THE MAGNETIZATION OF IRON, NICKEL, AND COBALT BY ROTATION AND THE NATURE OF THE MAGNETIC MOLECULE.[1]

By S. J. Barnett.

§ 1. In December, 1914, I described to the American Physical Society an extended series of experiments completed in that year on the magnetization of large steel rods by mere rotation.[2]

Before these experiments were made only one method of magnetizing a body was known, viz., placing it in a magnetic field. These experiments not only revealed another and entirely new method, but they also confirmed completely the fundamental assumptions on which the results had been predicted: They proved, in a direct and conclusive way, on the basis of classical dynamics alone, without the slightest dependence upon the ill understood theory of radiation, (1) that Ampèreian currents, or molecular currents of electricity in orbital revolution, exist in iron; (2) that all or most of the electricity in orbital revolution is negative; and (3) that it has mass, or inertia, so that each orbit behaves like a minute gyrostat and tends to set itself with the direction of revolution coincident with the direction of rotation impressed on the body. It is in this way that magnetization of the body results. Furthermore, if we admit the classical theory of radiation, these experiments, together with the existence of residual or permanent magnetization, prove (4) that the arrangement of the electricity in the Ampèreian orbits is Saturnian rather than planetary.

§ 2. The theory of these experiments is given in the earlier paper already referred to. If it is assumed that only one kind of electricity is in orbital revolution, and if the mass of a particle is denoted by m and its charge by e, it is shown that the rotation of a body with angular velocity n revolutions per second is equivalent to putting it in a magnetic field of intensity H, such that

$$\frac{H}{n} = 4\pi \frac{m}{e} \qquad (1)$$

[1] A paper read before the American Physical Society, December, 1916. A brief account of this work is published in the Proceedings of the National Academy of Sciences, March, 1917, p. 178.

[2] Barnett, S. J., Phys. Rev., (2), 6, 239, 1915.

with extreme precision for all angular velocities experimentally attainable. If electrons alone are assumed to be in orbital revolution, the second member of this equation becomes -7.1×10^{-7} E.M.U. for electrons in slow motion according to experiments which are well known; and H/n should be equal to this quantity and identical for all substances. If positive electricity also participates the magnitude of H/n should be smaller. The mean value of H/n obtained in my 1914 experiments was -3.6×10^{-7} E.M.U.; and H/n was found to be independent of the speed within the limits of the experimental error.

§ 3. Not very long after my first conclusive experiments were presented to the American Physical Society, Einstein and de Haas, in February and April, 1915,[1] described to the German Physical Society successful experiments on the effect converse to mine, viz., the rotation of an iron rod by magnetization, which had been predicted and looked for by O. W. Richardson in 1907;[2] and de Haas has recently continued this work in a somewhat different manner.[3] Both investigations are indirect but excellent confirmations of my own earlier work. This work has also been confirmed by further experiments of my own of increased precision described before the American Physical Society in April, 1915.[4]

§ 4. The fundamental character of the problem, whose importance with reference to molecular constitution is rendered greater by the extreme difficulties encountered by the electromagnetic theory of radiation in attempting to account for even the simplest cases of the Zeeman effect and other allied magneto-optical effects, has led me to extend the investigation, within the last year, to other specimens of iron and to cobalt and nickel. In all the earlier work the method of electromagnetic induction was used, a fluxmeter being the principal measuring instrument. The new work described in this paper has been done by the method of the magnetometer. It is more difficult to eliminate extraneous disturbances with the new method than with the old, but it is less difficult to attain adequate sensibility without the use of large rods, the cost of which, in the case of cobalt and nickel, would be great; moreover, on account of the complete novelty of the effect under investigation, it was considered desirable to use a method as nearly independent of the earlier one as possible.

§ 5. The magnetometer was an astatic instrument, and the rod under

[1] Einstein, A., and de Haas, W. J., Verh. d. D. Phys. Ges., 17, 152, 203, 420, 1915.

[2] Richardson, O. W., PHYS. REV., (1), 26, 248, 1908.

[3] de Haas, W. J., Science Abstracts A, 17, 351, 1916. The original paper has not yet reached me.

[4] Barnett, S. J., *loc. cit.*

experiment, or rotor, was mounted with its axis horizontal and normal to the magnetic meridian in the equatorial position of Gauss, which offered important advantages for this work.[1] Calibrations were made by means of solenoids wound permanently on the rotors and subsidiary solenoids wound on wooden cores. Rotation observations were made at equal intervals of time in sets of four as follows: The rotor was first driven (by means of an alternating current motor) at a determined speed in one direction, and the magnetometer scale read; then the motor was reversed and the scale again read for the same speed; then the readings were repeated in inverse order. From the double deflection obtained by subtracting the mean of the second and third readings from the mean of the first and fourth, together with the angular velocity of the rotor, and the calibration experiments, the quantity H/n could be determined. The details of the experimental work and the means used to eliminate extraneous disturbances are described below.

