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THE ELECTRON THEORY OF MAGNETISM[1]

EVER since the time of Faraday it has been known that all varieties of matter can be grouped in three classes on the basis of magnetic behavior, ferromagnetic, paramagnetic and diamagnetic.

It would be far too much to claim that the electron theory has as yet given anything like a complete account of the phenomena witnessed in connection with these three types of magnetism; but it is the only theory proposed which has been in any way satisfactory and which appears to hold out any hope for the future.

In accordance with the plans of this symposium I shall restrict myself to a consideration of the more general aspects of the theory and its simplest applications. For the sake of logical completeness I shall have to refer to many matters well known. The extension of the theory and its application to more special and complex cases, in so far as they can be handled on this occasion, will be treated by my colleagues.

The first electrical theory of ferromagnetism was proposed by Ampère just about one hundred years ago. On the basis of his own experiments on the behavior of electric circuits and magnets, and on the assumption, already justified, that magnetism is a molecular and not a molar phenomenon, he concluded that the molecule of iron is the seat of a permanent electrical whirl and thus essentially a permanent magnet with its axis perpendicular to the whirl. When the iron is fully magnetized, all the whirls are oriented alike, and

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[1] A paper read as a part of the symposium on recent progress in magnetism held at the joint meeting of the American Association for the Advancement of Science, Section B, and the American Physical Society, December, 1920. Revised, January, 1921.

the magnetic moment of the mass of iron is the sum of the moments of the elementary molecular magnets. Ampère undoubtedly considered that in a neutral mass of iron the molecular magnets are turned indiscriminately in all directions, but he did not enter into any discussion of the process by which their axes are made parallel by the field during magnetization, nor did he consider the nature of the electrical whirls themselves.

Ampère was the grandfather of the electron theory of magnetism. Wilhelm Weber was its father. In 1852 Weber[2] published a paper in which he developed a theory which, slightly modified by Langevin,[3] is still perhaps the most widely accepted theory of diamagnetism, together with a theory of ferromagnetism which formed the starting point for the well-known theory of Ewing. Weber adopted the molecular whirls of Ampère, but assumed in addition that these whirls, always present in the molecules of magnetic substances, are also present in the molecules of diamagnetic substances when placed in a magnetic field. Further, he took the very important step of attributing mass or inertia to the electricity in the whirls, and he assumed that the electricity moves as if in fixed circular grooves in the molecule, so that each whirl maintains its diameter and its orientation with respect to the rest of the molecule as if rigidly constrained. According to Weber's conception, a substance is paramagnetic or ferromagnetic when the molecule, or magnetic element, contains a permanent whirl, with a definite magnetic moment, and so tends to set with its axis in the direction of any magnetic field in which it is placed; and a substance is diamagnetic when the molecule contains one or more frictionless grooves, with the mobile electricity at rest before the creation of the magnetic field. Langevin merely substitutes electrons moving in fixed orbits for Weber's electricity in grooves; and assumes that in a diamagnetic substance more than one orbit exists in the molecule and that the orbits are so constituted and grouped that the magnetic moment of the whole molecule is zero in a neutral field.

In this case, which we shall consider in some detail, the complete molecule will suffer no change of orientation when introduced into a magnetic field, but the speed of the electricity in each orbit or groove will change on account of the electromotive force around the orbit or groove due to the alteration of the extraneous magnetic flux through it. Its magnetic moment μ will thus increase (algebraically) by an amount $\Delta\mu$, which can readily be calculated. If e denotes the charge of electricity circulating in an orbit (whether as a single electron, or a ring of electrons, or a continuous ring), m the mass associated with the moving charge, r the radius of the orbit, H the intensity of the extraneous magnetic field, and θ the angle between the axis of the orbit and the direction of the field,

