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LETTER TO THE EDITOR

Experimental evidence for a *c*-axis magnetic moment in single-crystal Dy below 4.3 K

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Abstract. The AC susceptibility and magnetization of a pure single crystal of Dy have been measured in the temperature region from 2 K to 200 K. The AC susceptibility data show an abrupt drop near 6.5 K for all three crystal axes. The magnetization has been measured using a SQUID magnetometer with an applied field of 0.002–0.005 T. The basal plane magnetization data show a sharp step as the crystal is warmed past 4.3 K. The *c*-axis magnetization data show a corresponding anomaly. From our data it appears that a component of the Dy moment lifts out of the basal plane at temperatures below 4.3 K. We also observe an anomaly in the susceptibility data near 167 K.

The magnetization properties of single-crystal Dy have been studied extensively in the past. Magnetization measurements made by Behrendt *et al* (1958) and neutron diffraction measurements made by Koehler (1965) show that Dy undergoes a transition to a spiral antiferromagnet at $T = 180$ K. As the temperature of Dy is further decreased, a second transition to a simple ferromagnet structure occurs at $T = 90$ K. In both of these phases, the magnetic moments were found to remain entirely in the basal plane. In addition to these transitions, an additional anomaly, which has been described to be a vortex state, has been observed near 171 K (see, for example, Amitin *et al* (1984) and Bessergenev *et al* (1985)). In this letter, we present AC susceptibility and SQUID magnetization data in the temperature region from 2 K to 200 K for a pure single crystal of Dy. We observe the Néel temperature near 180 K and the Curie transition near 90 K. We also observe an anomaly near 167 K in the *b*-axis AC susceptibility data. The anomaly in the *b*-axis data is observed while the crystal is warmed and is an excellent agreement with earlier observations of the so-called vortex state in Dy. This anomaly at 167 K in Dy may possibly be accounted for by using the spin-slip description of the rare-earth elements of Bohr *et al* (1986).

In addition to these transitions, the magnetization data along the basal plane and *c* axis show anomalies suggesting a small component of the magnetic moment lifting into the *c* axis at temperatures below 4.3 K. While much work has been done near the Curie and Néel transitions, there has been little detailed research done at temperatures below 10 K. This is the first experimental evidence of a *c*-axis magnetic moment component in single-crystal Dy at temperatures below 4.3 K.

The single crystal of Dy was purchased from Ames Laboratory. It is in the shape of a rectangular solid of dimensions (a, b, c) 3.2 mm × 4.2 mm × 5.0 mm. The mass of the

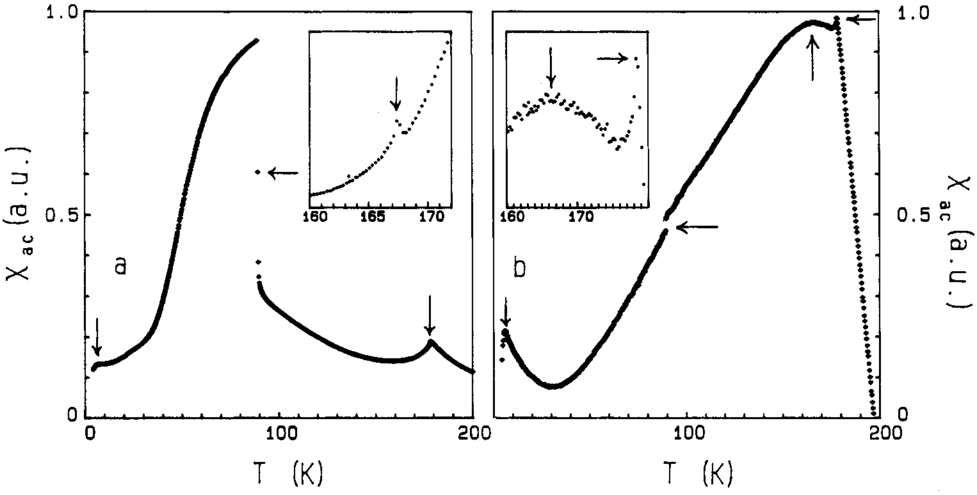

Figure 1. (*a*) The AC susceptibility (χ_{AC}, arbitrary units) of single-crystal Dy along the *b* axis in the temperature range from 4.2 to 200 K. An enlargment of the region around 170 K is shown in the inset. (*b*) The AC susceptibility (χ_{AC}, arbitrary units) of single-crystal Dy along the *c* axis. The inset shows the region around 170 K.

