THE FERROMAGNETIC SYMPOSIUM AND CONFERENCE AT THE SUMMER MEETING OF THE AMERICAN PHYSICAL SOCIETY AT SCHENECTADY, SEPTEMBER 12, 1931

APROPOS of the Faraday-Henry centenary celebration of the Society at Schenectady, the program committee appointed a sub-committee to arrange for a Magnetic Symposium. The interaction of ideas resulted in the plan for a symposium in the morning to be followed by a conference lasting through the afternoon for those more directly and intimately interested in ferromagnetics. The sub-committee has drawn up a detailed report covering its experience and the new ideas gained, and has sent copies to various officers of the Society. Here the sub-committee is submitting the two papers presented at the Symposium followed by abstracts of the conference papers, together with the discussion on them. The sub-committee feels that the space required for this will have been well used if, as a result, there is an increased use of the conference method at American Physical Society Meetings.

The sub-committee
F. BITTER
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ON THE INTERPRETATION OF SOME FERROMAGNETIC PHENOMENA

An Address presented before the Symposium on Ferromagnetism at the Meeting of the American Physical Society, Schenectady, New York, September 12, 1931

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DURING these first years of the twentieth century our knowledge of ferromagnetism has made great progress. In the first place we have learned empirically how to make those magnetic materials which are the foundation of the countless electrical circuits woven around the earth. Instruments have been built to work equally well under most varied conditions—at the equator and near the poles, in damp cellars and on the desert. Materials are available that will respond to the enormous forces produced by generators in power stations, and to the faint current signal produced by sounds thousands of miles away. And in the second place we are beginning to learn something of the mechanisms which are responsible for the existence of ferromagnetism and for the various phenomena associated with it. It remains one of the important tasks of the future to link together these two avenues of progress so that we may not only produce, but also understand how we produce the materials which we use, and so that we may have an intimate knowledge of the actual complex physical world around us and use it to check and clarify the fundamental laws of science. In the following I shall outline some of our present knowledge of ferromagnetism, and indicate a few places where progress along the above lines is to be expected.

Starting from the conception that magnetic materials are made up of elementary atomic magnets in thermal interaction, and that magnetization results from their reorientation, the classical theory, with modifications introduced by quantum considerations, leads to an expression relating the magnetization, the absolute temperature, and the field of the form

$$\frac{I_w}{I_0} = \tanh \frac{\mu_B}{KT}(H + N_w I_w) \tag{1}$$

I_w is the Weiss magnetization, or that value which satisfies Eq. (1). The subscript is used to differentiate it from the observed magnetization I of actual samples. I_0 is the absolute saturation, K is the Boltzmann constant, μ_B is a Bohr magneton, and N_w is a proportionality factor called the Weiss molecular field constant. The above equation states that I_w even for $H=0$ is different from zero up to a critical temperature $T=\theta$, or the Curie point. I_w for $T<\theta$ and $H=0$ is called the spontaneous magnetization. The dependence of I_w on H for temperatures below and not too near θ is slight because the term $N_w I_w$ is large compared to those values of H which can be obtained in the laboratory. If an entire sample is uniformly magnetized in one direction, then $I_w=I$. If, on the other hand, spontaneous magnetization occurs in regions, and I_w has different orientations in different parts of a sample, it will be found that $I<I_w$. A study of the constant N_w in the light of recent developments in atomic theory has led to the following conclusions: that the magnetic moments associated with electron spins are almost exclusively responsible for the magnetization of ferromagnetic bodies, (this has been substantiated by the Barnett and Einstein-de Haas effects, and by x-ray investigations) and that the spin interactions are responsible for the Weiss molecular field, or in other words, for spontaneous magnetization. Obviously the model on which Eq. (1) is based is much too crude. The only disposable constants are I_0 and N_w, and it is hardly to be expected that by varying these alone all the complexity of ferromagnetic phenomena can be reproduced. It is, nevertheless, surprising how far we can go. For numerical comparisons it is convenient to rewrite Eq. (1) with $H=0$ in the form

$$\frac{I_w}{I_0} = \tanh\left(\frac{I_w}{I_0}\frac{\theta}{T}\right) \tag{2}$$

$$\theta = \frac{\mu_B N_w I_0}{K}$$

and to deduce for the initial susceptibility in the paramagnetic state, $T>\theta$

