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MAGNETIC ORDERING IN AMORPHOUS Nd-Co, Gd-Co AND Er-Co ALLOYS*

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ABSTRACT

Previous studies of magnetism in amorphous rare earth-transition metal alloys have emphasized alloys rich in transition metal. We report here results on three rare earth rich amorphous alloys: $Nd_{64}Co_{36}$, $Gd_{65}Co_{35}$, and $Er_{65}Co_{35}$. Low field susceptibility, χ, was measured for T in the range $4.2\ K \leq T \leq 300$ K and magnetization was measured for $1.3 \leq T \leq 200$ K and applied fields, H, of $0 \leq H \leq 80$ kOe. Curie-Weiss fits were made to high temperature $\chi(T)$ data to determine average effective moments and Weiss temperatures. Hysteresis loops were used to determine the coercive force and the ordering temperatures, T_C. The effective moments and saturation moments are compared with values calculated on the assumption of local moments on both the rare earth and Co ions. T_C values for Nd, Gd, and Er alloys are 38 K, 170 K, and 12 K, respectively. The data are consistent with a ferrimagnetic structure in $Gd_{65}Co_{35}$. Local random anisotropy appears to play an important role in the Nd-Co and the Er-Co alloys.

INTRODUCTION

In recent years there has been strong interest in the magnetic properties of metallic glasses [1]. Metal-metal amorphous alloys of the type R_xT_{1-x}, where R is a rare earth, T is a transition element, and x is the atomic fraction of R, are particularly challenging because two magnetic species may be present in the same alloy. With alloys of this type fundamental questions about moment formation, exchange couplings, and transition temperatures still remain unanswered [2]. Most previous measurements of amorphous R_xT_{1-x} alloys have been made on binary or ternary alloys where the rare earth concentration did not exceed 50% [1,2,3]. We have begun an investigation of R-T alloys where the ratio of R to T is approximately 2:1. This paper presents the initial results of magnetization and susceptibility measurements on three amorphous rare earth-Cobalt alloys which span the rare earth series: $Nd_{64}Co_{36}$, $Gd_{65}Co_{35}$, and $Er_{65}Co_{35}$.

EXPERIMENTAL

All the alloys were made by first arc-melting the pure constituent elements several times. Then a small piece (approx. 0.12 g) was remelted and rapidly quenched from the liquid by a hammer-anvil technique. The resulting foils were about 50 μm thick and can be described as brittle according to a criteria established by Chen [4]. X-ray (MoK_α) diffraction patterns showed two diffuse halos indicating the samples were amorphous.

Magnetization was measured for applied magnetic fields up to 80 kOe in the temperature range, $1.3\ K \leq T \leq 200$ K, using a vibrating-sample magnetometer. Susceptibility measurements were made with a Faraday balance for $4.2\ K \leq T \leq 300$ K and for applied magnetic fields, H, of $0 \leq H \leq 10$ kOe.

RESULTS

The measured susceptibility, χ, for $Nd_{64}Co_{35}$ and $Er_{65}Co_{35}$ is shown in Fig. 1. A sharp transition is observed in both alloys shown in Fig. 1. For the third sample, $Gd_{65}Co_{35}$, the susceptibility shows a similar dramatic rise and sharp break near T_C but only a mild decrease in χ below T_C. Figure 2b shows the temperature dependence of the inverse susceptibility for $Er_{65}Co_{35}$. For temperatures above the ordering temperature, the data were fitted to a Curie-Weiss law,

$$\chi = N \bar{p}^2 \mu_B^2 [3k_B(T-\theta)]^{-1} \tag{1}$$

where $\bar{p}$ is the effective moment per average atom and N is the total number of atoms per unit mass. From the fit to Eq. 1, $\bar{p} = 3.0 \pm 0.1$, 6.6 ± 0.2, 7.8 ± 0.2, and $\theta = 35 \pm 3$ K, 187 ± 3 K, 10 ± 2K for the Nd, Gd, and Er alloys, respectively.

