# THE HALL EFFECT AND THE NERNST EFFECT IN MAGNETIC ALLOYS.

By Alpheus W. Smith.

Synopsis.

*Hall Effect in Magnetic Alloys.*—In the *iron-copper series* a maximum effect was obtained with 1.5 per cent. copper. The variation with composition is very similar to the variation of electric resistance. In the *nickel-copper series* the effect reaches a maximum with about 26 per cent. copper when the composition corresponds to the formula $CuNi_3$, and then drops suddenly to a small fraction of its maximum value. In the *iron-nickel series*, although the effect is positive for iron and negative for nickel, the effect increases linearly with the proportion of nickel added to iron until for 13 per cent. nickel it is six times as great as for pure iron. In certain alloys the *variation of the effect with the field strength* is anomalous, the effect being negative for weak fields and positive for strong ones. An *explanation based on the theory of Borelius* is suggested which assumes that in addition to the positive part of the effect which is proportional to the field strength there is a negative part which reaches a limiting value for strong fields.

*Nernst Effect in Magnetic Alloys.*—In the *nickel-copper series* the effect varies with composition in nearly the same way as the Hall effect does, reaching a maximum for the composition $CuNi_3$. In the *iron-nickel series*, the effect decreases with the addition of nickel, becoming zero for about 2.2 per cent. nickel and positive for higher concentrations. With 13 per cent. nickel the effect is about five times as great as in pure iron.

*Relation of the Hall and Nernst Effects to Crystal Structure.*—It is *suggested* that the amount and direction of these effects are determined by the crystal lattices and the fields of force in the intramolecular spaces.

THE Hall effect and the Nernst effect in magnetic alloys are of peculiar interest because of the fact that any theory of the reversa of these effects considers the molecular magnetic fields about the molecules as a large factor in determining the direction of these effects. That these molecular fields can not offer a complete explanation of these reversals is evident from the fact that the Hall effect is positive in iron and cobalt and negative in nickel,—the other magnetic element. Yet these molecular fields must have a part either directly or indirectly in determining the direction of these effects. Whether these molecular fields produce their effect by determining the polarization as the theory of Borelius[1] indicates or by producing a deflection of the free electrons opposite to that caused by the impressed magnetic field as the theory of Thomson requires,[2] is question for which there is now no answer.

[1] Borelius, Ann. der Phys., 58, p. 489, 1919.

[2] Thomson, The Corpuscular Theory of Matter, p. 70.

In view of the importance of the direction of the Hall effect and the Nernst effect in magnetic substances it seemed desirable to make some additional observations on these effects in magnetic alloys.

## The Alloys.

The magnetic, optical and thermal properties of a number of magnetic alloys prepared by Burgess and Aston[1] from very pure electrolytic iron have been studied in the Electrochemical Laboratory and in the Physical Laboratory[2] of the University of Wisconsin. Since these alloys were exceptionally pure and made with great care it was desirable to make the observations on the Hall effect and the Nernst effect in these same alloys as far as possible. This avoids the uncertainty which arises out of composition and methods of preparation. Professor Kowalke, of the Department of Chemical Engineering of the University of Wisconsin, kindly supplied me with the specimens of iron-copper and iron-nickel alloys used in this investigation. For this assistance I am greatly indebted to Professor Kowalke. These specimens were taken from alloys prepared by Burgess and Aston. Concerning their preparation and purity reference is made to the work of Burgess and Aston[3] and to that of Ingersoll.[4] From these specimens were forged plates of suitable dimensions for my observations.

The nickel entering into the nickel-copper series was kindly furnished me by Mr. John F. Thomson, of the International Nickel Co. It was electrolytic nickel giving according to Mr. Thomson the following analysis: nickel, 99.840 per cent.; copper, 0.108 per cent.; and iron, 0.130 per cent. The copper used in the nickel-copper series was obtained from the Baker Chemical Co. The analysis supplied with it showed only negligible traces of impurities.

The nickel-copper alloys were prepared by melting weighed amounts of nickel in a magnesia crucible heated in a gas blast furnace. When the nickel had melted weighed amounts of copper were dropped into the crucible and the mixture thoroughly stirred with a graphite rod. The alloy was then allowed to cool slowly until it had solidified and reached room temperature. This cooling took place without removing the crucible from the furnace and required about four hours. From the ingots thus prepared was cut a plate of suitable thickness and area for observations on the Hall effect and the Nernst effect. The compositions indicated in the following tables were determined from the weighed amount of nickel and copper entering into the alloys.