§ 6. Diagrams of important parts of the apparatus, drawn approximately to scale, are given in Fig. 1, and reproductions of actual photographs are given in Figs. 2, 3 and 4. All the figures have been lettered to correspond. In the earlier part of the work each magnet of the astatic system was carefully made of three small pieces of tungsten steel. In the rest of the work each magnet was made of eight steel cylinders of very nearly the same length. All were cut from the same wire and

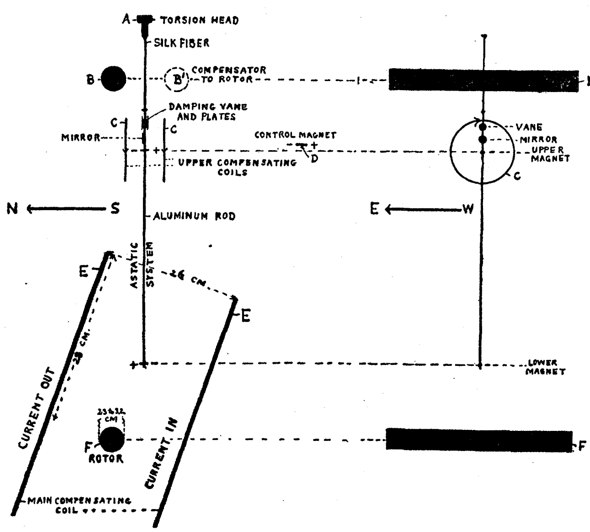

Fig. 1.

[1] Adoption of the polar position would have made it extremely difficult to make satisfactory calibrations and to eliminate sources of serious error.

hardened together. The two groups were magnetized in the same field after being mounted properly on the light aluminum rod shown in the figure. This rod carried also a small plane mirror and a thin aluminum damping vane, and was suspended from a torsion head A by a single silk fiber. The complete suspension was mounted in a groove milled in the bronze casting M, with enlargements cut for the mirror, damping vane, and two adjustable parallel damping plates. The long groove was covered with a strip of brass; and an opening for the mirror and two openings for observation of the damping arrangement were covered with glass. The enclosure was sealed with universal wax to prevent air currents. The casting M holding the magnetometer system was screwed to a heavy ribbed H-form bronze casting L. At its four corners the casting L was bolted to bronze cones sunk into the tops of the four concrete pillars K, K, K', K', cemented to the concrete floor. To make the mounting more rigid, heavy boards extending from arm to arm were screwed onto the lower surface of the H-form casting.

§ 7. Numerous experiments were made with four different rotors of the type and dimensions indicated in Fig. 5. In constructing each rotor

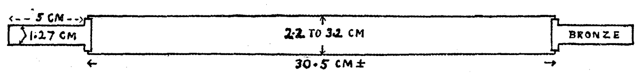

Fig. 5.

the magnetic material was first turned to the shape indicated by the central portion of the figure, except in the case of cobalt, where there was a slight difference; then the bronze bearing pieces, previously turned to the shape indicated but with centers at the ends, were soldered to the ends of the magnetic material. Then the complete structure was centered in the lathe and all the surfaces turned true to the same centers. One end of a fine insulated copper wire was then soldered to one end of the magnetic material and the wire was wound over its surface on the lathe into a solenoid with 16 turns to the inch. The wire and metal surface were then given a heavy coat of shellac and dried. Several centimeters of the free end of the solenoid were then wound with insulating tape and covered with several layers of tin foil. The free end of the copper wire was then stripped of its insulation and bent over this tin foil, and a number of additional layers wound on. Then the ends of the foil were thoroughly secured to the rotor with insulating tape. In calibrating experiments the tin foil and the bronze bearing piece near it were used as terminals. Before calibrating, the resistance of the solenoid was measured to make sure that no short-circuit existed.

Two of the rotors were of cold-rolled steel shafting: One of them

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July, 1917.

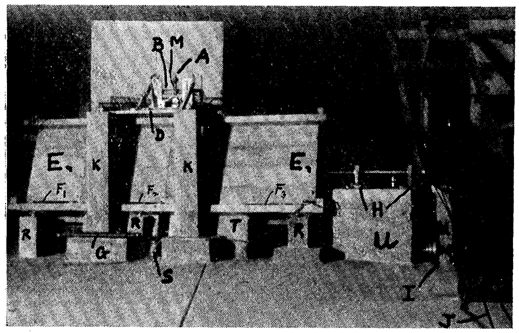

Fig. 2.

