Paramagnetic Behavior of Nickel just Above the Ferromagnetic Curie Temperature

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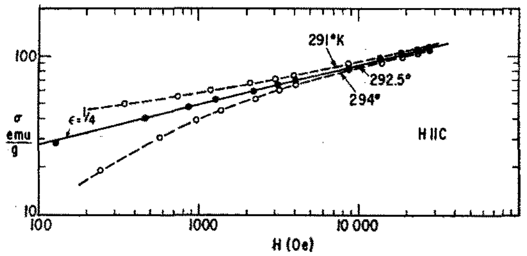

FIG. 3. Magnetization curves near $T=T_c$, $H \parallel \langle 0001 \rangle$. ϵ=slope.

tion curves for Gd near T_c for fields between 4.5 and 9 kOe, and have extrapolated these back to $H=0$ to suggest a nonzero spontaneous magnetization above T_c. In the present work, the magnetization curves showed curvature at all fields up to 29 kOe and at all temperatures up to 350°K; there was no obvious way to extrapolate to $H=0$ and no reason to suspect any spontaneous magnetization above T_c.

A recent Russian paper[7] reports a number of remarkable effects in a Gd crystal above T_c: kinks in the magnetization curves at 3 kOe from 20° to 100°C; *linear* magnetization curves above and below the 3-kOe kink, even at T_c; and paramagnetic anisotropy *increasing* with temperature, and with the $\langle 0001 \rangle$ axis the *hard* direction. None of these findings were confirmed here or in Ref. 4.

The intercepts on the H/σ axis of Fig. 1 give values of the reciprocal initial susceptibility $1/\chi_0=(H/\sigma)_0$. Various recent theoretical treatments suggest $1/\chi_0=A(T-T_c)^\gamma$, with $\gamma=\frac{4}{3}$ for the Heisenberg ferromagnet.[8] Figure 2 shows that the data for Gd fit this relationship reasonably well up to about $T_c+20°$. Similar values for γ have been reported for Fe[9,10] and for Ni,[8,11] but a somewhat lower value has been found for Co.[11]

Molecular field theory predicts $\sigma=CH^{\frac{1}{3}}$ at T_c. Kouvel and Fisher[8] show that the data of Weiss and Forrer for Ni obey $\sigma=CH^{0.24}$, although there is no strong theoretical foundation for such a relationship. Figure 3 indicates that $\sigma=CH^{\frac{1}{4}}$ for Gd at T_c, and also shows the rapid departure from this behavior as the temperature departs from T_c.

J. S. Kouvel contributed greatly to the interpretation of the results. The work was supported in part by the Air Force Materials Laboratory, Research and Technology Division, USAF.

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Paramagnetic Behavior of Nickel just Above the Ferromagnetic Curie Temperature

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Magnetic susceptibility of two nickel spheres of different purity has been studied between T_F and T_F+ 12°K, T_F being the ferromagnetic Curie temperature. The susceptibility is proportional to $(T-T_F)^n$ with the average value of $n=-1.29\pm0.03$. This result is slightly lower than that ($n=-1.33$) recently predicted theoretically for a three-dimensional Heisenberg ferromagnet.

RECENTLY the magnetic susceptibilities of iron[1,2] and cobalt[3] have been studied just above the ferromagnetic Curie temperature T_F. These studies were stimulated by recent theoretical advances[4–6] in the study of the magnetic behavior of Heisenberg ferromagnets below and above the ferromagnetic Curie point. According to these investigations the magnetic susceptibility χ above the Curie point can be expressed by the equation

$$\chi=A(T-T_F)^n, \tag{1}$$

where $n=-1.33$, A is a constant, and T is the absolute temperature. Noakes and Arrott[1] found experimentally that for iron $n=-1.37\pm0.04$ for temperatures between T_F and T_F+10°K. Our measurements on iron gave $n=-1.33$ in the temperature interval T_F to T_F+30°K. Thus, iron appears to obey the expected theoretical relationship derived for a three-dimensional Heisenberg ferromagnet. On the other hand, the magnetic susceptibility of cobalt[3] between T_F and T_F+13°K satisfies Eq. (1) with $n=-1.21\pm0.04$. Since the nature of magnetism in iron could be different from that in cobalt and nickel, it was felt that the above-mentioned experimental studies should also be extended to nickel. In this paper we briefly describe the results of such an investigation.

