# Magnetic Properties of Terbium Metal*

W. C. THOBURN,† S. LEGVOLD, AND F. H. SPEDDING
*Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa*
(Received June 2, 1958)

Results of magnetic measurements on metallic terbium over the temperature range from 4° to 375°K and in fields ranging from 50 oersteds to 18 000 oersteds are reported. The metal is found to have a paramagnetic Curie point of 237°K. Tests with fields of from 50 to 800 oe indicate an order-to-disorder transition at approximately 230°K which is evidently a Néel point. It appears that terbium has a weakly bound antiferromagnetic ordering for temperatures between 218° and 230°K, this ordering being gradually changed to ferromagnetic in fields exceeding 200 oe. Below 218°K the metal is ferromagnetic. The magneton numbers obtained from the paramagnetic susceptibility measurements and from the extrapolated ferromagnetic saturation moment are in good agreement with values calculated for the free ion.

## I. INTRODUCTION

TERBIUM, atomic number 65, is one of the rare-earth elements and has eight electrons in the $4f$ shell. The magnetic properties of this element have been measured previously by Klemm and Bommer.[1] They reported that their sample obeyed the Curie-Weiss law $\chi_{at}=10.1/(T\text{-}205)$ and that the room-temperature atomic susceptibility was $115\times10^{-3}$. Spedding *et al.*[2] have reported results of magnetic measurements on a pure sample and indicate that terbium is ferromagnetic below 230°K. Leipfinger[3] has examined the metal at very low temperatures and found that the magnetic moment is nearly independent of temperature for the range below 80°K and for fields less than 3 kilo-oersteds.

Specific-heat studies by Jennings *et al.*[4] reveal two anomalies in the heat-capacity curve of terbium, plotted as a function of temperature. These are a "bump" at about 221°K and a sharp peak at 227.7°K. The sharp peak is not far from the Néel point found in the magnetic moment determinations on a pure sample reported in this paper.

The terbium was prepared in a manner described previously.[5,6] Chemical analysis for carbon and nitrogen, and spectrographic examination for metallic impurities gave the following results and estimates in ppm: carbon 438, nitrogen 170, Ce, Pr, Nd, Er, Tm less than 5000, Sm less than 3000, Dy, Ta less than 2000, Gd less than 1000, Ca less than 250, Sc less than 200, La, Eu, Tb, Y, Mg, Cu, Fe, Si less than 50.

As indicated, the spectrographic estimates are only upper limits. Spectrographic standards for quantitatively determining impurities at low concentrations in these elements are not yet available. It is quite probable that the total ferromagnetic impurity did not exceed 0.1%.

## II. METHOD OF MEASUREMENT

The experimental procedure is basically the same as that described by Elliott *et al.*[7] The apparatus was improved by the addition of a current control for the field magnet, by regrinding the pole pieces to provide a more uniform field gradient and by providing a centering device for the sample. The last consisted of a mechanism which caused slow transverse oscillations of the sample holder in the field during weighing and was used whenever significant lateral forces made it necessary to overcome the effects of friction.

Two sample sizes were used. The ferromagnetic range was covered with a sample 1 mm square×10 mm long. For paramagnetic and low-field measurements a larger cylindrical sample, 2.4 mm in diameter by 10.6 mm long was used.

## III. RESULTS

The values of the magnetic moment $\sigma$ expressed in ergs per oe per g are shown as a function of the effective field in Fig. 1 and as a function of temperature for various fields ranging from 1 to 18 koe in Fig. 2. At the right in Fig. 2 is shown the plot of $1/\chi$ *vs* $T$ for the paramagnetic region, $\chi$ being the mass susceptibility. From the intercept and the slope of this line, the paramagnetic Curie temperature $\theta_p$ and the intrinsic magnetic moment $\mu_A$ in Bohr magnetons per atom were determined.

