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APPLICABILITY OF SPIN WAVE THEORY TO FERROMAGNETIC METALS

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The temperature dependence of the saturation magnetization of iron and nickel is measured in the temperature interval from 1.5 to 5°K and in magnetic fields up to 22 kOe. It is shown that the variation of the spontaneous moment of these metals can not be explained within the framework of spin-wave theory. The discrepancy between the theoretical dependence and the experimental data can be decreased by introducing into the temperature-dependent part of the magnetic moment an additional term AT^2, which follows from a theory[1] that takes into account the presence of Fermi excitations in ferromagnetic metals.

In the course of an investigation of the saturation magnetization M_S of ferromagnetic metals in the helium temperature region[2], it was observed that the temperature dependence of the value of dM_S/dT is determined by the external magnetic field H. The dependence of dM_S/dT follows the Bloch $T^{3/2}$ law only in small external fields ($\lesssim$ 2 kOe). On increase of the field the value of $|dM_S/dT|$ decreases, changing with temperature according to a more rapid law. Qualitatively, such a behavior of the magnetic moment of a ferromagnet can be explained by the presence of a gap $\sim 2\mu_0 H$ (μ_0 is the Bohr magneton) in the energy spectrum of the spin waves[3]. In a quantitative comparison, however, it turned out that the magnetic moment changes with field, apparently, according to a more gradual law than was to be expected from spin-wave theory. For comparison with theory, obviously, the results of greatest interest are those obtained in the region of highest possible magnetic fields. We have therefore continued the measurement of the saturation magnetization of iron and nickel, extending the field range from 10 to 22 kOe.

The method of measurement used was quite similar to that described in[2]. In the course of the experiment a direct measurement of the value of $dM/dT \equiv M'$ was performed. The samples studied were a polycrystalline specimen of iron and a single crystal of nickel, whose axis of easiest magnetization was directed along the specimen.

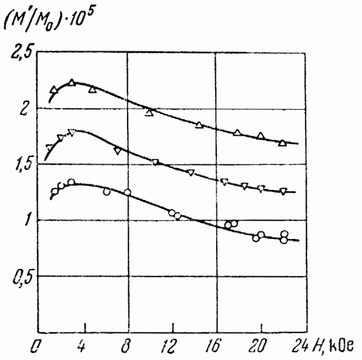

FIG. 1. Dependence of M'/M_0 on magnetic field for nickel: ○, at 2°K; ▽, at 3.3° K; △, at 5°K.

RESULTS AND DISCUSSIONS

Results of the measurement of the variation of M'/M_0 with H, for the nickel and iron specimens at various temperatures, are shown in Figs. 1 and 2. The change of the value of M'/M_0 with external magnetic field in the field range below 3 kOe for nickel and below 1 kOe for iron is determined by the dependence of the anisotropy constant on temperature[2]. The decrease of $|M'|/M_0$ in the

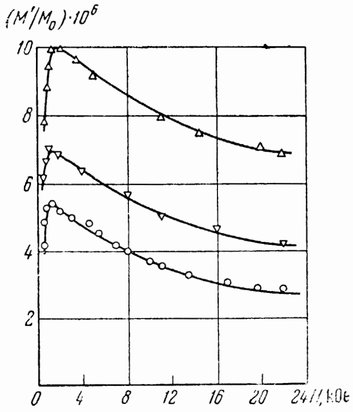

FIG. 2. Dependence of M'/M_0 on magnetic field for iron: ○, at 2°K; ▽, at 3°K; △, at 5°K.

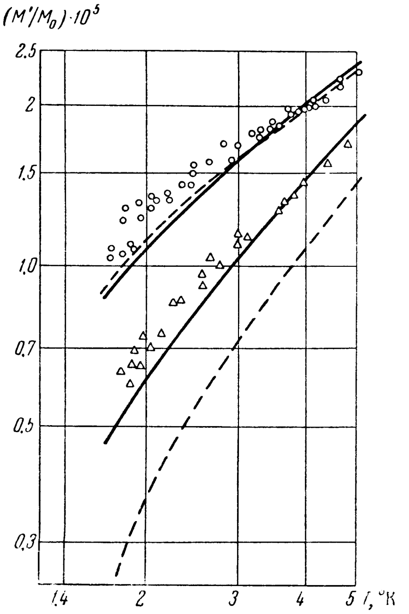

FIG. 3. Dependence of $|M'_s/M_0|$ on temperature for nickel. Experimental values in fields 3.0 kOe (○) and 22 kOe (△). The theoretical dependences are shown by the curves: dashed, according to relation (1); solid, according to relation (2).