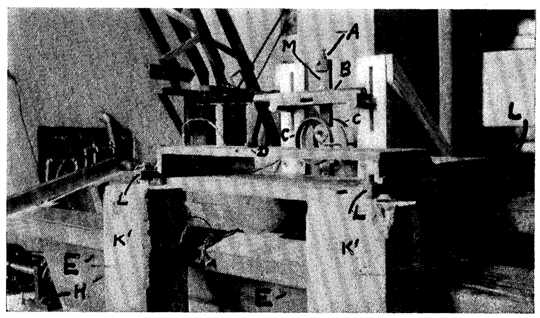

Fig. 3.

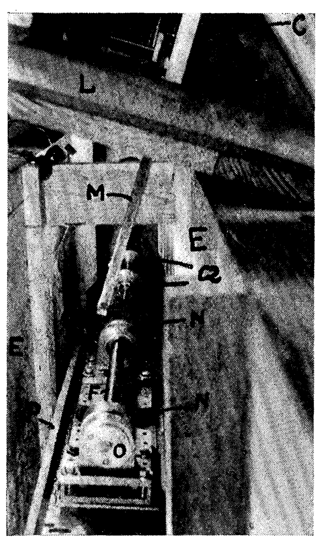

Fig. 4.

S. J. BARNETT.

was about 2.3 cm. in diameter and 30.6 cm. long; the other about 3.1 cm. in diameter and 30.4 cm. long. One of the rotors was nickel, about 2.2 cm. in diameter and 30.6 cm. long. Another rotor was of cobalt about 3.2 cm. in diameter and 30.4 cm. long. The main surface of the cobalt was a true cylinder like those of the other rotors, except that three shallow grooves which had been turned into it were filled with thin brass bands soldered in. Also, the cobalt casting was somewhat imperfect, being pitted with small holes. A fifth rotor, of Norway iron, was constructed like the others, except that a washer was added at each end—a fact which I discovered after finding that it failed to give satisfactory results. Only a few rough observations were made with this rotor.

Three of the rotors are shown at F_1, F_2 and F_3 in Fig. 2, and one of shown in its bearings at F in Fig. 4.

§ 8. The rotor moved in cylindrical lumen bearings, one of which, O, is visible in Fig. 4. These lumen bearings were screwed into bronze holders, themselves bolted into bronze castings NN, Fig. 4. The castings NN were bolted to a single casting of bronze, which was bolted to a heavy bronze bed plate P. The casting P was bolted to bronze cones sunk into the oblique concrete piers S and T, Fig. 2. To assist in reducing vibration, a considerable portion of the space between the casting P and the piers was filled with cement and the plate bolted down before the cement hardened. The magnetic meridian through the magnetometer magnets passed nearly, but not exactly, through the center of the rotor.

§ 9. The rotor was driven by a brass rod about 0.6 cm. in diameter and 24 cm. long from a small bronze shaft with lumen bearings mounted in bronze castings Q, Fig. 3, on the bed plate P. This countershaft was itself driven by a brass rod about 0.6 cm. in diameter and 42 cm. long from a larger bronze countershaft mounted with lumen bearings in brass and bronze castings H, Figs. 2 and 3, on the concrete pier U. The west end of this larger countershaft carried a three speed bronze pulley by means of which and a similar pulley J, Fig. 2, on the electric motor, and a round belt, it was driven at speeds near to 20, 30 and 45 revolutions per second. In the earliest part of the work another arrangement was used giving speeds over 50 revolutions per second, but this was soon discontinued.

The electric motor was a one horse-power Century alternating current single phase motor, and gave excellent satisfaction. On constant supply it gave constant speeds which were identical for both directions of rotation. It was reversed from a distance by simply pulling one of two strings fastened to a lever which was attached to the brush holder. Speeds were determined with a very small direct current dynamo, separately excited at constant voltage by a storage battery, and a millivoltmeter connected through a high resistance and a reversing switch with the brushes. A pulley on the armature was driven by a long belt, *J*, Fig. 2, from a pulley on the main countershaft driving the rotor. The voltmeter readings for the same speed differed slightly for the two directions of rotation, and depended slightly on the temperature of the field coils. In obtaining the speed from the voltmeter readings, these effects were allowed for.