$$K_0 = \left(\frac{\partial I_w}{\partial H}\right)_{H=0}$$

$$\frac{1}{N_w K_0} = \frac{T}{\theta} - 1. \tag{3}$$

A peculiar difficulty arises from the fact that experimentally the conditions at the critical point are found to be rather involved, and it is consequently difficult to decide on any one temperature as the one which is meant by θ in Eqs. (2) and (3). A plausible procedure is to use Eq. (3) to find θ, and use this same θ, called the paramagnetic Curie point, or θ_p, to check Eq. (2). The first part of this program has been carried out in Fig. 1 for nickel and cobalt. The theoretical curve is the heavy line having unit slope. The experimental data contain a certain amount of contradictory evidence. A fairly thorough review, however, indicates that the most probably correct results are those plotted. For a reasonable range of temperatures not too close to the Curie point the observations do lie along a straight line which has, however, a smaller slope than is to be expected on the basis of Eq. (3). The dotted lines indicate the deviations that are usually observed near the critical temperature. As a rule the paramagnetic susceptibility is independent of the field strength, but near the Curie temperature this is no longer true, and observations in small fields should be instructive. In plotting Fig. 1, the value of θ_p used for cobalt was 1413° and is between the values found by Bloch and Preuss, namely 1411°K and 1415°K respectively. For Ni the value 650°K was used.

The experimental points for iron, shown in Fig. 2, reveal much the same conditions as those found in nickel and cobalt. The occurrence of the γ-phase makes the determination of the relationship between K_0 and T rather difficult, especially since it appears that the true condition is perhaps not represented by a straight line. This point is of especial interest in connection with an article by Dehlinger[1] on the transformation points, A_3 and A_4, of iron to which the reader is referred for further discussion. The values of θ_p used in plotting Fig. 2 were those used by the authors; Terry, 1043°K; Weiss and Foex, 1043°K; and Ishiwara 1048°K. This is done because it is not easy to see from the above data how a revision had best be made. Ishiwara's points might be taken to lie on a straight line having an intercept slightly above $T/\theta = 1$, but the other results do not support the correctness of drawing a straight line from the γ through the α range. Further experimental work is needed to clear up the situation.

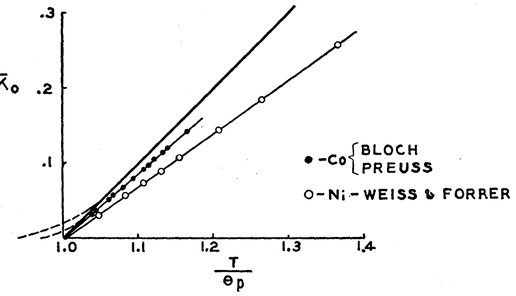

Fig. 1. The reciprocal of the initial susceptibility times the Weiss molecular field constant is plotted as a function of the reduced temperature. The heavy line is the theoretical curve expressed in Eq. (3). The experimental points are taken from O. Bloch, Thesis, Zürich, 1912; A. Preuss, Thesis, Zürich, 1912; P. Weiss and R. Forrer, Ann. de Physique **5**, 153 (1926).

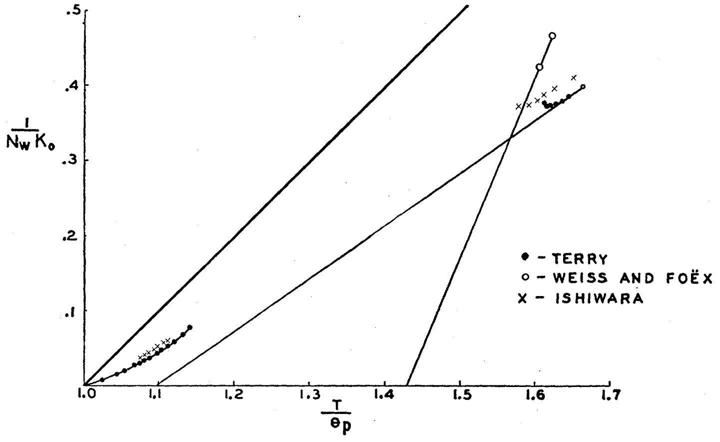

Fig. 2. The experimental points are for iron and are taken from E. M. Terry, Phys. Rev. **9**, 255, 394 (1917); T. Ishiwara, Sci. Rep. **6**, 133 (1917); P. Weiss and G. Foëx, Jour. de Physique **40**, 744 (1911). See Fig. 1 for an explanation of the symbols used.

