



LXXXIV. On the effect of a magnetic field on metallic resistance

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Conclusion.

In conclusion I wish to acknowledge the assistance of Mrs. Perkins in making the capacity adjustments and recording the beat of the pendulum at which deflexions began for actinium emanation, also to express my indebtedness to Prof. Sir Ernest Rutherford for his continued interest in the progress of the investigation, and to Mr. Marsden for many helpful suggestions.

LXXXIV. *On the Effect of a Magnetic Field on Metallic Resistance.* By WALTER A. JENKINS, M.Sc., 1851 Exhibitor, Research Student of Emmanuel College, Cambridge*.

[Plate X.]

THE following experiments were carried out in order to obtain further evidence on the above effect. Nickel was the metal used, as the author had previously carried out experiments on the elongation of nickel under a longitudinal magnetic field and, as will appear later, in all probability there is some relation between the two effects.

Apparatus.

The nickel resistance consisted of a short piece of very fine wire soldered at right angles to the ends of two thick copper wires. The copper wires fitted tightly into rather wide capillary tubing, attached rigidly to a block of wood. This arrangement allowed of the placing of the resistance in any desired position between the poles of the electromagnet.

The nickel wire—supplied by Hartmann and Braun, Frankfort—was about .5 cm. long and .0015 cm. diameter. Its resistance at 18° C. was 3.5173 ohms.

An electromagnet was used for supplying the magnetic field and, as the resistance was of very small dimensions, fairly large fields could be employed. The cross-section of the pole-pieces was large enough to ensure fairly uniform fields round the resistance. The resistance was measured by a Wheatstone bridge method—a compensating nickel resistance and two manganin resistances in oil formed the other three arms of the bridge. Deflexions of the galvanometer were noted instead of obtaining a balance every time and, as the galvanometer was calibrated before and after the experiments, this method proved quite satisfactory. There was a slight creep of the spot of light owing to

* Communicated by Sir J. J. Thomson, O.M., F.R.S.

temperature change of the nickel, as the compensating nickel resistance was of slightly larger resistance than the one under observation. This creep was corrected for in the results obtained.

Experiments were carried out at the temperature of the room 18° C. and at a temperature of 93°·5 C. This latter temperature was obtained by enclosing the nickel in a glass tube round which steam was passed. Liquid air was also used, but the low temperature affected the nickel wire in such a way, that the strain caused by switching on the magnetic field was sufficient to snap the wire. In all the experiments the wire was demagnetized by reversals before any readings were taken.

Longitudinal Field.

Fig. 1, Pl. X. shows the curve obtained when the nickel was placed in the field longitudinally. The resistance increases fairly rapidly with the magnetic field until $H=350$, then the increase becomes much less rapid until $H=1000$, when a maximum increase in resistance is observed. After $H=1000$, $\frac{dR}{R}$ decreases slightly, but this is probably due to the resistance being incorrectly placed in the longitudinal field. An error in setting of 1°·5 would account for the decrease, and in one experiment it was absent altogether. It was thought possible that with a constant magnetic field the resistance might vary with the electric force, *i.e.* with the current. Currents varying from ·1 to ·001 ampere were used, but $\frac{dR}{R}$ was found to be constant within these limits.

Fig. 2, Pl. X. shows a complete hysteresis cycle. The loops are to be expected on account of the slight decrease of resistance after reaching the maximum. The resistance alteration shows a distinct lag, and does not reach zero until a reverse field of $H=50$ is reached, after which $\frac{dR}{R}$ becomes negative before commencing to increase again at $H=72$.

Fig. 3, Pl. X. shows the hysteresis curve at a temperature of 93°·5 C. The maximum resistance increase occurs at $H=320$, a much lower value than is necessary at the ordinary temperature. The decrease, after reaching a maximum, is much greater than before and cannot be explained away so easily.

Fig. 4, Pl. X. shows the effect of a transverse magnetic field

on a nickel resistance. There is a slight preliminary increase, after which the resistance decreases uniformly until $H = 1800$, when the rate of decrease diminishes but does not reach a maximum. The form of the curve suggests that the increase is due to at least two distinct factors. One of these gives a decrease of resistance directly proportional to H until $H = 1800$, while the other gives an increase of resistance and soon reaches a maximum. On the assumption that such is the case the data for figure 5 have been calculated.

Fig. 5, Pl. X. shows the increase of resistance in a transverse magnetic field, which would result if the second factor, which gives a decrease of resistance, were absent. The shape of the curve is similar to that of figure 1 and the increase reaches a maximum in both curves at the same field strength. As the increase in resistance in figure 4 is approximately one-half of that of figure 1, it is probable that the cause of the increase of resistance in a longitudinal field is the same as is operative in the case of the preliminary resistance increase in a transverse field. This view is strengthened by consideration of figures 6 and 7.

Fig. 6, Pl. X. shows the transverse effect at $93^{\circ}5$ C.

