Guerin's suggestion of a symbiotic relationship. Such can be conceived of as arising from a former sclerotium- (or spore-) forming habit by the adoption of a new intra-seminal mode of infection.

"On the Effects of Magnetisation on the Electric Conductivity of Iron and Nickel." By GUY BARLOW, B.Sc., Research Fellow of the University of Wales. Communicated by Professor A. GRAY, F.R.S. Received February 20,—Read March 6,—Received in revised form June 18, 1902.

That magnetisation has an effect on the electric conductivity of metals was first noticed in 1856 by William Thomson* (Lord Kelvin), and since then, on account of its very great theoretical interest, this phenomenon has formed the subject of numerous experiments. These later investigations have been made by Tomlinson,† Righi,‡ Hurion,§ Leduc,|| Ettingshausen and Nernst,¶ Ettingshausen,** Goldhammer,†† Lenard and Howard,‡‡ Lenard,§§ Henderson,|||| Beattie,¶¶ Gray and Jones,*** and others.

Two cases of the phenomenon must be carefully distinguished—(i.) Longitudinal effect, when the direction of the electric current is parallel to the lines of magnetic force. (ii.) Transverse effect, when the current is perpendicular to the lines of force. The latter effect is closely connected with the Hall phenomenon, and has received the name of Longitudinal Hall Effect.

The following results obtained by previous experimenters are of interest in connection with the present investigation. For bismuth, Goldhammer found the change of resistance to vary as the square of the magnetic field, and since in this metal the magnetisation I is proportional to the field, this result may be written $\Delta\phi = aI^2$, where $\Delta\phi$ denotes the *fractional* increase of resistance, *i.e.*, the increase of resist-

* 'Math. and Phys. Papers,' vol. 2, p. 307.
† 'Phil. Trans.,' 1883.
‡ 'Journ. de Physique,' vol. 3, p. 355 (1884).
§ 'Compt. Rend.,' vol. 98, p. 1257 (1884).
|| 'Compt. Rend.,' vol. 98, p. 673 (1884).
¶ 'Wien. Ber.,' vol. 94, part 2, p. 560 (1886).
** 'Wien. Ber.,' vol. 95, p. 714 (1887).
†† 'Wied. Ann.,' vol. 31, p. 360 (1887); vol. 36, p. 804.
‡‡ 'Electro-technische Zeitschrift,' vol. 9, p. 341.
§§ 'Wied. Ann.,' vol. 39, p. 619 (1890).
|||| 'Phil. Mag.,' vol. 2, p. 488 (1894).
¶¶ 'Phil. Mag.,' vol. 1, p. 243 (1898).
*** 'Roy. Soc. Proc.,' 1900, vol. 67.

ance divided by the resistance in zero field; and a is a constant. It is therefore suggested by Goldhammer that the above relation may be also true for the ferro-magnetic metals. In order to verify this a direct determination of the magnetisation is necessary. Beattie has investigated the transverse effect in thin films of iron, nickel, and cobalt, and determined the magnetisation by means of Kundt's result that for such films the Hall effect and the magnetisation are proportional. The relation $\Delta\phi = a\text{I}^2$ was confirmed in the case of the cobalt films, but not in those of nickel. In iron the variation of resistance was so small that accurate results were not obtained. In the more recent investigation of Gray and Jones on the change of resistance of iron wire magnetised longitudinally, the relation $\Delta\phi = a\text{I}^4$ was suggested as approximately representing their results between the field strengths 30 and 250 c.g.s.

The present investigation had for its object a more exact determination of the relation between the change of resistance and the magnetisation in the two ferro-magnetic metals—iron and nickel. As in the experiments of Gray and Jones the metal was in the form of a wire, so that a close approximation to uniform longitudinal magnetisation could be obtained. In the course of the investigation the hysteresis of resistance was found to be of such importance that this phenomenon was separately examined. Some determinations of the transverse effect were also included.

Experiments in Ordinary Magnetic Fields.

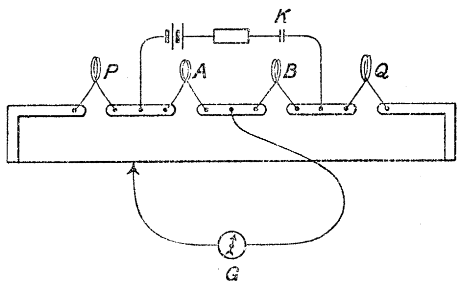
These experiments were made with three different specimens of wire, iron, steel, and nickel.