With critical temperatures determined as above, observational data bearing on Eq. (2) have been plotted in Fig. 3. Near the critical temperature all the points lie below the theoretical curve. This is most probably due to the fact that in the fields used $I < I_w$. In the intermediate temperature range pyrrhotite and magnetite seem definitely to follow some other law; nickel and cobalt (the latter has a face-centered cubic lattice in this region) follow the curve very well indeed; iron shows a distinct departure from the theoretical curve which may be partly due to a too low estimate of θ. Most probably, however, the discrepancy is real, and has its roots some-

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[1] U. Dehlinger, Zeits. f. Physik **65**, 535 (1931).

where in the statistics of atomic interactions. At low temperatures none of the observed points lie on the theoretical curve. In Fig. 4 the results have been replotted on a larger scale in which the square of the reduced temperature is used to bring out the linear relationship between T^2 and I_w at low temperatures. Curve 1 represents the classical equation in which the Langevin function $L(x)$ appears, and curve 2 represents Eq. (1). Weiss and Forrer, whose data are plotted in Fig. 4, emphasized the linear relationship here indicated. In addition it should be noticed that when plotted in this way the results for the cubic lattices fall together into one group, and those for the non-cubic orthorhombic lattices into another. As for cobalt and pyrrhotite at low temperatures, in which range both have hexagonal lattices, the comments made below will make clear that saturation is difficult to obtain except in the direction of easy magnetization. It would be of great interest to make observations on single crystals in this direction and determine whether the dependence on crystal form indicated above may be extended. A difficulty that would be encountered in plotting the data is that the Curie temperature of hexagonal cobalt is not known.

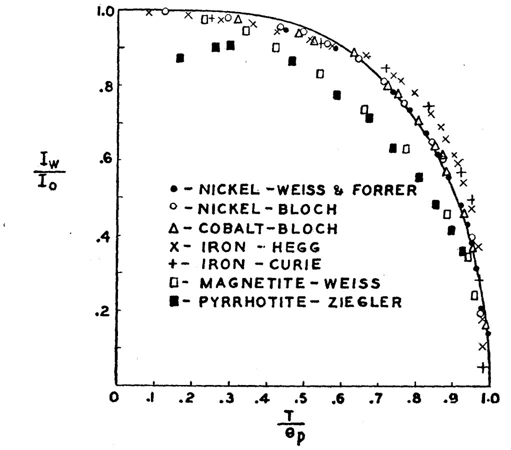

Fig. 3. The reduced saturation intensity is plotted as a function of the reduced temperature. The experimental results are taken from the papers referred to in Figs. 1 and 2, and from F. Hegg, Thesis, Zürich, 1910; P. Curie, Ann. de Chim. et de Phys. 5, 289 (1895), P. Weiss, Jour. de Physique 6, 661 (1907); and Zeigler, Thesis, Zürich, 1915.

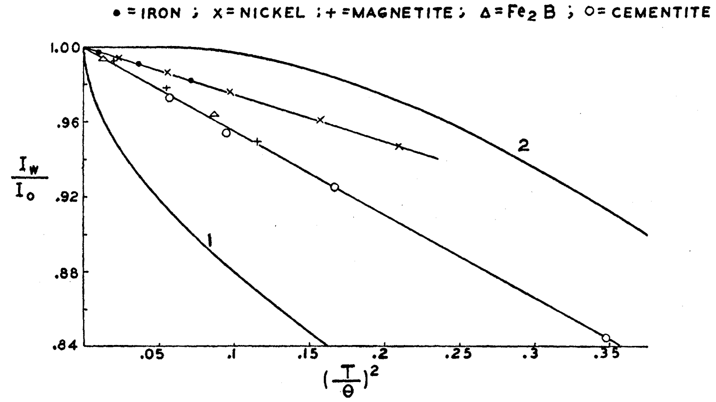

Fig. 4. The reduced saturation intensity is plotted as a function of the square of the reduced temperature. The experimental points are taken from P. Weiss and R. Forrer, Ann. de Physique **12**, 279 (1929).