[1] Burgess and Aston, Met. & Chem. Eng., 8, 23 and 79, 1910.

[2] Littleton, Phys. Rev., (33. p. 453. 1911) Ingersoll, Phys. Rev., N.S., 16, 126, 1920.

[3] Burgess and Aston, ibid.

ngersoll, ibid.

## The Hall Effect.

The observations on the Hall effect were made at room temperature by the method described by the author[1] in previous papers. The value of the Hall constant $R$ was calculated by means of the familiar equation,

$$E = R\frac{iH}{d},$$

where

$E$ = the Hall electromotive force in absolute units,

$H$ = the magnetic field in C.G.S. units,

$i$ = the current in the plate in C.G.S. units,

$d$ = the thickness of the plate in centimeters.

The observations on the iron-copper series have been plotted in Fig. 1;

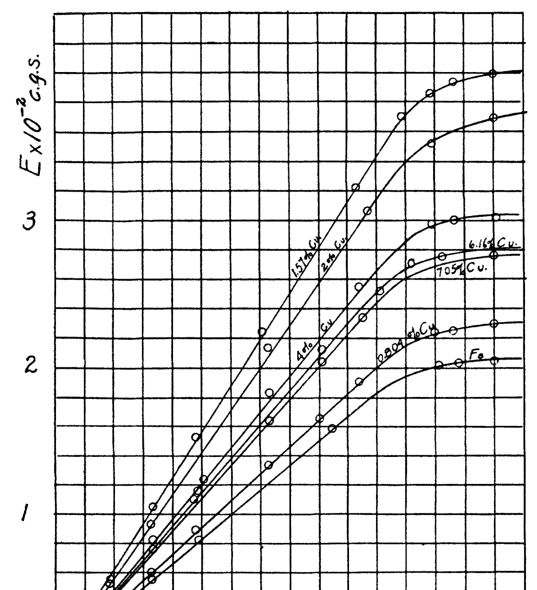


Fig. 1.

those on the nickel-copper series in Fig. 2 and those on the iron-nickel series in Fig. 3. In these figures the Hall electromotive forces in a plate 1 cm. thick, carrying a current of one absolute unit have been plotted as ordinates and the magnetic fields as abscissæ. These curves showing

[1] Smith, Phys. Rev., p. 30, 1, 1910.

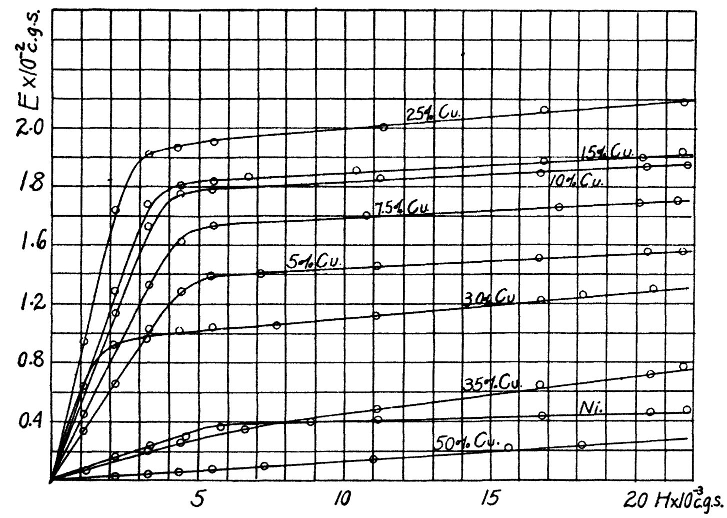
E×10⁻² c.g.s.
2.0
1.8
1.6
1.2
0.8
0.4
25% Cu.
15% Cu.
10% Cu.
7.5% Cu.
5% Cu.
3.0% Cu
35% Cu.
Ni.
50% Cu.
5
10
15
20 H×10⁻³ c.g.s.

Fig. 2.

