MAGNETIC SUSCEPTIBILITY OF NICKEL AND COBALT CHLORIDE SOLUTIONS.

BY LAURA BRANT.

SYNOPSIS.

The Magnetic Susceptibilities and Magneton Numbers of Nickel and Cobalt in Aqueous Solutions of their Chloride Salts.—The susceptibilities of solutions have been found by a modified form of the "Kelvin-Wills" method. Data is given for nickel chloride solutions ranging in molar concentration from 0.001000 to 3.765 and for cobalt chloride solutions from 0.001018 to 2.0353, for field ranges of 3,000 to 14,000 gausses for the lower concentrations and 3,000 to 10,000 for the higher. All measurements were made at a temperature of 20° C.

The susceptibilities of the salts have been computed from the susceptibilities of the solutions by application of the Wiedemann law, and the susceptibilities of the metals obtained by extending the Wiedemann relation to the salts.

The susceptibilities of the solutions measured were found to be independent of the field strength throughout the ranges of field used, and the susceptibilities of the salts, both nickel and cobalt, were found to be independent of the concentrations of the solutions. The value found for the molecular susceptibility of nickel is 0.004423 and of cobalt 0.010362. These values give upon application of Weiss's equation 16.0 and 24.5 magnetons respectively for the nickel and cobalt atoms.

Susceptibility of Air.—An auxiliary result obtained in the experiments is that the volume susceptibility of air at 20° C. and average conditions as regards pressure and moisture extending over a number of months is 0.0288×10^{-6}.

FROM a consideration of the values of Pascal[1] and of Liebknecht and Wills[2] for the magnetic susceptibility of paramagnetic salts in solution Professor Weiss conjectured[3] that the molecular magnetic moment was an integral multiple of an elementary moment which he called the "magneton." The existence of this natural magnetic unit is fundamental in his magneton theory. Whatever may have been, or may be, the fate of this theory, a result of it was a quickened interest in the magnetic study of solutions, a study which had held the attention of experimenters since the classical magneto-chemical investigations of Wiedemann. Of the large literature which has followed, five publications are of special interest in connection with the subject of this paper. Two of these deal with the susceptibility and magneton number of nickel in its salts in aqueous solutions and three with the susceptibility and magneton number of cobalt in aqueous solutions of its salts.

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[1] Ann. Chim. Phys., 8e Ser., T. xvi, p. 531; 1909: T. xix, p. 5; 1910.

[2] Ann. d. Phys., Bd. I., p. 178; 1900.

[3] Jour. de Phys., 5e Ser. T. 1, p. 965, 1911.

The first of these papers is by the Spanish physicists Cabrera, Moles, and Guzman,[1] and gives the results of precision work upon the normal salts, nickel sulphate, nickel chloride, and nickel nitrate. Measurements were made upon solutions varying in concentration over a considerable range. In the case of nickel chloride this was from 0.02208 to 0.34630 grams of salt per gram of solution. The second paper gives the values obtained from the careful measurements of Weiss and Mlle. Bruins[2] upon solutions of the same normal salts. The concentrations used for the case of nickel chloride ranged from 22.690 to 0.623 per cent. of nickel chloride. The results for the susceptibility of the solutions in both of these researches were obtained by means of a modified form of Quincke's ascension method, after the manner of Piccard in his determination of the susceptibility of water; and the value for the metal content found by an application of Wiedemann's law. The conclusions from the two experiments were in good accord. Both led to a susceptibility coefficient for nickel which was independent of the concentration, and to an integral number, 16, of magnetons for the nickel atom.

Of the papers on cobalt, the first gives the results of measurements by Cabrera, and his co-workers, Jimeno, and Marquina[3] on solutions of cobalt chloride, cobalt sulphate, and cobalt nitrate, obtained, as in the case of the nickel solutions, by Piccard's modification of Quincke's classical method, and application of the Wiedemann law. The susceptibility of cobalt was found to vary with the concentration. Fractional numbers of magnetons between 24 and 25 resulted, but in such a manner that whole numbers were approached as limiting values. Thus there were found 24 magnetons for the cobalt atom from measurements on the more dilute solutions, and from measurements on the stronger concentrations, 25. The second paper dealing with cobalt is by Trümlper,[4] a student at Zürich, who had completed two independent series of measurements on solutions of the chloride, nitrate, and sulphate salts at the time the earlier publication appeared. The first of these series was made by means of a magnetic balance of the Curie-Cheneveau type and resulted in a magnetic coefficient for cobalt which varied with the concentration. Comparison later with the work of Cabrera, Jimeno, and Marquina showed that there was not a close quantitative agreement, but that Trümpler's values were, nevertheless, consistent with the interpretation given by the Spanish physicists and pointed to the same integral numbers, 24 and 25, of magnetons for the cobalt atom in limiting conditions in

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[1] Sci. Arch., p. 325, 1914.

[2] Amst. Akad. Proc., p. 246, Vol. 18.

[3, 4] See "Le magneton et les sels paramagnetiques dissous," by P. Weiss, Revue Gen. de L'El., p. 925, Dec. 15, 1917. These papers are known to the writer only through this review.

solution. For the second series of measurements Trümpler also adopted the Quincke-Piccard ascension method. These measurements gave a value of the susceptibility of cobalt which did not depend upon the concentration of the solution, and a fractional number, approximately 24.5, of magnetons for the cobalt atom. The third paper contains results for cobalt obtained by Quartaroli[1] from dilute solutions of the same three cobalt salts by means of his differential method, a nickel chloride solution having been used as standard. Under the condition that the magneton number of nickel is a constant, 16, the results for the chloride solutions gave for cobalt a molecular coefficient which increased when the concentration was increased, and a magneton number ranging from about 24.5 to 25.3 for the concentrations used.

Experiments for determining the susceptibilities and magneton numbers of nickel and cobalt in aqueous solutions of their chloride salts by a method which differs from those mentioned above had been practically completed in this laboratory before Weiss's review (l.c.) came to the writer's attention. The experiments were entirely finished before Quartaroli's paper was known. To present the results obtained by the method here employed is the object of the present paper.[2]

METHOD.

Lord Kelvin[3] suggested, as a means of determining the susceptibility of diamagnetic and feebly magnetic solid substances, placing a suitably shaped portion of the substance, such, *e.g.*, as a cylinder or a rectangular slab, having known dimensions in a non-uniform magnetic field and measuring the mechanical force exerted by the field upon it. He observed that the field strength, which must be known, could be obtained conveniently through finding the force acting upon a chosen length of wire carrying a measured current across the magnetic lines of force. The susceptibility could then be computed from known relations. Professor Wills[4] determined the susceptibility of solids by a method in which these suggestions are embodied and pointed out that the process was applicable to measurements on liquids and gases. He later used it, adapted to liquids, in determining the susceptibility of water, and others have since made use of it in the study of other liquids. A particularly favorable feature of the method as developed by Professor Wills is that the determination of the field is made at the same time that the force upon the body is found.

