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By N. L. Brukhatov and L. V. Kirensky.

THE ANISOTROPY OF THE MAGNETIC ENERGY IN SINGLE CRYSTALS OF NICKEL AS A FUNCTION OF TEMPERATURE.

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The energy constant of the magnetic anisotropy of a single crystal of nickel as a function of temperature has been investigated by measuring the mechanical moments exerted on the sphere shaped crystal by the magnetic field. It has been established that the anisotropy constant can be represented very accurately in a large temperature interval by the empirical interpolation formula

$$K = K_0 e^{-aT^2},$$

where $K_0 = 40 \times 10^4$ e/cm^3; $a = 0.000034$ 1/grad^2. This relation satisfies Nernst's theorem, as

$$(dK/dT)_{T=0} = 0.$$

It can, however, not be extended to high temperatures in the region of the Curie point, since the disappearance of the anisotropy constant at the very Curie point does not result from this relation. Nevertheless, already at about 400° K very small values of K result, which becomes practically zero.

The results of the experiments have been compared with the theory of Akulov, which is based on an application of classical statistics. Akulov's theoretical relation represents the general character of the temperature curve K correctly, deviations in detail appearing in the region of low temperatures, as was to be expected.

1. Introduction.

The theory of the magnetisation curves of Akulov[1] and Heisenberg[2] leads to formulae which are universal functions of two parameters J_s and K for every direction along different axes of single crystals; J_s is the intensity of the magnetisation at the saturation for the given temperature and

[1] N. Akulov, ZS. f. Phys. **67**, 794, 1931; **69**, 78, 1931.

[2] W. Heisenberg, ZS. f. Phys. **49**, 610, 1928.

K is the constant of the energy anisotropy at the same temperature. The formulae can be applied at any temperature. A large number of theoretical as well as experimental papers deal with J_s as a function of temperature. Among these are the papers of Hopkinson,[1] Curie,[2] Weiss,[3] Weiss and Kamerlingh Onnes,[4] Weiss and Forrer,[5] Heisenberg,[6] Honda[7] and others.

The question of K as a temperature function has been raised only recently. The first step in this direction was taken by the theoretical paper of Akulov,[8] which was followed by a fair number of experimental investigations. The temperature change of the magnetic anisotropy for single crystals of iron has been investigated by Titov,[9] Piety[10] and Kirensky.[11] It was shown in these papers that the introduction of Akulov's equivalence principle yields for iron single crystals a relation which is in quantitative agreement with experiment.

Later Akulov has shown that the equivalence principle can only be applied in cases where the spin complexes can deviate only by very small angles. Hence only for this case we have a general formula for all materials linking K and J_s at various temperatures. Thus whereas the theory of the temperature change of J_s developed by Weiss[3] shows that J_s/J_0 is a universal function of T/Θ, this question remains open as far as the anisotropy constant K is concerned and is related to the question of the possible angles through which

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[1] J. Hopkinson, Phil. Trans. A 443, 1889; Proc. Roy. Soc. 144, 317, 1888.

[2] P. Curie, Oeuvres, Paris 1908.

[3] P. Weiss, Journ. de Phys. 4, 661, 1907; Ann. de Phys. 1, 134, 1914.

[4] P. Weiss and Kamerlingh Onnes, Ann. de Phys. 9, 55, 1910.

[5] P. Weiss and R. Forrer, Ann. de Phys. 12, 279, 1929.

[6] W. Heisenberg, loc. cit.

[7] K. Honda, H. Masumoto, J. Shirakawa, Sc. Rep. Tohoku Univ. 24, 391, 1935.

[8] N. Akulov, ZS. f. Phys. 100, 197, 1936.

[9] E. Titov, Journ. Exp. Theor. Phys. 6, 675, 1936 (Russ.).

[10] R. Piety, Phys. Rev. 50, 1173, 1936.

[11] L. Kirensky, Journ. Exp. Theor. Phys. 7, 879, 1937 (Russ.).

the spin complexes can be turned. From this point of view it appears especially interesting to investigate another ferromagnetic with a cubic lattice, i. e. a single crystal of nickel.

2. The Production of Single Crystals of Nickel and Their Investigation.

Single crystals of nickel were grown from a molt of pure Kahlbaum nickel by the slow cooling method. The metal was molten in a high frequency furnace in special cruicible placed in a quarz tube that was filled with hydrogen. By means of a special device the whole quarz tube together with the cruicible was slowly moved downwards through the induction coil of the high frequency furnace. When the nickel was cooled slowly by chosing the velocity of its motion accordingly, it crystallised in large single crystals collected in one mold. They were ground into spheres of 0.5 to 0.85 mm diameter. The orientation of the crystal axis was effected in a magnetic field with the help of a cardanic support. (For details see forthcoming papers).