Fig. 7, Pl. X. shows the increase in resistance due to a transverse field at temperature $93^{\circ}5$ C. Comparing figures 4 and 7 we notice that the maximum increase in a transverse field at $93^{\circ}5$ C, is about one-half of what it is in a longitudinal field at $93^{\circ}5$ C., and that the maximum increase occurs at the same field strength in both cases.

Figs. 8 and 9, Pl. X. show the hysteresis curves for the resistance effects in a transverse field at temperatures 18° C. and $93^{\circ}5$ C. respectively. The difference in the curves is interesting.

It will be advantageous at this point to describe some experiments carried out by the author a short time ago on the elongation effect of a longitudinal magnetic field on a nickel rod. The method used—suggested by Dr. Swann—was that of placing a pure nickel rod inside a solenoid and observing the length alteration by means of interference fringes. The solenoid was so constructed as to allow of a flow of water between the wire and the rod, while the rod was firmly fastened at one end.

Fig. 10, Pl. X. shows the hysteresis curve so obtained. Unfortunately the magnitude of the field used was not large, but Bidwell* has obtained results for large field values, and

* Phil. Trans. 1888.

his results are in fair agreement for small field values with those now obtained. The loop in the curve is peculiar, but its presence seems certain as Dr. Swann has previously noticed it, and it was observed in every experiment which the author carried out.

Fig. 11, Pl. X. shows the elongation effect under a gradually increasing magnetic field. The large field values are taken from Bidwell's results. It will be observed that the maximum elongation effect occurs at a field strength of about 850, which is not far removed from the field strength which gives the maximum resistance increase effect.

Fig. 12, Pl. X. shows a remarkable relation between the two effects, which holds for all small field values. The points on the curve are obtained by noting the corresponding values of $\frac{dR}{R}$ and $-\frac{dl}{l}$ for gradually increasing field values, and then plotting $\frac{dR}{R}$ against $-\sqrt{\frac{dl}{l}}$. The graph is a straight line at 45° to the axes for all small values of H . After $H = 80$, $\frac{dR}{R}$ increases more quickly than does $\sqrt{\frac{dl}{l}}$.

Discussion of Results.

In his 'Corpuscular Theory of Matter' Thomson puts forward two theories of the method of conduction in solids. On the first of these the current is carried by free electrons while on the second it is carried by a transmission of electrons from atom to atom which are supposed to be orientated by the electric field. On the first theory the following is deduced :

$$\text{Resistance} = \frac{4 \propto \theta}{\beta n e^2 \lambda v},$$

$$\text{or } R = \frac{K}{n \lambda v}, \text{ where } K \text{ is a constant.}$$

Thus any alteration of resistance on switching on the magnetic field must be due to an alteration of n , λ or v . Of these three an alteration of λ seems the most probable. Adams * has shown that in a transverse field,

$$\frac{dR}{R} = \frac{dT}{T} - \frac{1}{4} H^2 \frac{e^2}{m^2} T^2$$

* Physical Review, 1907.

where T is the mean free period of the corpuscle and consequently $= \frac{\lambda}{v}$. In a longitudinal field the second term disappears and we get

$$\frac{dR}{R} = \frac{d\lambda}{\lambda} - \frac{dv}{v}.$$

As is shown in figure 11 the switching on of a magnetic field causes a dimensional change and it seems probable that this change is accompanied by a change of mean free path. From Nagaoka and Honda's experiments we know that the volume alteration is negligibly small compared with the length and cross-section changes. Calculating the cross-section changes on the assumption that the volume change is zero, it is possible to obtain a rough estimate of the mean free path changes in different directions, corresponding to certain dimensional changes. Such calculations show that a dimensional change give a variation of mean free path of the same order. The resistance change and dimensional change are not, however, of the same order. Even should R vary as $\frac{1}{\lambda^2}$ or $\frac{1}{\lambda^3}$ the resistance change would only be -2 or -3 times that of the mean free path change. It does not seem probable therefore that the alteration in length is the cause of the conductivity change. There is, however, probably some relation between the two, as figure 12 indicates. The following also point to some connexion.

As saturation point is approached both effects diminish rapidly.

There is little difference between the field strengths which give maximum effects in both cases.

An increase in temperature gives a diminished resistance effect for a given magnetic field while Bidwell observed a similar effect with respect to the elongation effect. Some such connexion as both being dependent on a third factor would explain the similarities of the two effects. This view is strengthened by the following considerations. In a longitudinal magnetic field nickel shows a continuous decrease in length and a continuous increase in resistance. Iron shows an increase in length at first, after which it commences to decrease until a saturation value is reached. Its resistance change, however, shows a decrease at first and afterwards an increase.