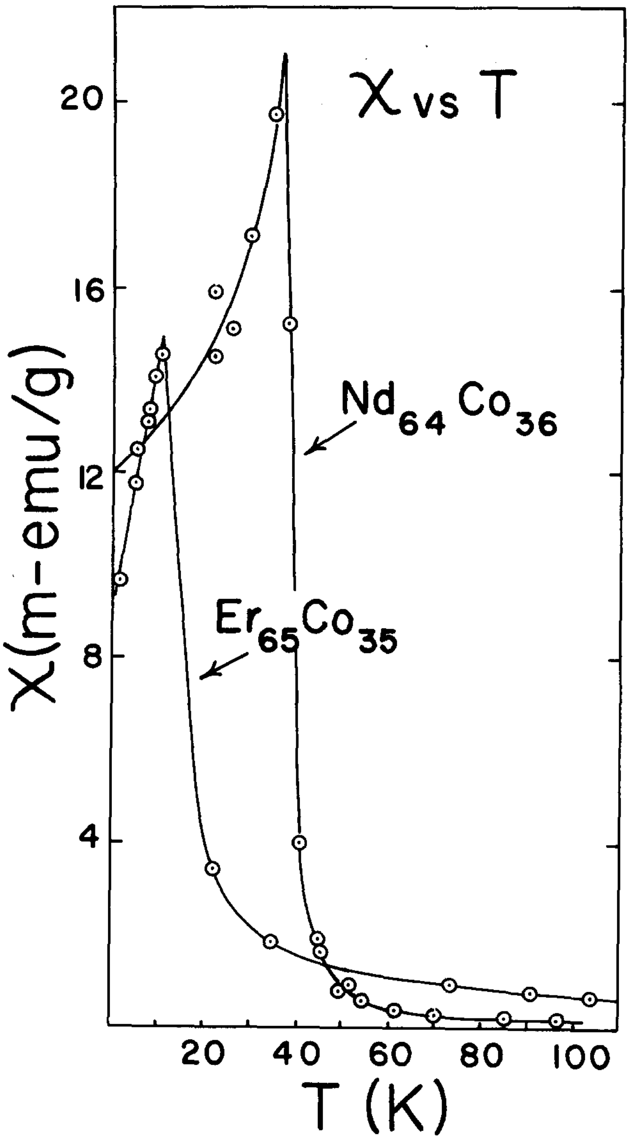

Fig. 1. Susceptibility for amorphous $Nd_{64}Co_{36}$ and $Er_{65}Co_{35}$. Solid lines run through data for respective alloys.

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We define the transition temperature, T_C, to be the temperature where the coercive field H_C goes to zero. We find for the Nd and Er alloys that $H_C^{1/2}$ is a linear function of T for T near T_C (Fig. 2a). The values of T_C are 38 ± 2 K, 170 ± 5 K, and 12 ± 1 K for the Nd, Gd, and Er alloys, respectively.

Hysteresis loops at T = 4.2 K are shown for $Nd_{64}Co_{36}$ and $Er_{65}Co_{35}$ in Fig. 3. M(H) for $Gd_{65}Co_{35}$ at several temperatures is shown in Fig. 4. $Gd_{65}Co_{35}$ shows very little hysteresis with the measured coercive field, H_C, being only 30 Oe at 4.2 K. $Nd_{64}Co_{34}$ and $Er_{65}Co_{35}$ show considerably more hysteresis and have H_C(T = 4.2 K) of 5200 Oe and 470 Oe, respectively.

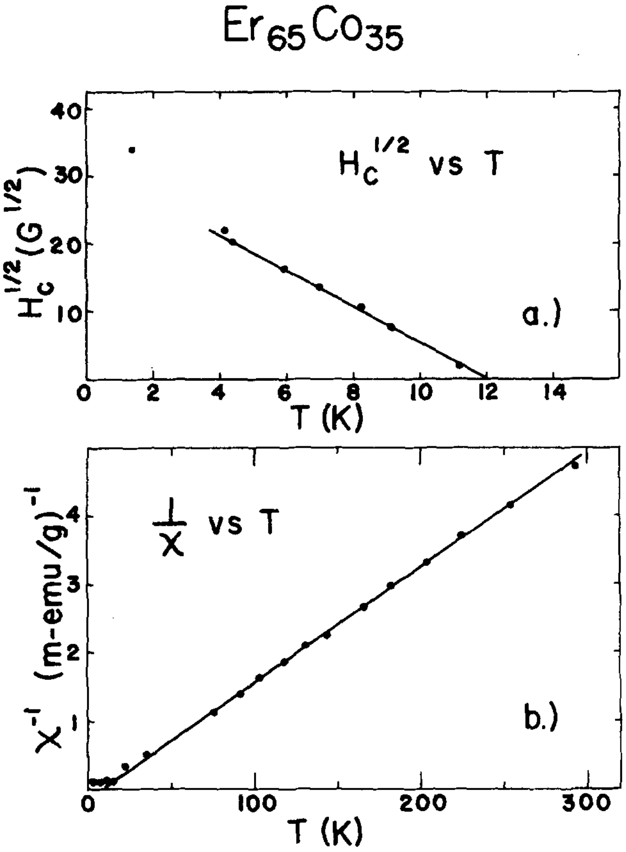

Fig. 2. a) $H_C^{1/2}$ vs. T for $Er_{65}Co_{35}$.
b) Curie-Weiss fit for $Er_{65}Co_{35}$.

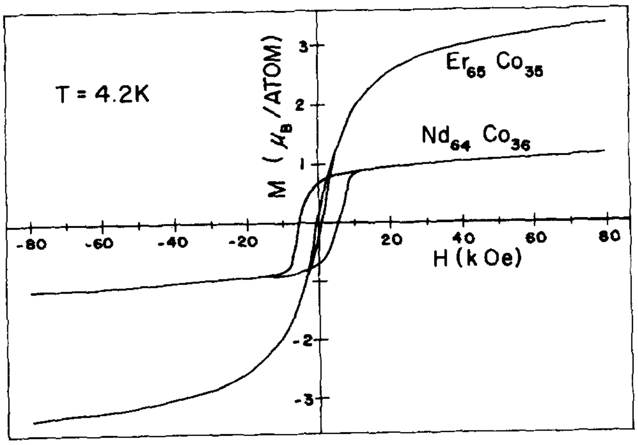

Fig. 3. Hysteresis loops for amorphous $Nd_{64}Co_{36}$ and $Er_{65}Co_{35}$.