The spherical shape of the crystals was chosen because to a single crystal in the shape of a sphere the method of determining K could be applied by means of which the mechanical moments are measured free of the influence of the demagnetisation factor, in contrast to the method based on the measurement of magnetisation curves. Moreover in samples of a different shape it is often difficult to suit the shape of the sample to the desired crystal axes accurately. In the case of a sphere the crystal axis can be oriented in any way with great accuracy. The mechanical moments were measured in the temperature region from $-195.5°$ C to $+90°$ C.

A peculiarity of the present investigation is the fact that the sample was immersed in a liquid during the measurements, which was held in a Dewar vessel. The measurements were made in liquid nitrogen, liquid oxygen, cooled ethyl alcohol and heated oil. In this way a uniform temperature of the sample and its accurate measurement were guaranteed.

Table 1.
Anisotropy constants K at various temperatures T.

T° K	$K \times 10^{-4}$ e/cm^3	T° K	$K \times 10^{-4}$ e/cm^3
77.4	32.30	261	3.90
90	29.80	267	3.52
187	12.25	269.5	3.34
193	11.80	272.5	3.22
196	11.00	275	3.10
199	10.70	277	3.02
202	10.20	279	2.89
205	9.75	282	2.77
208	9.32	284	2.71
210.5	8.75	287	2.53
213	8.60	288	2.56
216	8.21	291	2.46
219	7.87	293	2.37
221.5	7.85	295.5	2.28
224	7.25	297.5	2.16
227	6.85	300	2.08
230	6.55	303	1.94
233	6.23	308	1.82
235	5.90	312	1.62
238	5.73	317	1.50
241	5.56	326	1.26
244	5.33	330	1.15
247	5.07	335	1.03
250	4.81	340	0.91
255	4.26	344	0.81
258	4.10	354	0.67

3. Results and Discussion.

In table 1 the values of K obtained in the well known manner from the curves of the mechanical moments are given (for details see forthcoming papers).

Before we compared the experimental data with the theory we tryed to find a general empirical formula for the change of K with T; we therefore plotted lg K as a function of T^2 (fig. 1).

As is seen from the figure the curve obtained is in the whole temperature region very nearly a straight line. Thus on the basis of our experiment we have established the relation

$$\lg K = \lg K_0 - \alpha T^2, \qquad (1)$$

i. e. in other words the temperature change of the anisotropy constant can be represented by the formula

$$K = K_0 e^{-aT^2}, \qquad (2)$$

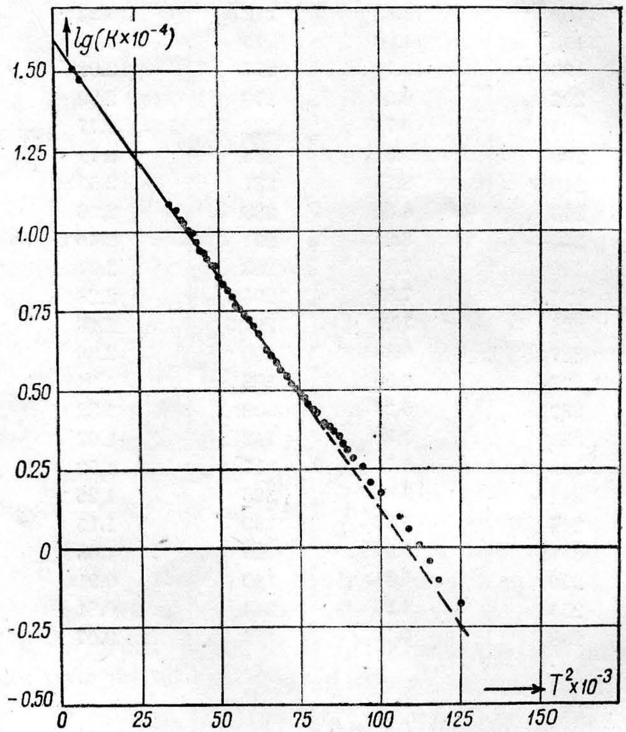

Fig. 1.

where

$$K_0 = 40 \times 10^4 \ \text{e/cm}^3; \quad a = 0.000034 \ 1/\text{grad}^2.$$

This formula is very convenient for the calculation of K in a very large temperature intervall. It is, however, unwarranted to overrate its principal significance since it does not take into account the fact that the anisotropy constant becomes zero at the Curie point.

The curves calculated according to formula (2) and the experimental values of K are given in fig. 2.

Let us discuss the principle features of the curve (2).