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[1] Soc. Chim. Ital, Gazz., 48^1, p. 79, 1918.

[2] The measurements reported in this paper were completed during the summer of 1919.

[3] Brit. Assoc. Report, p. 745, 1890.

[4] PHYS. REV., *6*, p. 223, 1898.

The method of obtaining the susceptibility of the solutions in the present experiments is also based upon the suggestions of Lord Kelvin. The method follows a different procedure for obtaining mechanical force than was used in the earlier adaptation by Professor Wills, but borrows from that adaptation the details for the field determination. In the earlier application the mechanical force was found by means of a balance from one arm of which a rectangular slab of the body, and the current element, were suspended in the field: in these experiments the force has been determined from the currents required to carry the body to positions of known displacements when suspended as a pendulum in the field.

Wiedemann's law has been applied in computing the susceptibility of the metal from that of the solution, and Weiss's equation in computing the number of magnetons.

Apparatus.

The line drawing (Fig. 1) gives a general idea of the distribution and relative size of the parts of the apparatus making up the suspended system. A narrow glass platform, *G*, upon which a rectangular glass vessel, *V*, for containing the liquid, rested by means of a point, dot, slot device (not indicated in the figure), was suspended horizontally between the poles, *P*, of an electromagnet by four fine copper wires *w*, *w*, *w′*, *w′*, of equal length which sustained equally the weight of the platform and its load. The wires *w* and *w′* passed through the capillary bore of small glass tubes (2.2 cm. in length) attached to the platform, and through two similar but longer tubes (9.7 cm. long) attached to a brass bar supported above. The tubes were parallel and symmetrically placed at the ends of the platform and bar, respectively, at right angles to their length. The ends of the tubes, forming the points of suspension, were well rounded to reduce friction, and slipping of the wires was prevented by a touch of china cement in the capillary bore. The planes *w*, *w* and *w′*, *w′* were parallel and 20.4 cm.

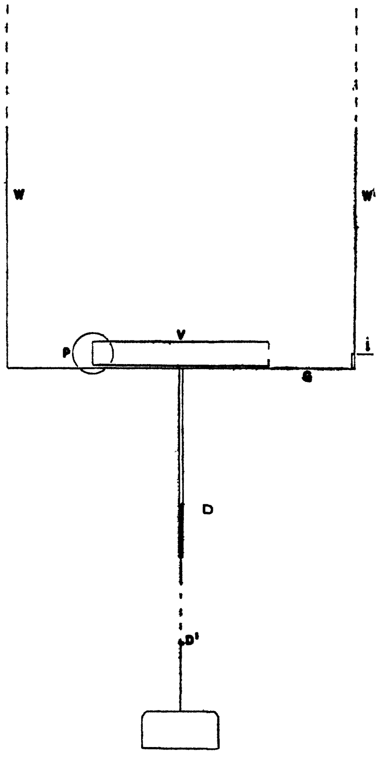

Fig. 1.

distant, and were cut by the horizontal planes containing the upper and lower suspension points to a length of 81.50 cm. The position with respect to the poles was such as to bring the length of the vessel, which was parallel to the long axis of the platform, perpendicular to the lines of force and one end (in the absence of a magnetic force), approximately in the position of the strongest part of the field. The other end was well out of the field.

The cell, *V*, measured about 10.4 × 1.4 × 1.0 cm. externally. Around the top, the end to be placed in the field, and the bottom was pasted a strip of tinfoil which served to conduct a current across the lines of force, the length of the foil across the field end of the cell forming an element of circuit used in the field determination. The ends of the tinfoil were in contact, at the outer end of the cell, with short lengths of thin copper sheet to which were soldered a few cm. of brass wire. Small slotted brass tips slipped over the ends of the wires connected the ends of the tinfoil to fine silk-covered strands of a long spiral of two-ply copper twist, which hung vertically from the brass support above, and formed part of a current circuit described further in a following paragraph. The width of the foil was equal to the internal width of the vessel. The field end of the vessel was cut from very thin glass, so that the tinfoil was separated from the inner surface by a small fraction of a mm. only. The side walls were about 1 mm. in thickness, and the outer end, which was bored to permit of filling and emptying the vessel, was about 3 mm. thick. When filled with liquid the cell was sealed by means of a thin coating of paraffin.

D and *D′* (of brass and copper respectively) are parts of an electromagnetic damper which was in position but not used when the readings recorded in this paper were taken.

A glass upright, at the outer end of the glass platform, supported a vertically ruled glass index, *i*, the plane of the rulings being parallel to the length of the platform. In the early part of the work the index was a square of glass lined with very light diamond traces about 0.5 mm. apart. Later this was replaced by the scale of a Bausch and Lomb stage micrometer ruled to 0.01001 mm.

The brass bar which supported the whole pendular system was pinned in a manner permitting rotation about a central axis perpendicular to its length to a brass plate the elevation and tilt of which was adjustable by means of screws; the plate was mounted upon two crossed, screw-controlled, guided brass slides, providing adjustment parallel and perpendicular to the field. A thermometer graduated at 0.2° C. hung from the guide above so that its bulb was just above the cell. The whole was borne by a brass arm extending from a heavy iron casting which was firmly bolted to the base of the magnet. The entire system was enclosed in a well-lighted wooden box as a protection against draughts.

A second iron casting bolted to the base of the magnet and finished with brass fittings furnished a rigid support and the necessary means of adjustment for keeping a microscope at the level of the index, *i*, and in focus upon the scale. A stout brass rod bracing the two castings against each other effectively eliminated any disturbing motion of either due to the field. The microscope was provided with a filar micrometer having a screw head divided into one hundred parts. For the optical combination as adjusted throughout the experiment, one division of the head of the screw was equivalent to 0.0000588 cm.; one tenth of a division could easily be estimated. A Leitz Wetzlar object micrometer reading to 0.01 mm. was used for the calibration. The observations of the index were made by means of the microscope through a window of very thin clear mica in the box enclosing the suspension.

