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MAGNETIZATION BY ROTATION.[1]

By S. J. Barnett.

§1. In 1909 it occurred to me, while thinking about the origin of terrestrial magnetism, that a substance which is magnetic (and therefore, according to the ideas of Langevin and others, constituted of atomic or molecular orbital systems with individual magnetic moments fixed in magnitude and differing in this from zero) must become magnetized by a sort of molecular gyroscopic action on receiving an angular velocity.

Thus consider a cylinder of iron, with zero magnetic moment in its initial state. If it is given an angular acceleration about its axis, each individual system, which we may suppose for simplicity to consist of a number of electrons revolving in fixed orbits with constant average velocities about an oppositely charged nucleus, will change its orientation in such a way as to contribute a minute angular momentum, and therefore a minute magnetic moment, parallel to the axis of the cylinder. This increment of angular momentum of each system is in the direction of the axis of rotation, and the corresponding increment of the magnetic moment is either in this direction or in the opposite direction according as the particles in revolution are positive or negative. If the revolving electrons are all negative, in conformity with most of the experimental evidence, the cylinder will become magnetized in the direction in which it would be magnetized by an electric current flowing around it in a direction opposite to that of the angular velocity imparted to it. This corresponds to the direction of magnetization of the earth and the sun.

§2. Preliminary experiments made at the Tulane University of Louisiana at the time this idea occurred to me appeared to show,[2] though doubtfully, a very minute effect of the sort in question, on the assumption that the revolving electrons are negative, in the case of a steel rod about

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[1] Revision of papers read before the Ohio Academy of Sciences, November, 1914, and the American Physical Society, November, 1913, December, 1914, and April, 1915.

[2] S. J. Barnett, Science, 30, 1909, p. 413.

7 cm. in diameter and half a meter long driven at a speed of about 90 revolutions per second. In these experiments two approximately cylindrical and similar electromagnets were mounted with their axes parallel and approximately perpendicular to the earth's intensity. One of the cores and both of the coils were fixed while the other core was rotated by an induction motor at a distance. The two coils were connected in series through a ballistic galvanometer in such a way as to compensate for any change of flux due to alteration of the earth's intensity. Changes of flux were determined by the galvanometer throws occurring on starting and stopping the motor. Later observations made in much the same way, but with an attempt at improvement in apparatus, failed to confirm this result with any certainty; and further investigation of the subject was postponed until better facilities were available.

§3. In 1912 a similar idea was advanced by Schuster[1] in his presidential address before the Physical Society of London. He also appears to have been led to his views by considering the origin of the earth's magnetism.

Referring to other hypotheses as to the production of magnetization by rotation, and assuming, for the sake of argument, that they account for terrestrial magnetism, he shows that one of the hypotheses cannot be correct, as it would then have been easily established by common observations on rotating bodies, and that the other leads to effects too minute to be detected by the most refined observations.

He then takes up the hypothesis similar to that introduced here,—a hypothesis according to which rotation, instead of *directly determining magnetization*, "determines magnetic intensity which may or may not cause magnetization according to the nature of the body." "It is," he says, " . . . quite in accordance with our present views that every rotating body should be subject to a magnetizing force along the axis of any rotation that may be impressed upon it. If magnetization be due to a circulation of electrons within the molecules these should to some extent behave like gyrostatic compasses, setting themselves parallel to the axis of rotation of the body which contains them. Further properties of molecular constitution have, however, to be specified before we can say whether any actual magnetization results. If the electron is free,[2] the main result, I believe, would be only a magnetic precession round the axis of rotation, and in this we may find a powerful argument [for this explanation of terrestrial magnetism], because the same cause which gives us the magnetic force, also gives us the secular variation[3] . . . "

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[1] A. Schuster, Proc. Phys. Soc. London, 24, 1911–12, p. 121.

[2] A hypothesis contrary to mine.

[3] In this address Schuster refers to an address made eleven years earlier in which he suggested the possibility "that terrestrial magnetism is due to the rotation of the electron round

"On the other hand, the theory [in order to account for terrestrial magnetism] would have to explain why the iron inside the earth becomes more strongly magnetized than the iron in our laboratories. There is, of course, always the possibility of some substance being subject to the effects of rotation in a much higher degree than iron. Such questions can only be settled by experiments which are now in progress." On the importance of these, and other such experiments, Schuster lays great stress.

§4. It soon occurred to me that the effect under investigation was the converse of the effect predicted and looked for by O. W. Richardson[1] in 1907–8, viz., the production of rotation by magnetization; and it became apparent that both effects were immediate consequences of an idea advanced long ago according to which a magnet must behave like a gyrostat if the Ampèreian currents consist in the motion of actual matter. This idea is due to Maxwell,[2] who constructed apparatus for experiments upon the subject as early as 1861.

In Maxwell's experiments an electromagnet was pivoted in a frame in such a way as to be free to rotate about a horizontal line through its center of mass and perpendicular to its magnetic axis. With the magnetic axis making an angle θ with the vertical, the frame was rotated at high speed about a vertical axis, and optical observations were made for a change in θ, stability having been secured by suitable adjustments of the principal moments of inertia. No change was detected, but only rough observations were possible.

My own experiment may be considered as a modification of Maxwell's, and the principal equation in the development of its theory, after that giving the relation between the angular momentum and the magnetic moment of a molecular magnet, is a special case of his equation for the torque acting to diminish the angle θ. In my experiment Maxwell's electromagnet is replaced by each of the countless multitude of molecular magnets of which the iron rod is constituted, and the total change in the orientation of all these magnets with reference to the axis of rotation of the rod is determined magnetically instead of optically.

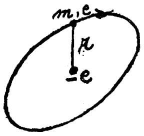

Fig. 1.

§5. A quantitative theory of the effect will now be developed.

Consider the simplest type of molecular magnet (Fig. 1), in which a single particle with charge e and mass m revolves in a closed orbit about

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the atom" as a means of explaining magnetic precession. The quotation from this earlier address, of which I first learned from the 1912 paper, would indicate that Schuster had probably in mind in 1901 the idea which he proposed definitely in 1912.

[1] O. W. Richardson, Phys. Rev., 26, 1908, p. 248.

[2] Electricity and Magnetism, § 575.

a much more massive nucleus with charge $-e$. If r denotes the radius vector, ω the angular velocity, $\alpha = \frac{1}{2}r\omega^2$ the areal velocity, μ the magnetic moment of the molecular system, and M the angular momentum due to the orbital motion, we have

$$\mu = e\alpha \quad \text{and} \quad M = mr^2\omega = 2m\alpha. \tag{1}$$

Hence

$$\frac{M}{\mu} = 2\frac{m}{e}, \quad \text{or} \quad M = 2\frac{m}{e}\mu; \tag{2}$$

so that the angular momentum is directly proportional to the magnetic moment.

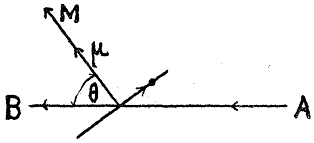

Fig. 2.

If the normal to the orbit (Fig. 2) makes an angle θ with any direction AB, the component of the magnetic moment μ in this direction is $\mu \cos\theta$, and that of the angular momentum is thus

$$M\cos\theta = 2\frac{m}{e}\mu\cos\theta.^{1} \tag{3}$$

If the body of which the molecular system of Figs. 1 and 2 is a part is set into rotation about the axis AB with angular velocity Ω, the angle between the vector representing M, the angular momentum of the system due to its orbital motion, and AB will decrease, just as in the case of a gyroscope, until the torque T' on the revolving system brought into existence by this displacement is just equal to the rate of increase of its total angular momentum in the steady state when kinetic equilibrium has been attained and the vector M is tracing out a conical surface with constant semiangle θ and angular velocity Ω. The effect in this steady

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[1] Assuming m/e identical for all the orbital systems, and summing over the unit volume, we have

$$\Sigma M\cos\theta = 2\frac{m}{e}\Sigma\mu\cos\theta = 2\frac{m}{e}I, \tag{4}$$

which is the formula developed by Richardson (l. c.), but by a complicated process. Here $I = \Sigma\mu\cos\theta$ is the intensity of magnetization, and $\Sigma M\cos\theta$ is the angular momentum of the electrons per unit volume, both reckoned in the direction AB.