Two nickel spheres designated by A (diameter 0.4750 cm) and B (diameter 0.3180 cm) were used in this study. The sphere A was produced from an electrolytic nickel. Purified Johnson and Matthey nickel was used for making the sphere B. Details on the purity of these

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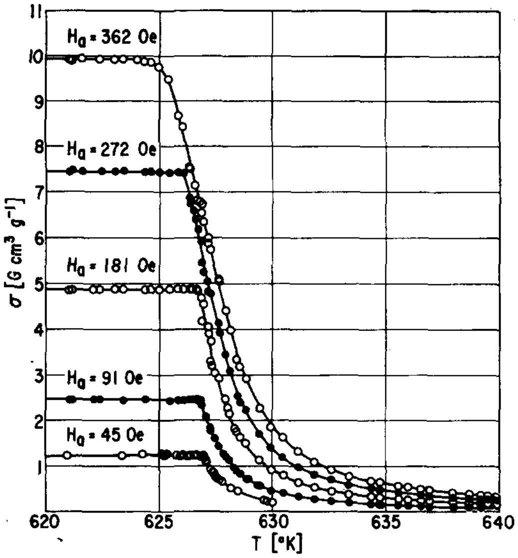

FIG. 1. Magnetization of nickel (sphere A) in various applied magnetic fields in the neighborhood of the ferromagnetic Curie temperature.

materials, which already have been used in some earlier studies,[7,8] can be found in Ref. 8. The magnetic moments of these spheres were determined by a force technique described elsewhere.[2]

The mass magnetization σ of the sphere A as a function of temperature in the neighborhood of T_F in the presence of various applied magnetic fields H_a is shown in Fig. 1. Similar results have also been obtained for the sphere B. It can be seen that the temperature T_F', defined as a temperature at which the σ vs T curve becomes temperature dependent, is a function of the applied magnetic field. This result was found also for cobalt but not for iron. Figure 2 shows T_F' as a function of the fields H_a. By extrapolating to $H_a=0$, we obtain 626.2° and 626.9°K as the ferromagnetic Curie temperature for the samples A and B, respectively. The difference in T_F between these samples is, very likely, due to impurities. In an absolute sense, for the same reasons explained elsewhere,[2] it is believed that the temperature T_F should be reported as 627±1°K which is somewhat lower than the "accepted" value 631°K.[9–10] A careful review of numerous earlier determinations reveals considerable variation in T_F. However, according to Kouvel's analysis[11] of the data by Weiss and Forrer,[12] using the Belov,[13] Arrott,[14] and Kouvel[11] technique, with extrapolation of the low magnetic field values, for the determination of the spontaneous magnetization, T_F is 627.6°K. Essentially the same result is also obtained by Arrott.[14] These latter results are in satisfactory agreement with our value.

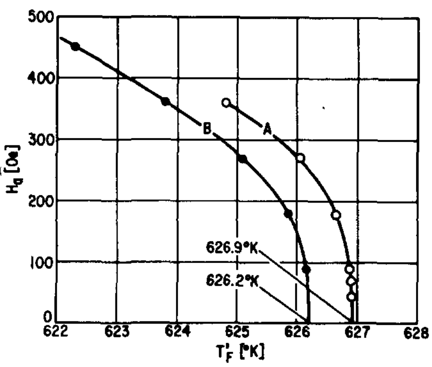

FIG. 2. T_F' as a function of applied magnetic field for the spheres A and B.

Figure 3 shows the determination of the quantity n

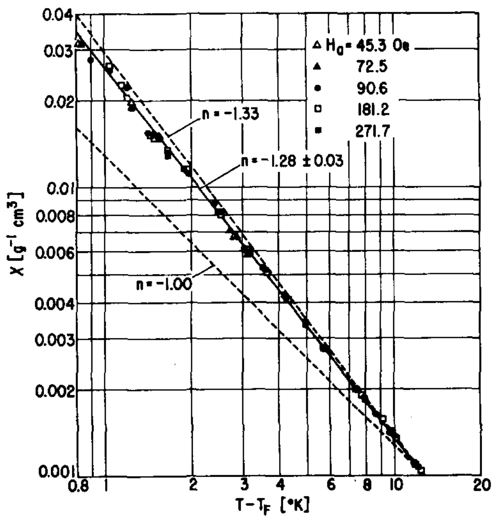

FIG. 3. Temperature dependence of the magnetic susceptibility of nickel (sphere A) above the ferromagnetic Curie temperature.

for the sphere A, for $T-T_F$ between about 1° and 12°K. We find $n=-1.28\pm0.03$. For the sphere B a similar plot gives $n=-1.30\pm0.03$. Thus, the experimental results on nickel indicate that the value of n is slightly lower than that expected theoretically for a three-dimensional Heisenberg ferromagnet with the nearest-neighbor interactions. For comparison, Fig. 3 also shows the behavior of the magnetic susceptibility resulting from mean molecular field[15,16] for which $n=-1.00$.

ACKNOWLEDGMENT

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