Some Magnetic Properties of Dy Metal*

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The magnetic moment of dysprosium has been measured in applied fields of 4000–18 000 oersteds, over the temperature range of 4.2–202°K. The susceptibility of dysprosium was found to be field dependent below about 175°K. Below 90°K, dysprosium appeared to have true though abnormal ferromagnetic properties, confirming the previous work of Trombe. At hydrogen and helium temperatures the magnetization isotherms fell below the 31°K isotherm. An absolute saturation magnetic moment of at least 8 Bohr magnetons was indicated by the data obtained in the temperature range of 31°K to 80°K. The magnitude of the measured values of the magnetic moment of dysprosium indicated that the orbital angular momentum of the 4f electrons contributes to the ferromagnetism.

I. INTRODUCTION

The magnetic properties of metallic dysprosium have been studied by Trombe[1–3] above 70°K. He has reported a magnetic anomaly at about 175°K. Below 175°K he notes that the susceptibility is field dependent and that the susceptibility *vs* temperature curve is such as to indicate an antiferromagnetic Curie temperature (Néel point) at 175°K. He further reports a transition to the ferromagnetic state at 85°K, this being the zero field ferromagnetic Curie temperature. This paper confirms the results of Trombe and extends the measurements to lower temperatures and higher fields.

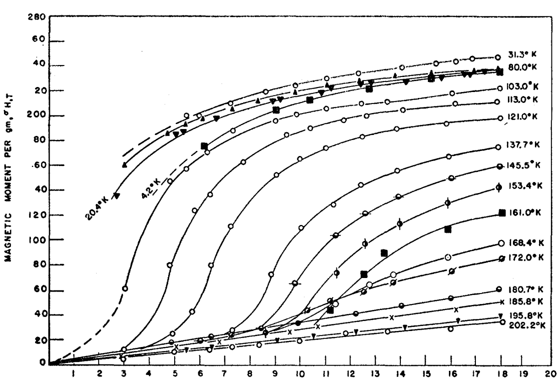

Fig. 1. Magnetic moment isotherms of dysprosium as a function of applied field.

The metal used in this study was prepared by methods previously reported.[4,5] Spectrographic analysis showed the following impurities: calcium, detectable but less than 100 ppm (parts per million); iron, detectable but less than 2000 ppm; holmium, detectable but less than 2000 ppm; erbium, detectable but less than 200 ppm; yttrium, detectable but less than 200 ppm; nickel, cobalt, and other rare earths not detected. Complete spectrographic standards for determining accurate quantitative amounts of impurities in dysprosium are not yet available; thus, the amounts of impurities cited are estimated upper limits.

The experimental procedure was similar to that used to measure the magnetic properties of gadolinium and is described elsewhere.[6,7]

II. EXPERIMENTAL RESULTS

Figure 1 shows a number of the magnetic isotherms of dysprosium as a function of applied field. Figure 2 is an enlarged portion of the low field region of Fig. 1. The initial susceptibility (i.e., the susceptibility calculated from the low field linear portion of the curves in Fig. 2) from 113°–202°K plotted as a function of temperature is shown in Fig. 3. One notes in Figs. 1 and 2 that for applied fields up to 18 000 oersteds the magnetization *vs* H isotherms remain linear down to about 175°K. Below 175°K the isotherms are linear

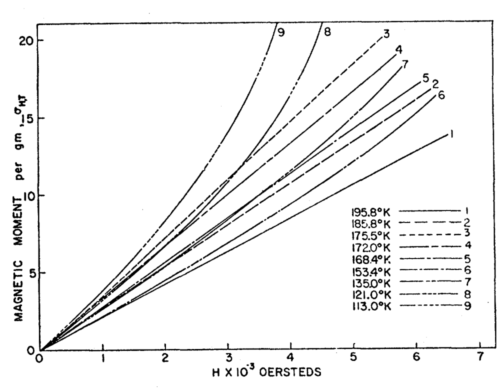

Fig. 2. An enlarged plot of the low field region of Fig. 1.

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[1] F. Trombe, Compt. rend. **221**, 19 (1945).

[2] F. Trombe, J. phys. et radium **12**, 222 (1951).

[3] F. Trombe, Compt. rend. **236**, 591 (1953).

[4] Spedding, Voight, Gladrow, and Sleight, J. Am. Chem. Soc. **69**, 2777 (1947).

[5] F. H. Spedding and A. H. Daane, J. Am. Chem. Soc. **74**, 2783 (1952).

[6] W. S. Sucksmith, Proc. Roy. Soc. (London) **A170**, 551 (1939).

[7] Elliott, Legvold, and Spedding, Phys. Rev. **91**, 28–30 (1953).

in the low field region, but at some higher field the susceptibility becomes field dependent. As the temperature is lowered below 175°K, the susceptibility becomes field dependent in progressively lower fields.