This fundamental equation of Richardson's theory is developed in essentially this same manner, in which it was presented in the first two papers which this article reports, in a more recent paper presented by Einstein and de Haas in February and April (D. Ph. Ges., No. 8, April 30, 1915). In this paper are described experiments on soft iron by the method of resonance which appear to confirm Richardson's theory. I had myself started experiments on this effect, beginning with the ballistic method but planning to use the method of resonance if necessary. From my ballistic experiments I can state that in the case of brass no effect exists comparable with that which the simple theory indicates should exist in the case of iron. Einstein and de Haas have found the same thing true of copper. Their paper contains no reference to the previous work of Maxwell, Schuster, Richardson, or myself.

state is exactly the same as if the body were at rest and the system were acted upon by a torque $T'' = -T'$ due to an extraneous magnetic field with strength H equal to the intrinsic magnetic intensity of rotation. The complete expression for T'' is known (and can readily be shown from first principles) to be

$$T'' = -T' = -M\Omega \sin\theta - B\Omega^2 \sin\theta \cos\theta, \qquad (5)$$

where B denotes the excess of the moment of inertia of the system about the axis of its orbital angular velocity ω over the moment of inertia about that diameter of the orbit making with AB the angle $90° - \theta$. If the orbit is circular

$$B = mr^2 - \tfrac{1}{2} mr^2 = \frac{M}{2\omega}. \qquad (6)$$

Eliminating B and M from (5), we get

$$T'' = -\mu \sin\theta \cdot 2\frac{m}{e}\Omega\left(1 + \tfrac{1}{2}\frac{\Omega}{\omega}\cos\theta\right). \qquad (7)$$ [1]

Dividing this expression by $-\mu \sin\theta$, as in the case of an ordinary magnetic field, we get the intrinsic intensity of rotation:

$$H = 2\frac{m}{e}\Omega\left(1 + \tfrac{1}{2}\frac{\Omega}{\omega}\cos\theta\right). \qquad (8)$$ [2]

The values of Ω experimentally attainable are so small in comparison with ω that the second term is negligible. If the orbit is not circular we obtain for H an expression whose first term is identical with that of (8) and whose second term has the same order of magnitude as that of (8).

If we assume that e/m has the value ordinarily accepted for the negative electron in slow motion, viz., -1.77×10^7, and put $\Omega = 2\pi n$, where n is the angular velocity in revolutions per second, we obtain for the intensity per unit angular velocity

$$H/n = -7.1 \times 10^{-7} \frac{\text{gauss}}{\text{r.p.s.}}. \qquad (9)$$

This is on the assumption that the negative electron alone is effective. According to this, all substances would be acted upon by precisely the same intensity for the same angular velocity.

If some or all of the positive ions also have orbital motions, proportionality with angular velocity will evidently still exist, but the coefficient of Ω will be reduced in magnitude or even changed in sign, and the intensities acting on different substances may differ for the same value of Ω.

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[1] This equation, as stated above, also follows immediately from Maxwell's equation for the torque when the conditions here assumed are put in.

[2] The first term of this equation has been given previously by Einstein and de Haas (l. c.), but is incorrectly derived in their paper, equations for a *molar* magnet instead of a *molecular* magnet being employed. All the terms of their equations reduce to zero unless the body is originally magnetized.

If the influence of the negative electrons is preponderant, the number in (9) gives the *maximum* magnitude of H/n, attained when the negative electrons alone are effective.

The relation of proportionality must hold also between the angular velocity and the magnetic flux density and intensity of magnetization, which are very minute and therefore proportional to the intrinsic intensity; but these quantities will depend not only upon the intensity but also upon the material and shape of the rotating body. Thus in the case of a diamagnetic substance each of the orbits in an atom or molecule tends to change its orientation precisely as an orbit in a magnetic molecule; but no gross magnetic effect can, on the theory advanced here, result, because the geometric sum of the individual magnetic moments of the particle is permanently zero.

§6. In the experiments performed here two modifications of the earlier method have been tried, in both of which the galvanometer was replaced by a fluxmeter. In one series of experiments the magnetic circuit was constituted almost wholly of iron. The iron cylinder under investigation rotated between the pole-faces of a large U-shaped electromagnet, with minute air gaps; and the similar coils on the two legs of the iron core, connected in series in the usual manner, were put in the series with the fluxmeter. This apparatus was very sensitive, but the large extraneous reactions were such as to mask or make impossible of interpretation such minute effects as were under investigation.

§7. The other series of experiments, which has given definite and conclusive results, will be described in considerable detail on account of the newness of the effect obtained.

In these experiments two nearly similar rods of steel[1] shafting A and B (Fig. 3) were mounted with their axes horizontal and approximately at right angles to the magnetic meridian, and two similar coils of insulated wire were mounted about their centers. These coils were connected in series with one another and with a fluxmeter, and were oppositely wound like the coils of an ordinary U-shaped electromagnet, so that any variations in the intensity of the earth's field, acting in the same way on both rods, might produce no effect on the fluxmeter. One of the rods, which will be called the compensator, as A, remained at rest, while the other, called the rotor, as B, was alternately rotated and brought to rest, the change of flux being determined by the fluxmeter.

The approximate dimensions of the rods A and B as they were used in nearly all of the work, are indicated in Fig. 3. The dimensions of the

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[1] Steel, even when soft, has the advantage of freedom, or approximate freedom, from magnetic lag in weak fields, as shown long ago by Ewing (Roy. Soc. Proc., June 20, 1889), and confirmed by experiments on the steel rods used in this work.

two coils used in most of the work are also indicated in the figure. Each of these coils was wound on a brass bobbin with about 5,000 turns of No. 14 D.C.C. copper wire, the winding being made very regular on account of other investigations for which they were primarily designed.[1] A third coil, of somewhat different construction, was substituted for one of the coils in some of the experiments (see below, §23).

§8. In the first part of the work the rotor was mounted in brass bearing pieces inserted in bronze castings bolted to the cement floor of the laboratory, all parts being accurately fitted so that there was as little play as practicable. The rotor was driven by a brass rod 1.4 meters long and 1.1 cm. in diameter, itself direct-connected to a counter-shaft and pulley system driven by belt from an alternating current motor of the repulsion type.[2] The countershaft and pulley system was entirely of brass, bronze, and wood, and moved in brass castings bolted to the floor, with thin iron sleeves for bearing pieces. The motor's pulley was similar to that of the countershaft, except that it was mounted on an iron sleeve. Excessive vibration of the connecting rod was prevented by three properly spaced pieces of wood fastened to the floor and pierced by holes of suitable diameter for the passage of the rod. This method of driving, together with frequent oiling and the slow starting of the motor by the insertion of a choke-coil in series with its field coils, eliminated almost completely magnetic changes in the rotor due to vibration. The compensator and rotor were mounted 2.8 meters apart in positions symmetrical with respect to the motor.

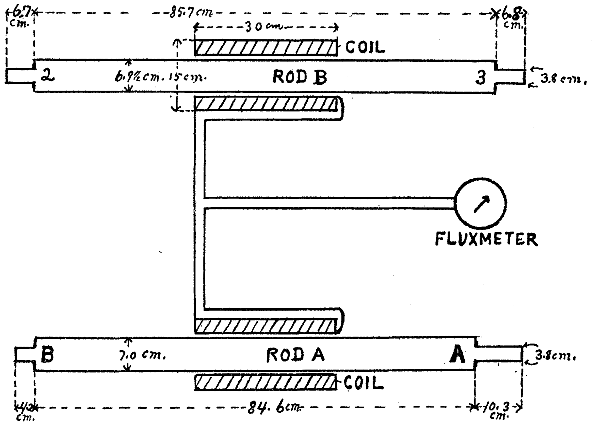

Fig. 3.

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[1] S. J. Barnett, "On electromagnetic induction and relative motion," Phys. Rev., 35, 1912, p. 323; "Some experiments on the magnetic field of two electromagnets in rotation," Phil. Mag., 26, 1913, p. 987; (London) Electrician, 74, 1914, p. 21.

[2] For the loan of this motor I am indebted to the department of electrical engineering.

§9. The fluxmeter was a Grassot instrument provided with a concave mirror with approximately 2 m. radius of curvature. It was mounted on a slate shelf cemented into the laboratory wall, and readings, with lamp and scale, were obtained to 0.1 mm. at a scale distance of approximately 2 m. Later on the scale distance was increased, usually to 8 m., a concave lens being added,[1] and all deflections have been reduced to this distance.

On account of the residual torsion of the suspension and the thermal electromotive forces in the circuit, the fluxmeter image usually drifts across the scale with greater or less rapidity, and it is necessary to compensate the drift by introducing suitable electromotive forces into the circuit. This was done by means of a potentiometer arrangement such as that commonly used in experiments on the Hall effect. As a result the drift was largely compensated, but ordinarily by no means as well as in the later experiments.

§10. In order to eliminate residual drift and other extraneous disturbances, readings were ordinarily taken in sets of eight, as follows: two with counter-clockwise or *negative* rotation (as seen from the west end of the rotor) four with clockwise or *positive* rotation, and two more with counter-clockwise or negative rotation, the order of the positive and negative rotations being sometimes reversed. The fluxmeter scale was read when the speed became steady, and again when the speed became so small that a minute quaver of the image became just visible, very slow rotation always producing a synchronous small vibration of the image. Mean deflections for the two directions were then obtained; and half the difference gave the change of flux produced by changing the speed from its maximum (which was the same in both directions) to a few revolutions per second.