$$\Delta\mu = -\frac{e^2r^2H}{4m}\cdot\cos\theta. \qquad (1)$$

If we assume that there are N orbits per unit volume, all alike; and if we furthermore assume that all the orbits are perpendicular to the direction of the field (as they would be in the case of a saturated ferromagnetic substance) we get for the magnetic moment of unit volume, or the intensity of magnetization:

$$I = -\frac{e^2r^2NH}{4m} \qquad (2)$$

and for the susceptibility

$$K = I/H = -\frac{e^2r^2N}{4m}. \qquad (3)$$

If the orbits are not all perpendicular to the field intensity, but are uniformly distributed between all values of θ from 0 to π, as in an isotropic diamagnetic substance, we get instead of (3) the expression

$$K = -\frac{e^2r^2N}{12m}. \qquad (4)$$

If in this equation we substitute the value of e/m known for electrons in slow motion, and assume for a given substance such as bismuth values of N and r which appear to be reasonable from other physical evidence, we obtain from (4) values of K of the same order of magnitude as those found by experiment,

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[2] W. Weber's Werke, III., p. 555.

[3] *Ann. chim. phys.* (8), 5, 1905, p. 70.

but the agreement is in general far from close. The equation requires that K should be independent of the temperature, unless e, m, r and N depend upon it. As is well known, the susceptibilities of many diamagnetic substances are independent of the temperature over wide ranges, while in other cases there is a marked dependence.

According to this theory also, effects of the same kind must exist in bodies which are ferromagnetic or paramagnetic superposed on effects of opposite sign, the resultant susceptibility being, as Larmor long ago pointed out, the sum of the two. The paramagnetic term may account for the variation of the resultant susceptibility with temperature in many diamagnetic bodies. From Weber's equation it may be shown that when $\theta = 0$

$$\frac{\Delta\mu}{\mu} = -\frac{eT}{m4\pi}H, \tag{5}$$

where T is the period of the orbit. If we assume that this period is that of sodium light, about 2×10^{-15} and that $H = 10^5$ (in excess of any intensity hitherto produced) (5) gives

$$\frac{\Delta\mu}{\mu} = -0.3 \times 10^{-3}, \tag{6}$$

so that the maximum diamagnetic effect is a very small part of the saturation effect in ferromagnetic substances. The fact that the intensity of magnetization of iron at saturation does not decrease appreciably even for great increases of intensity shows that $n = 1/T$ is very great.

From Weber's equations we may also calculate the change in frequency n of an orbit due to the magnetic field, and we find, after Langevin, but more generally,

$$\Delta n = -\frac{eH\cos\theta}{4\pi m}. \tag{7}$$

This may correspond in a way to the Zeeman effect in light, but gives a broad band instead of the sharp lines actually found, inasmuch as $\cos\theta$ has all values between -1 and $+1$.

It is unnecessary, however, to have recourse to electrons moving in orbits (or initially at rest and constrained to grooves) or to rotating electrified bodies, to explain the occurrence of diamagnetism, as has been shown by J. J. Thomson,[4] Voigt,[5] Lorentz,[6] and others, including very recently H. A. Wilson.[7] If a substance contains electrons either at rest or in plain rectilinear motion due to thermal agitation, and a magnetic field is created, an electrical intensity will evidently be developed with a curl equal to the negative rate of increase of the flux density, which will cause the electrons to move in paths curved in such a way as to produce a magnetic moment opposed to the direction of the applied field; and as the field becomes steady curvature will be maintained by the action of the field on the moving electrons normal to their velocities. Calculation on this hypothesis gives susceptibilities of the same order of magnitude as those given by the Weber-Langevin theory. This form of theory has the advantages over the other of greater freedom from assumptions and of giving, when applied to the optical case, a Zeeman effect with sharp lines. Weber does not attempt to justify his assumption that in a molecule the diameters of his orbital grooves remain constant, and that in a diamagnetic substance the grooves maintain their orientations independent of the applied magnetic intensity. With respect to the diameters, however, Langevin has shown that the magnetic field will produce no alteration provided the law of force is not precisely that of the inverse cube, which is quite improbable.