crystal is 0.5337 g. An analysis supplied with crystal gives the total rare-earth impurity as 11 ppm. The *a* axis is the easy axis for this crystal.

The AC susceptibility was measured in the temperature range from 4.2 K to 300 K using the standard mutual induction method. The magnetic field generated by the primary was approximately 1.5 G with a frequency of 80 Hz. The probe was cooled to liquid He temperature and the data collected as the system warmed to room temperature. Data were collected for each of the three crystal axes.

The magnetization was measured versus temperature using a SQUID magnetometer supplied by Quantum Design of San Diego, CA. The crystal was mounted in a length of plastic straw which was in turn connected to a Cu–Be rod. The crystal was cooled to 2 K in zero field and the data collected as the sample warmed. Data were collected along each of the three crystal axes in applied fields of 0.002–0.005 T.

The AC susceptibility data are shown in figure 1 for the *b* and *c* axes. In each case, we observe the Néel transition near 178 K and the Curie transition near 89 K. The *b*-axis AC susceptibility data show a small broad peak near 167 K. The *c*-axis AC susceptibility data show a maximum near 166 K and a minimum near 176 K. These anomalies in the AC susceptibility data correspond well with the so-called vortex state of Dy.

As the crystal warms from 4.2 K, we observe a peak in the susceptibility for all three axes at about 6.5 K. In the *c*-axis data, we observe the susceptibility decrease as the crystal warms past 6 K. The *c*-axis data then show a minimum in the susceptibility near 30 K. We do not observe a minimum in the *a*-axis or *b*-axis data.

The magnetization for the temperature range from 2 K to 200 K is shown in figure 2 for the *b* and *c* axes. The data for figure 2 were collected in an applied field of 0.005 T. We observe the Néel transition near 180 K and the Curie transition near 91 K. Additional data in the temperature region below 5 K in an applied field of 0.002 T are shown in figure 3. In the *b*-axis data (figure 3(*a*)), we observe a sharp rise in the magnetization as the crystal is warmed past 4.3 K. The *c*-axis data (figure 3(*b*)) show a sharp drop in the

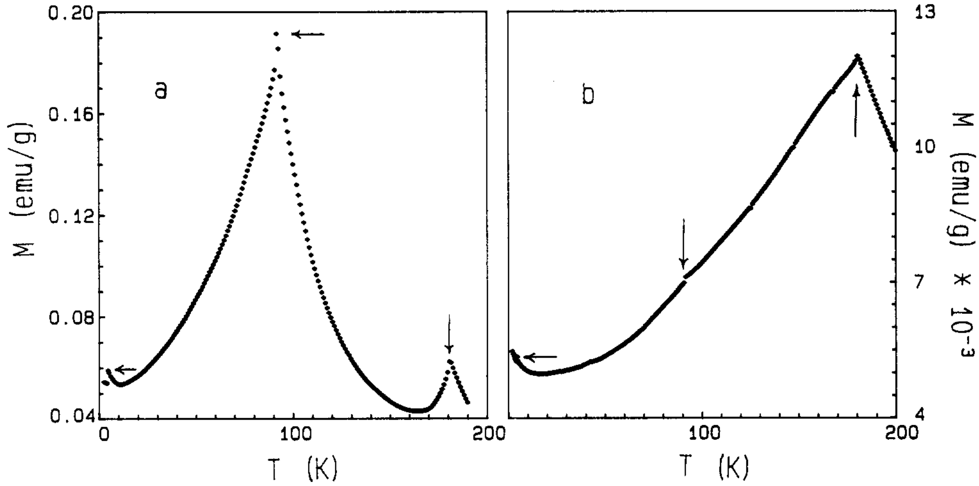

Figure 2. (*a*) The magnetization (M) versus temperature (T) of single-crystal Dy along the *b* axis in an applied field of 0.005 T. (*b*) The magnetization (M) versus temperature (T) of single-crystal Dy along the *c* axis in an applied field of 0.005 T.