1) This curve satisfies the fundamental condition, derived by Akulov from Nernst's heat theorem, and from Akulov's equivalence principle which is

$$(dK/dT)_{T=0} = 0. \quad (3)$$

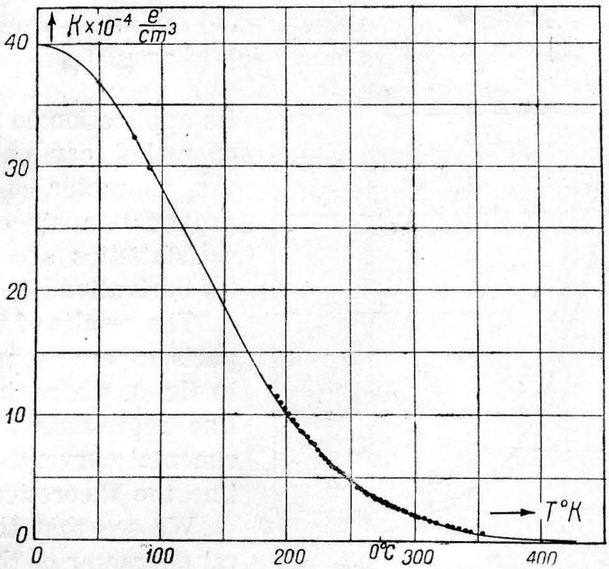

Fig. 2. Experimental curve $K = K_0 \cdot e^{-aT^2}$.

2) The empirical curve thus obtained differs markedly from that of iron in the steepness of its descent. Thus the universality of the function $K/K_0 = f(T/\Theta)$ for different metals is not corroborated, as against the universality of the curve $J_s/J_0 = \varphi(T/\Theta)$ which has been proved bei Weiss.[1]

3) The results of the measurements show that at $T = 400° K$, i. e. rather far from the Curie point, K becomes practically zero.

We did not succeed in finding out whether or not K changes sign in the neighbourhood of the Curie point, since K

[1] P. Weiss, loc. cit.

is too small; in any case, however, we can assert that such high values of K with the opposite sign as would follow from the magnetisation curve of a single crystal of nickel taken for various temperatures by Honda, Masumoto and Shirakawa,[1] are not observed in the region between 450 °K and the Curie point.

For the comparison of the results with the theory of Akulov we make use of a formula given by this theory[2]

$$\frac{K}{K_0}=1-\frac{10}{3}\left(\frac{T}{\Theta}\right)+\frac{35}{9}\left(\frac{J_0}{J_s}\right)^2\left(1-\frac{T}{\Theta}\right)\left(\frac{T}{\Theta}\right)^2. \qquad (4)$$

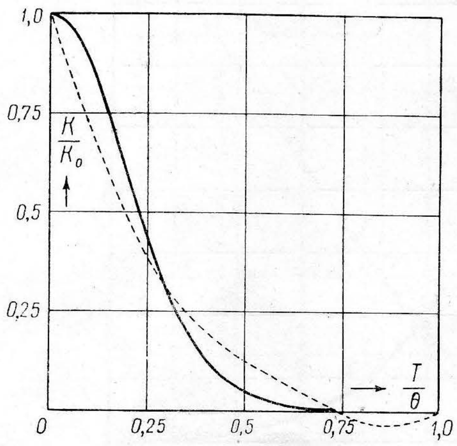

Fig. 3. The change of K/K_0 with T/Θ. The heavy line represents the experimental curve. The dotted line represents the theoretical curve (4) by Akulov.

Its application in the case of nickel can only have the character of an approximation since classical statistics are used in its derivation.

The results of the comparison are represented in fig. 3, where the heavy line represents the experimental curve, the dotted line the theoretical one.

We see that the general character of the curve K as a function of T is represented sufficiently well by the theoretical curve, unless we come to details and the peculiarity of the experimental curve, i. e. the very steep descent to 280°K and the subsequent approximation to zero at temperatures of the order of 400° K.

In the details, however, the experimental and theoretical curves do not agree, as was to be expected; for the theoretical relation $(dK/dT)_{T=0}\neq 0$ as a result of the application of classical statistics.

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[1] K. Honda, N. Masumoto and J. Shirakawa, loc. cit.

[2] N. Akulov, C. R. de l'Academie de l'URSS **15**, 445, 1937.

The character of the deviations between the theoretical and experimental formulae [see formula (4)] in the neighbourhood of absolute zero strongly recalls the well known phenomenon of cryomagnetic anomalies for paramagnetics;[1] whereas according to the theory of Langevin-Weiss the reciprocal magnetic susceptibility ought to depend linearly on the temperature, the experiment shows that near absolute zero marked deviations from the linear course occur.

All these facts are of great principal interest and importance for the further development of the theory of the magnetic anisotropy and the theory of the magnetisation curves.

In conclusion we express our gratitude to Prof. Akulov for his advices and the attention which he paid to our work.

Magnetic Laboratory. Physical Institute
of the Moscow State University.

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[1] P. Weiss and Foex, „Le Magnetisme". Paris, 1926.