The electromagnet used was of the Du Bois half-ring type. The core was of about 10 cm. diameter and was fitted with right conical pole pieces having a base angle of approximately 30° and faces initially 1.5 cm. in diameter. These faces were later cut away giving new surfaces about 2.5 cm. across. The distance between the faces was about 1.3 cm. The coils had a capacity of 25 amperes. Current was supplied by storage batteries at about 110 volts. A reversing key provided a means of demagnetizing the magnet. The magnet was mounted on foot-screws which rested upon steel rails placed across the top of a pier built up from the cement floor of a sub-basement chamber.

For some time before measurements were to be made, the temperature of this chamber was kept at approximately 20° C. by means of an adjustable electric heater which supplemented the steam heat provided in the building; due to the subterranean location of the room the temperature seldom went above 20° C. even in the hottest days of summer.

The upper end of the copper spiral previously mentioned was led out of the wooden box at the top and was then connected through a commutator, in series with storage batteries and resistances adapted to sending a desired current through the foil. A Weston milliammeter provided with shunts and a Siemens-Halske milliammeter placed in the circuit were used in determining the strength of the current, the instrument read for any particular value being the one giving the most favorable range of scale. Both ammeters were carefully calibrated by means of a potentiometer and the two were checked against each other at frequent intervals.

SOLUTIONS.

The nickel and cobalt salts used were pure products obtained from Kahlbaum, and were found, upon analysis in the Chemical Laboratory of this University, to be free from cobalt and nickel respectively and from other ferromagnetic material. Conductivity water was used for the solutions. The nickel chloride was analyzed by Professor Fales of the department of chemistry at Columbia. The solutions of this salt were made up and analyzed by Professor Fales about two years before being used and had been carefully kept in non-soluble glass bottles. The densities were determined shortly before the susceptibility measurements were made. The cobalt salts were analyzed and new solutions made up for this work under the direction of Professor Beans, also of the department of chemistry at Columbia. In preparing the solutions a stock solution of the highest concentration was first made up. The lower concentrations were prepared from this by dilution. The concentrations of the several solutions were later determined by analysis. These determinations were for a temperature of 20 ± .005° C. The data giving the concentrations were supplied by the chemists. The water used in the magnetic measurements was from the same conductivity water (this having been preserved together with the solutions), from which the nickel solutions had been prepared.

The densities were obtained by means of a pycnometer of about 10 c.c. capacity. They were found for a temperature well within 20 ± .02° C.

THEORY OF METHOD.

The theory of the method may be expressed in terms of well-known relations. Any magnetic substance placed in a non-uniform magnetic field is acted upon by a mechanical force due to the field. Considering Maxwellian stresses in the media, it can be shown that the resultant force, F_l, acting upon a liquid slab contained in the vessel, V, is, for the position of the vessel given in these experiments, a force in the direction of the length of the vessel and of magnitude

$$F_l = \tfrac{1}{2}KA(H_1^2 - H_0^2), \tag{1}$$

where A is the area of cross-section of the slab at right angles to the direction of F_l, K the product of the permeability of the medium in which the system is suspended and the susceptibility of the liquid against the medium, and H_1 and H_0, with close approximation, the impressed magnetic forces at the ends of the slab in the stronger and weaker parts of the field respectively.

On account of the symmetry of the suspended system with reference to the central vertical plane parallel to the pole faces, the resultant force, F, due to the field effective in deflecting the system has also the direction of the length of the vessel. If F_t and F_c denote this force when the vessel is filled with liquid and when empty, respectively, the difference between these forces for a given field is a measure of the force due to the field upon the liquid:

$$F_l = F_t - F_c \tag{2}$$

for a given field.

Let f be defined as any force acting upon the system in the direction of the length of the vessel. (F_t and F_c are then particular values of f.) If d is the displacement of the system due to the force f in the direction of the force, elementary mechanics gives the following relation applicable for the case of small displacements and negligible stiffness of the suspension:

$$f = \frac{M'gd}{l}, \tag{3}$$

in which M' is the mass suspended, l the length of the suspension, and g the acceleration due to gravity.

If a current I amperes is sent through the tinfoil of length l' across the end of the vessel when the foil is placed in a field H_I there results, in accordance with electromagnetic theory, a force f given by

$$f_I = \frac{H_I l' I}{10}. \tag{4}$$

With a given excitation of field suppose a current I', and again a current I'', to flow through the tinfoil. Let δ' and δ'' denote respectively the resulting displacements of the system. The displacements being due to the concurrent action of the field upon the system and upon the respective currents, we may equate the sum of the magnetic and electro-magnetic forces to the mechanical force, and thus obtain from (3) and (4)

$$F \pm \frac{H'l'I'}{10} = \frac{M'g\delta'}{l}$$

and

$$F \pm \frac{H''l'I''}{10} = \frac{M'g\delta''}{l},$$

where H' and H'' are the fields at the positions of the tinfoil at distances δ' and δ'' respectively from the undeflected position.

If the currents I are so directed that F and the respective forces f_I are opposing forces only the negative signs of the last two equations need be retained. If δ' and δ'' are small it may be assumed that $H' = H'' = H$, where H is the field at the undeflected position of the tinfoil. Under these conditions the equations give

$$H = \frac{10M'g}{ll'} \frac{(\delta'' - \delta')}{(I' - I'')}$$

and

$$F = \frac{M'g}{l} \frac{(\delta''I' - \delta'I'')}{(I' - I'')} .$$

This method of determining H and F may be made all but a zero method since δ may be made small at will by suitably adjusting I.

When (as here) displacements are measured by means of a micrometer screw, it is convenient to write $\delta' = kn'$ and $\delta'' = kn''$ in which k is the value in cm. of one head division of the screw, and n' and n'' readings in head divisions. We have, then,

$$H = \frac{10M'gk}{ll'} \frac{(n'' - n')}{(I' - I'')} \tag{5}$$

and

$$F = \frac{M'gk}{l} \frac{(n''I' - n'I'')}{(I' - I'')} . \tag{6}$$

It is assumed (a) that the equalities $H' = H'' = H$ given above hold for the range of displacements used in these experiments. Assuming (b) that the field H_1 at the field end of the liquid slab is sensibly equal to the field at the position of the tinfoil, and (c) that H_0^2 is negligible in comparison with H_1^2, equations (1) and (2) give for the undeflected position of the system,

$$K = \frac{2(F_t - F_c)}{AH^2} . \tag{7}$$

Equations (5), (6), and (7) serve for computing K by the method of these experiments. C.G.S. units are used throughout.