§ 10. To compensate as far as practicable for disturbances produced by variations in the earth's magnetic intensity, a rod *B*, Figs. 1, 2 and 4, called a compensator, was used. It was of the same material as the rotor, since both were cut from the same rod in the case of each substance investigated, and of nearly the same size, and was mounted in approximately the same position with respect to the upper magnetometer magnet as that occupied by the rotor with respect to the lower magnet. Usually the compensator was placed in approximately one of the symmetrical positions *B*, *B′*, Fig. 1, but the best position had to be found by trial.

§ 11. Although the earlier investigation on iron by the method of electromagnetic induction had shown that the rotation of the rotor in the earth's magnetic field gave the same or nearly the same results as were obtained when the intensity of this field was annulled by a suitable electric coil, it was considered important for the present investigation to provide means of neutralizing the earth's field throughout the region occupied by the rotor. For this purpose the large and accurately made coil, of rectangular cross-section, used in the last part of the earlier investigation was slightly modified. The frame work was shortened along the axis of the coil, and strengthened and made still more nearly true by brass bolts and internal wooden braces near the central section. The coil was reduced to 56 cm. in length, and was left about 26 cm. wide and 198 cm. broad. The coil and frame are marked with the letter *E* in Figs. 1–4.

As in the earlier experiments, the coil was mounted over the rotor and its oblique piers *S* and *T*, the centers of coil and rotor being made nearly coincident. The position of the frame was adjusted until the long edges were horizontal and perpendicular to the magnetic meridian, and the axis of the coil was parallel to the earth's intensity. Then the frame was bolted to bronze cones sunk into six concrete piers, three on each of the larger sides. The three piers on the north side are shown at *R R R* in Fig. 2.

After the coil had been clamped in position, with the heavier bronze castings in place, its magnetic field, when it was traversed by an electric current, was studied throughout a region including and extending somewhat beyond that to be occupied by the magnetic part of the rotors. This field was found to be uniform to one part in five hundred. By a method similar to that used in the earlier experiments, it was found that a current in the proper direction giving 91.4 divisions (equivalent to about 0.389 ampere) on a Weston instrument (with special shunt) compensated completely the earth's flux through a steel rod 33 cm. long and 3.2 cm. in diameter with center in the position to be occupied by the center of each rotor. The compensation was sensitive to a tenth division, or about one part in nine hundred. After the rotation experiments were completed the compensation was again tested by the same method and was found to have remained unaltered. The current was kept at the compensating value 91.4 divisions during nearly all of the observations, and was always kept within one tenth, or in a few instances two tenths, of a division of that value, except for testing purposes as indicated below.

The concrete piers and all the castings near the rotor were free from iron, and all the other bronze and brass castings were either free from iron or so nearly free that any effect on the field in the region occupied by the rotor was quite negligible.

§ 12. Since the lower magnetometer magnet hung, as seen from Fig. 1, in a region in which the earth's intensity was nearly annulled, it was necessary, in order to keep the magnetometer sensibility and zero reading approximately independent of the current in the compensating coil, to provide special coils *CC*, Figs. 1–4, to compensate approximately the horizontal component of the earth's intensity in the region occupied by the upper magnet. Each of these coils contained three turns of insulated wire. They were wound in vertical planes on brass rings 10 cm. in diameter, whose bases were moved for adjustment in brass slides by a right and left handed screw in such a way that the magnet was always approximately at the center of the system. The coils were connected in series with the main compensating coil, and both were connected to oppose the earth's intensity. The distance between the rings was adjusted in the different experiments until the earth's horizontal intensity at the upper magnet was nearly annulled.

The control magnet *D*, Figs. 1–3, was a small piece of hardened tool steel.

With the arrangement described the sensibility of the magnetometer was not altered when the compensating current was changed by one part in ninety, from 91.0 to 92.0 divisions on the indicating instrument, and the zero was altered but little.

§ 13. The magnetometer was almost always used with approximately critical damping, when it usually required from 15 to 20 seconds to reach its elongation.

The mirror was a small plane mirror and the opening in front of it in the bronze holder was covered with a convex spectacle lens. Deflections were read to tenths of millimeters by means of a single filament tungsten nitrogen-filled lamp and a translucent scale, distant about 4 m. from the mirror except in the very earliest part of the work.

§ 14. Calibration experiments were of two kinds. At the beginning and the end of a series of observations, except in rare instances, the approximate sensibility was carefully determined by the process described below; and on a single occasion for each rotor the correction necessitated by the presence and finite length of the solenoid permanently wound upon it was determined once for all. This correction was much less than the experimental error, but was nevertheless always made.

