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Ferromagnetic–Paramagnetic Transition in Iron

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Magnetization per gram of an iron sphere σ as a function of temperature T has been studied between the ferromagnetic Curie temperature T_{FC} and $T_{FC}+30°K$ with applied magnetic fields between 180 and 1360 Oe. The temperature T_{FC}, appearing as an abrupt decrease in the σ vs T curves, occurs at $1044\pm2°K$. Mass magnetic susceptibility of iron, above the ferromagnetic Curie temperature in small magnetic fields, is proportional to $(T-T_{FC})^{-4/3}$, which is the theoretical prediction for a Heisenberg three-dimensional ferromagnet.

INTRODUCTION

IT is well known from the results of neutron diffraction studies in ferromagnetic materials[1–4] that the transition from ferromagnetism to paramagnetism occurs over a temperature range. At temperatures above the ferromagnetic Curie point a short-range magnetic ordering exists which is describable by magnetic moment clusters. The nature of this transition also shows up in the magnetic susceptibility above the ferromagnetic Curie temperature T_{FC} as a deviation from the Curie–Weiss law. This deviation leads empirically to the concept of the paramagnetic Curie temperature T_{PC}. The experimental studies of the magnetic behavior of various ferromagnets between the temperature T_{FC} and T_{PC} are quite scarce. Because of recent advances[5,6] in the theory of the paramagnetic susceptibility of ferromagnetics above T_{FC}, detailed temperature variation of the magnetization expecially in this range is of importance for comparing the theories with the observations. Except for some quite old measurements,[7,8] the only information of this kind, of the requisite accuracy, is that reported by Noakes and Arrott.[9] The purpose of this paper is to present new magnetic moment measurements on high-purity iron between T_{FC} and $T_{FC}+30°K$. It is believed that these data, which supplement those of Noakes and Arrott, are useful for the comparison with the theoretical predictions.

EXPERIMENTAL CONSIDERATIONS

The magnetic moments as a function of temperature were determined using the apparatus based on the Faraday technique described elsewhere.[10,11] In order to account correctly for the demagnetizing field of the sample, an iron sphere, of diameter 0.1587 cm, was used as specimen. For a sphere the magnetic field inside the material is given by the equation

$$H_i=H_a-(4\pi/3)M=H_a-(4\pi/3)\rho\sigma, \qquad (1)$$

where H_a is the applied magnetic field, M and σ the magnetization per unit volume and mass, respectively, and ρ the density. The factor $4\pi/3$ is the demagnetizing factor for a sphere placed in an initially uniform magnetic field. Knowing H_i, the mass magnetic susceptibility above the temperature T_{FC} can be calculated from

$$\chi=\sigma/H_i. \qquad (2)$$

In the ferromagnetic region Eq. (1) also, of course, is applicable to a spherical sample. For a soft magnetic

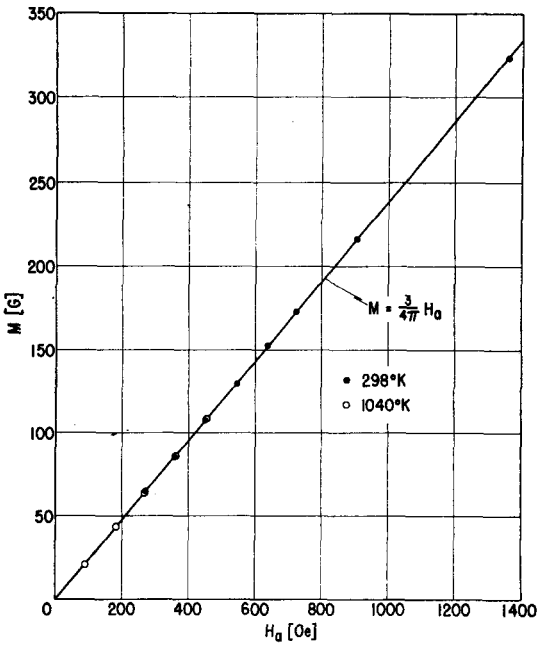

FIG. 1. Magnetization of a ferromagnetic iron sphere as a function of applied magnetic field.