To make the rotor run as smoothly as possible and to keep the bearings as free from deterioration as possible, the bearings were almost invariably oiled before taking each observation. Observations were made as the motor came to rest, instead of being made as it was brought to full speed, because the disturbances, both mechanical and electrical, were less for this procedure.

§11. The fluxmeter was standardized for changes of flux by introducing into its circuit, connected as in the rotation experiments, one coil of a

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[1] The equivalent radius of curvature of this optical system depended greatly on the temperature, varying within the course of the work by more than 2 m. The optical system was otherwise poor, but the readings could be obtained with precision by making use of the narrow diffraction pattern produced with a carbon lamp glowing at extra voltage, or one of the new nitrogen filled tungsten galvanometer lamps made by the General Electric Company. For the opportunity of using one of these excellent lamps before they were placed on the market I am indebted to Mr. L. T. Robinson of this company.

low resistance mutual inductance standard, and making and breaking a circuit containing the other coil traversed by a current measured with a standard ammeter. To a precision of about one per cent. the fluxmeter gave 1 mm. deflection for 90 maxwells at the scale distance 8 meters.

Drift being eliminated, special experiments showed that the fluxmeter deflections for minute flux changes of the order of those occurring in the rotation experiments recorded here were independent of the time in which the changes occurred—as they are well known to be for large flux changes.

§12. To determine H_0, the intrinsic magnetic intensity of rotation per mm. of fluxmeter deflection at the scale distance 8 meters, the procedure was as follows:

Two equal wooden cylinders turned to the same diameter as that of rotor B were fastened coaxially to its ends, and the complete cylinder thus formed was wound (in three parts) on a lathe with a nearly uniform solenoid of insulated wire, 8 turns to the inch. The complete solenoid was about three times as long as the rotor occupying the central part. The solenoid was connected in series through a key with a constant battery of electromotive force 2.02 volts and an adjustable standard resistance box. With a resistance of 5,000 ohms in the battery circuit, and the fluxmeter circuit arranged as in the rotation experiments, the fluxmeter deflection was obtained repeatedly when the battery circuit was reversed in both directions. Many previous experiments had proved that with such minute magnetomotive forces or currents as were involved in these experiments and the other calibrating experiments described below, fluxmeter deflections, as would be expected, were strictly proportional to currents.

If h_0 denotes the solenoid's magnetic intensity per mm. deflection at 8 m., and D the mean fluxmeter deflection at 8.5 m., the scale distance at which these observations were made, we have from what precedes and the well-known formula for the magnetic intensity within a long uniform solenoid

$$h_0 = \frac{\frac{4\pi}{10} \times \frac{8}{2.54} \times \frac{2.02}{5{,}000}}{\frac{8.0}{8.5} \times \frac{D}{2}} \frac{\text{gauss}}{\text{mm.}} \tag{10}$$

The experiments were made with two different distances between rotor and compensator, viz., 1.2 m. and 1.6 m. The values of D for the two sets did not differ by as much as one third per cent. The mean value of D was found to be 273 mm., at the scale distance 8.5 m.

The long solenoid was desirable in order to obtain as nearly uniform a calibrating intensity as practicable, the intrinsic intensity of rotation being strictly uniform throughout the rotor. On account of the fact that the calibrating intensity acts on both the iron and the aether which permeates it, while the intrinsic intensity of rotation acts upon the iron only, it was desirable to eliminate the effect of the solenoid alone by making a separate experiment with no iron in the solenoid. Experiments of this kind showed that the deflection produced by the solenoid alone was 1.6 per cent. of that produced by the solenoid and core.

From this fact and equation (10) we get for H_0

$$H_0 = h_0(1 + 0.016) = 1.26 \times 10^{-5} \frac{\text{gauss}}{\text{mm.}} \qquad (11)^1$$

Approximate calibrations were also made with a similar solenoid wound on the rotor alone,[2] with distances 2.8 m., 1/3 m. and 1/4 m., between rotor and compensator. These gave for H_0, in the unit used above, 1.25×10^{-5}, 1.14×10^{-5}, and 1.07×10^{-5}, respectively.

§13. To determine B_0 and I_0, the flux density and intensity of magnetization per mm. deflection at 8 m. produced by the rotation H_0, a second experiment was necessary. A coil of 200 turns of insulated copper wire was wound over the central 10 cm. of the long solenoid and connected in circuit with the fluxmeter, the total resistance of the fluxmeter circuit being made equal to its former value by the addition of extra resistance from a box. The mean fluxmeter deflection was then obtained on reversal of a solenoid current just four times as great (1,250 ohms being now in the solenoid circuit) as that used in the first experiment. For the rotor-compensator distances 1.2 m. and 1.6 m. the same deflection (within 1/7 per cent.), 70.6 mm., was obtained at the scale distance 8.5 m.

The cross-section of rotor B was 37.8 cm.^{2}, and the fluxmeter constant was, as stated in §11, 90 maxwells per mm. at 8 m. Hence if δB denotes the change of flux-density in the first experiment, and $\Delta B = 4\delta B$, therefore, that in the second, we have for the actual change of core flux in the second experiment

$$\Delta B \times 37.8 \text{ cm.}^2 = \frac{70.6}{200} \times \frac{8.0}{8.5} \times 90 \text{ maxwells.}$$

The same change of core flux with the first arrangement of coils would have produced at the scale distance 8 m. the deflection 4 × 273 × 8.0/8.5 mm. Hence, as this was the arrangement used in the rotation experiments, we have for the flux-density produced by rotation per mm. deflection at the scale distance 8 mm.,

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[1] Calibrations made before and after the principal experiments, and with methods and standardized instruments varied, were all in close agreement.

[2] Elimination of the extra length of solenoid almost exactly compensated for the small effect produced by the solenoid with iron removed.

$$B_0 = \frac{1}{37.8} \times \frac{70.6}{200} \times \frac{1}{4 \times 273} \times 90 \left(\frac{\text{maxwells}}{\text{cm.}^2}\right) \text{ per mm.} \tag{12}$$

$$= 7.7 \times 10^{-4} \left(\frac{\text{maxwells}}{\text{cm.}^2}\right) \text{ per mm.}$$

In connection with the approximate determinations of H_0 at the rotor-compensator distances 2.8 m., 1/3 m., and 1/4 m., mentioned in the last section, determinations of B_0 were also made giving the values 8.1×10^{-4}, 7.3×10^{-4}, and $6.9 \times 10^{-4} \left(\frac{\text{maxwells}}{\text{cm.}^2}\right)$ per mm., respectively.

The intensity of magnetization at the central section of the rotor per mm. deflection, which will be denoted by I_0, is approximately

$$I_0 = B_0/4\pi. \tag{13}$$

§14. With the apparatus now described over twenty-five sets of observations were obtained. The rotations of one group were made with rotor *A*, most of them at about 50 r.p.s., two at about 18 r.p.s. Those of the other group were made with rotor *B*, some of them with the end designated as "end 2" east, the remainder with the rotor reversed, all at about 50 r.p.s.

Each of the groups gave a mean result (differential deflection) in the direction predicted by theory on the assumption that the revolving electrons are negative, the mean deflection (reduced to 8 m. scale distance) per unit speed being about 0.04 mm.; but the discrepancies were large, partly on account of imperfect compensation of the earth's intensity owing to the large distance between rotor and compensator, partly on account of non-uniformity and imperfect compensation of fluxmeter drift, and partly on account of mechanical vibration and other causes.

§15. As had proved to be the case in the Louisiana experiments, there was always superposed on the deflection which apparently corresponded to the effect under investigation a deflection independent of the direction of rotation. Moreover, in one set of observations made on rotor *A* to see whether either effect was altered by reversing the residual magnetism of the rotor, it was found (and the same thing had been found in the earlier experiments), that no alteration occurred (see further, §34). But reversing the ends of a rotor invariably reversed the absolute deflection.

§16. In seeking an explanation of these phenomena and a justification of the method of investigation a number of experiments were made. In the first place it had been assumed that an alternating flux through the fluxmeter circuit would not affect the scale reading provided the frequency exceeded a few cycles per second. An alternating flux was always produced by the rotation of the rotor on account of lack of symmetry of its residual magnetization with reference to the coil, and by the stray flux from the alternating current motor.

To investigate this matter, one coil of a low resistance mutual inductance standard was placed in the fluxmeter circuit and the effect on the reading noticed when the other coil was traversed by an alternating current of such magnitude as to produce changes of flux through the other coil and fluxmeter of the same amount as occurred during the slow rotation of the rotor. Absolutely no effect was produced by making or breaking the alternator's circuit, the frequency being 40 cycles per second. Even changes of ten and one hundred times this amount, at frequencies of about 33 and 63 cycles per second, respectively, produced either no effect or (in the case of the latter) sometimes a slight effect on breaking the circuit. Neither was any change produced by driving the alternator from rest up to full speed, the circuits being permanently closed.