The approximate calibration for each series of rotation experiments was made as follows: A dry cell in good condition, with open circuit E.M.F. 1.50 volt, was connected through a suitable key and a standard high resistance—7,500 to 25,000 ohms—in series with the solenoid of the rotor under experiment, and magnetometer deflections on opening and closing, or (usually) double deflections on reversing, the key were obtained. Each solenoid, as stated above, was wound by lathe with 16 turns to the inch. If D denotes the double deflection, R the box resistance in the circuit (that of battery and solenoid being negligible) in ohms, and h the magnetic intensity which the solenoid, if very long, would impress on the rotor, and if d denotes the double deflection produced on reversing the rotor in the rotation experiments, the intrinsic magnetic intensity of rotation is approximately

$$H = \frac{d}{D} h = \frac{4\pi \times 16 \times 1.50\, d}{10 \times 2.54 \times R\, D} \text{ gauss};$$

and, if n denotes the rotor velocity in revolutions per second, the intrinsic intensity per unit velocity is approximately

$$\frac{H}{n} = \frac{4\pi \times 16 \times 1.5 \times d}{10 \times 2.54 \times R \times D \times n} \, \frac{\text{gauss}}{\text{rev. per second}}.$$

Since the magnetometer zero and sensibility depended on the position angle of the rotor, the mean value of D for three position angles differing successively by 120° was obtained in all the later experiments. The same value of the mean was obtained for three position angles half way between those just mentioned. In the case of the earlier observations on the larger rotor of steel and the rotor of cobalt, the omission of this precaution introduced a possible error of 2 or 3 per cent., which, however, is much less than the experimental error in the rotation experiments. In the case of the nickel rotor the error introduced in this way was only a half of one per cent., or less; and the same thing would be true of the smaller steel rotor, which, however, was always calibrated with the three or six position angles.

The calibrations at the beginning and end of a series always agreed closely. All calibrations were made with the proper current in the compensating coils, although, as already stated, considerable variations of the compensating current did not effect the sensibility appreciably.

§ 15. The experiment to correct for the departure from uniformity of the field produced by the rotor's solenoid and for the effect of the solenoid itself were most conveniently made with the rotors and coils near the upper magnet instead of the lower magnet.

In the case of each rotor it was found that adding to each end a solenoid 10 cm. in length, wound like the rotor but on a wooden core of approximately the same diameter, made no difference in the deflection produced by a given current.

The total length of the combined solenoids was about 50.5 cm. Solenoids of approximately the same diameters as those of the rotors and wound in the same way, but on wooden cores 50.5 cm. in length were mounted symmetrically in the place occupied previously by the rotors, and the deflections produced by known currents observed. From the ratio of the currents, and the ratio of the magnetometer sensibilities with rotor present and rotor absent, which precautions were taken to obtain, the ratio of the deflection produced by the solenoid alone to that produced with the same current by the solenoid and the rotor together was obtained for each rotor. The corrections thus found were 1.2 per cent. for cobalt; 0.6 per cent. for nickel; 0.9 per cent. for the smaller steel rod; and 1.3 per cent. for the larger steel rod.

Experiments were also made as a check and as a matter of interest with the central 30.5 cm. of the solenoids wound on wooden cores in place of the full lengths. Corrections obtained in this way are almost exactly twice those with the larger solenoids, which, being the true values, were applied to the observations.

§ 16. If C denotes the per cent. correction obtained above, and D_0 the corrected calibration double deflection, the true value of H/n will be obtained by substituting for D in the final equation of § 14 the quantity

$$D_0 = D\left(1 - \frac{C}{100}\right).$$

Thus we get, to a close approximation,

$$\frac{H}{n} = \frac{4\pi \times 16 \times 1.50 \times d \times \left(1 + \frac{C}{100}\right)}{10 \times 2.54 \times R \times n \times D} \frac{\text{gauss}}{\text{rev. per second}}. \qquad (2)$$

§ 17. The chief results of the observations are given in Table I. The sets (§ 5) are arranged in groups, each group containing from 2 to 14 sets, all at very nearly the same speed. The last two columns contain, for the series of observations occupying each horizontal row, the average departure of a single set from the mean value given in column 6 reckoned in two different ways. The value in column 6 is the weighted arithmetic mean calculated by assigning to the mean for each group a weight proportional to the number of sets in the group.

To obtain the departure given in the next to the last column the procedure was as follows: For each group of the series the average departure from the group mean was determined. This was multiplied by the number of sets in the group, and the sum of the products so obtained for all the groups in the series was divided by the total number of sets in the series. The departure given in the last column was obtained by taking the difference between the mean value given in column 6 and each of the group means, multiplying each difference by the number of sets in the group, adding and dividing by the total number of sets. The two columns together give a sufficiently good idea of the experimental errors.