By plotting the values of $\sigma$ at temperatures below 60°K against $1/H$ and extrapolating to $1/H=0$, the limiting values of $\sigma_{\infty,T}$ for various temperatures were obtained. These values of $\sigma_{\infty,T}$ were plotted against $T^{\frac{3}{2}}$ and extrapolated to $T^{\frac{3}{2}}=0$ to obtain $\sigma_{\infty,0}$ the saturation moment per gram. Thence the ferromagnetic moment per atom, $m_A$, in Bohr magnetons, was computed.

The results of these deductions from the data are as follows: $\theta_p=237\pm2$°K, $\mu_A=9.7$, $\sigma_{\infty,0}=322.4\pm2$ cgs units, $m_A=9.25$.

* Contribution No. 639. Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.
† Now at Forman Christian College, Lahore, Pakistan.
[1] W. Klemm and H. Bommer, Z. anorg. u. allgem. Chem. **231**, 138 (1937).
[2] Spedding, Legvold, Daane, and Jennings, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland Publishing Company, Amsterdam, 1957), Vol. II, p. 368.
[3] Hugo Leipfinger, Z. Physik **150**, 415 (1958).
[4] Jennings, Stanton, and Spedding, J. Chem. Phys. **27**, 909 (1957).
[5] F. H. Spedding *et al.*, J. Am. Chem. Soc. **69**, 2812 (1947).
[6] F. H. Spedding and A. H. Daane, J. Am. Chem. Soc. **74**, 2783 (1952).
[7] Elliott, Legvold, and Spedding, Phys. Rev. **91**, 28 (1953).

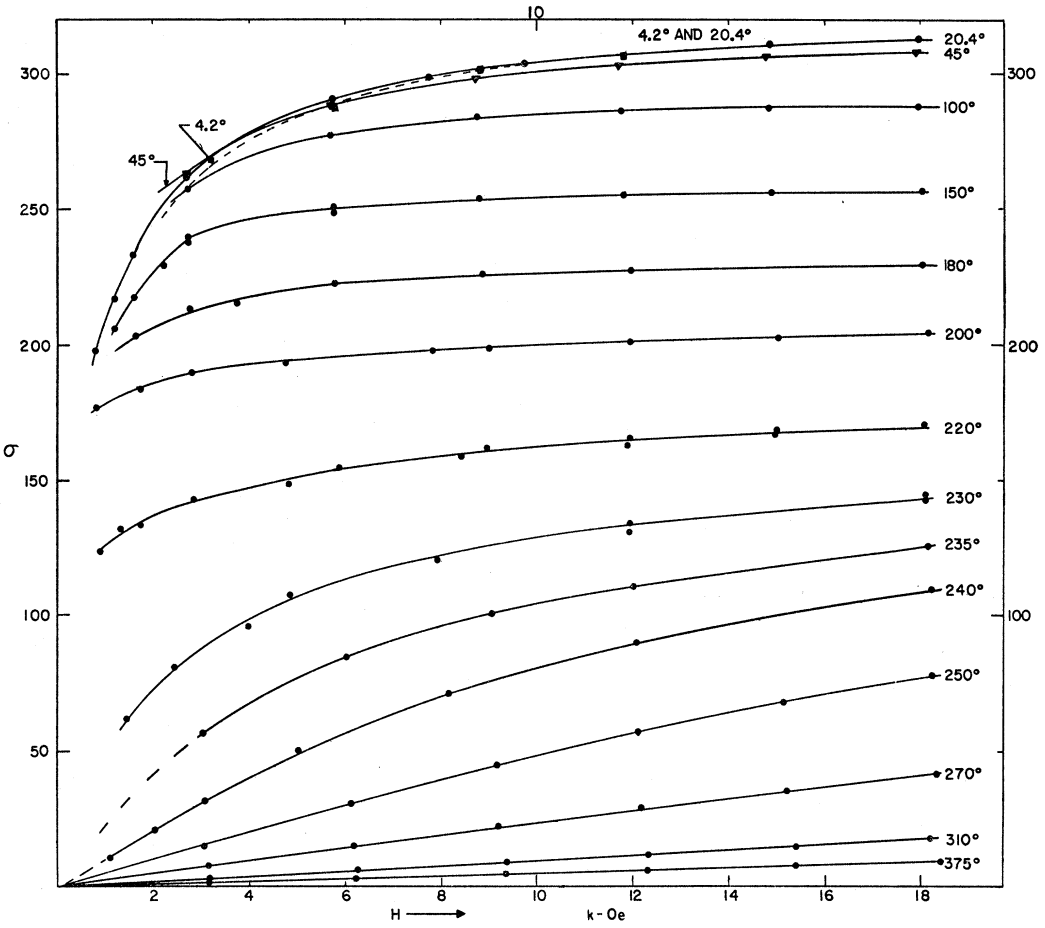


FIG. 1. Magnetization isotherms.