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TABLE I. Impurities in iron. Al and elements with atomic numbers less than 10 are not given. Other elements not listed would have been detected if present at level of 1–3 ppm or more.

Spectrographic analysis	
Ca	200 ppm
Ni	70
Ti	70
Mg	40
P	40
S	40
Cu	20
Ge	20
Co	10
Cr	10
Si	<10
As	4
Zn	2
Ga	1
Rb	0.7
Rh	0.4
V	0.4
Chemical analysis	
C	17
O_2	30
N_2	5

material such as iron, the demagnetizing field $4\pi M/3$ is of the order of 10^3 Oe for values of H_i of about 1 Oe. Thus, for applied magnetic fields $H_a \gg H_i$,

$$M \cong (3/4\pi)H_a, \tag{3}$$

i.e., the magnetization per unit volume of the sample is proportional to the applied magnetic field. This relationship extends up to the ferromagnetic Curie temperature for H_a of the order of 10^2 Oe. Hence by measuring magnetization in moderate applied magnetic fields as a function of temperature, one can accurately determine ferromagnetic Curie temperatures of ferromagnetic materials. This approach was originally suggested and applied to iron and some dilute iron alloys by Arrott.[12] The only difference between his and our method is the mode of the moment measurements. Arrott employs completely uniform magnetic fields using an induction technique based on an electronic integration for the determination of magnetic moments. We are, however, using a conventional force technique with a small field gradient of about 20 Oe·cm^{-1} imposed on a uniform magnetic field. Although this technique is not as elegant as the induction method, it possesses certain advantages over the former method. This technique allows us to determine directly the mass magnetization instead of volume magnetization. Furthermore, the force method is easier to adapt to high-temperature studies, for example, on cobalt and its alloys. The quality of our force technique for determining the magnetization is demonstrated in Fig. 1 which shows the measured values of M as a function of H_a. The solid line is the expected behavior according to Eq. (3). It can be seen that the experimentally determined magnetizations of a ferromagnetic iron sphere at 298° and 1040°K are in good agreement with Eq. (3). The moments M at these temperatures were obtained from the measured mass magnetization σ using 7.874 and 7.617 g·cm^{-3} as the densities of iron at 298° and 1040°K, respectively. The density ρ of iron as a function of temperature was calculated from the lattice parameters measured by Basinski *et al.*[13] by assuming $A = 55.85$ and $N_A = 6.025 \times 10^{23}$ mole^{-1}, A and N_A being the atomic weight and the Avogadro number, respectively.

The iron sphere whose magnetic properties were studied in this investigation was fabricated from Plastiron A104 purified by a floating-zone technique with 10 passes. The results of impurity analysis on this iron are summarized in Table I. The electrical resistivity ratio $\rho(4.2°K)/\rho(298°K)$ was 6.68×10^{-3} at an electrical current density about 15 A·cm^{-2}.

The iron sphere was sealed in a silica capsule evacuated to 10^{-5} Torr. The diamagnetism of the capsule was taken into account when calculating the magnetizations of iron from the observed force measurements.

RESULTS AND DISCUSSION

The mass magnetization of iron as a function of temperature at various applied fields is shown in Fig. 2. In the ferromagnetic region the quantity σ for a particular H_a value is independent of temperature as expected from Eq. (3). This behavior exists practically up to the ferromagnetic Curie temperature at which the magnetization, measured in a constant applied magnetic field, abruptly decreases. The breaks in the σ vs T curves, associated with H_a values of 181, 272, 362, and 453 Oe, occur at the same temperature, namely,