region of large magnetic fields is evidently connected with the change of the value of $|M'_s|$ itself in the field. Hereafter we shall consider only results obtained in the region of large fields. Figures 3 and 4 show the dependence of $|M'_s/M_0|$ on temperature for nickel and iron respectively. The relative change of the value of M' with H is shown in Figs. 5 and 6.

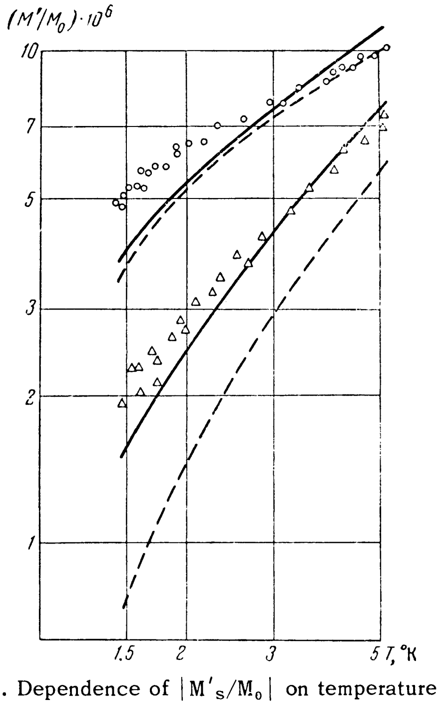

FIG. 4. Dependence of $|M'_s/M_0|$ on temperature for iron. Experimental values in fields 2 kOe (○) and 22 kOe (△). The theoretical dependences are shown by the curves: dashed, according to relation (1); solid, according to relation (2).

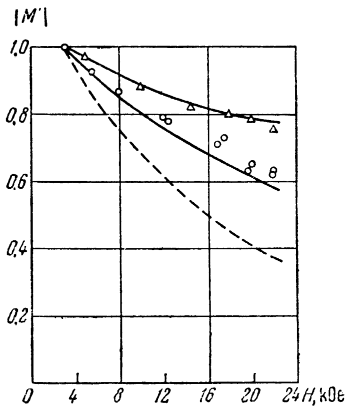

FIG. 5. Dependence of $|M'_s|$ on magnetic field for nickel, in relative units: ○, at 2°K; △, at 5°K. The theoretical dependences are shown by the dashed curve according to relation (1) at 2°K, and by the solid curve according to relation (2) at 2 and 5°K. The values of $|M'_s|$ at H = 3 kOe are taken as unity.

We now consider to what degree our experimentally obtained dependences of M'/M_0 on T and on H can be explained from the point of view of spin-wave theory (cf., for example, [3]). At sufficiently low temperatures, as was shown in the Appendix to [4], the magnetic moment of a ferromagnet is

$$\frac{M_s(T)}{M_0} = 1 - CT^{3/2}\frac{J(\alpha,\beta)}{J(0)},$$

$$\left|\frac{M_s'}{M_0}\right| = \frac{dM_s}{dTM_0} = \frac{C}{J(0)}T^{1/2}\left[\frac{3}{2}J(\alpha,\beta) + T\frac{dJ(\alpha,\beta)}{dT}\right]. \tag{1}$$

Here $J(\alpha, \beta)$ is a double integral tabulated in [4];

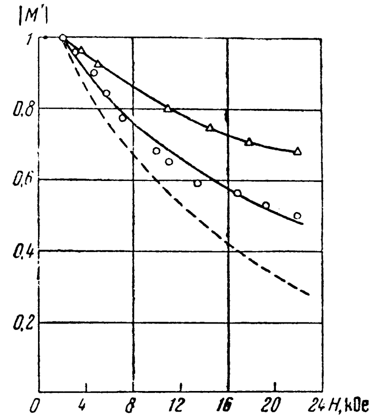

FIG. 6. Dependence of $|M'_s|$ on magnetic field for iron, in relative units: ○, at 2°K; △, at 5°K. The theoretical dependences are shown by the dashed curve according to relation (1) at 2°K, and by the solid curve according to relation (2) at 2 and 5°K. The values of $|M'_s|$ at H = 2 kOe are taken as unity.