Such a thing as an alteration in configuration of the atom might both alter the mean free path of the corpuscles and diminish the number of corpuscles which carry the

current. The resistance would be altered if the velocity of the corpuscles carrying the current were to change. Such an alteration of velocity might result upon a re-arrangement of the atoms. From such a re-arrangement one might expect slight velocity changes but not changes of the order 10^{-2} . As the velocity of the corpuscle is that due to its intrinsic energy and is not caused solely by its being pulled out of the atom by an adjacent atom ; such changes of velocity could not be expected as the dimensional change is only of the order 10^{-6} or 10^{-5} .

From the equation

$$R = \frac{K}{n\lambda v},$$

we see that a decrease in n , i. e. the number of free corpuscles, would give an increase in R . The specific resistance is given by

$$R = \frac{4 \alpha \theta}{\beta n e^2 \lambda v}.$$

By calculation λ is found to be 7×10^{-9} approximately, and substituting the known values for the other quantities we find that n is of the order 10^{32} . Thus to produce an alteration of the magnitude observed would require an absorption of 10^{30} corpuscles, when a fairly strong magnetic field was applied. This means that each atom must absorb 10^7 corpuscles, which is unthinkable. The high value of n is of course improbable from considerations of specific heat. None of the factors therefore give a satisfactory explanation of the resistance change.

On the second theory of conduction the specific resistance is given by

$$R = \frac{9}{2} \frac{\alpha \theta}{e^2 d p N b}.$$

which reduces on substitution of known values to

$$R = \frac{1}{3.5 \times 10^{-12} p b}$$

where p is the number of corpuscles discharged per second per atom and b the distance between the centres of the doublets. The change in " b " will be of the same order as the dimensional change and can be neglected in discussing the resistance alteration. Variation of " p " is the most likely cause of the resistance change. Substituting for " b "

its approximate value $\frac{1}{\sqrt[3]{N}}$ we find that " p " is of the order

10^{23} . This is exceedingly large and indicates an internal radioactivity far greater than any external radioactivity of which we have experience. It is quite possible, however, that the ease with which corpuscles pass from one atom to another in close proximity to it, is incomparably greater than the ease with which a corpuscle leaves an atom and flies into space. If such a transference of corpuscles actually does take place it is conceivable that the re-arrangement of atoms, which undoubtedly results upon the creation of a magnetic field, may cause a great diminution in the number of corpuscles which are so transferred. Moreover, after a certain field value the internal re-arrangement ceases and one would therefore expect to find a maximum value for the resistance effect.

All metals show a slight resistance change in a magnetic field but those which are very susceptible to magnetic influence show far greater effects than others, *i. e.* those metals whose internal structures are easily altered show the greatest resistance change. Such a diminution in transference of corpuscles as has been suggested would result in increased resistance whether the nickel were placed in the field transversely or longitudinally. This actually is the case as the diminution observed in large transverse fields is due to another factor. If the change were due to an alteration of mean free path, then the two effects would be of opposite signs, as the length of the wire is diminished in longitudinal fields and increased in transverse ones. We may therefore conclude that a magnetic field causes a re-arrangement of the atoms which results in a dimensional change and a diminution of "internal" radioactivity. To this latter factor the resistance change is due. As the dimensional change and the resistance change are both due to the atomic re-arrangement we should naturally expect to find a similarity between the two effects; figure 12 shows that such similarity exists.

The Transverse Effect.

The second part of the transverse effect has a different origin from the first and has no analogue in the longitudinal effect. Thomson* deduced theoretically that an effect proportional to H^2 was to be expected in a transverse field,

* Internationale Congrès de Paris, 1900.

and Adams gives the following equation as expressing the result

$$\begin{aligned}\frac{dR}{R} &= -\frac{1}{4} H^2 \frac{e^2}{m^2} T^2, \\ &= -\frac{1}{4} H^2 \frac{e^2 \lambda^2}{m^2 v^2} \\ &= -\frac{1}{3} H^2 \times 10^{-16} \quad \text{approximately.}\end{aligned}$$

For a field of $H=1000$ we get

$$\frac{dR}{R} = -\frac{1}{3} \times 10^{-10}.$$

The effect observed is of the order 10^{-2} , and although the value of λ used is not certain, the difference between the observed and calculated values is far too great to be accounted for by an error in λ . To reconcile theory and experiment λ would have to be 5×10^{-5} cm., i. e. more than five times greater than the mean free path of a molecule in air. Such a result is extremely improbable and we must conclude that the effect observed is not that given by Adams' equation. Moreover the resistance increase is not proportional to the square of the field strength. The effect in iron is so much greater than in other metals as to call for some special explanation. Heaps* has measured the effect in other metals and finds it to be represented by AH^2 where A is of the order 10^{-12} . This gives $\lambda=10^{-6}$ approximately which is still very large. A longitudinal effect of the same order is observed in these other metals, and its existence leads one to surmise that the small effect observed in the non-magnetic elements is not the one which has been theoretically deduced. The first term of Adams' equation would give an effect in a longitudinal field, but the fact that the effects in both fields are of the same order of magnitude, and the large value of λ which has to be assumed to reconcile theory and experiment, points to a common origin for the two phenomena in the case of non-magnetic elements. On the other hand, in the case of nickel the two effects possess different characteristics. The longitudinal effect reaches a maximum with a comparatively small field value while the second part of the transverse effect does not reach a limiting value. Abnormally large values of the effect are observed in the cases of iron, nickel, and bismuth. The

* Phil. Mag. 1912.

obvious explanation of this for the first two is their magnetic properties, but several reasons militate against this.