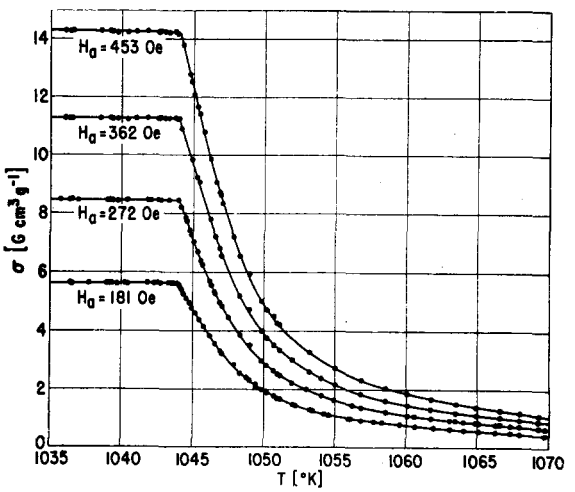

FIG. 2. Magnetization of iron in various applied magnetic fields in the neighborhood of the ferromagnetic Curie temperature.

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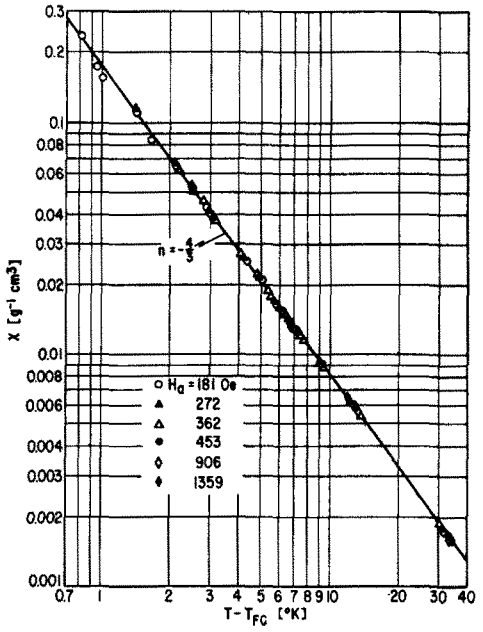

FIG. 3. Temperature dependence of the magnetic susceptiblity of iron above the ferromagnetic Curie temperature.

1044.1°K. This temperature is taken to be the ferromagnetic Curie point of iron. Since the platinum–platinum with 10% rhodium thermocouple, calibrated at the melting points of tin and gold, was not directly attached to the sample, it is felt that the absolute value of the Curie point should be reported as 1044 ± 2°K. This value is in very good agreement with electrical resistivity results[14] obtained on iron of practically identical purity. The commonly accepted[15] value for the ferromagnetic Curie point of iron is 1043°K.

The curves of σ vs T shown in Fig. 2 are independent of the direction and rate of temperature changes.

Figure 3 presents the mass magnetic susceptibility as a function of $T-T_{FC}$, calculated from Eq. (2). The demagnetizing field corrections were obtained from the measured values of σ and the density. Since we are primarily interested in the temperature dependence of the magnetic susceptibility at low magnetic fields, the plot shown in Fig. 3 does not include the higher field susceptibilities for the low $T-T_{FC}$ values. The solid straight line in Fig. 3 represents the relationship

$$\chi=K(T-T_{FC})^n, \tag{4}$$

where K is a constant and $n=-\frac{4}{3}$. It can be seen that the experimentally determined susceptibilities are in good agreement with Eq. (4). Essentially the same conclusion has been obtained by Noakes and Arrott[9] who find $n=-1.37\pm0.04$ in the temperature range $T-T_{FC}\leq10$°K. Their studies, made with applied magnetic fields from 25 to 100 Oe, also have clearly established that they have been measuring the true initial susceptibility. The quantity $n=-\frac{4}{3}$ is the theoretically expected result for a three-dimensional Heisenberg ferromagnet in the limit of zero magnetic field.[5,6] This observation is very interesting because according to some recent theoretical studies, the validity of the Heisenberg model of ferromagnetism for iron has been questioned.[16] Experimental studies, similar to those done on iron, are being extended to other ferromagnetic elements such as cobalt, nickel, and gadolinium.

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