We shall return to the subject of diamagnetism later.

The first detailed theory of paramagnetism was given for perfect gases by Langevin in 1905.[3] Following Langevin, I shall begin with a gravitational analogue. Let us consider an enclosure containing a gas at uniform temperature and let us suppose the gravitational field anulled. The density of the gas will then be uniform throughout the enclosure. If now the uniform gravitational field is brought into action every particle of gas will receive an acceleration downward,

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[4] Int. cong. phys., 1900, vol. 3, p. 138.

[5] *Ann. der Phys.* (4), 9, 1902, p. 130.

[6] "The Theory of Electrons," p. 124.

[7] *Roy. Soc. Proc. A*, 97, 1920, p. 321.

and the up and down velocities of the molecules will exceed the horizontal velocities, until after a short time involving many collisions, a redistribution, as required by the principle of equipartition, will have occurred, in which the component squared velocities are equalized and the whole mass of gas has a temperature greater than before. If D_0 denotes the density of the gas at the bottom of the enclosure, D the density at any height x, m the mass of one molecule, r the gas constant for one molecule, T the absolute temperature and g the acceleration of gravity, we have the relation

$$D/D_0 = e - \frac{w}{rT}, \tag{8}$$

in which $w = mgx$ is the work necessary to raise one molecule through the distance x against gravity.

Now suppose each molecule to have a magnetic moment μ and imagine a vertical magnetic field applied throughout the enclosure instead of the gravitational field. The molecules will be driven to set themselves with their magnetic axes parallel to the magnetic intensity just as before the molecules were driven downward, and rotational velocities about lines normal to the field intensity will be favored, but thermal agitation will redistribute them as before until the law of equipartition is satisfied. If now θ denotes the angle made by the axis of any molecular magnet with the (vertical) magnetic intensity H, ρ the number of molecules per unit volume with their axes between θ and $\theta + d\theta$, and ρ_0 the number between 0 and $d\theta$, we have, by strict analogy with the gravitational case,

$$\rho/\rho_0 = e - \frac{mH\,(1 - \cos\theta)}{rT}. \tag{9}$$

Starting from this formula we can readily calculate the total change produced in the magnetic moment of the gas (0 before the application of the field) and thus the intensity of magnetization I. If a is written for

$$\frac{mH}{rT} \tag{10}$$

we get the expression

$$I = N\mu\left\{\frac{e^a + e^{-a}}{e^a - e^{-a}} - \frac{1}{a}\right\}, \tag{11}$$

where N = the number of molecules per unit volume.

When a is small, as it is except for very intense fields and very low temperatures, this equation becomes, with negligible error,

$$I = N\mu \cdot \frac{1}{3a} = \frac{N\mu^2}{3rT} \cdot H, \tag{12}$$

which gives for the susceptibility

$$K = I/H = \frac{N\mu^2}{3rT}. \tag{13}$$

The susceptibility is thus independent of H, and inversely proportional to T. So far as temperature is concerned it expresses the law of Curie, which holds for the paramagnetic gas oxygen over a great range of temperatures, and which holds over a great range in many other cases in which the molecular magnets are so far apart as not to act appreciably on one another.

Inasmuch as r is known, and as N is known for any value of T at known pressure, we can calculate μ from the observed value of K. We thus obtain for oxygen, reckoning from 0° C. and 760 mm. pressure,

$$\mu = \sqrt{\frac{3rTK}{N}} = 2.5 \times 10^{-20}. \tag{14}$$

Langevin's theory of paramagnetism is not an electron theory, as it has been developed without regard to the permanent electrical rotations assumed on this theory to account for the permanent magnetic moment of the elementary magnet. Nevertheless, it has rendered great services and has important relations to the electron theory.