§ 18. In addition to the observations given in the table, a few observations were made with the larger steel rod at lower speeds when conditions

TABLE I.

Intrinsic magnetic intensity of rotation in iron, nickel and cobalt.

Rotor.	Series.	Groups.	Mean Speed R.P.S.	Number of Sets.	$-\frac{H}{n} \times 10^7$ E.M.U. Mean.	Average Departure from Mean (Sets).	Average Departure from Mean (Groups).
Steel (smaller).	1	1–2	44.8	21	5.1	0.5	0.5
Steel (larger) . .	2	3–4	47.8	21	5.2	1.2	0.6
Cobalt.	3	5–7	20.2	17	4.8	2.2	2.2
	4	8–11	30.3	23	5.6	1.2	1.4
	5	12–25	45.5	79	6.0	0.9	0.8
	6	22	45.0	7	6.5	0.3	
	7	24	44.8	9	5.9	0.4	
	8	25	44.8	5	6.1	0.4	
Nickel.	9	26	20.5	4	4.7	2.0	
	10	27–28	30.5	9	6.7	1.1	1.1
	11	29–32	45.3	37	6.1	0.5	0.9

were such that the extraneous disturbances largely masked the effect being looked for. Moreover, a few sets were taken with a fifth rotor, of soft Norway iron, which gave results consistent with those given in the table, but with large discrepancies in the magnitude of the deflections. This rotor was very troublesome, and was found, after the experiments were completed, to have been constructed differently from the others—accurate washers having been added at the ends because the rotor had been found too short to fit the bearings perfectly. This construction may explain a part, but will not probably explain all, of the rotor's behavior, which has not yet been adequately investigated. Furthermore, on one occasion several sets with the nickel rod gave discordant deflections several times as great as the normal deflections for the same speed. On examination it was found that the rotor had been improperly mounted with large longitudinal play, suggesting such an effect as is obtained by tapping an iron rod while in a magnetic field. On another occasion, just after the completion of a long and good series of observations on nickel, with normal compensating current, at the end of a night's work, three sets of readings were taken with the compensating current above and below normal value. All were discordant and abnormally low. These and the other observations mentioned were omitted from the table.

§ 19. Six of the observations in series 11 on nickel were made with compensating current above and below the normal value, at 91.0 and 92.0, instead of 91.4, divisions. They are all included in the table, however, because the alterations of the current produced no change. With the rods of iron and cobalt the change produced by altering the current as in the case of nickel, from 91.4 to 91.0 and 92.0 divisions, was but little if any greater than the experimental error; but the observations are not included in the table because of the difference. In the case of cobalt the observations were taken on the same occasion with those for group 25. Group 25, with current 91.4 divisions, gave the deflection 1.00 ± 0.06 cm. for 5 sets. The same number of sets for currents 91.0 and 92.0 gave deflections 1.13 ± 0.04 cm. and 0.96 ± 0.06 cm., respectively.

§ 20. The observations mentioned in the last section show that no appreciable systematic error was introduced on account of currents induced in the rotor by its motion in the field of the earth, compensated as it was to about one part in nine hundred.

The field intensity produced at the center of the rotor by the control magnet was about one one thousandth the earth's intensity. The intensity produced by the lower magnetometer magnet at the same point was about equal, and had always a large component opposite, to that due to the control magnet. The intensity at the rotor due to the upper compensating coils was about one three thousandth the earth's intensity; and that due to the magnetization, both permanent and temporary, of the compensating rods, was also negligible.[1] Hence it would be unreasonable to suppose that any appreciable systematic error was produced by the motion of the rotor in these fields. That no great error of this sort was introduced is proved experimentally, moreover, by the agreement of the results obtained with the two rotors of iron of different diameters, inasmuch as any eddy current effect would depend upon the diameter.