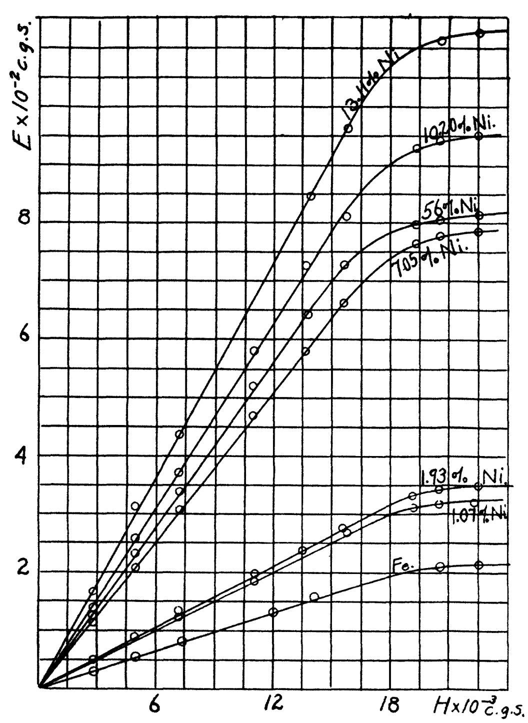
E×10⁻² c.g.s.
8
6
4
2
10.20% Ni.
5.6% Ni.
7.05% Ni.
1.93% Ni.
1.07% Ni
Fe.
6
12
18
H×10⁻³ c.g.s.

Fig. 3.

the relation between the Hall electromotive force and the magnetic field which produced it, consist of a part in which the electromotive force is proportional to the magnetic field followed by a part showing the electromotive force increasing slowly and approaching saturation for large magnetic fields.

The Hall constants for these alloys have also been plotted as functions of the composition in Figs. 4 and 5. In these figures the Hall constants

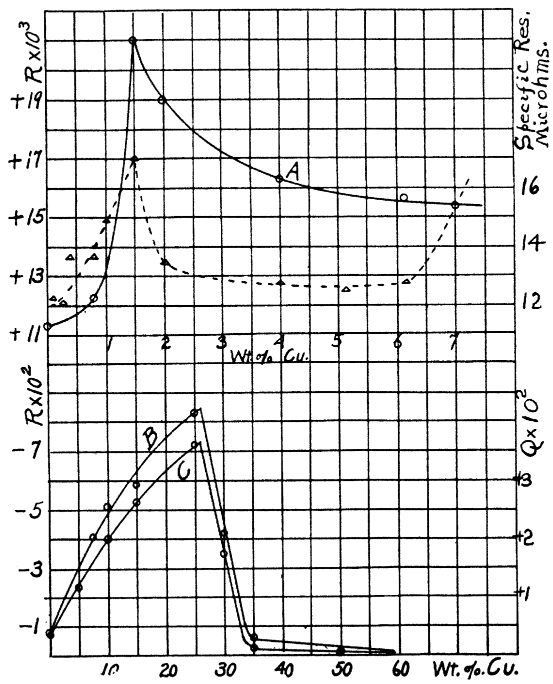

Fig. 4.

have been used for ordinates. In Fig. 4 the abscissæ are the percentage of copper in the alloys and in Fig. 5 they denote the percentages of nickel in the iron-nickel series. The values of the Hall constants plotted in these curves and also given in Tables I., II. and III. have been calculated for values of the magnetic field at which there is still proportionality between the magnetic field and the Hall electromotive force so that for these and smaller fields the Hall constant is independent of the magnetic field. Curve *A* (Fig. 4) showing the relation between the Hall constants and the percentages of copper in the alloys for the iron-copper series calls attention to the rapid rise in the Hall constant produced by adding a small amount of copper to iron. Although the Hall effect is positive in iron and negative in copper the addition of copper to iron causes an increase in the Hall effect. After the alloy contains 1.5 per cent. of copper a further increase in the percentage of copper produces a sudden drop in the Hall effect after which the effect decreases slowly with