A related test was made with the motor itself. The motor, on being started, usually produced a quick throw of a number of mm., sometimes in one direction, sometimes in the other. This irregular effect quickly disappeared and did not reappear on stopping the motor. To test the effect of the motor on the permanent deflection, the fluxmeter was disconnected from the rotor and compensator coils and connected to another short thick coil provided with an iron core and placed near the motor. With this arrangement, and the motor driving the rotor as before to insure the expenditure of the same power as in the principal experiments, irregular throws, similar to those which occurred in these experiments, were produced on starting the motor, but the change of reading on the motor's coming to rest was either very slight or zero.

Further experiments on the fluxmeter are described below.

Suspicion that the effects might be due to a very slight longitudinal displacement of the rotor, or a very slight angular displacement of its axis, was easily shown by experiments to be groundless. All possibility of electric disturbances, which gave considerable trouble in a part of the work referred to in §6, was eliminated by earthing the fluxmeter circuit.

§17. It seemed possible that the second effect mentioned in §15, also the curious difference between the effects of reversing the rod and reversing the magnetization, and perhaps also with them even the first effect could be explained as consequences of the induction of electric currents in the rotor by its rotation in the earth's magnetic field. An effect of such currents upon the rotor coil must ordinarily exist even though it is wound with the turns almost precisely perpendicular to the rotor.

The change in sign of the mean deflection on reversal of the rotor pointed toward inhomogeneity; and it seemed possible to account for the identity of sign of the deflections for both directions of rotation by the shift of the stream lines of the induced currents with the reversal of this direction.

Figs. 4 and 5 illustrate an extreme case, in which, on account of symmetry, the fluxmeter deflection would be the *same*, in both direction and magnitude, for both directions of rotation of the rotor, *A*. In the first figure the stream-lines, the cross-section of the symmetrical one of which is indicated by the black dots, are displaced anti-clockwise, in the second clockwise, with reference to the earth's intensity, with the result that the change of flux through the test coil *C* is the same in both cases. It is easy to arrange a test coil near the rotor in such a way as to obtain almost any relation between the deflections for the two directions of rotation.

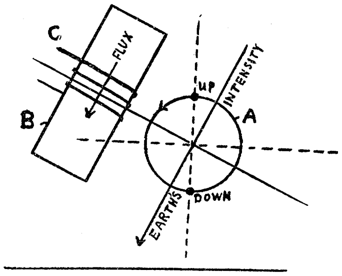

Fig. 4.

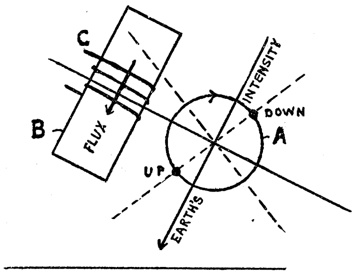

Fig. 5.

§18. An attempt was made to test this idea by altering as much as practicable the angle between the axis of the rotor coil and the axis of the rotor, although the free space between the rotor and bobbin was so small that only a small angular shift was possible. In the one complete and careful set of observations made, the mean deflections were altered considerably by the shift, but the sign of the deflections and the sign and magnitude of the differential deflections were not altered. In other, and rougher, experiments with different directions of the coil's axis, with one uncertain exception, no change of sign resulted. Moreover, later experiments, in which an irregularly wound coil was used, gave deflections in the same direction.

In another experiment the rotor coil was removed and mounted on a second compensating rod parallel to the first, the two being placed near and on opposite sides of the rotor. Rotating the rotor always produced a decided fluxmeter deflection.

§19. To get rid of the effects of induced currents in the rotor two methods were tried. First a rotor was constructed almost entirely of thin discs of iron, but its rigidity was insufficient. Resort was therefore had to the second alternative, viz., the compensation of the earth's intensity in the region occupied by the rotor by means of a large coil or cage of wire traversed by an electric current.

The framework of this cage was accurately constructed of brass and paraffined wood. The coil was about 1.5 m. in length (horizontal and approximately parallel to the rotor), $\frac{1}{4}$ m. in width (approximately normal to the earth's intensity), and $\frac{1}{7}$ m. in depth (approximately parallel to the earth's intensity). It was carefully wound of copper wire, uniformly except at the ends, where provision was made for the admission of the driving rod and rotor, and was mounted on the floor with its center approximately at the center of the rotor. A coil of these dimensions cannot, of course, produce a strictly uniform field in the region occupied by the rotor, and a much larger coil would have been made except for the expense involved in its construction and in properly mounting the rotating apparatus at a considerable height above the floor. Nevertheless it was capable of giving important information, and with it the first conclusive results were obtained.

§20. A few sets of observations on rotor *B*, with both end *2* and end *3* east, taken with the earth's field approximately annulled in this manner, gave results practically the same as those already described.

§21. In spite of the tests already described, suspicion still attached to the electric motor; and for a greater degree of certainty it was now replaced by a small air turbine made by adding to the countershaft and wooden pulley already described six uniformly spaced radial brass vanes. Compressed air was admitted to the vanes from four brass nozzles, two, symmetrically placed about the axis of the turbine, being open for each direction of rotation. The bronze shaft of the turbine was directly connected to the rotor by a brass rod 1.1 cm. in diameter and 0.3 m. long. For the final experiments the length was somewhat increased.[1]

Uncertainty as to the steadiness of the air pressure and speed made it necessary to add an instantaneous speed counter. For this purpose a very small separately excited dynamo, with a voltmeter across the armature terminals, was used. The dynamo was driven by a 24 ft. belt running on a pulley on the shaft of the turbine and the combination was properly calibrated, speeds in revolutions per second being obtained

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[1] The rotation of the bronze countershaft, turbine wheel, and connecting mechanism, while the rotor was clamped, produced no effect on the fluxmeter although the speed was greater than the maximum speed of the rotor in the principal experiments.

by multiplying the voltmeter reading by 0.566.[1] The speeds were sufficiently near to uniformity, the means for the clockwise and counterclockwise rotations in a set not differing usually by as much as one r.p.s., and the individual speeds often differing by much less than this.

§22. The observations with this apparatus were made in much the same manner as those already described, except that the fluxmeter reading for zero speed was obtained for a definite position angle of the rotor, instead of the reading for low speed. The turbine wheel was numbered at equal intervals around the periphery, and the zero reading was taken with a chosen one of these numbers uppermost, always the same throughout a set. The absolute deflection depends upon the number chosen, but the differential deflection does not, as was early found by direct experiment. This will be explained in §30.

§23. In this manner a number of sets of observations were obtained with both rotors and under various circumstances. These observations are given in Table I. For some of them the distance between rotor and compensator was made as small as ¼ or ⅓ meter, in order to compensate more readily the variations of the earth's intensity; but at such small distances apart the inductive action between the two rods is sufficient to modify the mean deflection greatly as is evident from the effect of reversing the compensator; though the effect on the differential deflection is very much less. In the last column but one, E signifies that the rotor was in the uncompensated field of the earth; $2E$ that the earth's field was approximately doubled in intensity by means of a current in the compensating coil; $-E$ that the earth's intensity was approximately reversed by a compensating current, and O that the earth's intensity was approximately compensated by the current in the cage.

It is to be remarked that in the case of every group (and the same is true of every set), however different the circumstances, the differential deflection has the same sign, and the positive sign, which, for the given arrangement of apparatus, means an effect in the direction predicted by theory on the assumption that the revolving electrons are negative.

Sets 13–18 were obtained with a rotor coil different from the two already described. It contained the same amount of the same kind of wire and had approximately the same dimensions and same constant in the fluxmeter circuit, but was not wound so regularly; and it was wound on a bobbin made of wood and fiber. This substitution was made in order to annul any possible effect of induced currents in the bobbin due to the lack of symmetry of the rotor's magnetization about

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[1] After all the rotations in this investigation were completed this calibration was checked and found to have remained unaltered.

TABLE I.

Deflections and Speeds.

Earlier Observations and Results.