The magnetic field was obtained by means of a solenoid 1 metre in length, which was placed vertically. The current for this solenoid was produced by a battery of storage cells, and measured by means of a Kelvin graded galvanometer which was standardised from time to time. The maximum field was 450 c.g.s.

The Wheatstone-bridge method was used to determine the change of resistance, the connections being shown in fig. 1. P is the iron or nickel wire under investigation, Q a *comparison coil* of equal resistance. A very thick but uniform wire of German-silver was used for the bridge, but for measuring very small effects this was replaced by a nickel-plated copper wire having a much smaller resistance per unit length. A and B are two equal *auxiliary coils* of German-silver wire, immersed in an oil bath to avoid temperature differences. A Kelvin astatic galvanometer G of resistance 3·6 ohms was used in these experiments. In some preliminary measurements on the resistance change in the iron wire, the comparison resistance Q consisted of a spiral coil of the same wire. This method was first used by Gray

and Jones, and theoretically it should eliminate the temperature effects due to (1) the Joule heating effect in the iron wire caused by the current which flows through it, (2) radiation and conduction of heat from the magnetising solenoid, (3) gradual changes of temperature in the whole apparatus. It was found, however, that the second of these effects still gave rise to serious difficulties, since the necessary insula-

Fig. 1.



tion between the coils P and Q prevented rapid equalisation of temperature. Thus the transmission of heat from the solenoid affected the spiral coil Q sooner than it affected the coil P, and hence the equilibrium of the bridge was disturbed. This method was therefore modified, the following arrangement being finally adopted. It will be sufficient to describe only the experiments on nickel, as in the case of the other two metals the apparatus was essentially the same.

The resistance P consisted of two complete turns (*i.e.*, four lengths) of the nickel wire wound longitudinally on a thin rod of wood 65 cm. long. The connections to the bridge were made of thick copper wire soldered to the ends of the nickel coil. The resistance Q was equal to P, but consisted of thin copper wire wound in a similar way on the same rod. All the wires had double silk insulation. The coils were then covered with two layers of white wool and placed in a long glass tube which fitted into the magnetising solenoid; also the latter was provided with an internal water jacket, through which flowed a stream of cold water from the mains, the temperature of the water on entering and leaving the solenoid being indicated by two thermometers inserted in capsules through which the water flowed. This arrangement prevented rapid transmission of heat to the coils P and Q, so that the heating effect was always small, and varied very slowly; moreover, the heating effect in Q sufficiently compensated that in P. The current in the nickel wire never exceeded 0·05 ampere, and the bridge circuit being only closed for very short intervals, this current caused no observable change of resistance through the Joule heating effect.

The changes of resistance are determined as follows:—The nickel is first thoroughly demagnetised by the process of reversals; the reading x_0 of the bridge is then taken as soon as the equilibrium becomes steady. The magnetising circuit is then closed, and after reversing the current a number of times to ensure reaching a point on the curve of ascending reversals, the new reading x is taken. Finally, the magnetising current is broken, and the residual reading x' determined. Then $\Delta x = x - x_0$ is the "step" on the bridge wire due to the induced magnetisation, and $\Delta x_r = x' - x_0$ is the corresponding residual step. In taking the readings, the sliding contact piece is moved along the bridge until the point is reached at which no *permanent* deflection of the galvanometer needle takes place when the bridge current is made or broken. This was found to be the most satisfactory way of eliminating the thermo-electric effects in the bridge wire. Before each set of readings the specimen was reduced to a neutral state by the process of demagnetisation, thus avoiding the errors due to slow changes of temperature.

The fractional change of resistance $\Delta\phi$ in the nickel wire P corresponding to the step Δx is calculated from the formula

$$\Delta\phi = \frac{\Delta P}{P} = \frac{A+B}{A.B}.\sigma\Delta x,$$

where σ is the resistance per unit length of the bridge wire. A slight correction is required for the resistance of the copper leads connecting P to the bridge.

