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Magnetic ordering in *Y*Gd alloys

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We present magnetization and resistivity measurements on single crystals of yttrium doped with small concentrations of gadolinium ($c = 1$, 2, and 3 at. %). The low-field susceptibility exhibits a spin-glass-like sharp cusp for the magnetic field along the c axis. However, there is no irreversible behavior below the temperature of the cusp, which rules out the existence of a spin-glass state. Moreover, our magnetization measurements show up a spin-flop transition for H in the basal plane. The existence of a long-range ordering is confirmed by our resistivity measurements. The resistivity parallel to the c axis exhibits a maximum just below the ordering temperature, which is reminiscent of the superzone effects observed in many rare-earth metals. The antiferromagneticlike properties of the *Y*Gd alloys contrast with the spin-glass behavior observed in other Y–rare-earth alloys at similar concentrations.

INTRODUCTION

There have been several recent studies of the magnetic properties of Y and Sc doped with magnetic impurities of rare earths. Most of these alloys exhibit spin-glass properties which are influenced by the existence of a uniaxial crystal field: alloys with Er are Ising-like spin glasses, alloys with Tb and Dy are *XY* spin glasses, while *Sc*Gd alloys, with a vanishingly small crystal field, represent a Heisenberg spin glass.[1–3] In contrast, the *Y*Gd alloys—which could be expected to behave as *Sc*Gd—do not show spin-glass properties (there is no irreversibility below the temperature of the maximum of susceptibility) but rather some complex long-range ordering, even at concentrations as low as 1 at. %.[3] In this communication we present magnetic and transport measurements which allow us to specify the type of magnetic ordering of the low-concentrated YGd alloys. These measurements have been performed on single crystals of *Y*Gd 1 at. %, *Y*Gd 2 at. %, and *Y*Gd 3 at. %. The single crystals were grown by a recrystallization technique.[4] The magnetization and resistivity measurements were done between 1.5 and 20 K, using a Foner-type magnetometer and a four-terminal potentiometric apparatus, respectively.

MAGNETIZATION

Figure 1 shows the dc susceptibility (M/H) as a function of temperature in a fixed field for the (a) 1 at. % Gd, (b) 2 at. % Gd, and (c) 3 at. % Gd single crystals. The field was applied in both directions parallel (open circles) and perpendicular (full circles) to the $\langle c \rangle$ axis. When the field is perpendicular to the $\langle c \rangle$ axis, the susceptibility shows a sharp cusp at a temperature T_c. For fields parallel to the $\langle c \rangle$ axis, the susceptibilities of the 2 and 3 at. % Gd alloys show a very small accident at T_c and a clear deviation from the normal Curie–Weiss behavior appears below T_c. For the 1 at. % Gd alloy no accident can be detected in the parallel susceptibility, in agreement with previous ac measurements.[1] Important features of all of these curves are the absence of "field cooling–zero field cooling" irreversibility effects, normally observed in spin glasses. Instead, these susceptibility curves might be viewed as a superposition of the normal susceptibility of a planar antiferromagnet with a Curie term due to isolated Gd spins. If this interpretation is correct, we can use the Curie-like excess of susceptibility parallel to the $\langle c \rangle$ axis below T_c (which should be a constant in a perfect planar antiferromagnet) to estimate the quantity of moments participating to an ordered structure. We obtain that about 60% of the spins are ordered in the 1 at. % Gd alloy. This proportion increases to slightly more than 90% for the 2 and 3 at. % Gd alloys.

To study further the type of magnetic order occurring at temperatures below T_c, we performed magnetization measurements as a function of H at fixed temperature. Figure 2 shows the results for the 2 at. % Gd single cyrstal at

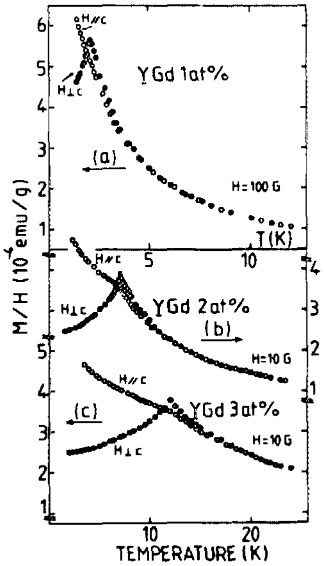

FIG. 1. (a) M/H vs T for *Y*Gd 1 at. %, (b) *Y*Gd 2 at. %, and *Y*Gd 3 at. % single crystals. H is applied parallel (open circles) and perpendicular (full circles) to the $\langle c \rangle$ axis.

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[a] Supported by CNPq, Brazil.