One of the outstanding problems connected with the part of the theory outlined above is that of determining the magnetic moment of the ferromagnetic atoms. Two methods have been used, the first being based on measurements of I_0, the absolute saturation, the second being based on observations of the slope of the susceptibility curves above the Curie point. These methods were found to give different results, and led to the adoption of the Weiss magneton as an experimental unit of magnetic moment. Recently Wolf[2] has shown that by assuming several states to exist simultaneously within a ferromagnetic crystal the experimental results can be satisfactorily accounted for without making use of other magneton numbers than those indicated by spectral analysis. The arrangement of atoms in different excited states in a solid is most probably influenced by impurities and strains, which may account for the discrepancies which exist between various observations of the quantities discussed above. Now that delicate methods are available for controlling and observing the condition of a piece of metal it should be possible to delve further into the questions raised by Wolf's paper by studying those factors which influence I_w and K_0.

While the above model is in many ways adequate and promising, it absolutely fails in one important respect. The presence of the applied magnetic field H next to the "molecular field" N_wI_w, which is of a much larger order of magnitude, makes Eq. (1) effectively independent of the applied field. In other words, there exists only spontaneous magnetization, and no magnetization as a function of H. The way around this difficulty, as has already been suggested, is to assume that Eq. (1) applies to small regions only. What the size and shape of these regions are to be, need for the present not be specified. Each one is to be capable of orienting its magnetization independently. The energy as a function of orientation depends on the crystal structure and the strains, and in the absence of strains assumes the following especially simple forms for single crystals[3]

$$E_{\theta,H} = K(I_{wx}^2I_{wy}^2 + I_{wy}^2I_{wz}^2 + I_{wz}^2I_{wx}^2) - (\vec{I}_w\cdot\vec{H}) \tag{4}$$

$$= K_1I_{wx}^2 + K_2I_{wy}^2 + K_3I_{wz}^2 - (\vec{I}_w\cdot\vec{H}). \tag{5}$$

Eq. (4) applies to cubic crystals, and Eq. (5) to hexagonal crystals. The direction in which the regions are magnetized is given by the absolute minima of $E_{\theta,H}$. If two or more equal minima exist it is convenient to assume that they are equally occupied. These statements form a perfectly definite set of rules for constructing magnetization curves, and even if they are somewhat over-simplified, it will be found useful to apply them as suggested. The chief difficulties will appear whenever $E_{\theta,H}$ has two or more minima of almost equal depth. The above rules say that only the lowest is occupied, whereas in truth this is the case only after the difference exceeds a certain value, and even then only if the intervening maxima are not too high. This is, then, a theory of magnetization in the absence of hysteresis, and as we shall apply it to single crystals, in which hysteresis effects are known to be slight, we may expect fair agreement.[4]

It is convenient, in plotting the magnetization curves derived from Eqs. (4) and (5), to introduce a reduced field, h, given by

$$\frac{H}{h} = \frac{KI_w^3}{8} \tag{6}$$

for cubic crystals, and

$$\frac{H}{h} = 2I_w(K_2 - K_1) \tag{7}$$

for hexagonal crystals, two of the three coefficients K_x being chosen equal, corresponding to the fact that hexagonal crystals are found to be magnetically isotropic in an (0001) plane. In

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[2] A. Wolf, Zeits. f. Physik **70**, 519 (1931).

[3] These considerations are based on the work of: G. S. Mahajani, Roy. Soc. Proc. **228**, 63 (1929); W. L. Webster, Proc. Phys. Soc. **42**, 431 (1930); N. S. Akulov, Zeits. f. Physik **67**, 794 (1931); F. C. Powell and R. H. Fowler, Proc. Cam. Phys. Soc. **27**, 280 (1931); F. Bloch and G. Gentile, Zeits. f. Physik **70**, 395 (1931); F. Bitter, Phys. Rev. **38**, 528 (1931).

[4] The magnetization of distorted lattices has recently been investigated by R. Becker, Zeits. f. Physik **62**, 253 (1930) and R. Becker and M. Kersten, Zeits. f. Physik **64**, 661 (1930).