Investigation of the behavior of *free* electron orbits, as distinguished from the fixed orbits of Weber, in a magnetic field, have been made by Voigt[5] and J. J. Thomson,[8] who independently, in 1902 and 1903, reached the conclusion that the existence, without damping, of such orbits in a substance would give it neither diamagnetic nor paramagnetic properties. The diamagnetic effects arising from change of velocities produced by the magnetic intensity are just balanced by the paramagnetic effects due to the change of orbital orientation. With suitable dissipation

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[8] *Phil. Mag.* (6), 6, 1903, p. 673.

of energy, however, Thomson has concluded that paramagnetism may result, and Voigt that either paramagnetism or diamagnetism may result, according to circumstances. But the conceptions they have presented of the manner in which these results may be brought about do not seem probable, and have not gained wide acceptance.

Voigt and, after him, Lorentz and Gans,[9] have examined the behavior in a magnetic field of magnetic elements, or magnetons, consisting of homogeneous uniformly charged solids or symmetrical electron systems, in rotation, and have reached interesting and important conclusions.

One of the most important cases is that of a magneton which may be treated as a solid of revolution, with initial angular velocity greater than $eH/2m$ about the unique axis. In this case in accordance with classical electromagnetic theory, the rotation proceeds undamped about the unique axis, while it is damped about the other (equal) axes, and the action of the field on the magneton is as follows: When the field is applied, precession of the magneton's axis about the direction of the field begins, accompanied by nutation. The nutation is damped out by dissipation or radiation, and the precession is retarded for the same reason. Hence the direction of the axis of the magneton gradually approaches coincidence with the direction of the field, when it is in stable equilibrium. During this process the velocity of rotation diminishes slightly, the motion being affected as in the case of the electricity in Weber's molecular grooves.

If there are N such magnetons in the unit of volume, and if the demagnetizing and molecular fields and the upsetting effect of collisions are negligible, all the magnetons will ultimately become oriented with their axes in the direction of the magnetic field. In this case the moment of unit volume will be

$$I = \frac{eNC}{2m}\left(u - \frac{eH}{2m}\right), \qquad (15)$$

when e is the charge of the magneton, C its moment of inertia about the axis of permanent rotation, u its angular velocity about this axis, and H the intensity of the applied field.

The first and principal term is entirely independent of H. The orientation is, of course, produced by the magnetic field, but only the time taken to arrive at the steady state is affected by its magnitude. The second term is a diamagnetic term, and arises from the fact that owing to the change of flux through the magneton during the process of its orientation its velocity is decreased, just as in the case of the Weber-Langevin theory.

In this case we have, except for the small diamagnetic term, which vanishes with the intensity, saturation for even the weakest fields; and we have less nearly complete saturation for stronger fields.

When collisions are not absent, a magneton's axis will be repeatedly deflected in its approach toward coincidence with the direction of the field, and the intensity of magnetization will not reach saturation; but it will increase with the field strength, being greater for a given field strength, the greater the mean time between collisions and the weaker the molecular and demagnetizing fields. Increase of temperature, shortening this time between collisions, and increasing their violence, will, if the magnetons remain unchanged, thus diminish the magnetization for a given field strength.

The precessional process described above is doubtless similar in a general way to the process by which in every case in paramagnetic and ferromagnetic substances the magnetons are aligned more or less completely with the magnetic field.

The exceedingly interesting ring electron recently proposed by A. L. Parson and extensively applied by him and others to a wide range of chemical and physical phenomena, is a special case of Voigt's magneton, and will be discussed by one of my colleagues.

Bearing in mind that, on the electron theory, the molecule or magneton must, with Voigt, be treated as a gyroscope and can not

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[9] *Gött. Nachr.*, 1910, p. 197.

execute true rotations,[10] such as Langevin assumed, except as very special cases of precession, Gans[11] has recently developed a general theory of diamagnetism and paramagnetism, proceeding in accordance with the methods of statistical mechanics. He assumes as his magneton a body rigidly built of negative electrons and placed inside a uniformly and positively charged sphere whose center is coincident with the center of mass of the electrons, and whose charge is equal in magnitude to that of the magneton, so that electrical actions do not have to be considered. The energy is assumed to be entirely electromagnetic.