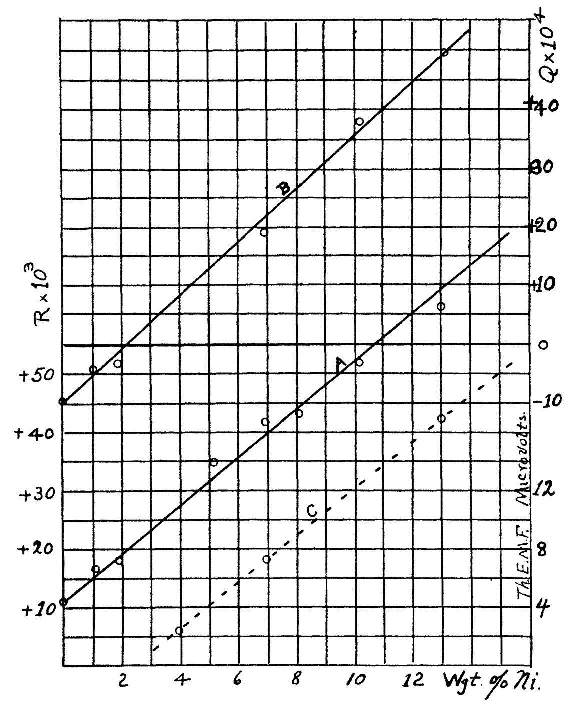


Fig. 5.

further increase in the content of copper. The form of this curve is quite similar to the dotted curve of Fig. 4 showing the dependence of the specific resistance on the percentage of copper in the alloys. This curve is from the work of Burgess and Aston[1] on these same alloys. The peaks in the curves occur at the same concentration and with the exception of the point representing the alloy containing 7 per cent. of copper the general characteristics of the curves are the same. Evidently the factors which determine the electrical resistance in this case must in large measure determine the Hall effect.

Curve *B* (Fig. 4) shows the influence of copper on the Hall effect in nickel. There is at first a rapid rise in the effect with the addition of copper. This rise continues until the alloy contains a little more than 26 per cent. of copper where the Hall effect has its largest value which is about eleven times its value in pure nickel. As the percentage of copper

[1] Burgess and Aston, Met. & Chem. Eng., 8, 79, 1910.

TABLE I.

*The Hall Effect in Iron-copper Alloys.*

| Per Cent. Fe. | Per Cent. Cu. | $R$ |
|---|---|---|
| 100 | 0 | $+ 11.2 \times 10^{-3}$ |
| 99.196 | .804 | + 12.2 |
| 98.49 | 1.51 | + 21.0 |
| 98.0 | 2.0 | + 19.0 |
| 96.0 | 4.0 | + 16.3 |
| 93.84 | 6.16 | + 15.6 |
| 92.95 | 7.05 | + 15.2 |

is still further increased the effect decreases rapidly reaching a value which is about eighty per cent. of the value in pure nickel for the alloy containing 35 per cent. of copper. As the percentage of copper is increased more and more the Hall effect continues to decrease evidently approaching the value in pure copper. The break in the curve showing the Hall constant as a function of the concentration of nickel indicates clearly the formation of the compound $CuNi_3$ when the proper amounts of nickel and copper are present in the alloy. It is worthy of note that although the direction of the Hall effect in nickel is opposite to that in iron, the effect produced by introducing small quantities of copper into iron or nickel is the same—a very large increase in the Hall effect. This increase is more rapid in iron than in nickel but continues to higher concentrations of copper in the case of nickel than in the case of iron.

TABLE II.

*The Hall Effect and the Nernst Effect in Nickel-copper Alloys.*

| Per Cent. Ni. | Per Cent. Cu. | $R$ | $Q$ |
|---|---|---|---|
| 100 | 0 | $- 7.65 \times 10^{-3}$ | $+ 3.48 \times 10^{-3}$ |
| 95 | 5 | − 29.8 | + 11.8 |
| 92.5 | 7.5 | − 40.9 | + 14.7 |
| 90 | 10. | − 52.0 | + 20.7 |
| 85 | 15. | − 59.1 | + 25.6 |
| 75 | 25 | − 83.7 | + 35.0 |
| 70 | 30 | − 41.9 | + 17.4 |
| 65 | 35 | − 6.31 | + 0.97 |
| 50 | 50 | − 1.33 | + 0.17 |