Number of Group.	Number of Sets.	Rotor Used.	End East.	Distance Between Rotor and Compensator.	Mean Speed.	Mean Deflection for Negative Rotation (−).	Mean Deflection for Positive Rotation (+).	Differential Deflection (−) − (+).	Intensity of Field.	Remarks.
				m.	r.p.s.	mm.	mm.	mm.		
1	5	*B*	2	$\frac{1}{4}$	42	+ 9.3	+ 7.1	$+2.2(1.9)^1\pm0.9$	0	
2	4	*B*	3	$\frac{1}{4}$	45	+ 3.0	− 1.4	$+4.4(3.7)^1\pm1.1$	0	
3	2	*A*	*B*	$\frac{1}{3}$	42	−11.0	−13.1	$+2.1(1.9)^1\pm0.2$	0	
4	2	*B*	2	$\frac{1}{3}$	23	− 0.6	− 1.7	$+1.1(1.0)^1\pm0.1$	0	Compensator reversed in Group 5. $\left\{\begin{array}{l}\text{Mean reduced diff. defl.} = +0.95\\ \text{Mean speed} \qquad\qquad = 26\frac{1}{2}\end{array}\right.$
5	1	*B*	2	$\frac{1}{3}$	30	+ 2.5	+ 1.5	$+1.0(0.9)^1$	0	
6	1	*B*	3	$\frac{1}{4}$	47	− 1.3	− 4.4	$+3.1(2.6)^1$	2*E*	
7	1	*B*	3	$\frac{1}{4}$	45	− 0.5	− 4.9	$+4.4(3.7)^1$	*E*	
8	1	*B*	3	$\frac{1}{4}$	45	+ 4.6	+ 3.1	$+1.5(1.3)^1$	− *E*	
9	1	*B*	2	$\frac{1}{4}$	45	+15.4	+10.5	$+4.9(4.2)^1$	*E*	
10	1	*B*	2	$\frac{1}{4}$	45	+11.6	+ 8.8	$+2.8(2.4)^1$	− *E*	
11	1	*B*	2	1	42	+ 4.4	+ 1.8	+2.6	0	End *B* of compensator east.
12	1	*B*	2	1	39	+ 5.1	+ 2.8	+2.3	0	End *A* of compensator east.
13	1	*B*	2	1	45	+ 4.9	+ 1.0	+3.9	*E*	Rotor coil on insulating bobbin.
14	2	*B*	2	1	46	+ 7.0	+ 4.3	+2.6±0.5	0	Rotor coil on insulating bobbin.
15	2	*B*	2	1	32	+ 3.6	+ 1.9	+1.8±0.5	0	Same, also rotor in wooden bearings.
16	1	*B*	2	1	33	+ 4.0	+ 1.8	+2.2	0	Same, also cage circuits broken.
17	2	*B*	2	1	39	+ 5.9	+ 3.3	+2.6±0.2	0	Same, also iron bolts removed.
18	1	*B*	2	1	40	+ 8.0	+ 3.2	+4.8	*E*	" " " " "

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[1] The quantities in parentheses are the deflections reduced to the sensibility for the case in which rotor and compensator were 1 meter or more apart.

its axis. For a similar reason wooden bearings were then substituted for the metal bearings, and the brass circuits of the cage were cut. It was finally discovered that four small iron bolts had been accidentally left embedded in the cement floor, two near each end of the rotor (whose axis was about 13 cm. from the floor). These were removed. Observations made after each of these changes showed that they were without effect.

§24. The relation between the differential deflection and the speed was plotted on cross-section paper for groups 4–5, 11–12, and 14–17. As the table shows, 11–12, and 14–17 are the only groups for which the earth's intensity was annulled and the rotor-compensator distance as great as 1 m.; and groups 4–5 are the only ones with smaller distance and with earth's field annulled and compensator in both positions. Within the limits of the experimental error the deflection was proportional to speed. The mean of 4 and 5 was taken in order to eliminate as far as was possible the effect of the compensator. A straight line was drawn from the origin with slope obtained by dividing the sum of all the differential deflections by the sum of all the speeds, each group being counted as many times as it contained sets, except in the case of 4–5, which was considered equivalent to only 2 sets. The slope of this line was the weighted mean differential deflection per unit speed and equals 0.057 mm. per revolution per second.

§25. After the completion of the work thus far described it was decided to repeat the rotations in a region in which the earth's intensity was still more completely annulled.[1]

For this purpose it was necessary to mount the rotor and turbine about half a meter above the floor, and suitable piers were constructed of concrete. The two piers which supported the rotor were necessarily narrow (though much longer than broad) and inclined to the horizontal at about the angle of dip, and were therefore reinforced with brass rods cemented with them into the floor. The iron bearing sleeves of the turbine were replaced by vulcanized fiber, the iron pipe carrying compressed air to the turbine tubes was replaced by brass, and the earth's magnetic field in the region to be occupied by the rotor was carefully examined. In passing from one end of the rotor to the other the declination varied by about one degree, and the dip was uniform to at least one tenth degree. The rotor was mounted with its axis horizontal and perpendicular to the mean meridian. The original brass bearings in bronze castings were used, as they had been shown to be without injurious

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[1] The desirability of this course was realized from the first and was also mentioned by Dr. Rosa at the Philadelphia meeting of the Physical Society, Dec., 1914.

effect. The box to hold the compensating coil was rectangular in cross-section and about ¼ meter wide, like that used before, but was about 2 meters long and 1 meter deep. The framework was strongly and accurately built, chiefly of 2 in. × 4 in. and 2 in. × 2 in. well seasoned yellow pine. Over the two larger sides of this frame were screwed, in small sections, accurately planed boards of well seasoned white pine provided with accurately cut parallel and equally spaced uniform grooves to hold the wire. Boards of the same kind, except that they were not grooved, completed the wooden surface over which the coil was wound. All materials were non-magnetic, and all the woodwork was coated with paraffine to prevent warping. The coil was wound with 151 turns of No. 20 copper wire, each turn being all in one plane, except for the short end portions, which went over the ungrooved surfaces and were somewhat irregular. The passage from one turn to the next was made by a sharp turn at one corner of the frame, and the return wire was carried close to this corner. The wires were fastened to the bottoms of the grooves and held in place by paraffine. The width of the box was about 26.8 cm. (26.9 at the middle, 26.7 at the ends), the length about 197.9 cm., and the coil was 95.9 cm. long.

§26. To test the degree of uniformity of the part of the magnetic field produced by the electric current in this coil in the region to be occupied by the rotor, the procedure was as follows: A test coil about 6 cm. long and 6 cm. in diameter, connected in circuit with the fluxmeter, was so mounted on a wooden support that it could be set with its axis parallel to that of the compensating coil and its center in the central horizontal line of 148 consecutive turns of the cage which alone were used in this part of the experiment. The test coil was moved along by measured steps from a point near one end of the cage to a point near the other, and in each position the fluxmeter deflections were obtained twice for reversals of the current in the cage; and the procedure was repeated with the coil moving in the other direction. The current remained constant within about one fourth per cent. during the whole process.

The mean fluxmeter deflections were then plotted on cross-section paper as a function of the position of the test coil. In this way it was found that the intensity produced by the cage did not vary by quite as much as 1 per cent. of its mean throughout the region occupied by the main cylindrical part of the rotor, and that it varied only 1.4 per cent. in passing from one end of the rotor to the other end, becoming of course greater as the ends were approached. Over the greater portion of the length of the rotor the intensity did not vary by more than one third or one quarter per cent. The variation would have been slightly less had the 151 turns been used as they were in the rotation experiments.

§27. The compensating cage (with 151 turns) was now mounted over the rotor and its coil, the centers of all three being made nearly coincident. The cage was adjusted with the longer edges parallel to the rotor and its axis parallel to the earth's intensity, and was clamped to the floor in this position. The cage current necessary to compensate the earth's intensity was then determined. With this end in view, a bunched longitudinal coil of thin insulated copper wire had been wound over the central four tenths of the rotor, two sides of the coil being diametrically opposite to one another, and the other two being semicircular and on the same side of the rotor. This coil was connected in circuit with the fluxmeter and set with its axis parallel to the axis of the cage and to the earth's intensity. Turning the rotor through 180° produced a deflection of 17.3 cm. with no current in the cage. With a current of 335 milliamperes in the proper direction in the cage, the deflection on reversal was not 0.1 mm. This current, therefore, compensated the earth's intensity through the central region of the rotor within a minute fraction of 1 per cent., and somewhat less completely throughout the rest of the rotor, as appears from §26.

After the determination of the compensating current the longitudinal test coil was removed from the rotor, and the fluxmeter and rotor and compensator coils connected for the main experiments.

§28. In studying the earth's intensity in the region to be occupied by the rotor it was found that rotation of the fluxmeter through 360° about the vertical in its former position caused the declination to vary through a range of about half a degree. For this reason and because it was desired to have a greater range of scale distances available, the fluxmeter was removed to a very large room adjacent to that in which the rotations occurred, and was again mounted on a slate shelf cemented into the wall. In the later and more precise of the experiments already described the compensation of the fluxmeter drift had been greatly improved by increasing the thermal insulation of many of the junctions of the circuit. For the final work this insulation was still further improved. By taking this precaution, and by working at night, when air currents were reduced, the drift was made so regular (when it did not vanish, as it usually did not) that its compensation was not difficult to make practically perfect. On the other hand the building, though sometimes completely free from vibration, was often disturbed. This however, is by no means so serious a trouble with a compensated fluxmeter as with an instrument whose readings are not permanent; and observations were obtained which were superior to most of those given above.

TABLE II.

Deflections and Speeds. Final Observations and Results.