A preliminary experiment was made to test the effect of the magnetic field on the resistance of the copper comparison coil Q. The nickel coil was disconnected from the bridge, an equal resistance of German-silver being substituted. Only the copper coil Q remained in the solenoid, and as no change of resistance was observed, it was concluded that in copper the effect is negligible.

The magnetisation curves were obtained by the ballistic method. Seven pieces of the nickel wire, each 65 cm. long, were enclosed in a thin glass tube, round the middle of which was wound a ballistic coil of 200 turns of fine copper wire. The glass tube was placed in the axis of the magnetising solenoid, and the coil connected to a ballistic galvanometer provided with telescope and scale. The galvanometer was standardised before and after each set of readings by means of a standard solenoid and secondary coil.

The true magnetic force H in the nickel is given exactly by $H = H' - NI$ where H' is the magnetic field, calculated from the known constant of the solenoid and the strength of the magnetising current, and N is the demagnetising factor for the bundle of wire. In both the resistance and magnetic apparatus the value of N was less than 0·0005, so that this term could be neglected.

Results.—The corresponding values of $\Delta\phi$, H, and I for the process of ascending reversals of magnetisation in nickel, iron, and steel are contained in Table II. The change of resistance is always an increase, and is about eight times greater in nickel than in iron or steel for the same field. If we take $\Delta\phi$ as ordinate and H as abscissa, the curves obtained will be found to have the same characteristics as the ordinary magnetisation curves, except that the points of inflection are not so strongly marked. The result is quite different if I be taken as abscissa. In this case we obtain for the three metals a curve which has no point of inflection, but which resembles in general form a semi-cubical parabola, the curve being remarkably flat near the origin and then rising very steeply. Figs. 2 and 3 show the relation of $\Delta\phi$ to I for nickel and iron respectively, the abscissa being the *square* of the magnetisation. The curve for steel differs very little from that of iron.

For the three metals it is found that the relation $\Delta\phi = a\mathrm{I}^4$, suggested by the experiments of Gray and Jones, is not generally satisfied (*i.e.*, the curves in figs. 2 and 3 are not parabolas), although it is nearly true for strong fields in the case of iron. In weak fields the variation of resistance appears to depend on a lower power of the magnetisation, and in order to represent the results for the three metals by the same formula it was found necessary to adopt the more general expression

$$\Delta\phi = a\mathrm{I}^2 + b\mathrm{I}^4 + c\mathrm{I}^6,$$

which must only be regarded as a convenient method of expressing the results. The relative values of the coefficients a, b, and c, are as follows:—

Nickel..............	$a : b : c$	$= 19 : 57 : -4$
Iron	$a : b : c$	$= 74 : 3 : 31$

Thus the term containing I^4 is relatively much more important in nickel than in iron.

An examination of the hysteresis effects in the three metals led to some interesting results which will be best understood by reference to fig. 4. This curve exhibits the variation of resistance in the nickel wire for a cycle of magnetisation corresponding to a double reversal of a magnetic field of about 165 c.g.s. The resistance hysteresis loops for the three metals possess the same characteristic features. As the field diminishes from its maximum value, H = +165 to zero, the descending branch of the curve lies above the ascending, and in zero field the two branches intersect at the point which represents the residual change of resistance. Then as the field is reversed to small negative values, the resistance continues to diminish until at a certain critical value of the field the curve reaches a minimum. After passing this point the curve rises rather steeply (especially in iron and steel),

Fig. 2.

