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INVESTIGATION OF THE MAGNETIZATION OF IRON, COBALT, AND NICKEL AT LOW TEMPERATURES

V. E. RODE and R. HERRMANN

Moscow State University

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A study was made of the temperature dependences of the saturation magnetization of polycrystalline iron, nickel and cobalt in fields up to 20 kOe in the temperature range 4.2—70° K, and the exchange parameters were determined. The intensity of the field used made it possible to ignore the influence of the anisotropy on the temperature dependence of the saturation magnetization. The accuracy of the method enabled the authors to investigate the deviation of the saturation magnetization of nickel from the $T^{3/2}$ law and to show that the saturation magnetization of nickel could be described by Eq. (3).

THE investigation of the temperature dependence of the saturation magnetization of ferromagnets is of interest as the means of obtaining information on the exchange interaction which is responsible for the existence of the ferromagnetic state.

The total magnetic moment of a ferromagnet can at present be measured to within 0.1%. However, it is much more convenient to measure not the total magnetic moment but the variation of the moment with temperature in order to determine more accurately the law describing the behavior of the magnetization at low temperatures.

At present, two methods are used to determine the temperature dependence of the saturation magnetization. Either the change of the magnetic moment on cooling from any temperature to that of liquid helium is determined directly by a ballistic method[1-3], or the oscillations of the magnetic moment due to low-frequency oscillations of the sample temperature about a fixed temperature are studied.

The latter method was used by Zavaritskiĭ and Tsarev to measure the field dependence of $\Delta I/\Delta T$ of polycrystalline nickel and iron at temperatures of 1.4—5° K in fields up to 10 kOe.[4] Pugh and Argyle[2] investigated single-crystal nickel at temperatures of 4.2—100° K in fields up to 12 kOe. The results are listed in Table I.

In our measurements, a sample with a heater wound on it was placed in a vacuum tube whose open end was immersed in helium. The upper end of the tube was closed with a valve. The sample was placed in the uniform region of an external magnetic field. On connecting the heater, helium evaporated (with the valve closed) and gaseous helium displaced liquid helium through the lower open end. The sample was thus heated and its temperature measured. Then the valve was opened and liquid helium filled the tube, cooling the sample to 4.2° K. The change in the magnetic flux on cooling the sample was measured by an induction method using an integrator of sensitivity up to 2.5×10^{-4} G/division. The apparatus and the method of measurement were described in detail, together with an analysis of the accuracy and sensitivity, in a recent paper of the present authors.[1] In this paper, it was shown that the method used made it possible to determine the change of the magnetization ΔI to within 3%, which corresponded to measuring I of nickel to within 0.006%, and hence the accuracy in determining the exchange integral was 1%.

The accuracy of measuring the temperature in the 4.2—10° K range was 0.4 deg K; above 10° K, the accuracy was of the order of 0.1 deg K.

In our measurements, we used cylindrical polycrystalline samples. All the samples were annealed for three hours at 900° C and then slowly cooled.

Since the anisotropy constant of pure ferromagnetic metals increased on approach to 0° K, it was

Table I

Sample	$c\cdot 10^6$	A, erg	Temperature range, °K	H, kOe
Fe	4.5±0.1	$(1.59\pm0.5)\cdot10^{-14}$	4.2—70	20
Co	2.4±0.1	$(2.92\pm0.05)\cdot10^{-14}$	11—70	20
Ni	9.3±0.25	$(2.3\pm0.04)\cdot10^{-14}$	4.2—70	20
Ni [2]	9.65±0.25		4.2—120	12
Fe [3]	3.7±0.37		1.4—5	up to 10
Ni [3]	10±1.0		1.4—5	up to 10

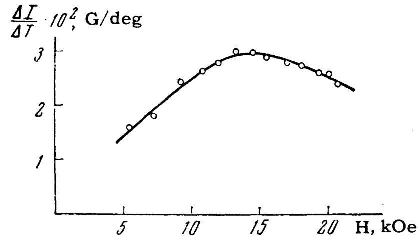

FIG. 1. Field dependence of $\Delta I/\Delta T$ of iron for temperatures varying from 4.2 to 13.3°K.

necessary to carry out the measurements in sufficiently strong fields. To estimate the contribution to the change of the magnetization ΔI due to the change of the anisotropy constant when the temperature was altered by ΔT, we measured the dependence of $\Delta I/\Delta T$ on the external magnetic field.

