The Magnetic Susceptibility of Nd Metal*

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The magnetic susceptibility of neodymium metal has been measured over the temperature range of 20.4°K–300°K. The metal was found to obey a Curie-Weiss law above 145°K with a paramagnetic Curie point of −16°K and an effective moment of 3.68 Bohr magnetons. Near 145°K there appears to be a change in slope of the curve of $1/\chi$ *vs* T. From 145°K to 31.5°K the metal again obeys a Curie-Weiss law with a paramagnetic Curie point of about 1°K and an effective moment of 3.35 Bohr magnetons. The low-field susceptibility at 20.4°K is much larger than predicted by the low-temperature Curie-Weiss law, and the susceptibility has a definite field dependence.

I. INTRODUCTION

THE magnetic susceptibility of neodymium has been measured previously by Klemm and Bommer,[1] and by Trombe.[2] The measurements of Klemm and Bommer showed the metal to obey the Curie-Weiss law over the temperature range of 90°K–292°K, with an effective moment of 3.65 Bohr magnetons. Trombe's measurements over the temperature range of 77°K–297°K showed a discontinuity in slope of the plot of $1/\chi$ *vs* T in the neighborhood of 110°K. Above 110°K the effective moment was found to be 3.59 Bohr magnetons, and below 110°K the effective moment was 2.08 Bohr magnetons.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The metal used in this study was prepared by methods previously reported.[3,4] The spectrographic analysis of the metal showed it contained the following impurities: Ca, detectable but less than 400 parts per million (ppm); Mg, detectable but less than 200 ppm; Si, detectable but less than 200 ppm; Pr, not detected with limit of detection of 800 ppm; Fe, not detected with limit of detection of 50 ppm.

TABLE I. The magnetic susceptibility per gram of neodymium.

T°K	χ_g, $\times 10^6$	$1/\chi_g$, $\times 10^{-4}$
20.4	707.4	0.141
31.5	348.7	0.287
44.0	248.6	0.402
65.3	167.4	0.598
84.0	126.1	0.793
89.0	120.5	0.829
119.7	88.87	1.125
157.7	68.07	1.469
199.8	54.60	1.832
238.5	46.05	2.172
287.7	39.01	2.563
297.5	37.68	2.660

The susceptibility measurements were made using the Gouy method. The sample was 25.15 cm long, 0.434 cm in diameter, and weighed 25.627 grams.

The magnetic field was calibrated with a proton resonance flux meter for three different magnitudes of field strength: 4000, 7000, and 12 000 oersteds. Most of the data were taken in applied fields in the neighborhood of 12 000 oersteds. However, at 20.4°K, 83°K, and at room temperature, measurements were made at all three fields to investigate the field dependence of the susceptibility.

The cryogenic apparatus used in the measurements employed a temperature-controlled helium gas stream flowing past the sample and was the same as that used in previous work.[5] The temperature difference between the two ends of the sample was less than one degree for all measurements. The cryogenic apparatus was used throughout except at 20.4°K and at room temperature where the sample was immersed directly in a liquid bath.

Temperatures were measured with copper-constantan thermocouples calibrated against a platinum resistance thermometer which had been calibrated by the Bureau of Standards.

The susceptibility of neodymium in a field of about 12 000 oersteds at various temperatures is shown in Table I. Figure 1 is a plot of the inverse of the susceptibility from Table I as a function of the absolute temperature. The plot seems to consist of two straight lines intersecting at about 145°K. Of interest also is the fact that the susceptibility at 20.4°K is much larger than would be predicted from the behavior in the temperature range from 31.5°K to 145°K.

Above 145°K, the indicated effective moment is 3.68 Bohr magnetons, and the indicated paramagnetic Curie point is about −16°K. Below 145°K the indicated effective moment is 3.35 Bohr magnetons and the paramagnetic Curie point is about 1°K. The molar Curie constants for the two ranges are 1.695°K/mole

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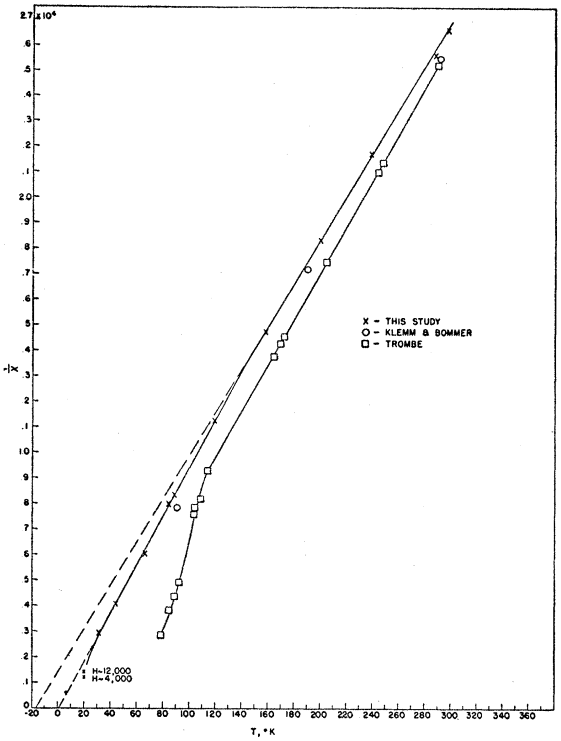

FIG. 1. The reciprocal of the magnetic susceptibility of neodymium metal as a function of temperature. The field was 12 000 oersteds except for the 20.4°K points where two values at different fields are shown.

and 1.396°K/mole, respectively. The effective moment calculated by Van Vleck[6] for the trivalent neodymium ion in 3.68 Bohr magnetons. Our data have not been corrected for the diamagnetism of the core nor for the paramagnetism of the conduction electrons.

The susceptibility at room temperature and at 82°K was found to be slightly field-dependent, being about one percent higher in a field of 4000 oersteds than in a field of 12 000 oersteds. This difference we believe to be outside the experimental error which we believe did not exceed 0.5 percent. At 20.4°K, the susceptibility was found to have a marked field-dependence; the susceptibility decreased with increasing fields. The values of the susceptibility per gram at 20.4°K in fields of about 4000, 7000, and 12 000 oersteds were $(793.3 \pm 1.5)\times 10^{-6}$, $(746.9\pm 0.3)\times 10^{-6}$, and $(707.4\pm 0.7)\times 10^{-6}$, respectively.

It appears from the data at 20.4°K that the weak-field susceptibility does not follow the Curie-Weiss law which apparently holds immediately above 30°K. In seeking an explanation for this anomalous temperature dependence of the weak-field susceptibility, it should be noted that there is an observed specific-heat anomaly[7] near 20.4°K, to which the magnetic behavior may be related. This specific heat anomaly has been described as conceivably arising from the crystal field splitting of the $4f$ electron energy states with a consequent redistribution of electrons among the split levels as the temperature is changed. In order to have a magnetic anomaly at temperatures where such transitions occur, it is only necessary to make the plausible assumption that the different states have different magnetic moments.

The field dependence of the susceptibility at 20.4°K is such as to indicate an approach to saturation, the susceptibility decreasing in increasing fields. This may conceivably be attributed to the expected field dependence of the susceptibility at low temperatures predicted by the complete Brillouin function, including possibly an internal field corresponding to $\theta = 1$°K and including the split states described above in the discussion of the temperature dependence of the weak-field susceptibility.

The electrical resistivity[8] and the Hall effect[9] of neodymium also indicate that the metal has some anomalous properties near hydrogen temperatures. The latter particularly indicates that the magnetic moment of the metal is increasing rapidly near this temperature.

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