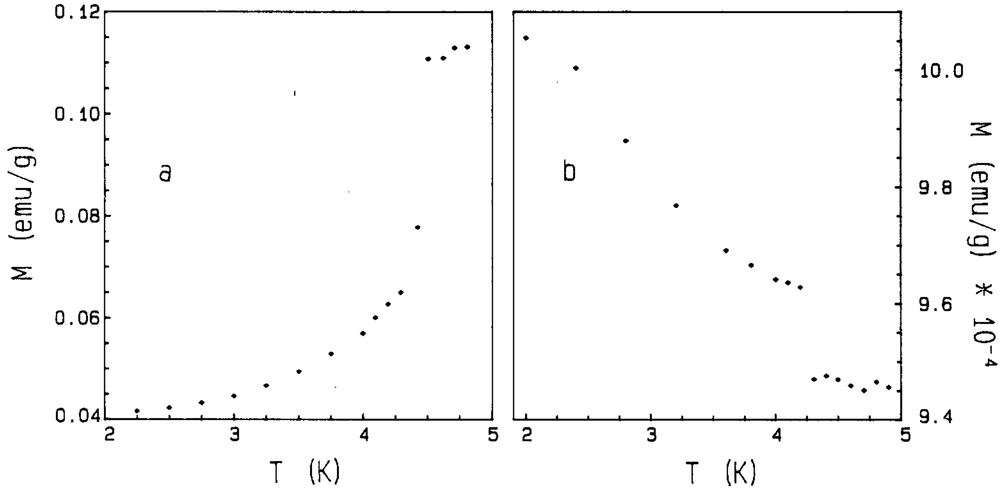

Figure 3. (*a*) The magnetization (M) of single-crystal Dy as a function of temperature (T) from 2–5 K with an applied field of 0.002 T along the *b* axis. (*b*) The magnetization (M) versus temperature (T) of single-crystal Dy in an applied field of 0.002 T along the *c* axis.

magnetization as the crystal warms past 4.3 K. This behaviour suggests that the magnetic moment may rise out of the basal plane at temperatures below 4.3 K and form a component along the *c* axis.

The step increase in the basal-plane magnetization and a step decrease in the *c*-axis magnetization, as the sample is warmed, suggest that at the lowest temperatures the magnetic moment of Dy has a small *c*-axis component. As the temperature of the sample increases past 4.3 K, the *c*-axis component collapses into the basal plane and gives rise to a step decrease in the *c*-axis magnetization. This is accompanied by a step rise in the basal-plane magnetic moment at 4.3 K. Above 4.3 K, all of the moments lie in the basal plane with a simple ferromagnetic alignment. This work provides the first evidence of a small *c*-axis moment component below 4.3 K in single-crystal Dy. The peaks in AC susceptibility at 6.5 K (figure 1) are most probably due to this *c*-axis moment formation at lower temperatures. From our magnetization data in an applied field of 0.002 T, it is estimated that the change in the *c*-axis moment component at the step is approximately $1.6 \times 10^{-6} \mu_B$ per atom while the change in the basal-plane moment at the step is $7 \times 10^{-3} \mu_B$ per atom. We feel it is necessary to confirm these results by neutron scattering studies on single-crystal Dy below 4.3 K. In addition, it is worth determining the magnetic structure of Dy in the basal plane and along the *c* axis at temperatures below 4.3 K.

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