If the magnetic properties were the origin of the effect one would expect a far greater effect in the case of iron than in the case of nickel, but such is not the case. Moreover the magnetic properties reach saturation values at field strengths which give no saturation value to the resistance effect. Both the magnetic properties and the resistance effect may be due to the ease with which structural alterations take place in metals which give large effects, but the one is probably not the cause of the other. The dimensional change, the resistance effect and the magnetic properties may be due to a structural alteration such as is given in a longitudinal field. In addition to this it is possible that when the electric field is on and the doublets are orientated transversely to the magnetic field, then a further steady and continuous structural alteration takes place, which gives rise to an increase of internal radioactivity and a consequent diminution of resistance.

Summary.

- i. Hysteresis curves for both longitudinal and transverse fields at different temperatures have been obtained.
- ii. The effect in a transverse field is shown to consist of two parts, one of which gives an increase and reaches a maximum, and a second which gives a decrease and does not reach a maximum.
- iii. The longitudinal effect and the first part of the transverse effect possess similar characteristics.
- iv. There is some relation between the dimensional change in a magnetic field and the resistance effect but one is not the cause of the other.
- v. Both are probably resultant on a structural alteration.
- vi. The ordinary theory for the effect in a transverse field does not explain the results obtained. The effect is possibly due to a further structural change.

In conclusion I wish to express my thanks to Dr. Hicks for his interest in the work and for kind permission to use his laboratories.

My thanks are also due to Professor Sir J. J. Thomson and Dr. Swann for their interest in the work.

Cavendish Laboratory,
Cambridge.

FIG. 1.

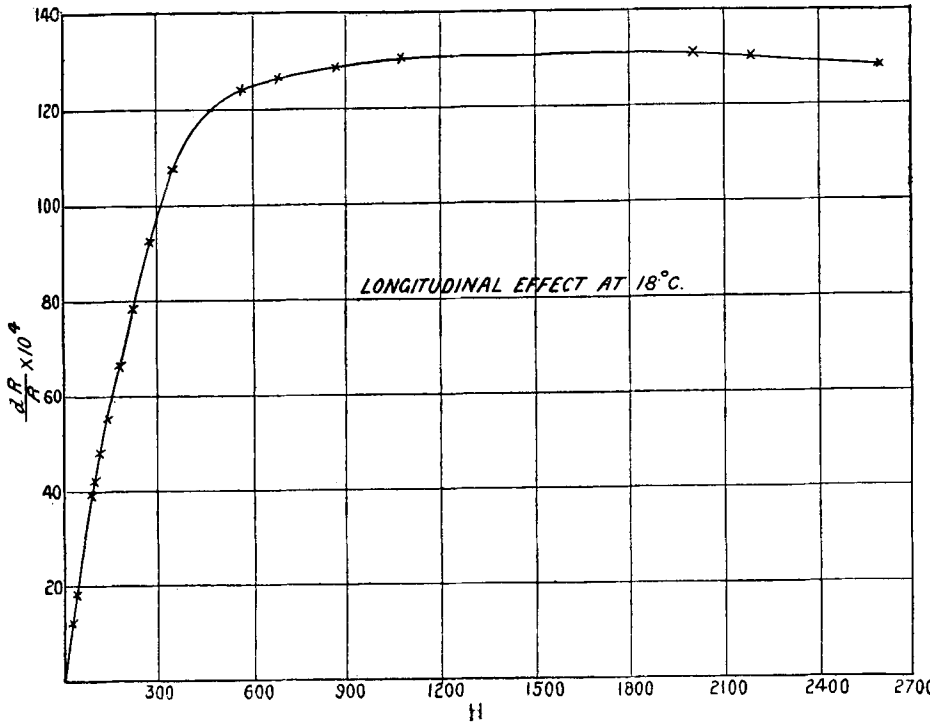


FIG. 3.