§ 21. Another possible systematic error which had to be avoided was the error arising from the shift of the rotor's axis in azimuth or altitude, the shift being probably different for the two directions of rotation. If the residual field intensity normal to the axis of the rotor is Z and the maximum angular shift possible on reversal α, the maximum change of longitudinal intensity impressed on the rotor by an angular displacement is $Z\alpha$. The difference between the internal diameter of the lumen journals and the diameter of the bronze bearings was about 0.004 cm., and the distance between the far ends of the journals was about 35 cm. For the maximum possible value of α these data give $(2 \times 4)/35{,}000$. If we assume that Z is as great as 1/500 the earth's intensity, or about 0.6/500 gauss, we obtain as the maximum value of αZ the quantity $(8 \times 6)/(35{,}000 \times 5{,}000)$ gauss, or about 3×10^{-7} gauss. This intensity, which is certainly greater than any intensity of the sort which could have been produced, is only about one fourth the change of intensity which would be produced in the rotation experiments, by reversing the direction of rotation at a speed of one revolution per second. Any such

[1] Before beginning experiments with the smaller iron rotor, and before making the later experiments with the other rotors, their compensating rods were heated to whiteness and otherwise treated to demagnetize them as thoroughly as practicable. On making tests with a magnetometer, after the rotations were concluded, it was found that the maximum magnetic intensity which the temporary diametral magnetization of any of the compensators, placed in the undisturbed field of the earth, produced at a distance somewhat less than the normal distance between compensator and rotor was about one sixteenth hundredth of the earth's intensity. The actual intensity produced in the region occupied by the rotor during the rotation experiments was much less than this, since the compensator was then in a field of reduced intensity and since the plane containing the axes of rotor and compensator made a considerable angle with the earth's intensity. The maximum intensity in the region occupied by the rotor due to the permanent diametral magnetization of any compensator was found to be less than one ten thousandth of the earth's intensity; and the maximum intensity due to the permanent longitudinal magnetization was found to be about the same. The agreement between the results obtained before and after the compensators received the treatment described shows that the effects of the compensators were negligible in the early part of the work as well as in the later.

effect in these experiments was therefore negligible. So far as angular displacements of the rotor's axis in the plane parallel to the largest side of the compensating coil are concerned, this is also proved experimentally by the observations mentioned in § 19.

§ 22. Possible systematic errors due to the longitudinal motion of the rotor, carrying its magnetization with it and undergoing changes of magnetization on account of the space variation of the longitudinal components of the residual field intensity, were avoided by mounting the rotor free from appreciable longitudinal play and observing always only the effect of reversing the angular velocity. For a given speed there is no reason to expect a different longitudinal displacement, if any should occur, on reversal of the direction of rotation. Error due to the bodily motion of the magnetization with the rotor would also be eliminated in part by the process mentioned in the next section.

§ 23. As follows from the earlier investigation on iron no error due to torsion was to be expected. Nevertheless, the rotors were made reversible in their bearings, and in the cases of nickel and cobalt many sets of observations were made with the rotor turned in each direction, a process which would eliminate the torsion error if existent. No difference was found.

§ 24. Although the rotors were demagnetized until the residual longitudinal magnetization was in no case greater than about one tenth that of the principal rod of iron used in the earlier investigation, it always happened that when a rotor was rotated very slowly by hand the image of the lamp filament moved up and down on the scale—over many centimeters in the case of the cobalt and Norway iron rotors, and over smaller ranges in the case of the others. This is one of the reasons for the necessity of always making observations while the rotor was in motion. The procedure adopted of obtaining the difference of scale readings for both directions of rotation at the same speed avoided difficulty from this source. This procedure also avoided error due to the change of magnetization by centrifugal expansion of the rotor, discovered in iron in the course of the earlier investigation. This effect was doubtless much smaller in these experiments than in the earlier ones, as the residual magnetization was much less, but the method of observation did not permit its examination.

§ 25. All bearing parts were carefully turned and adjusted, and were oiled almost invariably before each set of four readings. These precautions, with the heavy mountings and special method of driving already described, eliminated almost completely, if not completely, mechanical disturbances due to the rotation. Other mechanical disturbances and magnetic disturbances were reduced as much as possible by beginning work in nearly all cases after one o'clock, and quitting before four o'clock, or sometimes a little later, in the night. Except during a few sets on one night, when a high wind was blowing, mechanical disturbances were never troublesome; but magnetic disturbances, in spite of the precautions taken to secure an astatic system and to adjust the magnetic compensator, were always present; and they account for the chief part of the accidental experimental error. The temperature during the night work was usually very nearly constant, and the compensating current varied very slowly, often requiring no adjustment for many sets. The speed of the driving motor also remained very nearly constant.