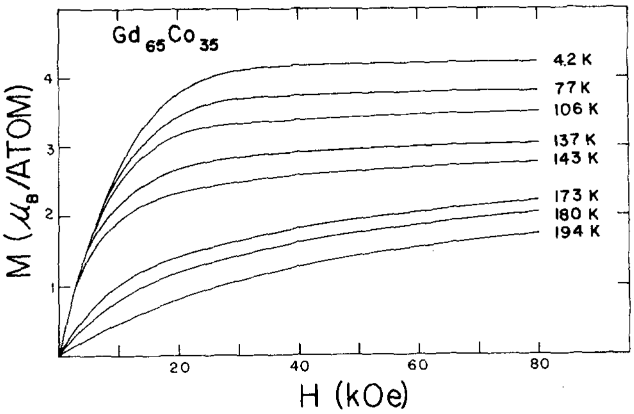

Fig. 4. Field dependence of average moment per atom for $Gd_{65}Co_{35}$ at several temperatures.

DISCUSSION

The near lack of hysteresis in $Gd_{65}Co_{35}$ is a significant difference between it and the other two rare earth alloys. This difference suggests the presence of local random anisotropy (LRA) in the Nd and Er alloys and the absence of this anisotropy in the Gd alloy. A second indication of LRA is in the Nd magnetization curve (Fig. 3). Above 10 kOe there is a slow linear rise in the measured moment of $Nd_{64}Co_{36}$. This behavior is associated with the closing of the fan-like structure of anisotropically oriented spins in amorphous alloys which exhibit LRA [5]. On the other hand, the $Gd_{65}Co_{35}$ alloy appears to saturate with almost no increase in magnetization for applied fields greater than 30 kOe. This is reasonable since the Nd and Er ions have orbital angular momentum whereas Gd is an S state ion. Similar behavior has been seen in the rare earth amorphous alloys such as $Zr_{40}Cu_{60-x}M_x$, where M = Tb or Gd, and $DyCo_{3.4}$ [6]. Recent model calculations for the amorphous magnetic state have also emphasized the importance of LRA for these materials [7].

For all three R-Co alloys the inverse susceptibility shows Curie-Weiss behavior for temperatures above T_C. This suggests that a local moment model is appropriate and that the average effective moment per atom for R_xCo_{1-x} alloys may be calculated from a weighted average of the form

$$\bar{p}^2 = x p_R^2 + (1 - x)\, p_{Co}^2 \, . \qquad (2)$$

Assuming the rare-earth ions retain their normal R^{3+} character (p(Nd) = 3.62, p(Gd) = 7.94, and p(Er) = 9.58), Eq. 2 may be inverted to solve for the Co spin. Assuming g_{Co} = 2 we find J_{Co} = 0.4 ± 0.15, 1.0 ± 0.5, and 0.5 ± 0.5 for the Nd, Gd, and Er alloys, respectively. Thus it appears that for these R-Co alloys the Co ion retains its moment even at a Co concentration as low as 35 percent, i.e., the trivalent rare earth ions do not provide so much charge transfer that the Co ions completely lose their d character.

For a simple localized moment model in which one assumes perfect ferromagnetic or ferrimagnetic order the moment per average atom $\bar{\mu}$, will be

$$\bar{\mu} = x(gJ)_R \pm (1 - x)\,(gJ)_{Co} \, . \qquad (3)$$

Because the effects of LRA are expected to be small for the Gd ion, Eq. 3 may be used for the $Gd_{65}Co_{35}$ alloy where the measured average magnetic moment is $4.1 \pm 1\ \mu_B$ per atom. We assume that the sample is nearly saturated at 4.2 K (Fig. 4), that $(gJ)_{Gd} = 7$, that $g_{Co} = 2$, and that the Gd and Co spins are ferrimagnetically coupled [8]. Eq. 3 then yields $J_{Co} = 0.6 \pm 0.3$ in agreement with the value of J_{Co} determined above from $\overline{p}$ (Eq. 2). The existence of ferrimagnetic coupling is consistent with the negative exchange coupling seen between Gd and Co moments in the Gd-Co-Mo alloys [9].

By similar analysis Eq. 3 suggests that $Nd_{64}Co_{36}$ and $Er_{65}Co_{35}$ have canted ferrimagnetic order with a fan-like arrangement of their rare earth spins. However, this conclusion is tentative because for the Nd^{3+} ion the moment may not sample the full $J = 9/2$ manifold due to crystal field splitting. For $Er_{65}Co_{35}$ the use of Eq. 3 is suspect because the measured value of $\overline{\mu}$ is not well defined at 4.2 K (Fig. 3).

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