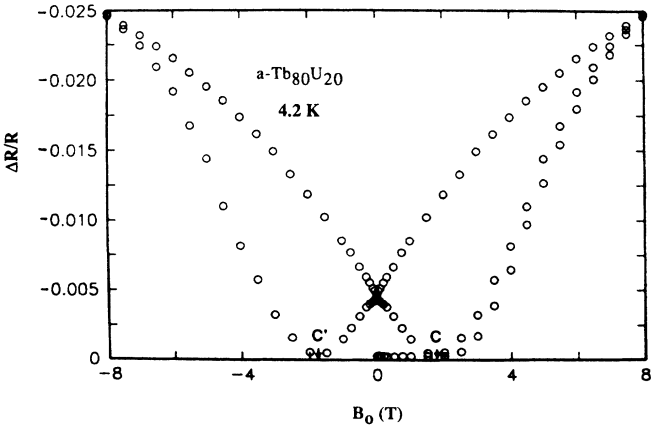

FIG. 4. Complete butterfly hysteresis curve for the transverse magnetoresistance of a-$Tb_{80}U_{20}$ at 4.2 K.

paramagnetic state well above the magnetic ordering temperature), m is the local magnetization averaged over the mean free path, and $m_\perp$ is its component perpendicular to the direction of current flow. Since λ is so short, m will depend essentially on correlations between Tb moments on neighboring sites. Furthermore, the similarity of the magnetoresistance in the longitudinal and transverse directions [Fig. 3(a)] and the absence of any peak in the transverse magnetoresistance at the coercive field (compare Figs. 1 and 4) indicate that the anisotropic term $\beta m_\perp^2$ is not as important as the isotropic term am^2 in the present case. The contrary is true in uranium-rich amorphous alloys where the uranium bears a moment.[9]

The constant virgin transverse magnetoresistance up to 2.5 T [Fig. 3(a)] shows that the disorder of the transverse spin components is essentially unchanged up to this field. In other words, the amorphous alloy can be magnetized to a substantial fraction of saturation *without changing the local magnetization.* This is achieved by reversing the direction of magnetization of the spins in the asperomagnetic domains without inclining them away from their local easy directions, a process that is analogous to the "180°-domain-wall propagation" postulated by Senoussi for reentrant spin glasses.[8] That process generates no hysteresis of the magnetoresistance, although the hysteresis of the magnetization lies mostly in this range of field. The magnetization of an asperomagnet reflects the macroscopic longitudinal magnetization, whereas the magnetoresistance is most sensitive to local correlations of the transverse spin components, since the longitudinal components are locally parallel in any case. The subsequent stage of magnetization involves "closing the cone" as the spins are gradually turned from their random local easy directions towards the direction of the applied field; this generates most of the hysteresis in the magnetoresistance, but little hysteresis in the magnetization.

Magnetic hysteresis of any sort is difficult to model quantitatively. The hysteresis of the magnetoresistance arises because there is some modification of the short-range order among the transverse components as the spin configuration falls back from its aligned state with the removal of the applied field. These correlations may be antiferromagnetic in the virgin state,[3] then tend to become ferromagnetic as saturation is approached, turning antiferromagnetic again when the field is reversed. The local spin correlations pass through a minimum at the points C and C' on the butterfly curve (Fig. 4), where they are similar to those in the virgin state. Analogous points on the magnetization hysteresis loops would be at the coercive field where $M=0$.

In conclusion, we have found that the magnetoresistance provides a rather direct probe of the disorder of the frozen transverse spin components in a random magnet. A remarkably large hysteresis effect is observed. The method should be of value in those systems where the transverse spin components are believed to freeze at a transition which is distinctly below the ordering point of the longitudinal spin components.[10]

We are grateful to A. Toressen and H. Lilenthal for help with the conductivity and magnetization measurements, respectively. We thank S. von Molnar and T. Penney for helpful discussions.

---

*Permanent address: Physics Department, Trinity College, Dublin 2, Ireland.

†Permanent address: Centro de Física Nuclear, Av. Prof. Gama Pinto 2, 1699 Lisbon, and Instituto de Engenharia de Sistemas e Computadores (INESC), R. Alves Redol 9-3, 1000 Lisbon, Portugal.

[1]K. Moorjani and J. M. D. Coey, *Magnetic Glasses* (Elsevier, Amsterdam, 1984), p. 525.

[2]J. M. D. Coey, T. R. McGuire, and B. Tessier, Phys. Rev. B **24**, 1261 (1981).

[3]B. Boucher, A. Liénard, J. P. Rebouillat, and J. Schweizer, J. Phys. F **9**, 1421 (1979); **9** 1433 (1979).

[4]P. P. Freitas, T. S. Plaskett, J. M. Moreira, and V. S. Amaral, J. Appl. Phys. **64**, 5453 (1988).

[5]G. Bergman, Phys. Rep. **107**, 1 (1984).

[6]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[7]J. B. Bieri, A. Fert, G. Creuzet, and A. Schuhl, J. Phys. F **16**, 2099 (1986).

[8]S. Senoussi, Phys. Rev. Lett. **56**, 2314 (1986).

[9]P. P. Freitas and T. S. Plaskett, J. Appl. Phys. (to be published).

[10]For example, D. H. Ryan, J. M. D. Coey, E. Batella, Z. Altounian, and J. O. Strom-Olsen, Phys. Rev. B **35**, 8630 (1987), and references therein.