Magnetoresistance of yttrium alloys with dilute rare-earth solutes

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(Received 20 August 1984)

The magnetoresistance (MR) of some yttrium–rare-earth alloys has been investigated in the liquid-helium temperature range in magnetic fields up to 30 kOe. A negative MR is observed for the "Kondo" alloy, Y-Ce(3 at.%), which is consistent with theory based on isotropic conduction-electron–f-electron scattering between the conduction electron and the magnetic ion. In the paramagnetic phase the spin-glass alloy, Y-Dy(2 at.%), shows a negative MR at low fields but at higher fields and temperatures the MR becomes positive. The positive MR is thought to be associated with "normal magnetoresistance" due to the Lorentz force. A contribution due to anisotropic k-f scattering is also expected in the MR data. The MR of antiferromagnetic Y-Tb(3 at.%) is positive and increases with field up to $H_c \simeq 12$ kOe at 4.2 K. For $T < T_N$ ($T_N = 5.2$ K), the positive MR is interpreted to be the result of field-induced enhancement of the spin fluctuations. The MR is negative for $T > T_N$ and $H > H_c$ as expected in the paramagnetic phase. The longitudinal and transverse magnetoresistances are not equal. It is believed that this anisotropy arises from an anisotropic scattering between the conduction electrons and the f electrons. The sign of the anisotropy is found to be consistent with the present theory.

Yttrium alloys with small concentrations of rare-earth ions (Y-R) show various magnetic properties depending on the nature and concentration of the rare-earth ions. For example, Y-Ce (Refs. 1 and 2) shows the Kondo effect while a few atomic percent of Tb, Dy, or Gd can produce either a spin-glass or long-range magnetic order at low temperatures.[2,3] Because of the localized nature of $4f$ electrons, which are responsible for magnetism in rare earths, the interaction between two neighboring magnetic moments is mainly indirect. The conduction electrons interact with the magnetic ions according to the s-d (for transition metals) or s-f (for rare earths) exchange Hamiltonian

$$H_{s\text{-}f} = -J\mathbf{s}\cdot\mathbf{S}\ , \tag{1}$$

where $\mathbf{s}$ and $\mathbf{S}$ are the spins of conduction electron and magnetic ion and J the coupling constant. Each magnetic ion spin polarizes the conduction electrons in the immediate vicinity and at sufficient concentrations the polarization interacts with the spin polarization on neighboring magnetic ions. This indirect interaction via the conduction electrons is called the RKKY interaction and is expressed as

$$H_{ij} = -\mathcal{J}\mathbf{S}_i\cdot\mathbf{S}_j\ , \tag{2}$$

where $\mathcal{J}$ is called the exchange integral and is normally assumed to be isotropic. The Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction is long range and oscillatory behaving as $\cos(2K_F r)/r^3$, where K_F is the Fermi wave vector and r the spacing between two interacting magnetic ions. The RKKY interaction can account for various magnetic properties of metallic rare-earth systems, e.g., ferromagnetism, antiferromagnetism, spiral spin arrangements, and spin glasses.

It has been shown in a recent study[2] that Y-Ce(3 at.%) is a Kondo alloy with a resistance minimum at ~ 22 K, Y-Dy(2 at.%) is a spin glass with a freezing temperature $T_f \simeq 4$ K and Y-Tb(3 at.%) orders antiferromagnetically below $T_N \simeq 5.2$ K. Thus, we have three alloys exhibiting three different kinds of magnetic properties. Y-Ce(3 at.%) can be treated as a dilute magnetic alloy where the interaction between the magnetic moments is insignificant and the Kondo effect is caused by s-f scattering. In Y-Dy(2 at.%) the neighboring magnetic ions interact via the conduction electrons but instead of producing spin alignment the interaction freezes the spins in random directions below temperature T_f called the spin freezing temperature. And finally, in Y-Tb(3 at.%) the magnetic moments are aligned by the RKKY interaction in an antiferromagnetic order below ~ 5.2 K.