If the atmosphere in which the system is suspended has a volume susceptibility κ_a, the volume susceptibility of the liquid, κ_l, is

$$\kappa_l = K + \kappa_a. \tag{8}$$

The specific (mass) susceptibility of the liquid, χ_l, is determined from this by the defining equation for χ_l, namely,

$$\chi_l = \frac{K_l + \kappa_a}{\rho_l} , \tag{9}$$

ρ_l being the density of the liquid.

Under the assumption that the additive relation expressed in Wiedemann's law[1] holds for the solutions used in these experiments, (an

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[1] Ann. der Phys. und Chem., 126, 1, 1865.

assumption made tentatively but allowed to stand in view of the constancy of the respective results obtained for χ_s),[1] we have

$$m_l'\chi_l = m_s'\chi_s + m_w'x_w, \tag{10}$$

in which m' denotes mass (in grams), χ specific susceptibility, and the subscripts l, s, and w refer to the solution, salt, and water respectively. If m is molecular weight, M the concentration (molar) of the solution, and L the number of c.c. in a liter, equation (10) may be written

$$\chi_l = \frac{m_sM}{L\rho_l}\chi_s + \left(1 - \frac{m_sM}{L\rho_l}\right)\chi_w. \tag{11}$$

Equations (9) and (11) give

$$\frac{m_sM}{L}\chi_s + \left(\rho_l - \frac{m_sM}{L}\right)\chi_w - \kappa_a - K_l = 0, \tag{12}$$

from which χ_s may be computed if both χ_w and κ_a are known, or if K_w is measured, ρ_w being given, and either χ_w or κ_a is known.[2]

In these experiments K_w has been determined, ρ_w taken from tables, and Piccard's[3] value for χ_w found for a temperature of 20° C. used.

Postulating that susceptibility is an additive (atomic) property of the dissolved salts[4] for the solutions used, we have in conformity with the Wiedemann law,

$$m_s\chi_s = m_m\chi_m + m_j\chi_j, \tag{13}$$

subscripts m and j relating to the metal and acid radical of the salt respectively. From this equation the molecular susceptibility, $m_m\chi_m$, may be computed if $m_j\chi_j$ is known. Pascal's[5] value for $m_j\chi_j$ (corrected) has been used.

Weiss's equation from which the number of magnetons has been found is:

$$N = \frac{\sqrt{3RT\chi_m}}{1123.5}, \tag{14}$$

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[1] Wiedemann, himself, pointed out, and others have since noted again and again, that results for the susceptibility of the solute obtained by the application of this law were dependent upon the chemical state of the solution. Among the more recent papers of interest with reference to this (and to the additive relation, equation 13), are:

A. E. Oxley, Camb. Phil. Soc. Proc., Vol. 16, p. 421, 1912; Vol. 17, p. 65, 1912.

A. Quartaroli, Soc. Chim. Ital. Gazz., 46^1, p. 371, 1916, and the review by P. Weiss (l.c.).

[2] The three equations of the form (12) corresponding to three solutions of the same salt having different concentrations (for one of which M may be zero) may be solved, if χ_s and χ_w are constants, for χ_s and also χ_w and κ_a in terms of accepted constants, m, L, (and ρ_w) and the quantities measured in these experiments: the data given in this paper have not been found with the precision desirable for use in the solution of these equations.

[3] C. R., 155, p. 1234, 1912.

[4] See note 2 above.

[5] C. R., 148, p. 413, 1909.

in which R is the gas constant, T the absolute temperature, and 1123.5 the moment of the gram magneton.

MEASUREMENTS.

Test experiments showed the assumptions (*a*), (*b*), and (*c*) of the preceding section to be permissible. The values of M', l, l', and A were found by usual methods. The quantities n and I were obtained as follows: with a given mass suspended, preliminary trial gave the approximate value of I required for a chosen current through the magnet in order that the resulting electromagnetic force, f_I, and the force, F, due to the field should balance. This current I was then passed through the tinfoil and the field excited; the current through the foil was then so adjusted as to bring the index alternately to within n' and n'' units of the undeflected position, and the corresponding readings of the ammeter I_r' and I_r'' recorded. The displacements n' and n'' were observed through the microscope and recorded in terms of "head divisions" of the micrometer screw. The readings I_r' and I_r'' multiplied by the ammeter constant, s, gave the currents I' and I'' respectively. An odd number of settings (sometimes three, sometimes more) were made so that the initial and final readings were for the same position. A set of five or more readings could easily be obtained in a few seconds; the averages of the values for I_r' and I_r'' were used. These readings were taken at a temperature which did not differ from 20° C., as shown by the thermometer above the cell, V, by more than ± 0.2° C.[1] The determination of l, l', and A, and of M', n', n'', I_r' and I_r'' for the system with the empty cell in position and with the cell filled with each of the several liquids, together with the microscope and ammeter constants, k and s, completed the measurements required (the densities and chemical data being obtained) for the determination of the values $m_m\chi_m$ and N.

DATA AND COMPUTED VALUES.

The following have been taken as constants in this work:

Accepted Values.	*Measured Quantities.*
$g = 980.2$ cms/sec^2,	$l = 81.50$ cms.,
$L = 1000$ c.c.,	$l' = 1.387$ cms.,
$R = 83.155 \times 10^6$ ergs/degree,	$A = 0.848$ cm^2.,

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[1] A variation within a half degree or less in temperature had no noticeable effect upon the observations; but a temperature range of a few degrees resulted in marked differences in the values obtained. Since it was the aim in these experiments to determine the susceptibility at a constant temperature no quantitative work was done with the purpose of determining accurately the value of the temperature coefficient. Qualitative work however showed clearly that the coefficient was far greater for the glass or other parts of the suspended system han for the liquids used.

$\rho_w = 0.99823$ gms/c.c., $k = 0.00005883$ cm.
$\chi_w = -0.71927 \times 10^{-6}$,
$m_i\chi_i = -40 \times 10^{-6}$,