Below 110°K the magnetization curves for dysprosium as shown in Fig. 1 are much the same as those of gadolinium,[6] and are nearly typical of a ferromagnetic substance. It is observed that the element is very magnetically "hard" in comparison to iron, or even gadolinium, and is far from saturation in a field of 18 000 oersteds. One also notes that below 103°K, dysprosium becomes rapidly temperature saturated, i.e., temperature has little effect upon the magnitude of the magnetization.

Of particular interest is the fact that the 20.4°K and the 4.2°K data fall below the 31.2°K isotherm.

The anomaly observed by Trombe is quite evident in Figs. 2 and 3. The general shape of the curve in Fig. 3 is not unlike the corresponding curve for an antiferromagnetic substance in the neighborhood of its Néel temperature.[8]

In order to discuss the magnetic behavior of dysprosium, four temperature regions or magnetic states may be distinguished. The first state *A* occurs above 176°K where the element appears to be truly paramagnetic. The second state (hereafter called state *B*) occurs in the temperature range bounded by the anomaly at 176°K and by the ferromagnetic Curie point at 92°K. (The Curie point determination is discussed below.) The magnetic behavior of dysprosium in this temperature range is characterized by the field dependence of the susceptibility, and the apparent lack of spontaneous magnetization.

The third magnetic state of dysprosium (hereafter called state *C*) occurs below about 92°K. Here the element appears to be in a true though abnormal ferromagnetic state, characterized by spontaneous magnetization, saturation effects, and hysteresis effects.

The fourth magnetic state for dysprosium (hereafter called state *D*) is in the temperature range below about

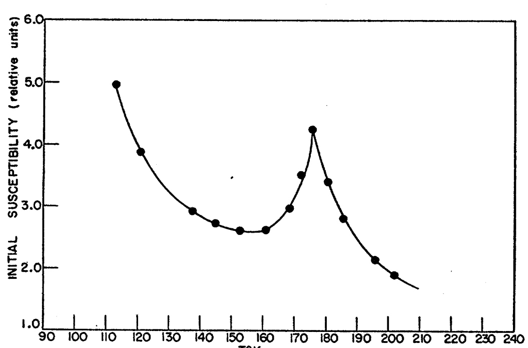

FIG. 3. The initial susceptibility of dysprosium in the temperature range from 110° to 200°K.

[8] F. Trombe, Compt. rend. **236**, 591 (1953).

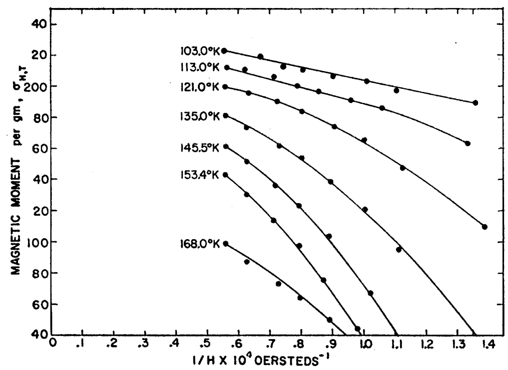

FIG. 4. Representative curves of the isothermal variation of the magnetic moment of dysprosium with $1/H$ in the temperature range 103° to 168°K.

25°K as indicated by the anomalous behavior of the isotherms in this temperature region.

The difficulty encountered in attempting to obtain the Curie point from spontaneous magnetization data may be seen from the magnetization curves (Fig. 1). In order to determine the Curie point by this method it is necessary to obtain spontaneous magnetization curves above and below the Curie point. Because of the strange behavior of dysprosium immediately above its ferromagnetic Curie point (i.e., in state *B*), it was found impossible to obtain spontaneous magnetization data which were complete enough to allow an accurate determination of the Curie point by this method. Consequently, the Curie point for state *C* was obtained from measurements in an applied field of 1200 oersteds by extrapolation of the linear portion of the magnetization squared *vs* temperature curve to the temperature axis. The value of the Curie point determined by this method was found to be 92°K.

Figures 4 and 5 are plots of the magnetic moment *vs* $1/H$ for several of the isotherms of Fig. 1. These curves differ considerably from the corresponding curves of gadolinium. The curves in the neighborhood of 100°K are nearly linear above 5000 oersteds. At temperatures above 100°K, the curves are concave downward. The curves below 80°K seem to consist of two nearly straight intersecting lines although it is also possible that the upward trend of the data at higher fields (low $1/H$) might continue. Both of the linear sections of the curves below 80°K have been extrapolated to infinite fields to estimate the saturation moments.