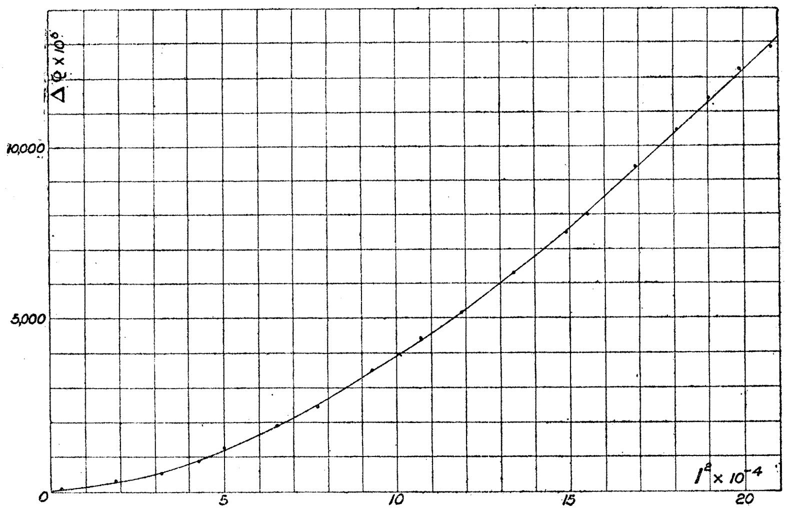
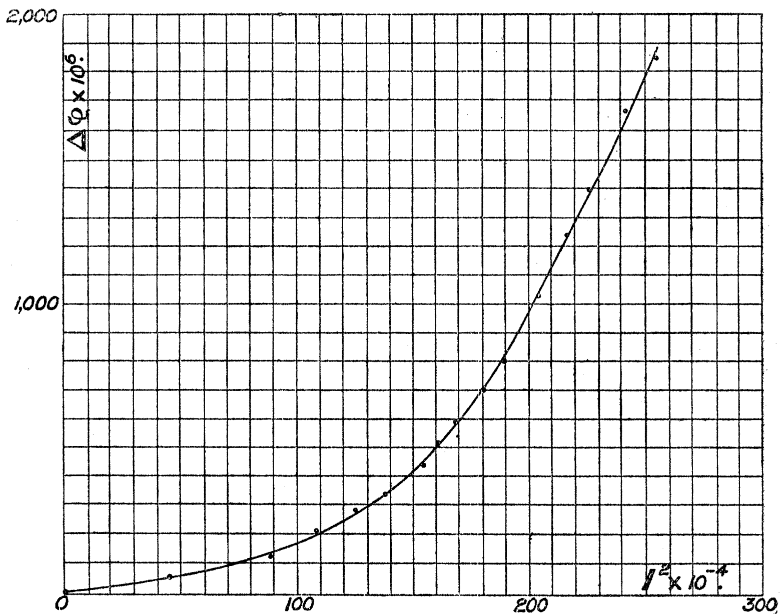


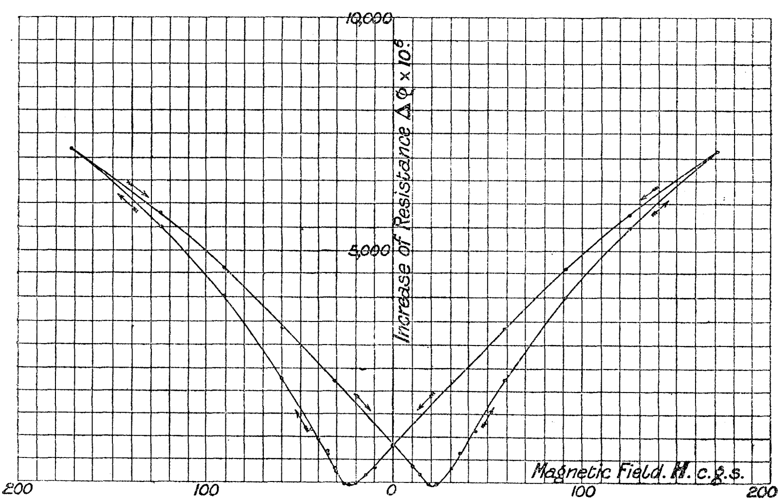
Fig. 3.



and, after inflection, attains its highest point with the maximum field H = −165. The loop is completed by a similar curve as the field changes from −165 to +165 units. At the two minimum points the

curve appears to *touch* the axis. The magnetic hysteresis loops were also obtained for exactly the same cycle, and a comparison of the two sets of curves indicates that the change of resistance is very closely related to the magnetisation. Thus the "minimum points," described above, appear to be identical with the points where the magnetisation loops *cut* the axis; or in other words, when the field is such as to reduce the magnetisation to zero, the change of resistance also vanishes. Thus this critical value of the field is approximately equal to the "coercive force" of the specimen. In all cases the curves represented the cyclic state that is obtained after a large number of reversals of the field.

FIG. 4.



It may be remarked that the corresponding $\Delta\phi$, I curves also possess loops, and hence it appears impossible to express $\Delta\phi$ as a function of I simply. Unfortunately the magnetisation loops were not accurate enough to allow of any attempt to establish a relation between the quantities $\Delta\phi$, H, and I for the general case of hysteresis.