The relation between the Hall constant and the percentage of nickel in the iron-nickel series is given in Curve $A$ (Fig. 5) for alloys containing not more than 13.11 per cent. of nickel. It is seen from this curve that there is a proportionality between the Hall constants and the percentages of nickel in the alloy for these alloys. Although the effect is positive in iron and negative in nickel, the addition of nickel to iron causes a marked increase in the Hall effect so that an alloy containing 13.11 per cent. of nickel has a Hall effect which has the same direction as the effect in pure iron and about five times its magnitude. This increase does not of course continue indefinitely as is seen by noting the observations on an alloy containing 56 per cent. of nickel. The Hall effect in this alloy (Table III.) is considerably less than it is in an alloy containing 13.11 per cent. of nickel. Consequently somewhere between these two concentrations the Hall effect must cease to increase and begin to decrease with increasing concentration of nickel. The increase in the Hall effect with increasing concentration of nickel probably continues until the alloy has a nickel content of about 35 per cent. corresponding to the compound $Fe_2Ni$ where these alloys have been found to show a number of unusual properties. As soon as this concentration is passed there is a decrease in the effect with further increase in the concentration of nickel giving values of the Hall constant which finally approach the value in pure nickel as the percentage of nickel is increased indefinitely. In Curve *C* (Fig. 5) are represented the thermoelectric heights of these alloys against copper as a function of the concentration of nickel for concentrations lying between 4 per cent. and 13.11 per cent. The data for this curve are from the work of Ingersoll. Curve *A* and Curve *C* (Fig. 5) are nearly parallel to each other. Hence in this case as in a number of other cases the thermoelectric heights of the metals or alloys are nearly proportional to the Hall constants.

TABLE III.

*The Hall Effect and the Nernst Effect in Iron-nickel Alloys.*

| Per Cent. Fe. | Per Cent. Ni. | *R.* | *Q.* |
|---|---|---|---|
| 100 | 0 | $+ 11.2 \times 10^{-3}$ | $- 9.75 \times 10^{4}$ |
| 98.93 | 1.07 | + 16.9 | − 4.21 |
| 98.07 | 1.93 | + 17.8 | − 3.06 |
| 92.95 | 7.05 | + 42.5 | + 19.03 |
| 91.83 | 8.17 | + 43.1 | —— |
| 89.80 | 10.20 | + 52.0 | + 38.0 |
| 86.89 | 13.11 | + 61.5 | + 49.5 |
| 44.0 | 56.0 | + 46.9 | + 1.33 |

## THE NERNST EFFECT.

The Nernst effect was measured in the manner described by the author[1] in preceding papers on this effect in metals and alloys. The temperature gradients in the plates were measured by means of advance-copper

[1] Smith, PHYS. REV., 32, p. 192, 1911.

thermal couples used with a Wolff potentiometer. Observations were made at only one strength of magnetic field and this field was so chosen that it was not great enough to produce the beginning of saturation which always occurs when the Nernst effect or the Hall effect is studied in magnetic metals or alloys. With fields less than that at which saturation begins to manifest itself, the Nernst electromotive force is proportional to the magnetic field and the constant which describes the effect is independent of the magnetic field. This constant which is usually designated as $Q$ was calculated from the following familiar equation,

$$E = Q\beta H \frac{\partial T}{\partial X},$$

where $E$ = the Nernst electromotive force in absolute units.

$\beta$ = the width of the plate in centimeters.

$H$ = the intensity of the magnetic field in C.G.S. units.

$\frac{\partial T}{\partial X}$ = the temperature gradient in the plate in degrees Centigrade per centimeter.

The temperature at which $Q$ was determined was found by taking the mean of the temperatures indicated by the thermal couples which were used to determine the temperature gradient in the plate. This mean temperature was between 55° and 56° C. The values of $Q$ recorded in Table II. and III. are, therefore, the values of the Nernst constant at 55° or 56° C.

In Fig. 4 (Curve $C$) the values of the Nernst constant $Q$ have been plotted against the percentages of copper in the nickel-copper series of alloys. The data from which this curve was plotted have also been recorded in Table II. The form of the curve obtained in this way is very similar to the corresponding curve for the Hall effect in these alloys (Curve $B$, Fig. 4). The break in each of the curves occurs at the same place indicating the formation of the compound $CuNi_3$. The other characteristics of the curves are quite similar and it is evident that the Hall effect and the Nernst effect in this case are intimately associated, since the presence of the copper in the nickel changes the two effects in the same way.