The theoretical values of the atomic moments were obtained from the relations $\mu_A = gJ(J+1)$ and $m_A = gJ$, where $g = \frac{3}{2}$ and $J = 6$ for terbium. These yielded values of $\mu_A = 9.72$ and $m_A = 9.0$. The experimental value of $\mu_A$ agrees very well with theory, but it must be remembered that the figure is uncertain by at least 1%, as indicated by the uncertainty of $\theta_p$ obtained from the same graph. The saturation moment $\sigma_{\infty,0}$ seems to be relatively more accurately known.

In view of the two anomalies present in the specific-heat curve[3] the larger sample of terbium was examined under weaker fields ranging from 50 to 800 oe in the region between 215° and 236°K. The results are shown in Fig. 3. As expected with a material as susceptible as terbium, the large demagnetization corrections applied to the data taken at the lowest fields tended to reduce the precision of the results, as did also the small forces observed. Nevertheless, the presence of an antiferromagnetic region ranging from roughly 218°K to the Néel point in the neighborhood of 230°K is clear enough. The curves indicate that the antiferromagnetic ordering is progressively overpowered by fields above 200 oe. The ferromagnetic-to-antiferromagnetic transition point is only estimated. Further observations will be required to determine more accurately the limits of this region of easily disturbed antiferromagnetism.

## IV. DISCUSSION

Somewhat in agreement with the finding of Leipfinger,[3] the present study shows little temperature dependence of the magnetization in the range below 80°K and for fields under 3 koe. However, the initial susceptibility as estimated from our results for this temperature region would be at least six times his value.

It is to be noted that in the case of both dysprosium and holmium[2] there is a minor peak in the heat-capacity curve corresponding to the magnetic order-order transition at the Curie point and a much greater peak at a higher temperature, corresponding to the magnetic order-disorder transition at the Néel point. These two transitions are not resolved with strong magnetic fields in the case of terbium. In the case of dysprosium, the element of next higher atomic number, the field required to overpower antiferromagnetic ordering is of the order of 11 koe. With holmium, the fields used hitherto are not sufficient to cause the disappearance of antiferromagnetism.