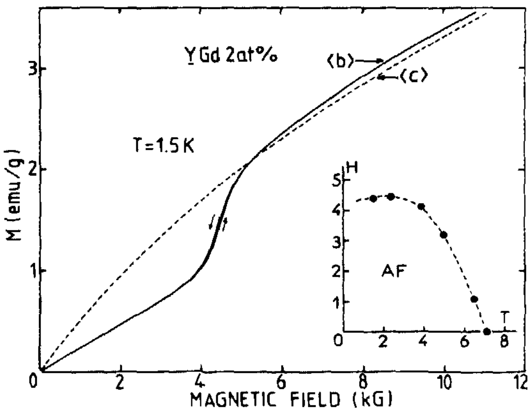

FIG. 2. M vs H at $T = 1.5$ K for YGd 2 at. %. For $H \parallel \langle b \rangle$ the arrows indicate the field scan. The inset shows the field and temperature dependence of the spin-flop transition.

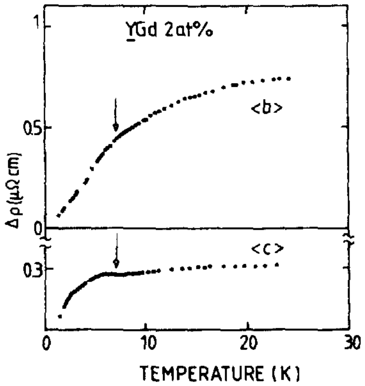

FIG. 3. Electrical resistivity vs T for YGd 2 at. % single crystal along the $\langle b \rangle$ and $\langle c \rangle$ axes. The arrows indicate the temperature of the susceptibility cusp. The corresponding resistivity components of pure Y have been subtracted.

$T = 1.5$ K. A spin-flop-like transition is clearly observed for fields in the basal plane. For fields along the $\langle c \rangle$ axis the magnetization varies monotonously with H. Below the critical field the magnetization is strongly anisotropic; above, the magnetization becomes almost isotropic. The magnetization jump corresponds approximately to 50% of the total magnetization. The H-T dependence of the spin-flop transition is shown in the inset of Fig. 2.

We observed similar behaviors for the magnetization of the single crystals doped with 1 and 3 at. % Gd. These experiments rule out the existence of a spin-glass state in our YGd alloys and strongly suggest the occurrence of an antiferromagnetic ordering with spins lying in the basal plane.

RESISTIVITY

The existence of long-range magnetic ordering in our systems is confirmed by resistivity measurements on an YGd 2 at. % single crystal. Figure 3 displays the impurity resistivity of this alloy. The resistivity for a current in the basal plane shows a weak but perceptible change of slope at the temperature T_c of the susceptibility cusp. On the other hand, the resistivity in the direction of the $\langle c \rangle$ axis exhibits a maximum just below T_c before going to zero at 0 K.

This resistivity behavior can be interpreted as reminiscent of the superzone effects observed in several rare-earth metals.[5] If a helical antiferromagnetic ordering with spins pointing on the basal plane takes place in the YGd alloys, the superzone discontinuities on the Fermi surface should affect the resistivity in the way shown by our experiments.[6]

DISCUSSION

The above presented measurements of magnetization and resistivity in diluted YGd alloys completely rule out a low-temperature spin-glass state, which is otherwise observed in other yttrium–rare-earth alloys at similar rare-earth concentrations. Our experiments are consistent with a long-range antiferromagnetic ordering, with the Gd moments lying on the basal plane and forming a helical arrangement, as first suggested by Sarkissian and Coles.[7] Neutron diffraction results on the 2 and 3 at. % Gd single crystals allow one to specify this helical order.[8]

It is rather difficult to conceive such a helical arrangement in dilute spin systems without ascribing a role to the conduction electrons. However, the exact nature of such a mechanism is not completely clear. The original suggestion of Sarkissian and Coles involves the stabilization of a spin-density wave[9] in the conduction band of yttrium by the magnetic impurities. A somewhat different mechanism, first suggested by Freeman[6] to explain the antiferromagnetic ordering in the rare-earth metals, can also be proposed. The approach of Freeman considers the nesting properties of the Fermi surface of the rare earths as giving a maximum to the electron gas susceptibility at a given wave vector $\mathbf{Q}_0$ (nesting vector). These result in a RKKY exchange integral $J(\mathbf{Q}_0)$ which can explain the observed helical spin structures.

Whichever the mechanisms inducing magnetic ordering in our YGd alloys, it is interesting to note that such mechanisms should also exist in Y doped with non-S ion rare-earth impurities. It could be that in these alloys, the strong crystal-field anisotropy favors a spin-glass freezing instead of a helical ordering. But it could also be that helical spin correlations coexist with the spin-glass freezing.

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