The relation between the Nernst effect and the concentration of nickel in the iron-nickel series is represented in Curve $B$ of Fig. 5. The data from which this curve was obtained are recorded in Table III. The Nernst effect is regarded as negative in iron and positive in nickel. The introduction of nickel into the iron causes the Nernst effect to decrease in magnitude and become zero when the alloy contains about

2.2 per cent. of nickel. When the concentration of nickel becomes higher than about 2.2 per cent. the direction of the effect reverses and becomes that in nickel. When the concentration of the nickel is still further increased the Nernst effect increases and reaches in an alloy containing 13.11 per cent. of nickel a value which is about five times its value in pure iron. For these lower concentrations of nickel the relation between the Nernst effect and the concentration of nickel is represented by a straight line. In this respect the behavior of the Nernst effect for this series of alloys is like the behavior of the Hall effect and the thermoelectric heights. From Fig. 5 it is evident that the curve in each case is a straight line and that the lines are nearly parallel to each other. From the observations on the Nernst effect in an alloy containing 56 per cent. of nickel (Table III.) it is clear that the increase in the Nernst effect with increasing concentration of nickel ceases at some concentration lying between 13.11 per cent. and 56 per cent. of nickel. The concentration at which this increase in the Nernst effect ceases and a decrease begins is probably the concentration at which the compound $Fe_2Ni$ is formed. This is also the concentration at which the Hall effect ceases to increase and begins to decrease with further increase in the concentration of nickel. The behavior of the Nernst effect at this point is very similar to the behavior of the Hall effect and some of the physical properties of the alloys. This relationship between the Hall effect, the Nernst effect and the other physical properties of these alloys suggests that these effects are intimately associated with the structure of the alloys. The similarity of the behavior of the Hall effect, the Nernst effect and the thermoelectric heights in these alloys for the lower concentrations of nickel is of considerable interest. It suggests clearly an intimate relation between these effects and the possibility that this relation may not be very complicated. The nickel produces the same kind of change in each of these cases.

## POSITIVE AND NEGATIVE HALL EFFECTS.

The existence of positive and negative Hall effects has been the subject of much difficulty in the electronic theory of metals. Recently Borelius[1] has pointed out that his conception of magnetism leads to an explanation of positive as well as negative Hall effects. In this theory of the electrical and magnetic properties of metals use is made of the space lattice theory of the solid state. The space lattice is assumed to consist of alternate positive metal ions and negative electrons. Each atom of the metal has lost a single electron. Under the action of repulsive force

[1] Borelius, Ann. der Phys., 58, 489, 1919.

arising from the fields of force surrounding the metal ions, these electrons are equally spaced between the atoms at positions of equilibrium. When an atom in a crystal lattice swings out from its position of equilibrium, it pushes the electron in front of it in the same direction. The electron moves forward in a curved path to occupy the free space behind the atom. When the atom swings back in the opposite direction, an electron moves forth now in the opposite direction. Assuming that all the electrons move on paths of equal radius a magnetic field perpendicular to $X-Y$ plane in the direction of the positive $Z$-axis will exert a force on the electrons revolving in this plane causing a change in their magnetic moment. This change in magnetic moment may be regarded as made up of two parts—that arising from the change in the radius of the path of the electron and that arising from the change in the angular velocity of the electron in its path. From these changes in magnetic moment—one radial, the other circular—Borelius calculates the radial and circular diamagnetic susceptibilities.

The action of the magnetic field on the electrons revolving in the $X-Z$ and $Y-Z$ planes is to cause a sort of polarization by which the electronic paths lying in these planes are rotated in such a way that they tend to set their planes of rotation perpendicular to the magnetic field—that is, perpendicular to the $Z$-axis. With this polarization is associated a change in magnetic moment in the direction of the $Z$-axis. This change will be an increase in magnetic moment and is, therefore, a paramagnetic effect.

Suppose that in addition to the magnetic field which points in the direction of the positive $Z$-axis there is applied to the metal an impressed electromotive force so that the negative or electron current flows in the direction of the negative $X$-axis. The current consists of an excess of those electronic paths which convey the current in the direction of the negative $X$-axis. Assume that one half of these electronic paths lie in the $X-Z$ plane and the other half in the $X-Y$ plane. Consider first the $X-Y$ plane. The cause of the transverse Hall current when the primary current is closed or the magnetic field is established, is thought of as an electric polarization which exists as the combined action of the magnetic field and the primary current. This polarization is from considerations of symmetry parallel to the $Y$-axis. Since change in the angular velocity of the electrons produces no polarization, this polarization arises only in connection with radial diamagnetism, in which there is a displacement of the electrons in the $X-Y$ plane due to the action of the magnetic field. This displacement is along the radius of the path of the electron. The direction of the resulting polarization is such as would be set up by an electric force acting in the direction of the negative $Y$-axis. Such a force would shove an electron moving in a curved path along the negative $X$-axis in the direction of the positive $Y$-axis. The Hall effect arising from such a displacement of electrons is in the customary notation called positive. It is important to notice that the displacement of the electrons obtained on the basis of this theory is opposite to the displacement of electrons obtained under corresponding conditions on the basis of the gas free electron theory of Drude and others.