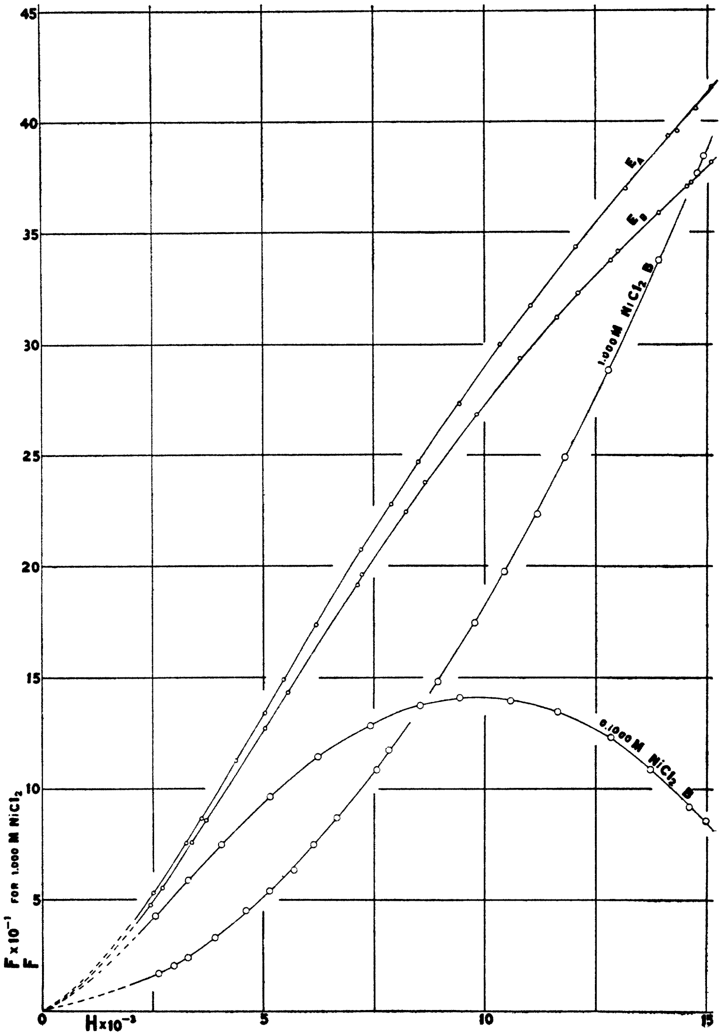

Fig. 2.

Figures 2–6 present graphically values obtained for F and H. Curves E are $F_c - H$ curves, others $F_t - H$ curves for the several liquids as indicated. Subscripts A, B, C, and D designate the particular $F_c - H$ curve, E, which obtained when the measurements giving the respective $F_t - H$ curves A, B, C, and D were taken. (In all cases points on the

$F_c - H$ curve were determined both before and after the observations for an $F_t - H$ curve were made.) The difference in the curves E are attributed to incidental changes in the apparatus.

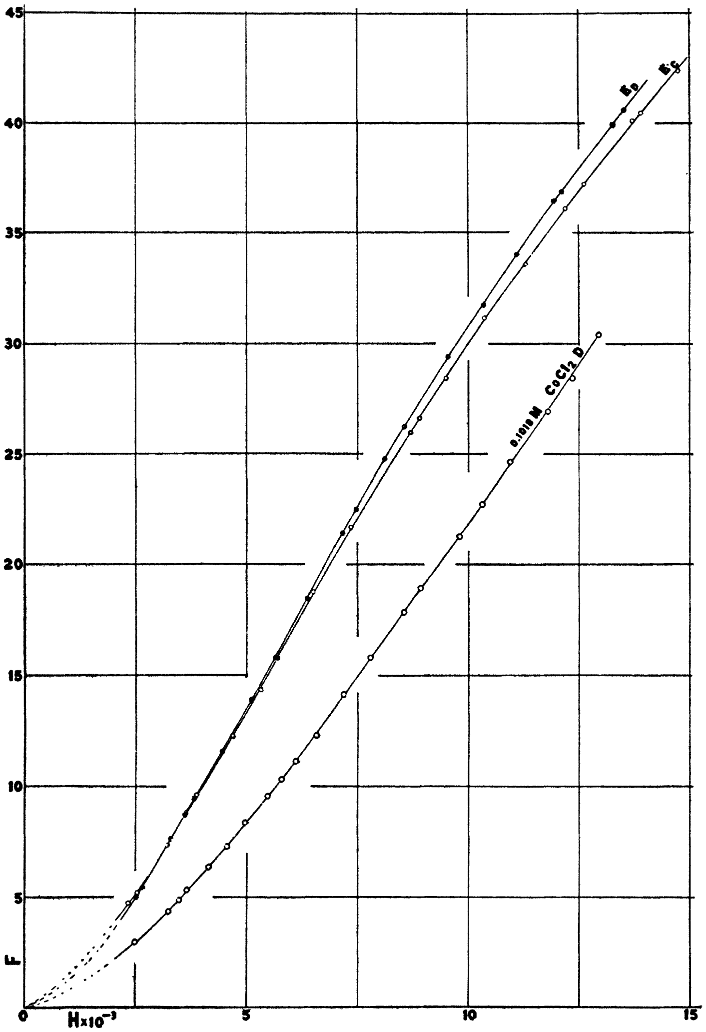

Fig. 3.

Tables I., II., and III. (curves E_A, H_2O A, and 0.001000 M $NiCl_2$ A) are illustrative of the 17 similar tables containing data from which, together with given constants, the $F - H$ curves were obtained.

Tables IV. and V. are representative of tables giving K for each of the liquids (including two for water). The values of H (at 1,000 gauss intervals within the range used) and of F used in computing K are averages of several determinations read from curves so plotted that the fourth significant figures (where given) of the F columns were estimated tenths of millimeters along the axis of ordinates, and that estimated tenths of millimeters along the axis of abscissas corresponded to 5 units in the H columns. The several tables are summarized in Table VI.

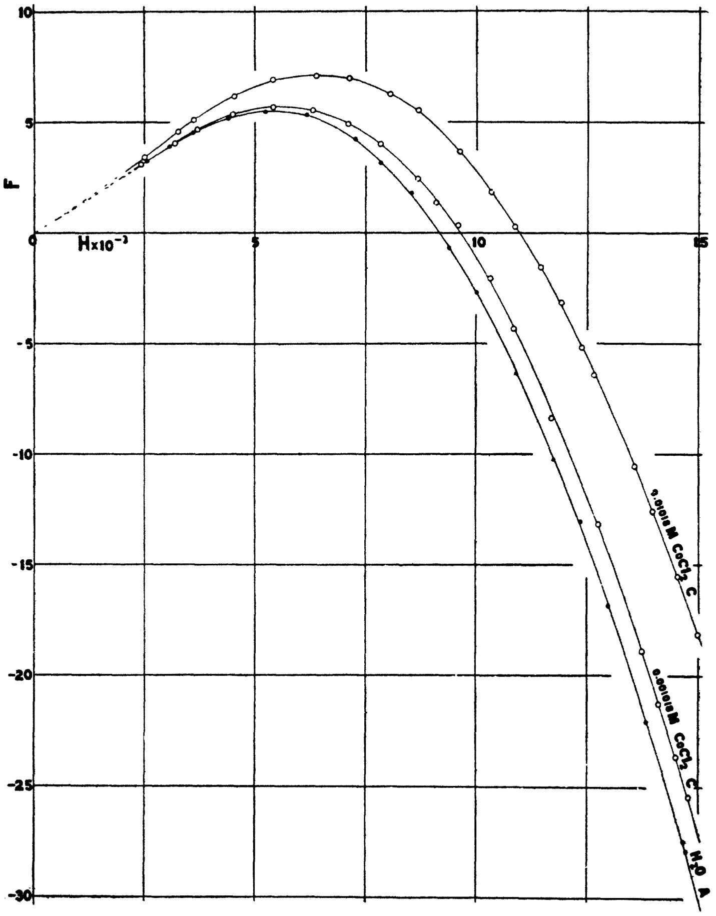

Fig. 4.