Fig. 5 are plotted the results of Honda, Masumoto, and Kaya[5] for iron. The solid curves are those deduced from Eq. (4). The bend in the curve for the (111) axis near $h=12$ has no particular significance as the minimum of $E_{\theta,H}$ is very flat in this region, and allows of a considerable range of orientations without the expenditure of any appreciable amount of energy. The experimental points are fitted to the theoretical curves at one point which determines the ratio H/h. This ratio, which measures the difference in energy for various directions of magnetization, varies with the temperature as shown in Fig. 6. There is as yet no theoretical interpretation of this curve. The magnetization curves for hexagonal crystals at room temperature are shown in Fig. 7. In Co the direction of easy magnetization is (0001), the plane perpendicular to this axis being magnetically isotropic. In pyrrhotite the situation is reversed. The (0001) axis is the direction of difficult magnetization. The plane perpendicular to this axis is isotropic, and is sometimes referred to as the magnetic plane. While the agreement shown in the figure is fair, the discrepancy for cobalt in the direction of difficult magnetization is considerable. Further

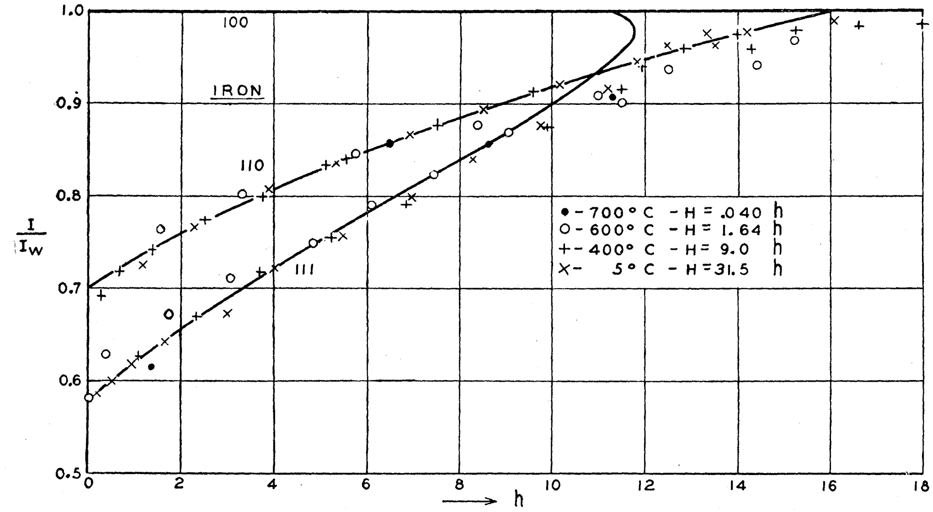

Fig. 5. Theoretical and experimental magnetization curves for single crystals of iron. Experimental points are by Honda, Masumoto, and Kaya.[5]

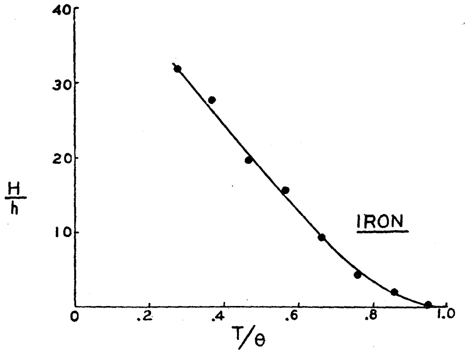

Fig. 6. The ratio H/h is plotted as a function of the reduced temperature for iron. H/h measures the magnetic anisotropy of a crystal.

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[5] K. Honda, H. Masumoto, and S. Kaya, Sci. Rep. **17**, 111 (1928).

experimental work should be undertaken to check the shape of this curve, especial care being taken to aline the crystal in the field. The above considerations make certain predictions concerning the thermal behavior of hexagonal crystals possible. There is no reason for supposing that the coefficients K_2 and K_1 have identical temperature coefficients, and if they have not, a temperature T' may be reached for which $K_2 = K_1$. At this temperature every direction will be one of easy magnetization. If below this temperature the (0001) axis is easily magnetizable, it will not be so above T', and vice versa. This is the behavior that Honda and Masumoto[6] have recently observed in cobalt. They found T' at approximately 250°C. Above this temperature the magnetic behavior of cobalt is similar to that of pyrrhotite at room temperature. It is quite possible that a similar phenomenon takes place in pyrrhotite at low temperatures, and is responsible for the anomalous behavior shown in Fig. 3. That is, if for temperatures below $T/\theta_p = 0.35$ there were only a magnetic axis, and *two* directions of difficult magnetization instead of one, the material would be magnetically harder, and would consequently be difficult to magnetize to saturation. An investigation of crystalline pyrrhotite at low temperatures could settle the point.