The magnetoresistance (MR) of dilute Kondo alloys has been theoretically calculated by Béal-Monod and Weiner[4] using an isotropic Hamiltonian of the form shown in Eq. (1). It is found that the MR is negative and for $(g\mu_B H/k_B T) < 1$ the isothermal MR has a H^2 field dependence, where g, μ_B, H, k_B, and T are the Landé g factor, Bohr magneton, external magnetic field, Boltzman constant, and temperature, respectively. This behavior is exhibited because of the freezing out of the spin-flip scattering due to the alignment of the magnetic moments in an external magnetic field. At temperatures above T_f it should be possible to treat the MR of a spin glass using the dilute alloy approximation. On the other hand, the interactions that cause the MR in an antiferromagnetic metal are more complicated, particularly for systems containing rare-earth ions where the magnetic interaction is indirect. However, there is a theoretical calculation of the MR for an antiferromagnet by Yamada and Takada[5,6] for systems where the conduction electron-magnetic moment interaction strength is much smaller than the ordering temperature. This assumption does not hold true for rare-earth systems so it is not possible to make quantitative comparisons of theory with experimental results, but the qualitative conclusions of Yamada and Takada[5,6] may provide a guide to understanding the experimental results. They find that (i) the MR of an antiferromagnetic metal is positive and increases with increasing field for $T < T_N$ up to a critical field H_c, the antiferromagnetic to paramagnetic phase transition field, and (ii) in the paramagnetic phase ($T > T_N$) the MR is negative because of the field-induced alignment of the spins.

In this Brief Report we present the experimental results of the MR of a Kondo alloy Y-Ce(3 at.%), a spin glass Y-

Dy(2 at.%), and an antiferromagnetic alloy Y-Tb(3 at. %). We discuss our results within the framework of existing theories. We have found that there is an anisotropy in the MR depending on the direction of the external magnetic field (H) with respect to the sample current (I_x). This anisotropy can be accounted for by including an anisotropic conduction-electron–f-electron interaction along with the isotropic interactions given by Eqs. (1) and (2).

We have measured the longitudinal magnetoresistance (LMR) and the transverse magnetoresistance (TMR). Specimens were prepared in an arc furnace and annealed at 800 °C for about 8 h in an argon atmosphere. The samples were mounted individually on an insulated surface of a copper plate in helium gas in a conventional liquid ^{4}He cryostate. A standard four terminal technique was used to measure the sample resistance $R_x=(I_s/I_x)R_s$, where $R_s=0.1\ \Omega$ is a standard resistor and I_s and I_x the currents through R_s and R_x. A direct current comparator and a galvanometer amplifier with a sensitivity of $\sim 10^{-8}$ V were used to measure R_x/R_s.

The longitudinal

$$(\Delta\rho/\rho_0)_{\parallel}=\left(\frac{\rho(H,T)-\rho(0,T)}{\rho(0,T)}\right)_{\parallel}$$

and transverse

$$(\Delta\rho/\rho_0)_{\perp}=\left(\frac{\rho(H,T)-\rho(0,T)}{\rho(0,T)}\right)_{\perp} \tag{3}$$

magnetoresistances were measured in a magnetic field up to 30 kOe. Here, $\rho(H,T)$ is the resistivity in field H at temperature T and $\rho(0,T)=\rho_0$ is the resistivity in zero field at temperature T.

The isothermal MR of Y-Ce(3 at.%), Y-Dy(2 at.%), and Y-Tb(3 at.%) are presented in Figs. 1, 2, and 3 for several temperatures. The MR of Y-Ce(3 at.%) is negative in the entire range of the external field and it has a field dependence of H^n $(1<n<2)$, which is expected within the Béal-Monod and Weiner[4] theory for single impurity dilute magnetic alloys. In Fig. 1 only the longitudinal MR is shown but the transverse MR differs only in that it is slightly larger in magnitude. The magnetoresistance of Y-Dy(2 at.%) is shown in Fig. 2 in the paramagnetic temperature range. The MR is negative at low fields for the 4.2-K iso-

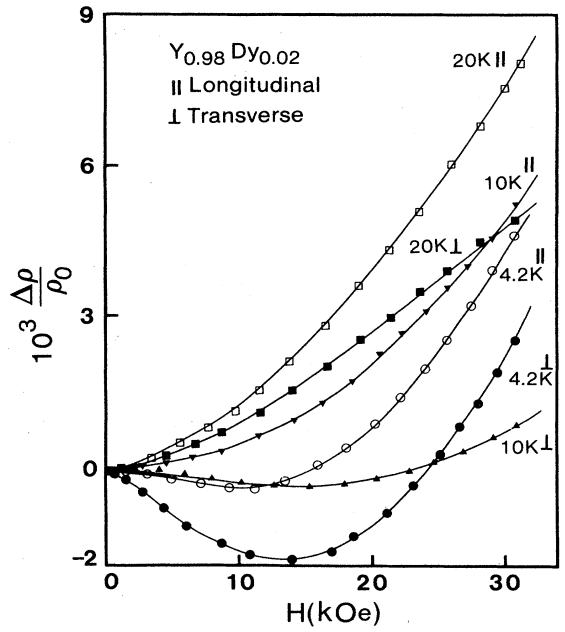

FIG. 2. Isothermal magnetoresistance ($\Delta\rho/\rho_0$) vs magnetic field (H) at different temperatures for Y-Dy(2 at.% Dy).