The densities ρ_l recorded in Tables VII. and VIII. are average values written, as in the case of the values of K, (Table VI.), with two deviation figures. Columns 5 and 6 of Tables VII. and VIII. give the values found by these experiments for the molecular susceptibility and magneton number of nickel and cobalt respectively. The deviations in the respective values are shown in columns 7.

If K_l, K_w, ρ_l, χ_w, and M are known to within approximately the same percentage of error, the effect upon $m_s\chi_s$ of the errors in χ_w and M are negligible in comparison with the errors in K_l, K_w and ρ_l (which contribute about equally to errors in $m_s\chi_s$) for the dilute solutions: for the more concentrated solutions errors in K_w, ρ_l and χ_w are negligible in comparison with errors in K_l and M.

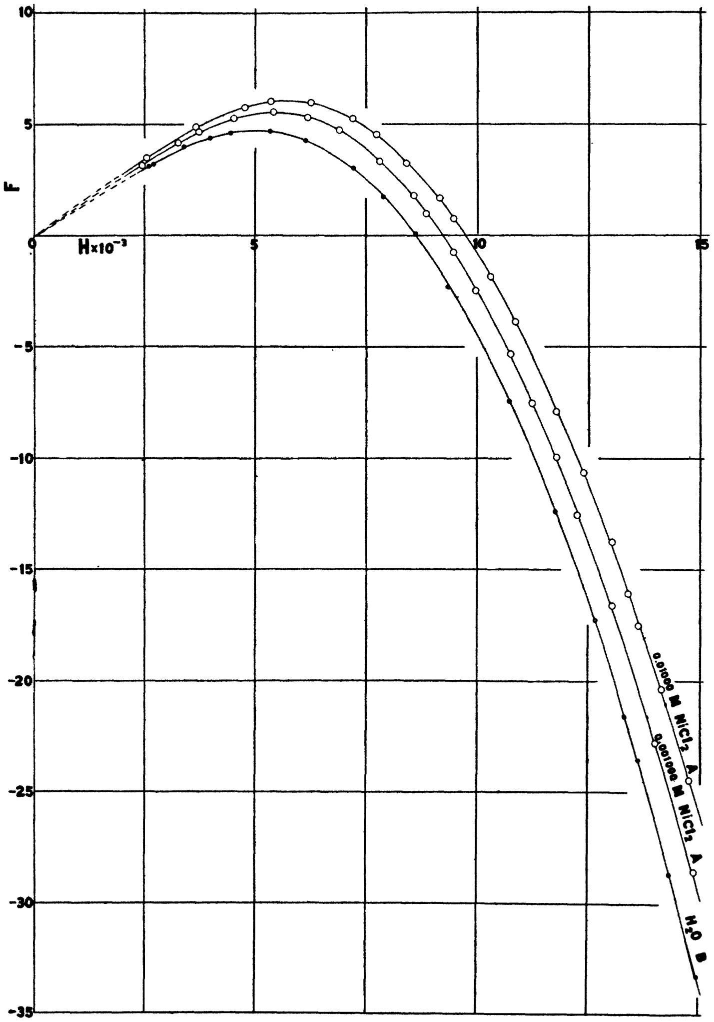

Fig. 5.

For the results in this paper, if the deviations in the values of K and ρ are taken as indicating the magnitude of errors in K and ρ, the value of

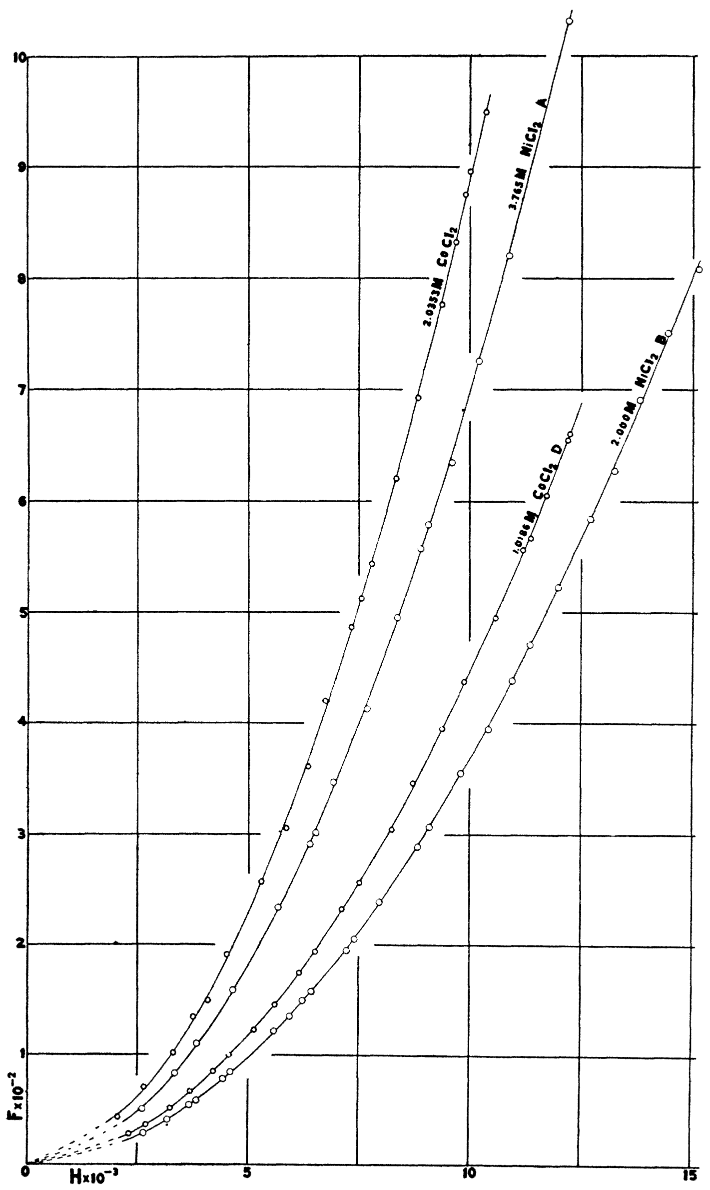
$F \times 10^{-2}$
$H \times 10^{-3}$
0
1
2
3
4
5
6
7
8
9
10
5
10
15
2.0353M $CoCl_2$
3.765M $NiCl_2$ A
1.0186M $CoCl_2$ D
2.000M $NiCl_2$ B

Fig. 6.