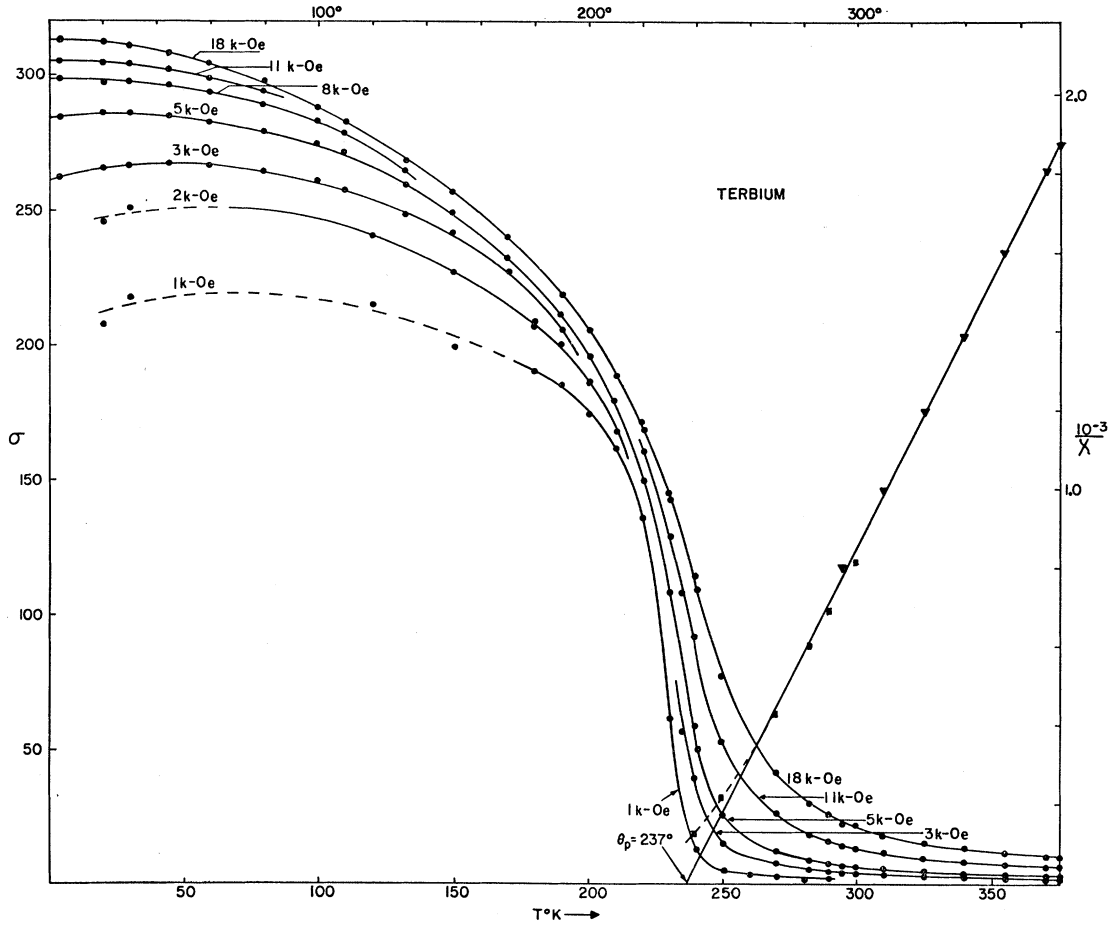


FIG. 2. Isofield curves $1/\chi$-*vs*-$T$ plot.

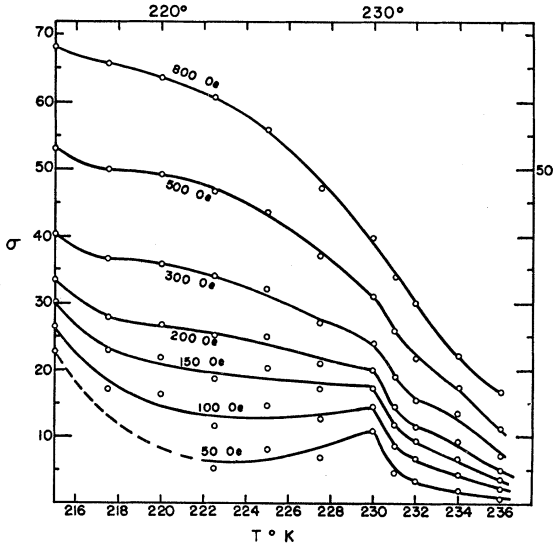


FIG. 3. Low-field curves between 218° and 236°K.

Further collateral evidence for the restricted antiferromagnetic region of terbium should be mentioned:

(a) Tests made by Jennings,[8] using a mutual inductance method in which the maximum applied field was not more than a few oe, indicate a magnetic susceptibility peak for terbium in the neighborhood of 228°K.

(b) Resistivity studies on a sample of pure terbium by Colvin[9] indicate two anomalies in the resistivity-*vs*-temperature curve at temperatures of approximately 219° and 230°. The anomaly at 219°, however, is not observable if the sample is subjected to a field of a few hundred oe.

## ACKNOWLEDGMENTS

The authors wish to thank the staff of the Ames Laboratory for the provision of the terbium and its examination for purity, and B. L. Rhodes for his work with the preliminary observations.

[8] L. D. Jennings, Iowa State College (private communication).
[9] C. B. Colvin, Iowa State College (private communication).