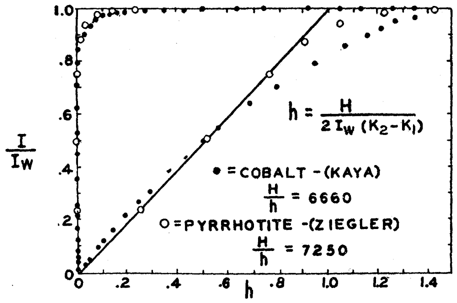

Fig. 7. Theoretical and experimental magnetization curves of nickel and pyrrhotite crystals at room temperature. Experimental points are by S. Kaya, Sci. Rep. **17,** 1157 (1928), and Ziegler, Thesis, Zürich, 1915, or Int. Crit. Tables **6,** 413 (1929).

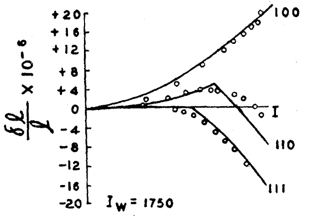

Fig. 8. Magnetostriction as a function of magnetization in iron crystals. Theoretical curves are by Heisenberg,[8] experimental points by Webster.[3]

Any quantity that depends on the direction of magnetization of the elementary regions can be calculated in a manner similar to the above. One of these is magnetostriction. The elementary regions do not possess perfect cubic lattices, but are distorted by their magnetization, and the shape of a macroscopic sample will evidently depend on the direction of magnetization of these regions. Calculations of the magnetostriction of single crystals have been made by Akulov[7] and Heisenberg.[8] In Fig. 8 the result is plotted as found by Heisenberg, with observations on iron by Webster. The assumptions made are somewhat different from those used in this paper, but

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[6] K. Honda and H. Masumoto, Sci. Rep. **20,** 323 (1931).

[7] N. S. Akulov, Zeits. f. Physik **69,** 78 (1931).

[8] W. Heisenberg, Zeits. f. Physik **69,** 287 (1931).

the curves obtained are not greatly affected by this difference. In both cases the derivations are of a preliminary character, and the agreement shown in Fig. 8 may be taken as satisfactory. For further detail the reader is referred to the above papers.

These and related problems which concern the structure-insensitive properties of ferromagnetic substances are at least on the road to being solved. The structure-sensitive properties, on the other hand, are not at all understood, and require further knowledge of the detail of the structure of solids. Before it is possible to apply the ideas which have been advanced, especially those of Zwicky on block structure, it will be necessary to have more definite observations to work on. Two promising directions are illustrated in Figs. 9 and 10. In the first of these the initial susceptibility of various substances is plotted as a function of temperature. The data are taken from Renger[9] and Weiss and de Freudenreich.[10] Curve 1 represents qualitatively the behavior of iron and nickel. In iron an anomaly is reported at −11°C which is plotted on a larger scale in curve 2. This peculiar behavior is related to a time lag and to a magnetic aging. That is, at −11°C the time required for a steady value of I to set in after a change in H, is much greater than either above or below this temperature. Further, the exact shape of the kink depends on how long the material was kept at a temperature near 120°C during its previous heating. It should be useful for our understanding of the subject to investigate such critical temperature ranges in some detail. In curve 3 the peculiar behavior of an iron-nickel alloy is

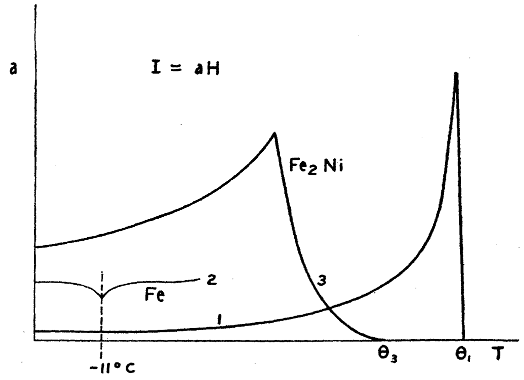

Fig. 9. Initial susceptibility as a function of temperature.[9,10]

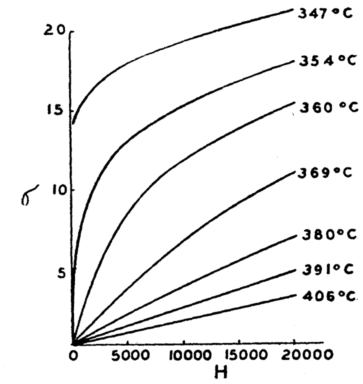

Fig. 10. Magnetization curves of polycrystalline nickel near the Curie point after Weiss and Forrer.[11] σ is the specific intensity of magnetization.