The value of the Hall constant $R_d$ for electrons revolving in the $X-Y$ plane is found to be

$$R_d = \frac{3}{4en}.$$

It is, therefore, independent of the magnetic field, the current in the plate and the thickness of the plate. Moreover, it is always positive.

Consider now the action of the magnetic field on the electrons revolving in the $X$–$Z$ plane. The effect here will be the sort of polarization which gives rise to paramagnetism. The nature of the polarization in this case may be made clearer by comparing it with the polarization which arises in the doublet theory of electrical and thermal conductivity which has been proposed by J. J. Thomson.[1] Let $AB$ be a doublet lying in the $X$–$Z$ plane with a magnetic field acting in the direction of the positive $Z$-axis and an electric field in the direction of the positive $X$-axis. Assume that the doublet is free to turn about the positive charge $A$. The electric field gives a force tending to bring the axis of the doublet in line with the $X$-axis. As soon as the negative charge at $B$ begins to move, it will be acted on by a downward force by making $B$ dip below the $X$–$Z$ plane, and thus making the negative end of the doublet below the positive. This has the effect of making more doublets have their negative ends below their positive ends than above them. This is equivalent to the action of an electric force in the direction of the positive $Y$-axis. Such a force would drive electrons down the negative $Y$-axis; that is, in the opposite direction to that in which they were driven in the diamagnetic part of the Hall effect. Borelius gives for this part of the Hall constant which is associated with paramagnetism,

$$R_p = -\frac{1}{ne}F(\psi),$$

where $F(\psi)$ is a function of the magnetic field and is always positive. For this reason this part of the Hall constant is always negative.

The total Hall constant is the sum of its positive and negative parts

[1] Thomson, Corpuscular Theory of Matter, p. 100.

and is therefore given by the equation,

$$R = \left[\frac{3}{4ne} - \frac{1}{ne}F(\psi)\right].$$

For the case of unit current flowing in a plate of unit thickness, the Hall electromotive force becomes,[1]

$$E = \left[\frac{3}{4ne} - \frac{1}{ne}F(\psi)\right]H,$$

where $H$ is the magnetic field; $n$, the number of electrons per cubic centimeter and $c$, the electronic charge.

This electromotive force may then be regarded as made up of two parts—a positive part which is represented by a straight line through the origin and a negative part represented by the function $F(\psi)H$ about which we know little. For values of $\psi$ lying between $\psi = 104°$ and $\psi = 157°$ Borelius states that the function $F(\psi)$ decreases. Hence $F(\psi)H$ which measures the negative part of the Hall electromotive force would increase less rapidly than if proportional to the magnetic field.

### Reversal of the Hall Effect in Alloys.

It seems to me that the reversal of the Hall effect in alloys offers some evidence for the correctness of this theory. In the study of the Hall effect in alloys of bismuth and tin von Ettingshausen and Nernst[1] found that the effect in these alloys is either positive or negative according to the intensity of the magnetic field. With small magnetic fields the effect is negative. It increases to a maximum value as the magnetic field is increased, then decreases and reverses its direction when sufficiently large magnetic fields are used. The magnetic field necessary to produce this reversal is larger for alloys containing a small amount of tin than for alloys containing a large amount of tin. More recently Becquerel[2] has studied this reversal of the Hall electromotive force in a plate cut from a crystal of bismuth. In such plates the magnetic field at which the reversal takes place depends on the direction of the crystalline axis with respect to the magnetic field and the plane of the plate. A similar reversal was found by the author[3] in alloys of bismuth and lead. A curve showing the relation between the Hall electromotive force and the magnetic field for these alloys is given in Fig. 6. Now as Becquerel pointed out, such curves can be split up into two parts—Curve $A$, a straight line passing through the origin, and Curve $B$, which rises to a

[1] von Ettinghausen and Nernst, Ann. der Phys., 33, p. 474, 1888.
[2] Becquerel, Comp.-Rendu., 154, pp. 1795–1798, 1912.
[3] Smith, Phys. Rev., N.S., 10, p. 358, 1917.