For nickel it was observed that if at any point of the cyclic process the field be suddenly reduced to zero, the residual resistance will depend on the particular point of the cycle which has been reached. In the neighbourhood of the minimum points reducing the field to zero may cause an *increase* of resistance. The minimum residual effect was only about half that corresponding to the fields ± 165 c.g.s. In the other two metals a similar effect was noticed, but the investigation was not carried further, owing to the difficulty of observing such very small changes of resistance. These effects cannot be explained as resulting from the action of the earth's field.

It should be mentioned that the change of length produced by magnetisation in iron and nickel is too small in moderate fields to account for the observed variation of resistance; it is, however, possible that this effect may give rise to an important correction in strong fields.

It is obvious that the method employed in these experiments completely eliminates any change of resistance which is reversed in sign by reversal of the field; but such an effect has never been observed.

Experiments in High Fields.

Experiment I.—Longitudinal Effect in Nickel.

Another specimen of wire was used having a diameter of 0·33 mm., and covered with double silk insulation.

It being desirable to determine the magnetic field and magnetisation under exactly the same conditions as the change of resistance, the apparatus was arranged so as to allow the three measurements to be made with the same nickel coil. A modification of the "isthmus" method was adopted. The magnetic field was produced by means of a large electromagnet provided with conical pole pieces having faces 1·7 cm. in diameter.

The essential part of the apparatus is represented diagrammatically in figs. 5 and 6. The nickel wire was wound in a single layer, in and out the thin glass cylinder C, 1·1 cm. long and 1·1 cm. in diameter, so that the turns of the coil, 88 in number, were *parallel* to the axis of the cylinder, as shown in fig. 5. The glass being thin, the *transverse* end elements of the coil were small in comparison with the length of the cylinder. There were three ballistic coils; the innermost was wound on a glass tube D, the second on the brass cylinder B, and the outermost on the brass flange A, which extended over half the cylinder B. This system of coils was attached to one end of a wooden arm, having a pivot at the other extremity, by means of which the coils could be suddenly placed in the proper position between the poles of the magnet. Before every reading the nickel was demagnetised by a separate arrangement. The ballistic deflections as well as the resistance change were produced by placing the coils in the field, the effects of residual induction in the nickel being thus avoided. There being no compensation for temperature variations, it was necessary to make the observations as quickly as possible. It was arranged that the ballistic deflections measured the differences of the total induction through the consecutive coils. The values of H and I were then easily calculated from the two observed deflections.

As usual, it is assumed that the value of the field just outside the nickel is the same as that in the metal. The innermost ballistic coil

merely served to eliminate the value of the field near the axis. This method of determining I becomes insensitive when H is very great; it was therefore found impossible to obtain measurements of the magnetisation in this case. It is probable, however, that the saturation stage of magnetisation was practically reached within the range of the experiment.

FIG. 5.

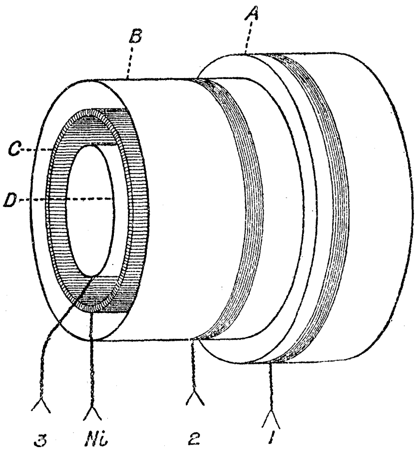
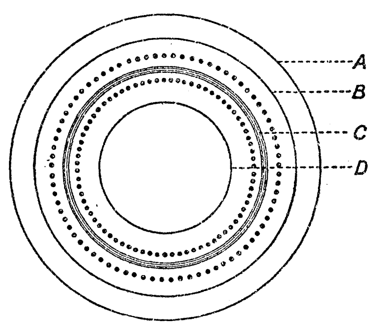


FIG. 6.



Conclusions.—That for fields ranging from 1000 to 11,000 c.g.s., the value of $\Delta\phi$ for longitudinal magnetisation in nickel wire is practically *constant*. This constant value

$$\Delta\phi = 0{\cdot}017$$

is greater than the values obtained in the experiments in ordinary fields.