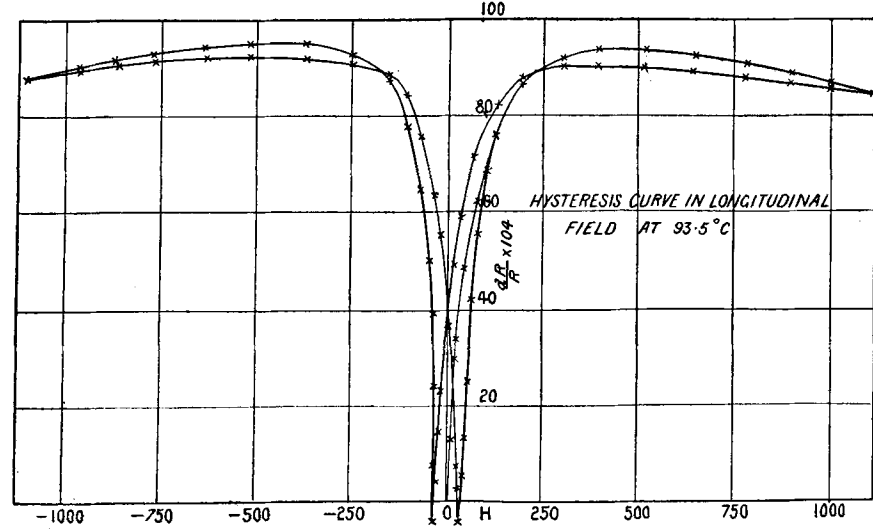


FIG. 5.

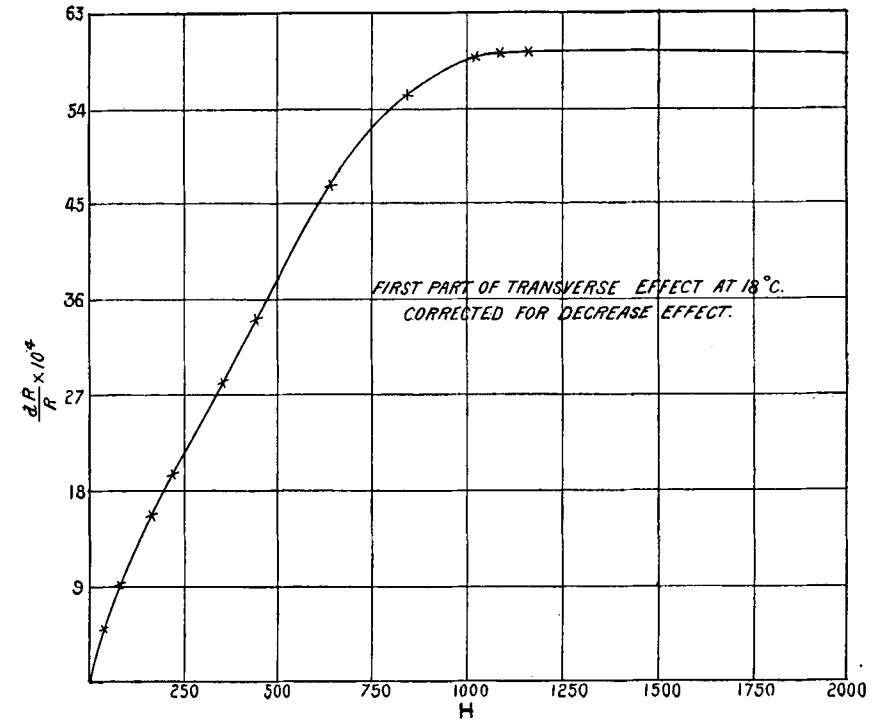


FIG. 7.

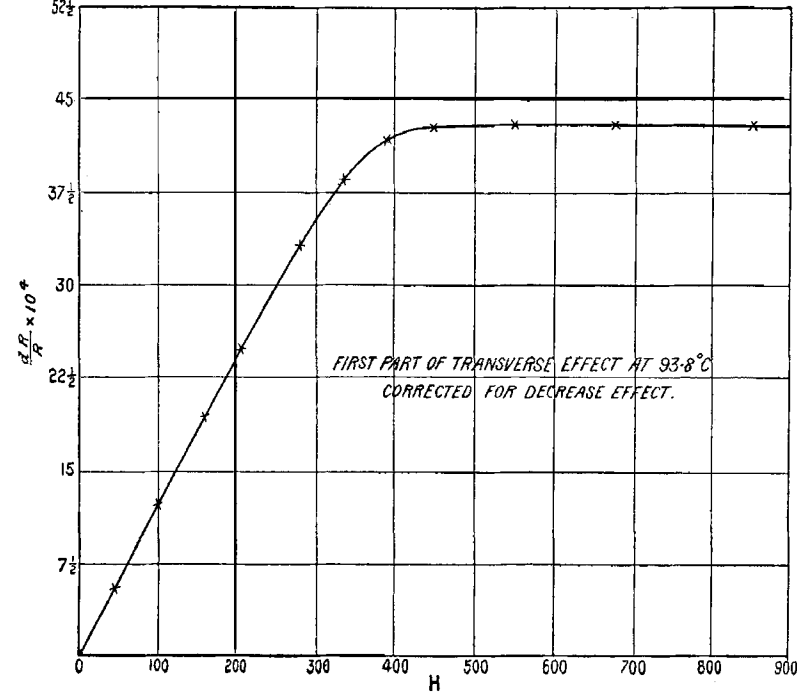


FIG. 9.