1915 Date.	Number of Set.	Rotor End *E*.	Compensator End *E*.	Deflection for Negative Rotation (−).	Deflection for Positive Rotation (+).	Differential Deflection (−) − (+).	Zero Correction.	Speed for (−).	Speed for (+).	Mean Speed.	Field Intensity.	Distance from Rotor to Compensator.
				mm.	mm.	mm.	mm.	volts	volts	r.p.s.		m.
March 5	1	2	*B*	−4.7	−3.2	−1.5	−0.6	61	61	34.5	0	1.2
" 5	2	2	*A*	−5.0	−3.3	−1.7	−0.6	65	65	36.8	"	"
" 12	3	2	*A*	−4.9	−3.6	−1.3	−0.6	60	64	35.1	"	"
				(−5.4)[1]		(−1.8)[1]		(64)[1]		36.2		
" 12	4	2	*A*	−5.0	−3.4	−1.6	−0.6	60	60	34.0	"	"
" 13	5	2	*A*	−4.8	−2.7	−2.1	−0.6	64	59	34.8	"	"
				(−4.2)[1]		(−1.5)[1]		(59)[1]		33.4		
" 13	6	2	*A*	−3.2	−1.3	−1.9		63	63	35.7	− *E*	"
" 13	7	2	*A*	−7.2	−5.7	−1.5		66	61	35.9	+ *E*	"
" 16	8	2	*A*	−3.4	−2.1	−1.3	+0.6	61	65	35.7	0	"
				(−4.0)[1]		(−1.8)[1]		(65)[1]		36.8		
" 16	9	2	*A*	−4.3	−2.7	−1.6	+0.6	69	69	39.1	"	"
" 16	10	2	*A*	−1.4	−0.4	−1.0	+0.6	42	41	23.5	"	"
" 16	11	2	*A*	−1.3	−0.5	−0.8	+0.6	40	40	22.6	"	"
" 18	12	3	*A*	+2.5	+4.4	−1.9		70	68	39.1	"	"
				(+2.3)[1]		(−2.1)[1]		(68)[1]		38.5		
" 18	13	3	*A*	+2.4	+4.6	−2.2		70	69	39.3	"	"
				(+2.3)[1]		(−2.3)[1]		(69)[1]		39.1		
" 18	14	3	*A*	+1.9	+4.0	−2.1		70	67	38.8	"	"
				(+1.6)[1]		(−2.4)[1]		(67)[1]		37.9		
" 22	15	2	*A*	−3.9	−1.4	−2.5	+1.2	70	68	39.1	"	1.6
				(−3.6)[1]		(−2.2)[1]		(68)[1]		38.5		

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[1] The quantities in parentheses are the deflections for negative rotations, the differential deflections, and the speeds for negative rotations corrected to the speeds of the positive rotations.

TABLE II.—*Continued.*

1915 Date.	Number of Set.	Rotor End *E.*	Compensator End *E.*	Deflection for Negative Rotation (−).	Deflection for Positive Rotation (+).	Differential Deflection (−) − (+).	Zero Correction	Speed for (−).	Speed for (+).	Mean Speed.	Field Intensity.	Distance from Rotor to Compensator.
				mm.	mm.	mm.	mm.	volts	volts	r.p.s.		m.
March 22	16	2	*A*	−3.9	−1.3	−2.6	+1.2	71	68	39.3	"	"
				(−3.5)[1]		(−2.2)[1]		(68)[1]		38.5		
" 22	17	2	*B*	−3.8	−1.7	−2.1	+1.2	71	71	40.2	"	"
" 22	18	2	*B*	−3.7	−1.5	−2.2	+1.2	72	72	40.8	"	"
" 22	19	2	*A*	−3.7	−1.6	−2.1	+1.2	71	71	40.2	"	"
" 23	20	2	*B*	−0.7	+0.4	−1.1	+1.2	37	35	20.4	"	1.3
				(−0.5)[1]		(−1.0)[1]		(35)[1]		19.8		
" 23	21	2	*B*	−0.8	+0.2	−1.0	+1.2	41	40	22.9	"	"
" 23	22	2	*B*	−0.5	+0.3	−0.8	+1.2	38	38	21.5	"	"
" 23	23	2	*B*	−0.5	+0.4	−0.9	+1.2	37	37	20.9	"	"
" 23	24	2	*B*	−0.6	+0.5	−1.1	+1.2	36	36	20.4	"	"

[1] The quantities in parentheses are the deflections for negative rotations, the differential deflections, and the speeds for negative rotations corrected to the speeds of the positive rotations.

§29. The results of 24 sets of observations made under the improved conditions are given in Table II. Two sets were rejected because of great difference in the speeds for right handed and left handed rotations; and one set, in the middle of which an accident happened to the turbine, was rejected because of great speed differences and also because it was obtained on an *afternoon*, when the fluxmeter could not be well compensated either for thermal effects in its own circuit or, apparently, for variations of the earth's field (the distance from rotor to compensator on this occasion was about 2.2 meters). The retention of the rejected observations, which were quite consistent with those retained, would not have affected in any way the conclusions to be drawn from the experiments.

For these observations the fluxmeter circuit happened to be connected up in such a way that a negative value of the differential deflection corresponded to an effect in the direction predicted by theory on the assumption that the electrons in revolution are negative. The negative sign here is thus consistent with the positive sign in Table I.

In most of the sets the speeds for the two directions of rotations were nearly the same. When they differed by more than one volt (or about half a revolution per second), except in the case of those observations made in a magnetic field, the deflections for the negative rotation and the corresponding differential deflections, have been reduced to the speed of the positive rotation by the method explained in §32. The reduced values, along with the common reduced speeds are given in parentheses.

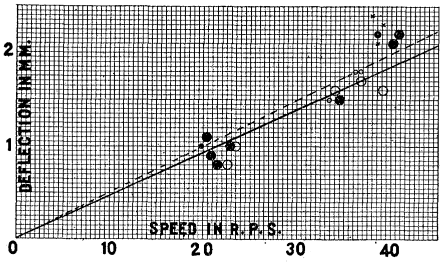

Fig. 6.

Differential Deflection and Speed.

All the deflections were obtained at 8 meters scale distance except those of March 22, which were obtained at 8.7 meters. In the table the deflections for these observations are reduced to 8 meters.

The differential deflection is plotted as a function of the speed in Fig. 6, sets 6 and 7, which were obtained with the rotor in the magnetic field of the earth, or that field reversed, being omitted. The large circles designate the observations which needed no reduction for speed differences; the smaller circles and crosses, those for which reductions were made. The circles designate observations made with end *2* of the rotor east; the white circles corresponding to those made with the compensator end *A* east, the black circles to those made with compensator end *B* east; the crosses designate observations made with the rotor end *3* east and compensator end *A* east.[1]

The continuous straight line in the figure is drawn with a slope obtained by dividing the sum of all the differential deflections for the observations which needed no reductions by the sum of all the corresponding speeds, and thus gives the weighted mean deflection per unit speed, on the assumption of proportionality between them. This quantity is 0.046 mm./r.p.s.

The broken straight line is drawn in the same manner for all the observations made with the earth's intensity compensated, reductions having been made when necessary, as indicated above. From this line, the mean deflection per unit speed is 0.050 mm./r.p.s.

It is clear from the figure that the assumption made above is justified: the deflection is proportional to the speed within the limits of the experimental error. It is also clear that within these limits this deflection is independent of the orientation of the rotor or compensator or the distance between them, this distance being always at least as great as 1.2 meter. The average departure of the differential deflection for a single set from the ordinate of the (broken) straight line corresponding to the speed is 12 per cent.

§30. In the observations just described the readings for zero speed of the rotor throughout each set were, as before, obtained with the rotor set at a definite position angle. The absolute deflection depended upon this setting; but, as has already been said, it was early proved that the differential deflection did not. It was nevertheless considered important to investigate this matter more fully.

For this purpose a permanent bar magnet was mounted so as to be free to rotate in a horizontal plane about a vertical axis passing through its center, and arrangements were made to rotate it at the speed of about 26 revolutions per second by a small alternating current motor at a distance from the magnet and the coils of the fluxmeter circuit. Near the magnet was clamped a small low resistance coil of insulated copper wire connected in the fluxmeter circuit arranged (except for this addi-

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[1] In the original drawing, in the upper right-hand corner, two small white circles on the same center are shown in place of the smallest of the group of three black circles shown in the reproduction. Also, the second spot in the group appears in the original as a large white circle surrounding a large black circle with the same center.

tion) as in the principal experiments. Another coil, with ten turns of insulated wire, was wound on the compensator close to the coil, and was connected through a key and an adjustable high resistance box with the terminals of a storage battery.

By means of this coil and battery circuit any desired change of flux could be produced in the fluxmeter circuit; and by means of the rotating magnet and the adjacent coil in the fluxmeter circuit the effect of the iron rotor in sending an alternating current through this circuit, and in producing a motion of the lamp's image up and down on the scale for very slow rotations, could be closely imitated.