The results indicated, however, that a slight *decrease* in $\Delta\phi$ takes

place in the highest fields, a peculiarity that could not be accounted for by the experimental errors. In order to investigate this effect in still higher fields, the following experiment was made :—

Experiment II.—Longitudinal Effect in Nickel.

The method used was the same as in Experiment I, but the apparatus was simplified and made as small as possible. The nickel wire was wound on a glass cylinder as before, the number of complete turns being thirty-four and length of cylinder only 5 mm. A small ballistic coil was placed in the axis of the nickel coil in order to determine the field. Finer pole pieces were used and the distance between them reduced to 7·5 mm. No attempt was made to measure the magnetisation, and the field determined by the ballistic coil is assumed to be the same as that in the nickel: as this had been proved to be approximately true in the former experiment.

Results.—The change of resistance now exhibits a decided maximum—

$$\Delta\phi = 0{\cdot}0156, \qquad H = 2000 \text{ c.g.s.},$$

and in higher fields decreases continuously to the value

$$\Delta\phi = 0{\cdot}0100, \qquad H = 18{,}000 \text{ c.g.s.}$$

To explain this result it appears necessary to consider the effect of the end-elements of the nickel coil. In this apparatus the end-elements formed a considerable fraction of the whole coil, whereas in Experiment I this fraction was small. These elements of the wire are magnetised *transversely*. Even if there were no transverse effect in nickel, the existence of the end elements reduces the observed change of resistance, and the necessary correction cannot be estimated. But the electrical resistance of nickel is diminished by the transverse magnetisation, and this effect may therefore easily explain the peculiar results of the above experiment.

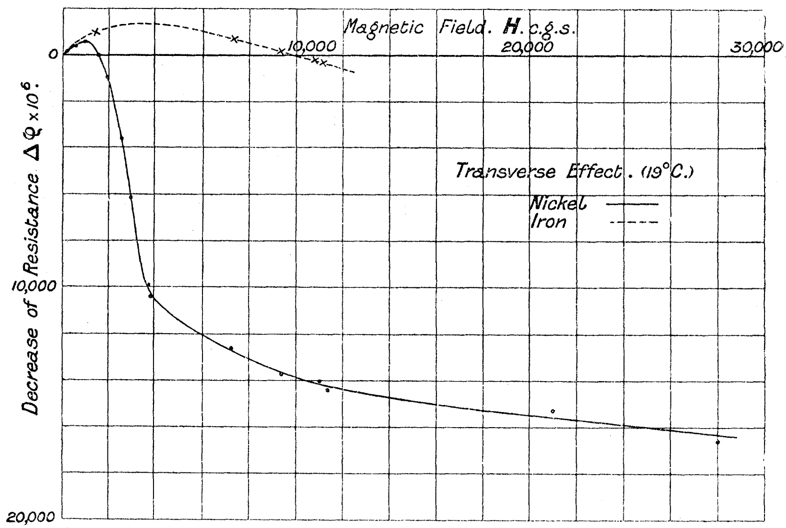
Experiment III.—Transverse Effect in Nickel.

The above experiments suggested that an examination of the transverse effect in the same specimen of nickel would prove of considerable interest. For this purpose a coil of the nickel wire was wound non-inductively on a short brass bobbin provided with wide flanges. The plane of the coil was placed at right angles to the lines of force, so that the whole of the wire was magnetised transversely. Very strong fields were obtainable on account of the small thickness of the coil, 3 mm. only. It is impossible to measure the magnetic field which exists in the metal in such a case, but the field undisturbed by the nickel coil was determined for each measurement of the

resistance change. The nickel coil was subjected to the demagnetising process before each reading.

The variation of resistance is shown in fig. 7.

FIG. 7.



In weak fields, $\Delta\phi$ has a small positive value, but a reversal takes place in a field of 1500 c.g.s. For higher fields $\Delta\phi$ is negative and increases continuously; even in the highest field, H = 28,000, there is no indication of $\Delta\phi$ having a definite limit. The general form of the curve is similar to the curves obtained by Beattie for certain nickel films.

From these results it was found that the decrease observed in Experiment II might be accounted for by assuming that about one-fifth of the wire was transversely magnetised. The slight decrease observed in Experiment I is also to be explained in the same way.

Experiment IV.—Transverse Effect in Nickel.