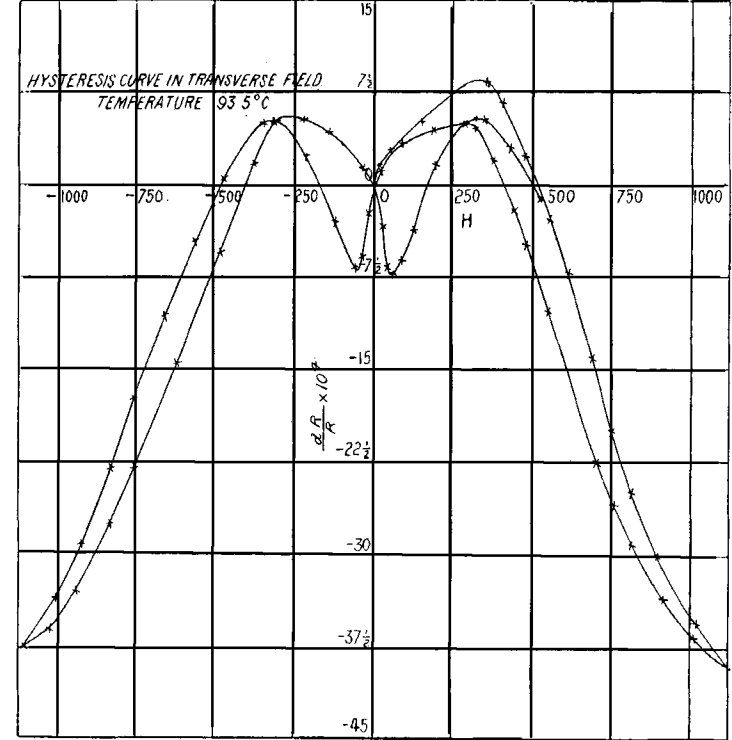


FIG. 11.

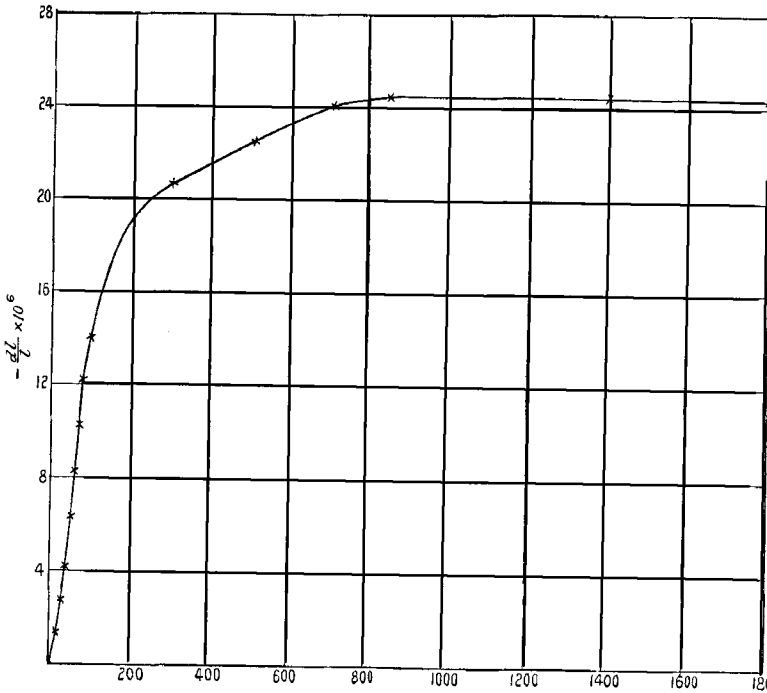


FIG. 2.