TABLE I.

Data for System with Empty Cell. Curve (E_A).

$M' = 51.412$ gms.

$n' = 0$; $n'' = 100$ head div.

$s = 2.674 \times 10^{-4}$. $t = 20°$ C.

I_r' (Amp/s).	I_r'' (Amp/s).	F_c (Dynes).	H (Gauss).
56.70	96.00	5.248	2,512
62.78	93.10	7.532	3,256
65.15	92.60	8.634	3,596
69.85	92.40	11.27	4,378
72.55	92.20	13.43	5,024
74.00	92.05	14.91	5,469
76.05	92.00	17.35	6,191
78.00	91.70	20.71	7,206
78.30	90.80	22.79	7,898
78.70	90.30	24.68	8,510
78.45	88.90	27.31	9,447
78.75	88.30	30.00	10,340
78.05	87.00	31.71	11,030
77.40	85.60	34.34	12,040
76.20	83.70	36.96	13,160
75.70	82.70	39.34	14,100
75.00	81.90	39.54	14,310
74.70	81.40	40.56	14,730
74.75	81.30	41.51	15,070

TABLE II.

Data for System with Cell Filled with Water. Curve H_2O *A*.

$M' = 59.990$ gms.

$s = 2.674 \times 10^{-4}$ $t = 20°$ C.

I_r' (Amp/s).	I_r'' (Amp/s).	n' (Head Div. = Cm/k).	n'' (Head Div. = Cm/k).	F_t (Dynes).	H (Gauss).
34.50	79.70	0	100	3.240	2,548
34.70	72.30	"	"	3.917	3,068
34.20	66.25	"	"	4.529	3,594
32.00	58.20	"	"	5.184	4,397
28.40	50.40	"	"	5.479	5,236
23.50	60.90	"	200	5.334	6,160
−16.00	47.40	−200	"	4.245	7,268
−62.80	84.60	−500	500	3.155	7,820
−61.80	73.20	"	"	1.792	8,533
−63.30	59.40	"	"	− 0.675	9,388
−64.90	50.20	"	"	− 2.710	10,010
−68.60	36.90	"	"	− 6.377	10,920
−72.60	25.40	"	"	−10.22	11,750
−75.20	−28.60	"	0	−13.02	12,360
−79.60	−35.20	"	"	−16.83	12,970
−85.00	−43.30	"	"	−22.04	13,810
−90.20	−50.90	"	"	−27.47	14,660
−90.50	−51.40	"	"	−27.92	14,730

Table III.

Data for System with Cell Filled with 0.001000 *M* $NiCl_2$ *Solution. Curve* 0.001000 *M* $NiCl_2A$.
M' = 59.975 gms.
$s = 2.674 \times 10^{-4}$ t = 20° C.

I_r' (Amp/s).	I_r'' (Amp/s).	n' (Head Div. = Cm/k).	n'' (Head Div. = Cm/k).	F_t (Dynes).	H (Gauss).
35.10	82.10	0	100	3.169	2,450
35.00	70.40	"	"	4.196	3,253
34.10	65.00	"	"	4.683	3,727
31.75	57.30	"	"	5.273	4,507
27.90	49.20	"	"	5.558	5,407
23.30	41.95	"	"	5.302	6,175
18.80	35.50	"	"	4.777	6,896
−47.40	70.80	−400	400	3.359	7,792
−61.50	72.90	−500	500	1.800	8,569
−62.10	68.10	"	"	0.978	8,845
−63.00	58.60	"	"	− 0.768	9,471
−64.50	50.90	"	"	− 2.500	9,979
−67.00	40.20	"	"	− 5.304	10,743
−69.40	33.10	"	"	− 7.514	11,240
−71.90	−23.00	"	0	− 9.980	11,780
−78.20	−34.00	"	"	−12.55	12,250
−78.80	−34.60	"	"	−16.61	13,030
−85.20	−44.10	"	"	−22.77	14,010
−90.80	−52.10	"	"	−28.56	14,880

Table IV.

$K \times 10^6$ *for Water Computed from Data Read from Curves* E_A *and* H_2O *A.*
t = 20° C.

H (Gauss).	F_c (Dynes).	F_t (Dynes).	$K \times 10^6$.	Deviation.
3,000	6.725	3.875	−.7469	.00015
4,000	9.933	4.868	.7466	15
5,000	13.35	5.43	.7472	45
6,000	16.75	5.35	.7468	05
7,000	20.08	4.57	.7465	25
8,000	23.13	2.87	.7466	15
9,000	26.15	0.50	.7468	05
10,000	28.95	− 2.70	.7465	25
11,000	31.65	− 6.66	.7467	05
12,000	34.20	−11.40	.7469	15
13,000	36.62	−16.90	.7469	15
14,000	38.98	−23.07	.7466	15
			−.74675	.00017 (0.02%)

TABLE V.

$K \times 10^6$ for 0.001000 M $NiCl_2$ Solution Computed from Data Read from Curves E_A and 0.001000 M $NiCl_2$ A.
$t = 20°$ C.

H (Gauss).	F_c (Dynes).	F_t (Dynes).	$K \times 10^6$.	Deviation.
3,000	6.725	3.891	−.7427	.00031
4,000	9.933	4.900	.7419	49
5,000	13.35	5.48	.7424	01
6,000	16.75	5.42	.7423	09
7,000	20.08	4.65	.7427	31
8,000	23.13	2.98	.7426	21
9,000	26.15	0.65	.7425	11
10,000	28.95	− 2.53	.7424	01
11,000	31.65	− 6.43	.7422	19
12,000	34.20	−11.12	.7423	09
13,000	36.62	−16.57	.7423	09
14,000	38.98	−22.72	.7424	01
			−.74239	.00016 (0.02%)

TABLE VI.

$K \times 10^6$ for Water and Solutions of Nickel and Cobalt Chloride. Summary.
$t = 20°$ C.