In Fig. 6 the saturation moments obtained from Fig. 5 are plotted as a function of $T^{\frac{3}{2}}$ to obtain the absolute saturation moment. The saturation moment at absolute zero for dysprosium appears to be about 299 ± 5 cgs units if one uses saturation moments from the high field extrapolations, and about 273 ± 3 cgs units, if one uses the low field extrapolated saturation moments. These moments correspond to 8.7 and 8.0 Bohr magnetons, respectively.

It is noted that these absolute saturation moments were obtained using data from the temperature range of 31°–80°K only, and therefore only attempt to point out what the approximate magnitude of the saturation moment at absolute zero would be assuming no anomalies between 0°–31°K. The magnitudes of the standard deviations cited are estimates based on attempts to fit various straight lines to the experimental data.

III. DISCUSSION

The nature of the magnetization data for dysprosium particularly in the temperature range below 30°K might indicate ferromagnetism with two sublattices accounting for the decreasing saturation magnetization with decreasing temperature. On the other hand, it is also possible that a decrease in temperature could cause a change in the population of split 4f electron states of different magnetic moments.

The high magnetic moment of dysprosium is of considerable significance. Magnetic moments have been measured of the order of 245 cgs units. Such a magnetic moment corresponds to about 7 Bohr magnetons. The spectrographic state of the dysprosium ion is a $^6H_{15/2}$, and from the paramagnetic theory of Hund and Van Vleck, one would expect an absolute saturation moment of 10 Bohr magnetons. These data indicate that the absolute saturation moment of dysprosium is probably not this large, which may be interpreted as meaning that the 4f electrons are not completely free from the influence of neighboring atoms. On the other hand, the measured values of the magnetic moment are much larger than the 5 Bohr magnetons expected on the basis of spin only.

While the above data suggest interesting modifications in the present theories of magnetism, we feel more data must be obtained before an attempt is made in this direction. We are therefore leaving the interpretation of the data for later papers.

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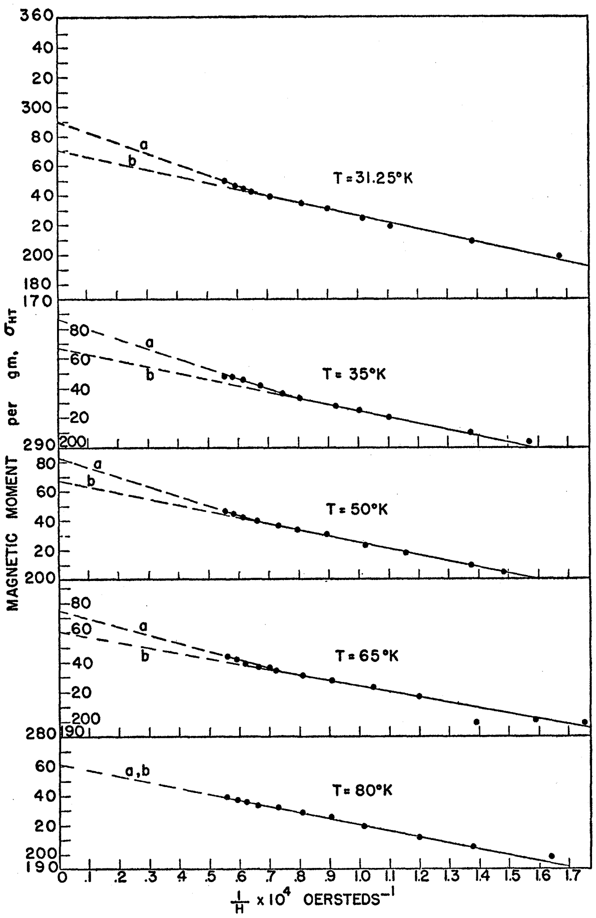

FIG. 5. Representative curves of the isothermal variation of the magnetic moment of dysprosium with $1/H$ in the temperature range 31° to 80°K.

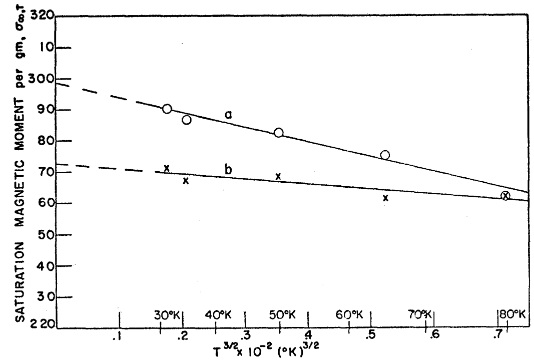

FIG. 6. The saturation magnetic moment of dysprosium as a function of $T^{3/2}$, open circles are values obtained from high field extrapolations and crosses are values obtained from low field extrapolations.