fixed value and then remains parallel to the horizontal axis. The sum of the ordinates of these two curves gives the ordinates of the observed curve. This analysis regards the Hall electromotive force as made up of two parts which are opposite in sign. That part which is positive is a linear function of the magnetic field. The negative part increases rapidly at lower fields but reaches a limiting value at higher fields beyond which it does not increase. Because the negative part reaches a limiting value while the positive part increases indefinitely, it is obvious that at sufficiently high magnetic fields the positive part will predominate. As the percentage of lead in the alloy is increased the form of the curve is not changed but the slope of the curve showing that part of the Hall electromotive force which is proportional to the magnetic field is smaller the greater the percentage of lead or tin in the alloy.

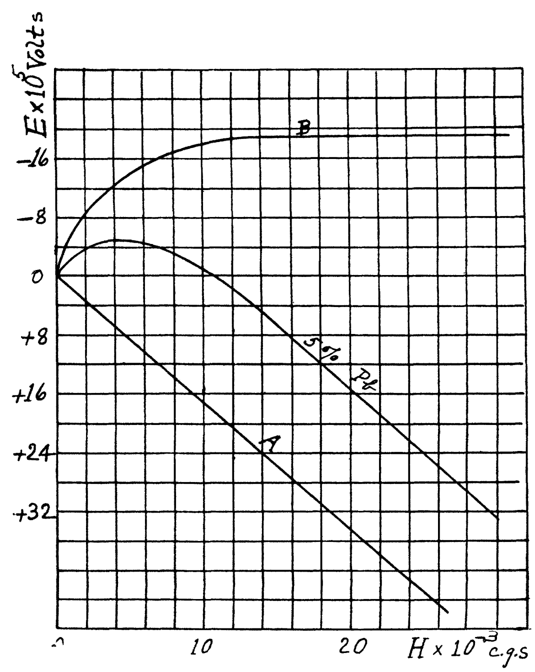


Fig. 6.

Now the splitting up of a Hall electromotive force into two such parts as those shown in Curve $A$ and Curve $B$ of Fig. 6 is precisely what the theory of Borelius would require. The theory requires that one of these parts be a linear function of the magnetic field and that this part be positive. Curve $A$ in Fig. 6 represents then both the theoretical and the observed relation between this part of the Hall electromotive force and the magnetic field. The qualitative agreement between the theory and observations for this part of the Hall effect seems satisfactory. The gas free electron also requires that the Hall electromotive force be a linear function of the magnetic field but the slope of the curve is opposite to that obtained from the theory of Borelius and, therefore, opposite to the slope of Curve $A$ (Fig. 6). The gas free electron theory can not, therefore, offer an explanation of that part of the Hall electromotive force represented by Curve $A$ (Fig. 6). With respect to the second part of the Hall electromotive force the agreement between the theory of Borelius and the observations is less certain. This uncertainty arises out of the fact that we do not know how the function $F(\psi)$ depends on the magnetic field. For certain values of the angle $\psi$ Borelius states that this function $F(\psi)$ decreases. If we are at liberty to assume that $F(\psi)H$ at first increases with the magnetic field and at higher fields reaches a limiting value beyond which it does not increase, then curves of the form of Curve $B$ would represent the requirements of the theory as well as the observations. In view of the dependence of $F(\psi)$ on the magnetic field such as assumption is reasonable. If such an assumption can be accepted the reversal of the Hall effect in alloys agrees qualitatively with the theory proposed by Borelius.

## Conclusion.

From this study of the Hall effect and the Nernst effect in these magnetic alloys it is seen that these effects are intimately associated. In some cases as in the iron-copper series there is also an intimate relationship between the Hall constant and the electrical resistance and in other cases as in the iron-nickel series an intimate relationship between the Hall constants and the thermoelectric heights of the alloys. All of these phenomena are evidently intimately related to each other and to the other physical properties of the alloys. In view of the dependence of these effects on the mechanical properties of the metals and alloys, the most inviting suggestion for a theory by which to explain them is that made by Borelius who undertakes to use the conception of the crystal lattice and the intermolecular fields of force as the basis of his theory. In the vibration of the atoms in the crystal lattice and in the variation of the fields of force about them rather than in the action of the magnetic field on the free electrons in the interstices between the atoms, the explanation of these rather complicated effects will probably be found.

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