A flat spiral of the nickel wire was inclosed between two plates of mica. Using the fine pole pieces at a distance apart of only 1 mm., the following result was obtained:—

$$\Delta\phi = -0{\cdot}0199, \qquad H = 34,000 \text{ c.g.s.}$$

The field strength was determined before placing the spiral in the field. This value of the resistance change is the greatest effect observed in these experiments.

Experiment V.—Transverse Effect in Iron.

An attempt was also made to measure the transverse effect in iron, using the same method as in Experiment III. The effect observed

Table I.—Dimensions of Wires used in the Experiments.

Experiment.	Diameter of wire in millimetres.	Resistance. Ohms per centimetre. 15° C.	Actual resistance of coil in ohms. 15° C.	Total length of wire in centimetres.
Ordinary fields—				
Iron	0·330	0·01450	1·83	127
Steel	0·765	0·00382	1·01	263
Nickel	0·765	0·00217	0·573	264
High fields—				
Nickel. Exp. I ..	0·200	0·02900	6·90	—
,, ,, II ..	,,	,,	1·31	—
,, ,, III ..	,,	,,	4·65	—
,, ,, IV ..	,,	,,	0·57	—
Iron ,, V ..	—	—	1·40	—

Table II.—The Longitudinal Effect for Nickel, Iron, and Steel.
(Ascending reversals for mean temperature 10° C.)

H.	Nickel.		Soft iron.		Steel.	
	I.	$\Delta\phi \times 10^{-6}$.	I.	$\Delta\phi \times 10^{-6}$.	I.	$\Delta\phi \times 10^{-6}$.
10	10	—	680	50	70	—
20	60	100	1040	210	800	—
30	178	550	1180	340	1150	300
40	225	1250	1230	440	1230	470
50	256	1900	1270	520	1260	545
60	277	2450	1300	590	1280	600
80	305	3500	1340	700	1320	710
100	327	4400	1370	800	1360	823
150	366	6300	1430	1040	1420	1055
200	393	8050	1470	1240	1470	1270
250	411	9400	1500	1400	1500	1460
300	426	10500	1530	1550	1530	1640
350	436	11400	1560	1670	1560	1780
400	446	12300	1580	1760	1580	1920
450	456	12900	1590	1850	1600	2030
790*	474	} 17000				
11000*	—					
Resid. (max.)	250	900	840	70	1120	180

Note (*) refers to Experiment I in strong fields.

was very small, but, as in the case of nickel, exhibited a change of sign, the reversal taking place in a field of 9500 c.g.s. (See fig. 7.)

The highest field obtained was only 11,000 c.g.s., and as the self-demagnetising force must be very great in this case, it is possible that with much stronger fields the effect may increase rapidly. The same specimen of iron was used as in the experiments with ordinary fields.

All the experiments described above were carried out in the Physical Laboratory of the University College of North Wales; and, in conclusion, I desire to acknowledge my great obligation to Professor E. Taylor Jones for the interest he has taken in the work, and also for much valuable help and advice.

"Influence of Temperature on the Conductivity of Electrolytic Solutions." By W. R. Bousfield, M.A., K.C., M.P., and T. Martin Lowry, D.Sc. Communicated by Professor H. E. Armstrong, F.R.S. Received and read June 19, 1902.

The phenomenon of electrolysis is characteristic mainly of the liquid state, a liquid electrolyte usually ceasing to conduct when it passes into the gaseous or into the crystalline state. The influence of temperature on the conductivity of a liquid such as an aqueous solution of hydrogen chloride is, however, of such a character as to indicate that an upper and a lower limit of conductivity may exist apart altogether from the boiling point and freezing point of the solution. The present communication contains a summary of the evidence for the existence of these limits of conductivity, a brief discussion of their probable position on the scale of temperature in the case of some aqueous and other electrolytes, and a review of the influence of temperature on conductivity over the whole range of temperature within which electrolysis can take place.

Whatever view be taken of the nature of the process by which a conducting solution is formed on dissolving a salt, acid, or base, in an "ionising solvent," there is every reason to believe that the process is only complete in presence of a very large excess of solvent, and that usually only a part of the solute is concerned in carrying the current. The proportion of the solute that is thus rendered active in electrolysis is represented by a "coefficient of ionisation," and two general methods are in use for determining its magnitude. In the first method, the "equivalent conductivity," λ, of the solute is determined for a series of dilutions, and the ratio $\lambda v/\lambda_\infty$ of this constant at a dilution of v litres per equivalent to that at infinite dilution is taken to represent the coefficient of ionisation at volume v. This method is based on

FIG. 5.