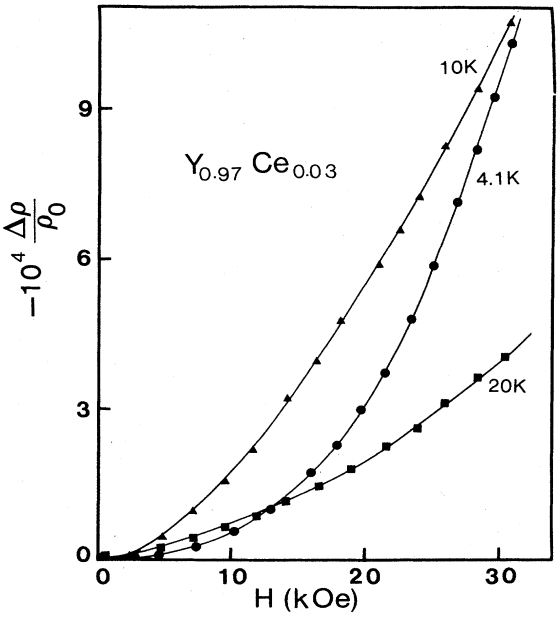

FIG. 1. Isothermal magnetoresistance ($\Delta\rho/\rho_0$) vs magnetic field (H) at different temperatures for Y-Ce(3 at.% Ce).

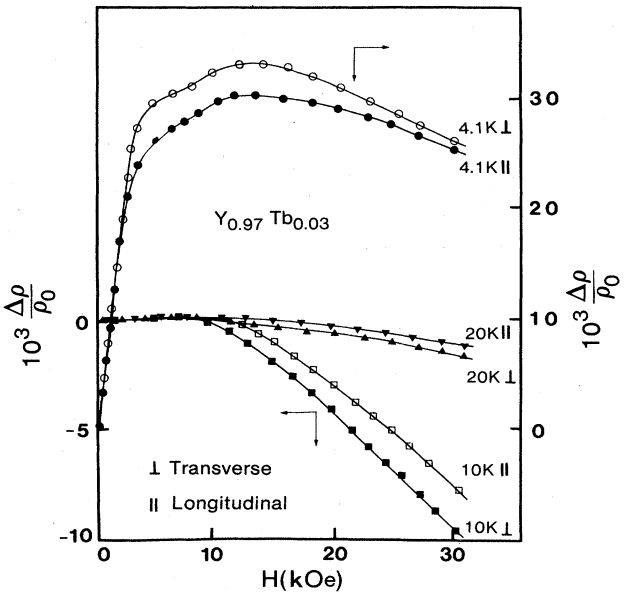

FIG. 3. Isothermal magnetoresistance ($\Delta\rho/\rho_0$) vs magnetic field (H) at different temperatures for Y-Tb(3 at.% Tb).

therm and for the 10-K transverse isotherm, and becomes positive with increasing field. At higher temperatures the MR remains positive at all values of the field and increases with increasing field as $\sim H^2$. Another interesting feature of the MR data for the Y-Dy(2 at.%) alloy is that the LMR is always greater than the TMR.

In the paramagnetic range it is reasonable to treat the Y-Dy(2 at.%) alloy as a dilute magnetic alloy in the context of the Béal-Monod and Weiner[4] theory. We then expect a negative MR with $(\Delta\rho/\rho_0)\propto -H^n$, $1<n<2$. The negative MR at 4.2 and 10 K for low fields is mainly caused by the reduction of spin-flip scattering due to the field-induced alignment of the magnetic spins as expected in the case of a dilute magnetic alloy. The positive MR in Y-Dy(2 at.%) probably arises from the dominance of the "normal magnetoresistance" at higher fields and temperatures.[7] This term is small in dilute Au-R and Ag-R alloys[8] (R = rare earth) but is expected to be large in Y-R alloys. From the magnetoresistance study on the parent metal by Young,[9] we estimate that $\Delta\rho/\rho_0\simeq 0.32$ at 26.5 kOe and 4.2 K for Y, which is quite large compared with the MR we observe for dilute Y-R alloys. Of course, the asphericity of the electron energy surfaces and the variation of the relaxation times on the Fermi surface, on which the normal MR depends, are not quantitatively similar in an alloy and a parent metal.