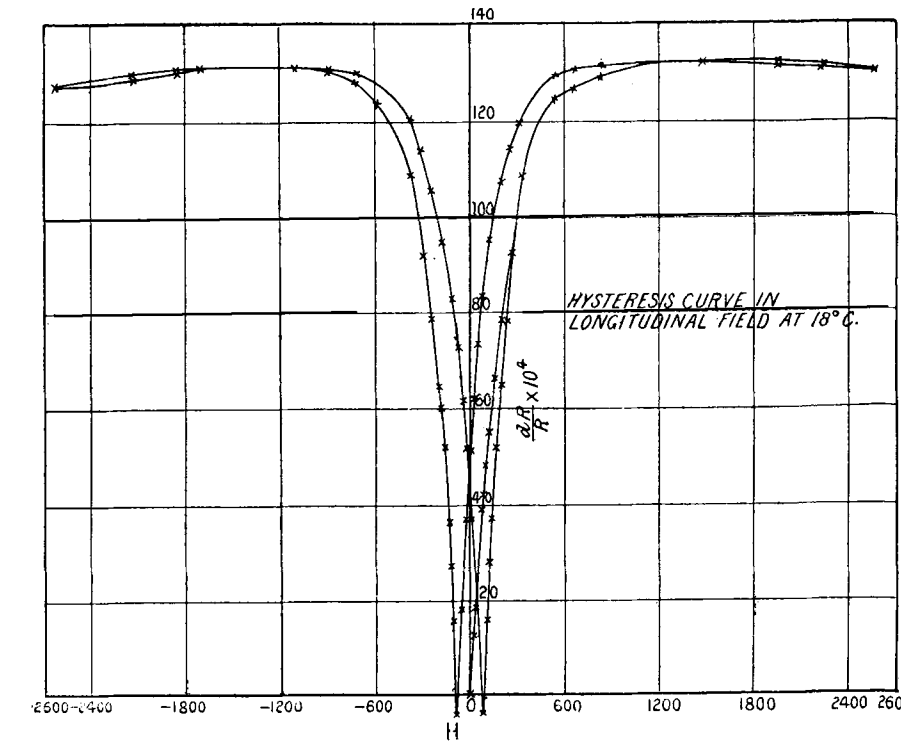


FIG. 4.

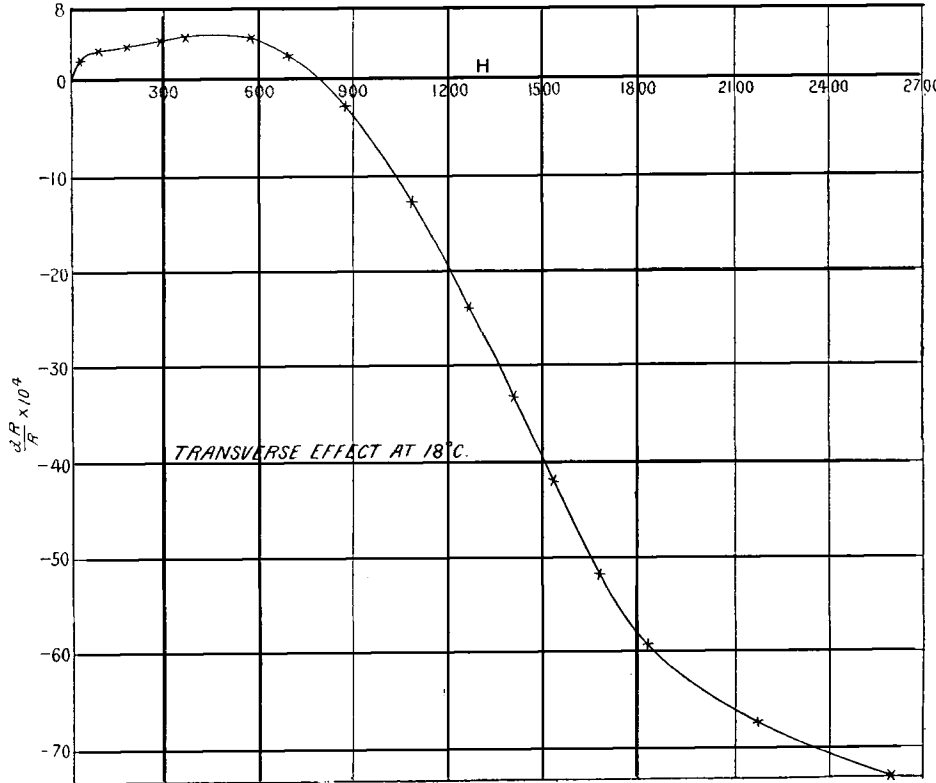


FIG. 6.