The magnet was rotated slowly and the extreme scale readings A and B $(B > A)$ noted. On the magnet's being rapidly rotated the scale reading C always became the mean of the two readings, viz.,

$$\tfrac{1}{2}(A + B).$$

The fluxmeter deflection D produced by closing the battery circuit was determined while the magnet was at rest. Then the circuit was closed, and the magnet driven up to full speed, and the scale reading E determined; then the magnet was brought to rest and set in the position giving one of the extreme scale readings A. It was always found that

$$D = (E - A) + \tfrac{1}{2}(A - B).$$

These observations were made with two quite different values of $A - B$, and two quite different values of D; some of the experiments were made with the battery circuit closed before the rotation of the magnet was started, others with this order reversed. But the result was always the same.

We have thus conclusive proof that, as would be expected, the fluxmeter deflection, when reckoned from the proper zero C, gives correctly the flux changes. If one of the extreme points A or B has been taken as the zero, the true change of flux is given by the above equation.

For most of the observations given above the rotor was set for the zero reading at or close to one of the positions giving the readings A and B, and $A - B$ was determined. The corrections to the true zero C could then be readily made. These corrections are given, for the sets for which they are available, in Table II. This correction is of course of no consequence for the differential deflection, but it affects the absolute deflection greatly.

§31. When the means of the absolute deflections for positive and negative rotations are corrected to the true zero in accordance with the last article and compared with the speeds, a very simple relation is found to exist between them. In Table III. the observations are divided

Table III.

Mean Deflections and Squares of Speeds.

Numbers of Sets.	Sum of Deflections (Observed).	Sum of Deflections (Reduced).	Mean Deflection (Observed).	Mean Deflection (Reduced).	Sum of Speeds Squared (Observed).	Sum of Speeds Squared (Reduced).	Mean Square of Speed (Observed).	Mean Square of Speed (Reduced).	Mean Deflection per Unit Speed Squared (Observed).	Mean Deflection per Unit Speed Squared (Reduced).
1–5, 8–9, 15–19	43.8 mm.	43.7 mm.	3.65 mm.	3.64 mm.	16,920 (r.p.s.)^2	16,870 (r.p.s.)^2	1,410 (r.p.s.)^2	1,406 (r.p.s.)^2		
10–11, 20–24	9.4	9.3	1.34	1.33	3,320	3,290	474	471		
1–5, 8–9, 10–11, 15–19, 20–24	53.2	53.0			20,240	20,160			$\frac{\text{mm.}}{(\text{r.p.s.})^2}$ 0.00263	$\frac{\text{mm.}}{(\text{r.p.s.})^2}$ 0.00263

into two groups, those at lower speeds and those at higher speeds, and for each group are given the sum of the observed deflections and the mean deflections (both corrected to the true zero), the sum of the squared speeds, and the mean of the squared speeds; while for both groups together there is given the quotient of the sum of the deflections by the sum of the squared speeds, or the mean deflection per unit speed squared, all quantities being given both as observed and also as reduced to the same speed for both directions of rotation.

In Fig. 7 the mean squared deflections for the two groups are plotted as a function of the mean squared speed. The straight line is drawn with the slope given by the last two columns in the table, which is identical for both observed and reduced quantities, as are the mean deflections within the experimental error. The figure shows that within the limits of the experimental error the absolute deflection is proportional to the square of the speed.

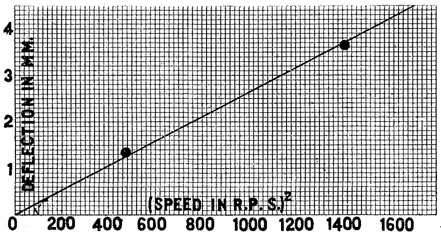

Fig. 7.

§32. The method of reducing a deflection observed at one speed to the deflection which would have been produced at another, and thereby correcting the differential deflections obtained when the speed for left hand rotations did not equal that for right hand rotations can now be readily explained. If we denote by D the deflection (from the true zero) obtained for a speed S, and by D' the deflection which would have been obtained for a speed S' near S, we have

$$D = aS + bS^2$$

and

$$D' = aS' + bS'^2,$$

where a and b are constants known very approximately from the observations which needed no correction. The correction, or small quantity which must be added to D, is

$$D' - D = a(S' - S) + b(S'^2 - S^2).$$

From Fig. 6 we get

$$a = \pm \tfrac{1}{2} \times 0.046 \frac{\text{mm.}}{\text{r.p.s.}} \quad \text{or} \quad \pm 0.013 \frac{\text{mm.}}{\text{volt}},$$

and from Fig. 7 we get

$$b = \pm\, 0.00263\, \frac{\text{mm.}}{(\text{r.p.s.})^2} \quad \text{or} \quad \pm\, 0.00084\, \frac{\text{mm.}}{(\text{volt})^2}.$$

As an example, what precedes may be applied to set 5, Table II., to reduce the deflection for left handed or negative rotations at speed 64 volts to the speed of 59 volts. In this case we have

$$D' - D = \{ -0.013(59-64) - 0.00084(59^2-64^2) \} \text{ mm.} = +0.6 \text{ mm.}$$

By adding this quantity to the observed deflection − 4.8 mm., and subtracting − 2.7 mm., we obtain the differential deflection − 1.5 mm. for the speed 59 volts.

In this way all the differential deflections given in parentheses in Table II. were obtained. The total correction being always small, it is not important that the values of a and b should be accurately known. By using *all* the differential deflections for zero intensity of field, reduced in this manner when necessary, we obtain a more nearly correct value of a, viz.: $a = \pm\, 0.025$ mm./r.p.s., corresponding to the slope of the broken line in Fig. 6.

§33. The intensity of the magnetic field in which the rotor moved having been reduced in the final experiments to a minute portion of the earth's intensity, it is clear that that part of the deflection which is proportional to the square of the speed, or the mean deflection, is not produced by induced currents in the rotor.

The proportionality of the deflection to the square of the speed, and the reversal of the deflection with the reversal of the rotor, strongly suggest that the effect is due to the radial expansion (and accompanying longitudinal contraction) of the rotor produced by its rotation.

It has long been known that the longitudinal magnetic flux through an iron rod in or out of a longitudinal field is altered by the application or removal of longitudinal tension;[1] and that the longitudinal flux through the walls of an iron tube in a longitudinal field is altered by radial expansion or contraction produced by the application of hydraulic pressure from within or its removal.[2] The application and removal of longitudinal tension produce opposite effects; likewise radial expansion and contraction produce opposite effects. But longitudinal contraction and radial expansion produce effects of the same sign.[2]

Most of the experiments on this subject have been made on iron wires or cylinders in longitudinal fields, only a few having been made on iron rods with residual (or permanent) magnetization. For permanently

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[1] Ch. Matteucci, Ann. de chim. et de phys. (3), 153, 1858, p. 416; E. Villari, Pogg. Ann., 126, 1865, p. 87.

[2] W. Thomson, Roy. Soc. Phil. Trans., 170, 1880, p. 64.

magnetized iron rods Matteucci[1] and Villari[1] found that elongation produced an increase of flux in the case of soft iron, but a decrease in the case of hard iron or steel. All gradations were found to exist between the two extremes.

In all of the very numerous experiments made with the two different rotors A and B used in this work, with the exception of one set mentioned below (§34), the mean deflection produced by rotation was in the direction indicating that the longitudinal flux through the rotor was *increased*. To test the above explanation of the effect it was necessary, on account of the dependence of the known mechanical effect upon the nature of the rod and perhaps upon the intensity of magnetization, to make direct experiments on the effect of *longitudinal compression* (and its removal) on the magnetization of the two rotors. The residual flux density in the central section of rotor A was about 7 maxwells per cm.^{2}; that in rotor B about 4 maxwells per cm.^{2}

Each rotor in turn was therefore placed in a strong wooden frame constructed for the purpose, and longitudinal compression was applied by means of a brass screw working in a brass nut and operated with a brass wrench. With the fluxmeter and coils arranged as in the principal experiments and the axes of the rods in the magnetic equator, it was repeatedly verified that *compression increased* the magnetic flux through the rod, and that removal of the compression brought the flux back to its initial value. In the case of rod A, 4 or 5 cm. deflection was produced by a half-turn of the screw; in the case of rod B the deflection produced by a half-turn was 3 or 4 cm. These experiments thus confirm the explanation given above of the mean deflection produced by rotation.

A part of the effect may be due to possible unsymmetrical distribution of the rotor's mass about its axis and consequent centrifugal distortion. This also would give an effect proportional to the square of the speed. Experiments in which rotor B, with ends fixed, was subjected to a lateral force of about 150 lbs. near one end of its coil gave a deflection of a few mm. in the direction indicating increase of magnetic flux when the force was applied and decrease when it was removed.