Figure 1 gives the field dependence of $\Delta I/\Delta T$ for iron. Above 15 kOe, $\Delta I/\Delta T$ falls, which corresponds to a very small contribution to ΔI of the change of the anisotropy constant.[4,5] Analysis of similar curves for nickel and cobalt shows that correct measurements of ΔI as a function of ΔT may be obtained in fields stronger than 16 and 18 kOe, respectively.[6] The results of the measurements of $\Delta I(T)$ at 20 kOe are given in Table II.

Table II

Fe		Co *		Fe		Co *	
T, °K	ΔI, G	T, °K	ΔI, G	T, °K	ΔI, G	T, °K	ΔI, G
4.2	0	11.0	0	25.0	0.90	30.3	0.40
5.4	0.05	14.4	0.06	27.6	1.05	32.7	0.46
7.1	0.08	15.9	0.09	30.4	1.24	35.0	0.55
9.0	0.15	17.0	0.11	34.9	1.53	40.0	0.68
10.0	0.19	18.0	0.14	40.0	1.84	44.8	0.86
12.0	0.27	19.1	0.16	44.8	2.22	49.1	1.00
13.3	0.33	20.1	0.17	49.1	2.58	53.5	1.17
15.9	0.44	21.8	0.20	53.4	2.95	61.0	1.45
18.0	0.54	23.5	0.25	61.0	3.50	68.2	1.73
21.8	0.75	27.6	0.32			74.8	2.0

*Values of ΔI of Co are given with ΔI at 11°K subtracted from them.

Analysis of the results obtained shows that Bloch's law is satisfied by iron, nickel and cobalt in the temperature range given in Table I. From these data, we calculated the values of c in Bloch's law (Table I):

$$\Delta I = I_0 - I = I_0 c T^{3/2}. \tag{1}$$

Using the formula for the exchange integral, given in [7], we find that

$$A = kT\left(0.1173\ \frac{N_a \mu_B}{\Delta I}\right)^{2/3}, \tag{2}$$

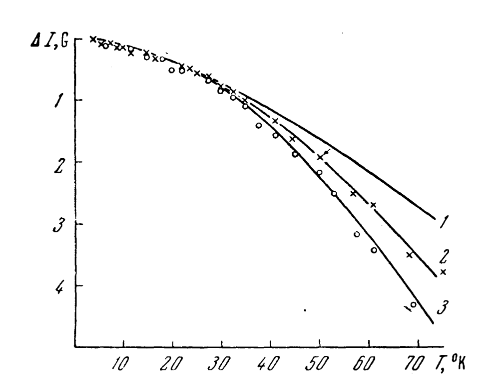

FIG. 2. Temperature dependence of the saturation magnetization of nickel: o – 18.6 kOe; x – 20 kOe.

where μ_B is the Bohr magneton, k is Boltzmann's constant, and N_a is the number of atoms in the sample. We calculated the value of the exchange integral A for the three metals (Table I) using only the $\Delta I(T)$ data.

Above 30° K, nickel exhibits a considerable departure from the $\Delta I/I_0 = cT^{3/2}$ law (Fig. 2). Analyzing this deviation, we obtain the following temperature dependence for nickel:[7]

$$\Delta I/I_0 = cT^{3/2} + dT^{3/2} e^{-\Delta/kT}. \tag{3}$$

The value of the parameter d decreases with increase of the field: in 18.6 kOe, $d = 2.3 \times 10^{-5}$; in 20 kOe, $d = 1.3 \times 10^{-5}$. The value of Δ/k is found to be (98 ± 4) deg K.

Figure 2 shows the temperature dependence of the saturation magnetization of nickel. Curve 1 was calculated using Eq. (1). Curves 2 and 3 were calculated from Eq. (3), using $d = 1.3 \times 10^{-5}$ and 2.3×10^{-5}, respectively. The experimental data are plotted for 18.6 and 20 kOe.

Analysis of the experimental data for iron and cobalt shows that the deviations from Bloch's law are small in the investigated range of temperatures and fields.

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