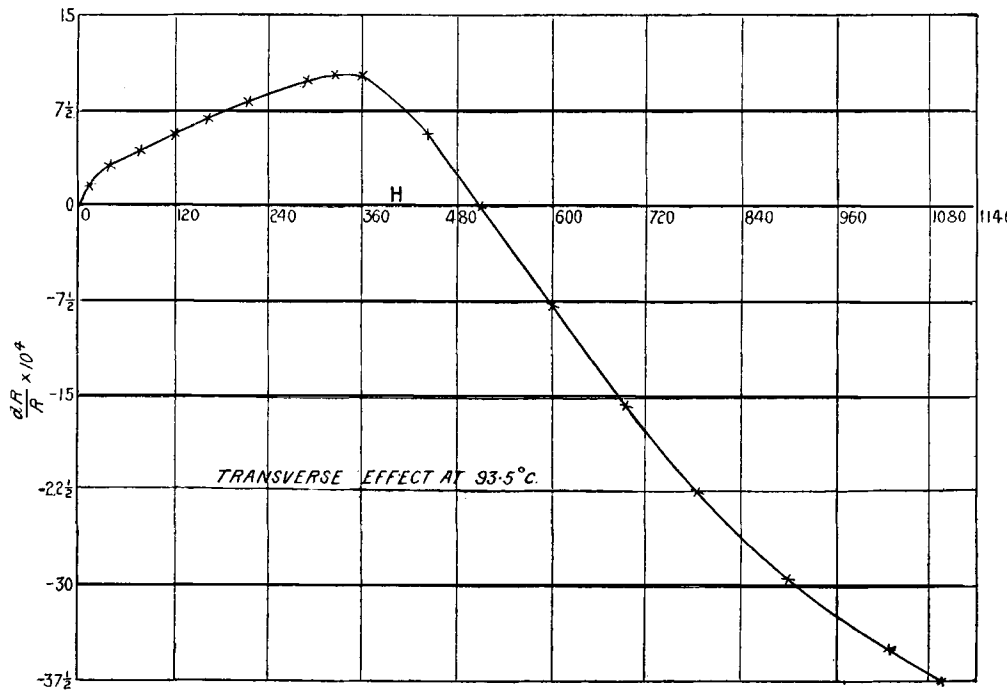


FIG. 8.

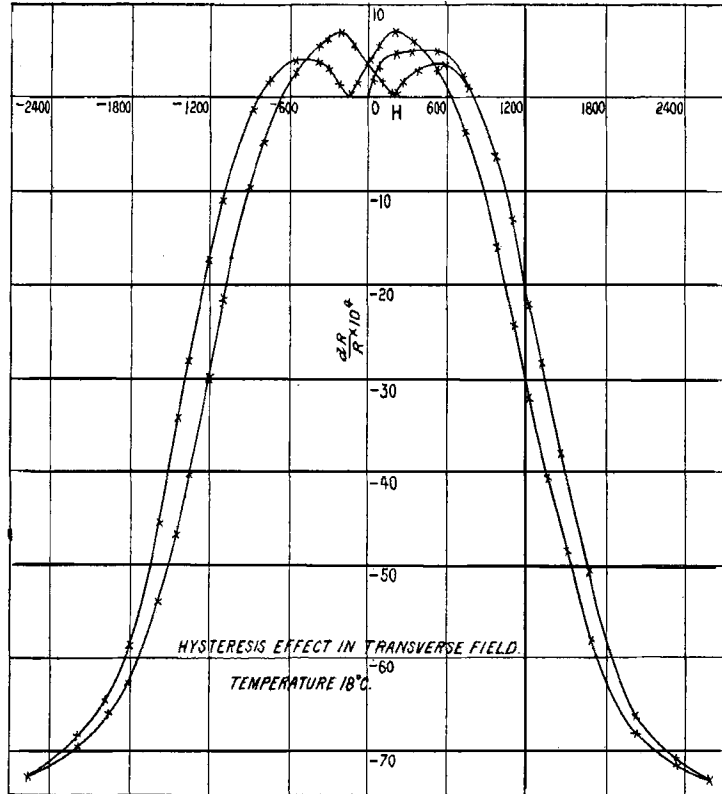


FIG. 10.

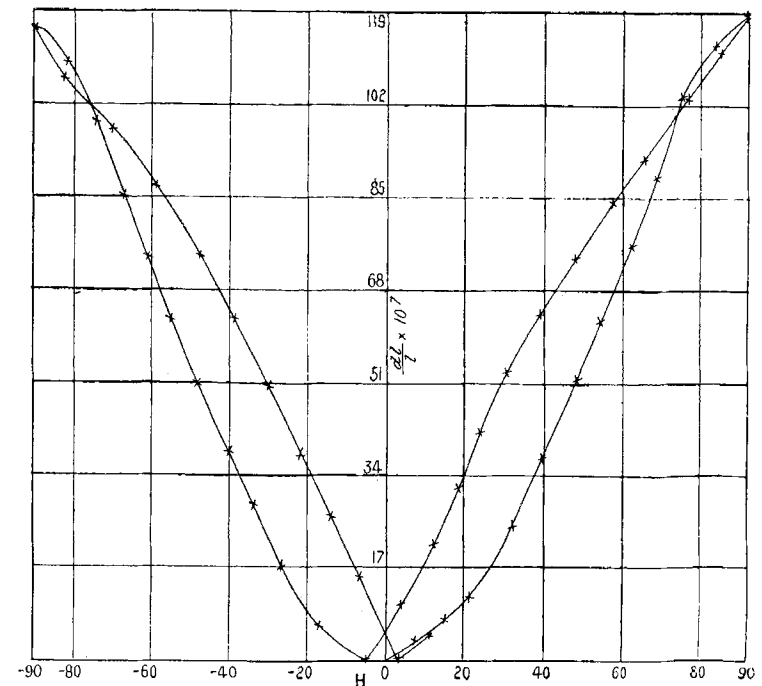


FIG. 12.