At the same time there is a contribution to the MR due to the anisotropic scattering between the conduction electrons and f electrons that is not included in the theory for dilute magnetic alloys.[4] It has been shown by Fert and coworkers[8,10,11] that the anisotropy $A[\equiv(\Delta\rho/\rho_0)_{\parallel}-(\Delta\rho/\rho_0)_{\perp}]$ of dilute Au-R and Ag-R (R = rare earth) alloys is due to the anisotropic conduction-electron–f-electron scattering and it is mainly of quadrupolar type. The sign of the anisotropy changes as

$$A=(\Delta\rho/\rho_0)_{\parallel}-(\Delta\rho/\rho_0)_{\perp}\propto L\left(S-\tfrac{7}{4}\right), \tag{4}$$

where L is the total orbital angular momentum of the magnetic ion and S the spin. One expects zero anisotropy for Gd^{3+} ions ($L=0$) and such behavior is observed for AuGd and AgGd alloys.[8,9] The sign of A is expected to be positive for Dy^{3+} ($L=5$, $s=\frac{5}{2}$) and for Y-Dy(2 at.%) A is observed to be positive at all temperatures. The difference between LMR and TMR is very small for the Y-Ce alloy; hence, the anisotropic k-f scattering must be insignificant in this material.

The MR data of the antiferromagnetic Y-Tb(3 at.%) can be discussed in two temperature regimes: one for $T<T_N$ ($T_N\simeq 5.2$ K) and the other for $T>T_N$. For the 4.2-K isotherm in Fig. 3, the MR is positive, increases with increasing field and reaches a maximum at a critical field $H_c(T=4.2K)\simeq 12$ kOe, and above H_c the MR decreases monotonically with increasing field. The critical field $H_c\simeq 12$ kOe is the field at which the transition from the antiferromagnetic to the paramagnetic phase occurs at 4.2 K. The increase in the positive MR with increasing field is consistent with the Yamada and Takada[5,6] theory in which an increase in the MR arises from an enhancement in the spin fluctuations with increasing field up to the critical field H_c. This is a mechanism opposite to the ferromagnetic or paramagnetic case where the spins align in the presence of an external magnetic field causing a suppression in the spin fluctuations and, hence, a negative MR. That is why the MR decreases with increasing field for fields above $H_c\simeq 12$ kOe as observed on the 4.2-K isotherm of Y-Tb(3 at.%) in Fig. 3.

The MR of Y-Tb(3 at.%) for the paramagnetic temperatures (i.e., $T>T_N$) is always negative and decreases with increasing field as expected in a paramagnetic alloy. The field dependence of the MR is $\Delta\rho/\rho_0\propto -H^n$ ($1<n<2$). The anisotropy (A) in the paramagnetic regime has a positive sign; that is, LMR is greater than TMR. This is consistent with the expectations of Eq. (4) for Y-Tb(3 at.%) with Tb^{3+} ($L=3$, $S=3$). A final remark should be made that the anisotropy (A) decreases with increasing temperature again in qualitative agreement with the results of Fert and co-workers.[8,9]

We thank T. Valian for his technical assistance. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada.

[1]T. Sugawara, J. Phys. Soc. Jpn. **20**, 2252 (1965).
[2]Naushad Ali and S. B. Woods, Solid State Commun. **49**, 241 (1984).
[3]B. V. B. Sarkissian and B. R. Coles, Commun. Phys. **1**, 17 (1976).
[4]M. T. Béal-Monod and R. A. Weiner, Phys. Rev. **170**, 552 (1968).
[5]H. Yamada and S. Takada, Prog. Theor. Phys. **49**, 1401 (1973).
[6]H. Yamada and S. Takada, J. Phys. Soc. Jpn. **34**, 51 (1973).
[7]J. M. Ziman, *Electrons and Phonons, The Theory of Transport Phenomena in Solids* (Clarendon, Oxford, 1960), pp. 494 and 501.
[8]A. Fert, R. Asomoza, D. H. Sanchez, D. Spanjaard, and A. Friedrich, Phys. Rev. B **16**, 5040 (1977).
[9]R. C. Young, J. Phys. F **12**, 1931 (1982).
[10]A. Friederich and A. Fert, Phys. Rev. Lett. **33**, 1212 (1974).
[11]A. Fert, R. Asomoza, G. Creuzet, and J. C. Ousset, in *Crystalline Electric Field and Structural Effect in f-Electron Systems,* edited by J. E. Crow *et al.* (Plenum, New York, 1980), p. 381.