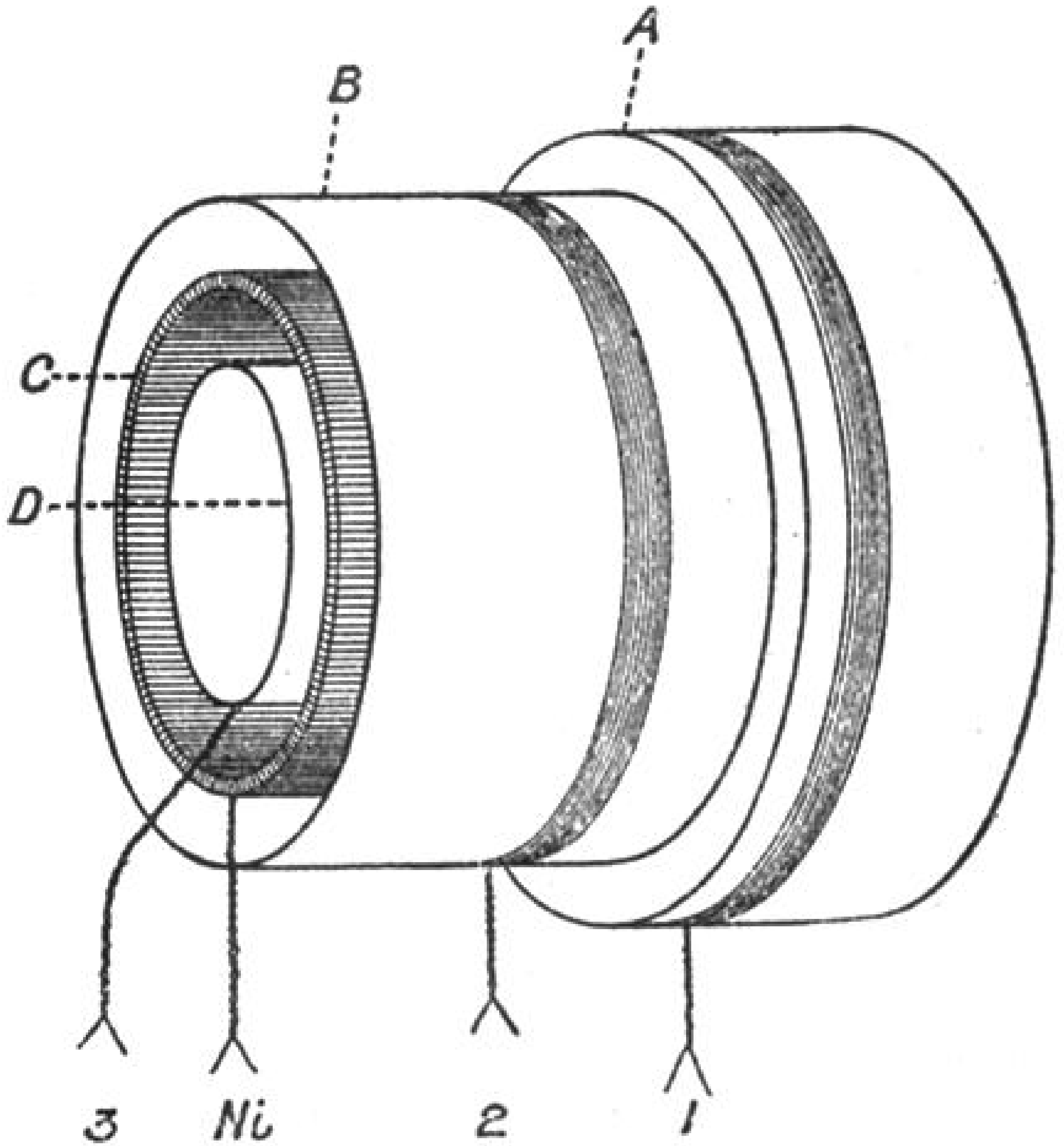


Fig. 6.