Liquid.	Field Range (Gauss $\times 10^{-3}$).	$K \times 10^6$ (Average).	Number of Values of $K \times 10^6$.	Percentage Deviation.
Water (*A*)	3 to 14	− .74675	12	.02
Water (*B*)	"	− .74681	"	.02
		− .74678		
0.001000 *M* $NiCl_2$ solution	"	− .74239	"	.02
0.01000 " " "	"	− .70304	"	.02
0.1000 " " "	"	− .30841	"	.07
1.000 " " "	"	+ 3.6660	"	.04
2.000 " " "	"	+ 8.0333	"	.02
3.765 " " "	3 to 10	+15.7968	8	.02
0.001018 *M* $CoCl_2$ solution	3 to 14	− .73621	12	.03
0.01018 " " "	"	− .64148	"	.03
0.1018 " " "	3 to 12	+ .30534	10	.07
1.0186 " " "	"	+ 9.7819	"	.03
2.0353 " " "	3 to 10	+20.305	8	.04

Table VII.

Data for Nickel Chloride Solutions. (Susceptiblity of Air.) Molecular Susceptibility and Magneton Number of Nickel.

$m_s = 129.60$ $t = 20°$ C.
$\kappa_a = 0.02878 \times 10^{-6}$.

Solutions.			$\chi_s \cdot m_s$	$\chi_{Ni} \cdot m_{Ni}$	N	Deviation.
M (mols/liter).	ρ_l (gms/c.c.).	$\kappa_l \times 10^6$				
0.001000	0.99836	− .71361	0.004388	0.004428	16.01	.005
0.01000	0.99946	− .67426	0.004369	0.004409	15.98	25
0.1000	1.01044	− .27963	0.004379	0.004419	16.00	05
1.000	1.11618	3.6948	0.004405	0.004445	16.04	35
2.000	1.22827	8.0621	0.004380	0.004420	16.00	05
3.765	1.42042	15.826	0.004379	0.004419	16.00	05
				0.004423	16.005	.013 (0.08%)

Table VIII.

Data for Cobalt Chloride Solutions. (Susecptibility of Air.) Molecular Susceptibility and Magneton Number of Cobalt.

$m_s = 129.89$.
$\kappa_a = 0.02878 \times 10^{-6}$. $t = 20°$ C.

Solutions.			$\chi_s \cdot m_s$	$\chi_{Co} \cdot m_{Co}$	N	Deviation.
M (mols/liter).	ρ_l (gms/c.c.).	$\kappa_l \times 10^6$				
0.001018	0.99825	− .70742	.010300	.010340	24.47	.028
0.01018	0.99939	− .61274	.010330	.010370	24.51	12
0.1018	1.01007	.33412	.010326	.010366	24.50	02
1.0186	1.11364	9.8128	.010325	.010365	24.50	02
2.0353	1.22427	20.326	.010330	.010370	24.51	12
				.010362	24.498	.011 (0.05%)

$m_s\chi_s$ for the most dilute nickel chloride solution should be within about 2 per cent. (giving N to about 1 per cent.), and for the most dilute cobalt solution, within 1 per cent. (giving N to about 0.5 per cent.): the results for the second most dilute nickel solution should hold to about 0.2 per cent. (0.1 per cent. for N), and the results for all other solutions to about 0.1 per cent. (0.05 per cent. for N). These percentages were determined assuming an error of 0.1 per cent. in values of M.

Results and Discussion.

The principal results obtained from these experiments are:

1. Within a field range of 3,000 to 14,000 gausses for the lower concentrations and of 3,000 to 10,000 for the higher, the magnetic suscepti-

bilities of the liquids used are shown to be independent of the strength of the field.

2. Nickel chloride in aqueous solutions varying in concentration from 0.001000 to 3.765 M and cobalt chloride in concentrations varying from 0.001018 to 2.0353 M have magnetic susceptibilities independent of the concentrations.

3. Under these conditions the molecular susceptibility of nickel at a temperature of 20° C. is found to be 0.004423, and of cobalt 0.010362. The corresponding magneton numbers for nickel and cobalt respectively are 16.0 and 24.5.

4. It follows from (2) that for the solutions used in these experiments the Wiedemann law holds.

Another result obtained in these experiments is that the volume susceptibility of the air of the laboratory at a temperature of 20° C. is, if Piccard's value for water is accepted, 0.0288×10^{-6}: this represents the value for air as regards moisture and pressure for the average conditions obtaining over a period of a number of months.

The susceptibility of air found in these experiments agrees closely (within about 2 per cent.) with Piccard's[1] value given at a temperature of 20° C. and 760 mm. pressure, and (within 0.2 per cent.) with the value recently obtained by Soné.[2]

The values obtained for nickel are in good agreement with the results found by Cabrera, Moles and Guzman, and by Weiss and Mlle. Bruins: the values for cobalt agree with those obtained by Trümpler in his second series of measurements. These results, both for nickel and cobalt, show that in the case of the solutions used no changes in chemical constitution of such a nature as to affect the susceptibility of the salt have accompanied concentration changes. This is not in accordance with the results obtained by Trümpler working with his earlier solutions, or by Cabrera, Jimeno and Marquina for the solutions used by them, or with the results obtained by Quartaroli.

The lack of agreement between the results for cobalt by different observers points to the desirability of a more detailed study of cobalt solutions.

The magneton number for nickel found in these experiments supports the Weiss magneton theory. The number for cobalt presents again the half-magneton already found in the case of other solutions:[3] it would accord with Weiss's theory if the gram-magneton were assigned half the value given in equation (14).

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[1] C. R., 155, p. 1234, 1912; Sci. Arch., p. 458, Vol. XXXV, 1913.

[2] Phil. Mag., Ser. 6, p. 309, Vol. 39, 1920.

[3] K. Akad., Amst. Proc., 18, 1915.

ACKNOWLEDGMENTS.

The writer takes this opportunity to express her thanks to Professors Fales and Beans for their work on the chemistry of the solutions.

The electromagnet was loaned by the department of physics of Barnard College through the courtesy of Professor Maltby: for this and other courtesies shown by Professor Maltby and Miss Langford of that department the writer wishes to express her appreciation. She is indebted to Mr. Cooey, research mechanician at Fayerweather Hall, both for the construction of apparatus and for suggestions used in improving the design of certain parts. She is most deeply indebted to Professor Albert P. Wills, who suggested the problem and directed the research during the earlier part of the investigation, and to Professor Bergen Davis who assumed the direction of the work during the absence of Professor Wills from the university.

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