§ 26. In order to avoid all extraneous disturbances as far as possible the method of observation already described (§ 5) was adopted and was carried out on a regular time schedule. All being in readiness, the motor was started at a certain time T. After a fixed interval of t seconds (usually either 15^s or 20^s) the magnetometer scale and speed voltmeter were read, and the motor then stopped and the motor and voltmeter switches thrown for reversal. At the time $T + 1^m$ the motor was started in the opposite direction, and the readings taken t seconds later as before. Then observations for the two directions of rotation were made in inverse order, the motor being started at the times $T + 2^m$ and $T + 3^m$, and the readings being taken in each case t seconds later. The magnetometer double deflection obtained by subtracting the mean of the second and third scale readings from the mean of the first and fourth was independent of any slow drift and corresponded to the mean of the four speeds, always close together. In a few sets the constant interval between successive observations differed from 1^m; in a few the interval between the second and third differed from the other intervals, which was legitimate; and in some cases sudden magnetic disturbances made it necessary to observe the scale at a time differing from the schedule time; but the usual procedure was that given above, and departures from it were unimportant.

§ 27. With nickel and cobalt observations were made at three speeds. As shown in Table I., H/n was found to be independent of the speed within the limits of the experimental error, a result already obtained in the earlier experiments with iron. Since the chief disturbances were magnetic, the observations at lower speeds were less precise than those at the highest speeds. The results at the highest speeds are given in series 1, 2, 5 and 11. Series 6, 7 and 8 are a part of series 5, viz., the last three groups of results obtained with cobalt in a neutral field, one group of 5 sets (group 23), obtained shortly before group 24 while a strong wind was blowing and the magnetometer was imperfectly damped, being excepted.

§ 28. Every set of observations[1] gave the sign of H/n negative like that of $4\pi m/e$ for an electron. The mean magnitude of H/n is in all cases somewhat less than the accepted magnitude of $4\pi m/e$, viz., 7.1×10^{-7} E.M.U., obtained from other experiments on electrons in slow motion, ranging from 5.1 to 6.5×10^{-7} E.M.U. for the most reliable observations in Table I., viz. those at the highest speeds. The differences are in the same direction as in the earlier experiments on iron, which gave 3.6 and 3.1 in place of 7.1; but the experimental errors, on account of the great difficulties involved, are such that importance cannot in my opinion be attached to the discrepancies. The investigation must rather be taken as confirming equation (1) both qualitatively and quantitatively on the assumption that only electrons are in orbital revolution in the molecules of all the substances investigated. It shows moreover that the effect is independent of the size of the body in rotation, which is an implicit requirement of equation (1).

§ 29. This investigation has been made with the aid of a grant from the university for which I am indebted to the interest of the dean of the graduate school, Professor Wm. McPherson. I am indebted to Mr. Arthur Freund, mechanician in this laboratory, for most of the finer mechanical work necessary; and I am indebted to Mrs. Barnett for a great deal of help in making the experiments.

The Physical Laboratory,
Ohio State University,
March 13, 1917.

[1] Except one, at a low speed, among the early observations mentioned in § 18, in which the discrepancies were great and the effect was reached by extraneous disturbances.

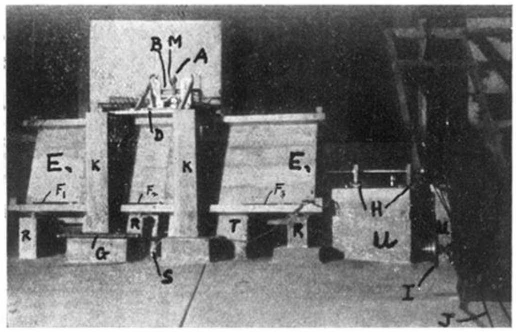

Fig. 2.

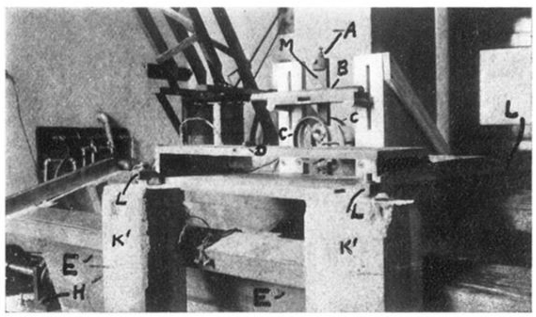

Fig. 3.

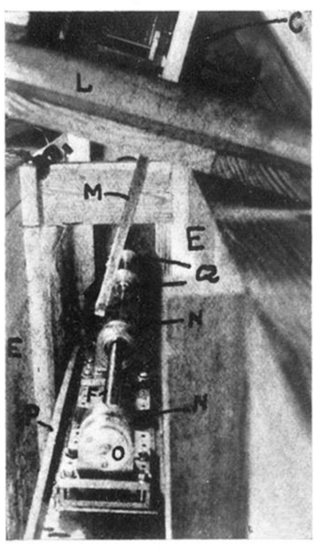

Fig. 4.