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[9] K. Renger, Thesis, Zürich, 1913.

[10] P. Weiss and J. de Freudenreich, Arch. des Sci. **42**, 449 (1916).

shown. Another set of phenomena that requires further experimental investigation is that accompanying the transition from the ferromagnetic to the paramagnetic state. For some purposes it is sufficient to speak of a single critical temperature, but a closer inspection shows that in some substances, at any rate, the various properties change more or less continuously over a range of temperatures, and that there may even be two or three distinct critical temperatures quite close to each other. In Fig. 10 are plotted magnetization curves of nickel taken by Weiss and Forrer[11] near the Curie point. It would be of great interest to study these curves in relationship to the constant K of Eq. (4), whose behavior for iron is plotted in Fig. 6, and so to separate these effects which are due to the orientation of the regions as discussed above from those which are due to other mechanisms.

[11] P. Weiss and R. Forrer, Ann. de Physique **5**, 153 (1926).

SOME NEW EXPERIMENTAL METHODS IN FERROMAGNETISM

An address presented before the Symposium on Ferromagnetism at the meeting of the American Physical Society, Schenectady, New York, September 12, 1931

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When your Committee honored me with an invitation to address this body on the subject "New Experimental Methods in Ferromagnetism," I accepted on condition that I be permitted to prefix this title with the adjective "Some." Taking advantage of this bit of forethought, I propose this morning to limit my remarks to a brief description of certain methods which have been devised for observing the magneto-elastic, mechanical and thermal properties of single crystals of nickel, as well as of polycrystalline specimens of the same substance.[1]

Attention should first be directed to the process used in refining the nickel.[2] The initial stage in this process is the preparation of a nickel chloride bath by dissolving Mond nickel in hot hydrochloric acid. Iron is then removed from the bath by precipitation of the hydroxide, and copper by electrolytic deposition on a rotating platinum cathode. Finally the pure nickel is deposited electrolytically on a stationary carbon cathode. This nickel is spectroscopically free from iron, cobalt and all other metallic impurities except a trace of copper too small to be detected by chemical means.

I shall now describe the apparatus used for the manufacture of single crystals of nickel. The specimens are desired in the form of rods 4 to 6 mm in diameter and 5 to 10 cm long.

The crystals are grown in a molybdenum-wire-wound vacuum electric furnace, following the method developed by Bridgman for the production of single metallic crystals. The novelty of the present arrangement consists in those features of design which permit the use of this method at a temperature of 1500°C.

Fig. 1 is a cross section silhouette of the furnace. On the outside is a fused quartz tube $5\frac{1}{2}$ inches in diameter and 28 inches high. A clear quartz window is fused in at the top to permit the use of an optical pyrometer. The bottom is ground flat and makes a vacuum tight seal with the flat iron plate which forms the base of the furnace. Next is a radiation trap consisting of a tubular alundum furnace core 3 inches in diameter. Next is an alundum tube 2 inches in diameter and 24 inches long on the upper 9 inches of which are wound 80 turns of molybdenum wire. The diameter of the wire is 0.036 inches. Next is an alundum tube 1 inch in diameter and 10 inches long upon which are wound 90 turns of molybdenum wire. The space between these

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[1] These methods have been developed through the cooperative activity of the following group working in the Physics Laboratories at Columbia University: Lewis Balamuth, W. T. Cooke, Fred Rose, Sidney Siegel, Clarke Williams, and Jerrold Zacharias. Detailed descriptions thereof will appear in due course in separate papers under appropriate authorship.

[2] F. A. Rohrman, Transactions of the Electrochemical Society **57**, 325 (1930); **58**, 403 (1930); **59**, 359 (1931).