M_0 is the saturation magnetic moment, equal for nickel [5] and for iron to 510 and 1750 cgs emu respectively; $\alpha = \mu H_i/T$, $\beta = 2\pi M_0/H_i$, $H_i = H + H_a$, where H is the external magnetic field and H_a is the effective anisotropy field, amounting for nickel and for iron to 2 kOe [6] and to 0.25 kOe respectively; $\mu = 2\mu_0$.

The calculated dependences of M_s'/M_0 on H and on T, according to relation (1), are shown by the dashed curves in Figs. 3-6; it is clear that in both the metals studied, the value of $|M_s'/M_0|$ changes in an external field more slowly than is predicted by spin-wave theory. Thus the variation of the magnetic moment of ferromagnetic metals in the low-temperature region cannot be completely explained from the point of view of spin-wave theory—which, as was shown earlier [4], explained excellently the properties of ferromagnetic dielectrics.

In contrast to ferrodielectrics, the carriers of the elementary magnetic moments of a ferromagnetic metal possess a certain mobility. In this case, as was shown by Kondratenko [1], Fermi excitations exist in the ferromagnet besides the Bose excitations—"spin waves." It is possible that the discrepancy between the deductions of spin-wave theory and the experimental data is also connected with a manifestation of these Fermi excitations.

When account is taken of the contribution of Fermi excitations, the magnetic moment of a ferromagnetic metal depends on temperature [1] thus:

$$\frac{M_s}{M_0} = 1 - CT^{3/2}\frac{J(\alpha,\beta)}{J(0)} - AT^2$$

$$\left|\frac{M_s'}{M_0}\right| = \left|\frac{dM_s}{M_0 dT}\right| = CT^{1/2}\frac{1}{J(0)}\left[\frac{3}{2}J(\alpha,\beta) + T\frac{dJ(\alpha,\beta)}{dT}\right] + 2AT, \qquad (2)$$

where the constant A depends in a complicated manner on details of the Fermi surface of the magnetic d-electrons. We shall compare the relation (2) with our experimentally obtained results, regarding C and A as parameters to be determined. It turned out that agreement of results calculated by relation (2) with the experimental data occurs in the case of nickel with $C = 7.4 \times 10^{-6}$, $A = 9.5 \times 10^{-7}$, and for iron with $C = 3.6 \times 10^{-6}$ and $A = 3.2 \times 10^{-7}$. The results of the calculation of $|M_s'/M_0|$ for these values of the parameters C and A are shown in Figs. 3 to 6 by the solid lines. If the values of C and of A are changed by ±15% and by ±30% respectively, the deviation of the theoretical curves from the experimental data does not increase appreciably. In view of the fact that the error in the determination of the absolute value of M′ may amount in our experiments to 10% [2], the possible error in the values of C and of A given above amounts to about 25% and 40% respectively.

As is evident from Figs. 3 to 6, introduction into the relation (1) of an additional term, which follows from a theory that takes account of the existence of Fermi excitations, made possible an appreciable diminution of the discrepancy between the theoretical dependence and the experimental data. The results of our work, however, do not yet permit an unambiguous confirmation that the deviation from the Bloch $T^{3/2}$ law is actually due to a manifestation of these excitations in ferromagnetic metals. For final clarification of this question, it is necessary to carry out additional measurements, above all in the region of such large magnetic fields that the contribution of Bose excitations to the temperature-dependent part of the magnetic moment would be practically suppressed by the field.

We shall compare the results obtained with measurements of the spontaneous moment in the region of higher temperatures. The most detailed measurements of the dependence $\Delta M(T) = M(T) - M_0$ for iron and nickel, in the temperature interval from about 10 to 70 or 100°K, were made in [7,8]. The experimental results of these researches differ somewhat. The value of $\Delta M(T)$ calculated by relation (2), with the values of the constants C and A given in the text, agrees with the data of the research [8] and exceeds the data [7].

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20