§34. The apparently exceptional set of observations referred to above, in which the mean deflection appeared to indicate a diminution of magnetization, was made over a year ago with rotor A. When the magnetization of this rotor was reversed, as it was thought, the deflection remained exactly the same. The reversing magnetic intensity applied, however, was small; and in view of the well-known van Waltenhofen phenomenon it is quite possible that true reversal did not occur. The

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[1] Ch. Matteucci, Ann. de chim. et de phys. (3), 153, 1858, p. 416; E. Villari, Pogg. Ann., 126, 1865, p. 87.

direction of the magnetization was tested, but only by noting the direction of the deflection when the rod was smartly tapped, a test which has not always been found conclusive. A conclusive test is always to determine the direction of the fluxmeter deflection on the removal of the rod from its coil. This same result was obtained in the preliminary observations made in Louisiana, with a rod about half as long. To this, however, but little weight can be attached.

Anomalous effects of perhaps the same kind were noted by Villari (l. c.) in the case of longitudinal tension. He found that it was possible by magnetizing a steel rod with a current in one direction, and then with a weaker current in the opposite direction, to make it behave like iron—so that elongation increased its magnetization instead of decreasing it.

The exceptional cases mentioned therefore do not invalidate in any way the explanation of the mean deflection presented in the last article. It is of course not credible that reversal of the magnetization throughout a rod should have a different effect on the deflection produced by rotation from that of simply reversing the rod, an extraneous field being excluded as in the final experiments described here.

§35. In connection with the Louisiana experiments one of my friends suggested that the effects might be due to torsion, but was inclined to withdraw his suggestion when he found that the rotating rod was about 7 cm. in diameter.

In the case of a permanently magnetized rod of soft iron, according to the experiments of G. Wiedemann,[1] opposite small twists produce equal and opposite reversible effects on the magnetization.[2] It follows from this that the differential deflection would be increased by torsion for one orientation of the rotor, and decreased by the same amount for the opposite orientation. The experiments show, as would be expected, no difference produced by such a reversal.

Some direct experiments on rotor *B* confirmed Wiedemann's statements. For a torque of about 20 lb.-ft. applied to one end of the rotor while the other end was clamped, a mean deflection of about 2 mm. was produced. Experiments were made with both orientations of the rotor and for both directions of twist.[3] When the rotor was running at a speed of 38 r.p.s. in the principal experiments, the torque applied to one end of the rotor by the driving rod was only 1.1 lb.-ft., and the other end of the rod was of course free, except for the frictional torque. The effect

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[1] G. Wiedemann, Elektricitaet, III., p. 676.

[2] The effects are similar in the case of steel except that hysteresis also occurs.

[3] Wiedemann does not give the direction of the effect. My experiments gave a diminution of flux when the positive end of the rod was twisted clockwise relative to the negative end to one looking along the rod from the negative to the positive end.

of torsion on any of the deflections observed in the experiments on rotation must thus have been far less than the smallest readable quantity.

§36. As a result of all that precedes we are forced to the conclusion that the rotation of a rod of steel[1] produces therein an intrinsic magnetic intensity proportional to the angular velocity and acting in a direction opposite to the intensity which would be produced by an electric current flowing around the rod in the direction of rotation, as required by the theory proposed in §§1 and 5.

To obtain the intrinsic magnetic intensity per unit speed it is now necessary only to multiply half the mean differential deflection per unit speed, given in §29, by the intrinsic intensity per unit deflection, H_0, given in §12. In this way we obtain

$$\frac{H}{n} = -\tfrac{1}{2} \times 0.050 \frac{\text{mm.}}{\text{r.p.s.}} \times 1.26 \times 10^{-5} \frac{\text{gauss}}{\text{mm.}} = -3.1_5 \times 10^{-7} \frac{\text{gauss}}{\text{r.p.s.}}. \quad (13)$$

Similarly, from §§29 and 13, we obtain for the magnetic flux-density per unit speed produced by the intrinsic intensity of rotation in the central part of the rotor, the quantity

$$-\tfrac{1}{2} \times 0.050 \frac{\text{mm.}}{\text{r.p.s.}} \times 7.7 \times 10^{-4} \left(\frac{\text{maxwells}}{\text{cm.}^2}\right) \text{per mm.}$$

$$= -1.9 \times 10^{-5} \left(\frac{\text{maxwells}}{\text{cm.}^2}\right) \text{per r.p.s.}$$

This quantity divided by 4π gives an approximate value of the intensity of magnetization at the center of the rotor per unit speed, viz.,

$$-1.5 \times 10^{-6} \text{ c.g.s. unit per r.p.s.}$$

The magnitude of H/n given in equation (13) as a result of the last series of experiments is, within the experimental error, equal to one half the maximum value computed in equation (9) on the assumption that negative electrons alone are effective. The same is true of the result of the earlier observations given in §24.

§37. For the same intrinsic magnetic intensity of rotation and the same material, the intensity of magnetization depends upon the shape of the rotating body and is less for a sphere than for a long cylinder.

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[1] In the experiments of Lebedew (Ann. der Phys., 39, 1912, p. 840) the magnetic effect of rotating at high speed anyone of the several *non-magnetic* substances tried was nil, in conformity with the theory set forth in this paper. Lebedew's experiments were performed for a different purpose from that of this investigation, their object being to study the effect of centrifugal electron displacement, and the data he gives are insufficient for an exact calculation of the superior limit they give for the effect considered here. An approximate calculation, however, can be made and shows that the intensity of magnetization produced in Lebedew's non-magnetic bodies was not greater than about one hundredth of the value here obtained for steel, reduction being made to the same speed.

The earth's intensity of magnetization is about 0.08 c.g.s. unit, and its angular velocity is 1/86,400 r.p.s. If therefore our iron were spherical in shape and rotating at the speed of the earth, its intensity of magnetization would be less than the fraction $\frac{1.5 \times 10^{-6}}{86,400 \times 0.08}$, or 2×10^{-10}, the earth's intensity of magnetization.

Inasmuch, however, as we have no knowledge of the magnetic behavior of any substance under the conditions prevailing at more than a very small distance within the surface of the earth, it is still possible that this effect, which has the same sign as the earth's magnetization, may also account for its magnitude. It seems probable, however, that at least two other effects are prominently involved, viz., the centrifugal displacement and the thermionic displacement of electrons, which give, when rotation occurs, magnetic intensities in the direction required.

§38. Summary.

1. On the electron theory it is shown that by a sort of molecular gyroscopic process a body of any substance set into rotation becomes the seat of a uniform intrinsic magnetic intensity parallel to the axis of rotation, proportional to the angular velocity, and (like the magnetization of the earth and the sun) directed, provided the effect of the negative electrons is preponderant, oppositely to the intensity which would be produced by an electric current flowing around the body in the direction of rotation. If the substance is magnetic, magnetization results; otherwise not. If only the negative electrons are involved, the intensity per unit speed has its maximum numerical value and is calculated to be

$$\frac{H}{n} = -7.1 \times 10^{-7} \frac{\text{gauss}}{\text{r.p.s.}}.$$

2. The theory of the converse effect (rotation by magnetization) is developed in a very simple manner.

3. An extended series of experiments on the magnetization of steel rods by rotation is described. All suspected sources of systematic error have been eliminated by the elaborate precautions taken, and it is believed that the effect predicted by theory has been discovered. The method of electromagnetic induction was used, a fluxmeter, whose deflections were read to tenths of mm. at the scale distance 8 m. (usually), being the chief measuring instrument. The intrinsic magnetic intensity of rotation, and the change of magnetic flux density, per unit speed were found to be about

$$-\ 3.1 \times 10^{-7}\,\frac{\text{gauss}}{\text{r.p.s.}}$$

and

$$-\ 1.9 \times 10^{-5}\left(\frac{\text{maxwells}}{\text{cm.}^2}\right)\text{ per r.p.s.,}$$

respectively. Experiments made by Lebedew for a different purpose are quoted as showing that non-magnetic substances are not magnetized by the process by which iron is here shown to be magnetized.

4. Experiments, incidental to the work, on the use of a fluxmeter when unidirectional and alternating flux changes occur either alone or superposed, and in the change of residual magnetization by torsion, are described.

5. Together with the change of flux proportional to the speed, another change proportional to the square of the speed has been found and accounted for by the radial expansion of the rod produced by rotation. In support of this view experiments are described in which the change of (residual) longitudinal flux through the rods was determined when the rods were longitudinally compressed and when the stress was removed.

6. The intensity of magnetization produced in the rotating iron per unit speed was about 1.5×10^{-6} c.g.s. unit per r.p.s. If the rod had been rotated at the speed of the earth, viz., 1/86,400 r.p.s., its intensity of magnetization would have been about 2×10^{-10} that of the earth. This, however, does not prove that the earth's magnetization may not be due largely to the effect in question, as we are entirely ignorant of the magnetic properties of all substances under the conditions prevailing within almost the whole of the earth. Other causes are mentioned as probably accounting for at least a part of the earth's magnetism. Schuster has suggested that an effect of the sort chiefly investigated in this paper may explain the secular variation as well as the mean magnetization of the earth.

I am indebted to Mrs. Barnett for a great deal of help throughout the experimental part of this work, and to Mr. Arthur Freund, mechanician in this laboratory, for constructing most of the special apparatus and for other mechanical assistance.

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