For simplicity it is assumed that two of the principal (electromagnetic) moments of inertia are equal, but it is not assumed in general that the magneton is a body of revolution; thus the cross-section normal to the unique axis might be a square, and rotation about it subject to the effects of thermal collisions, instead of a circle, with rotation independent of such collisions.

The method of statistical mechanics is then applied to the two cases to be considered: first, that in which the magneton is not a body of revolution so that the rotations about the three axes must all be treated as statistical coordinates; and second, that in which the magneton is a body of revolution so that rotation about the axis of figure is not affected by collisions and can not be treated as a statistical coordinate.

In the first case it is found that the susceptibility is always negative, or the substance diamagnetic.

When the three principal moments of inertia are equal, the susceptibility is independent of the temperature and of the intensity of the magnetic field, which is the case with many diamagnetic substances.

When but two of the moments are equal, however, the susceptibility depends on both the temperature and the intensity in somewhat complicated ways. Fig. 1 shows the general relation between the susceptibility and the intensity according to Gans's theory, while Fig. 2 shows the type of curve found experimentally by Honda in many cases. The importance of carrying the measurements down into weaker fields is manifest; and this has recently been done for bismuth and antimony by Isnardi and Gans,[12] who, working with pure materials, find no dependence on the field strength. As Honda suggests, the dependence on intensity suggested by his curves is probably due to the presence of iron, whose positive susceptibility, opposing that of the diamagnetic substances, decreases with increasing magnetic intensity. Curves obtained by Honda and Owen, and by Isnardi and Gans, are shown in Fig. 3.

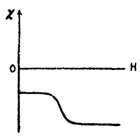

Fig. 1.

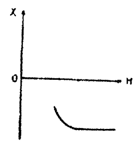

Fig. 2.

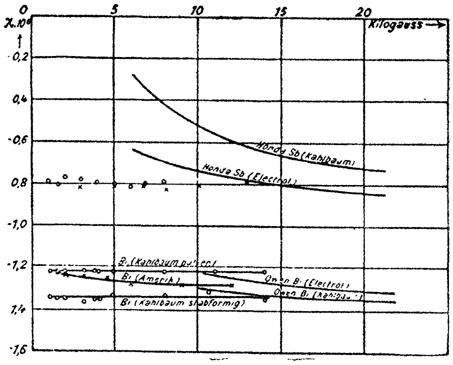

Fig. 3.

Fig. 4 shows the way in which, according to the theory, the susceptibility χ depends upon the absolute temperature θ, while the type of curve found in Honda's experiments is shown in Fig. 5. Little weight can be given the lower part of the theoretical curve, inasmuch as equipartition of energy and also absence of inter-molecular action were both assumed in its derivation, and it is improbable

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[10] See also F. Krueger, *Ann. der Phys.* (4), 50, 1916, p. 364.

[11] *Ann. der Phys.* (4), 49, 1916, p. 149.

[12] *Ann. der Phys.* (4), 61, 1920, p. 585.

that either is true at low temperatures. There is a general agreement between theory and experiment. The trend of the experimental curve can not be explained by the presence of iron, as the positive susceptibility of the iron would become less with temperature increase.

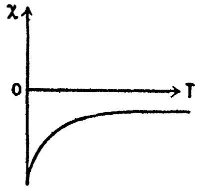

FIG. 4.

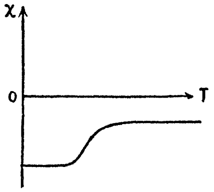

FIG. 5.

We come now to the second case, in which the magneton has a true axis of figure and an essentially permanent angular momentum about this axis, and therefore a magnetic moment in the direction of this axis, unchangeable by collisions. On account of this permanent magnetic moment and angular momentum, paramagnetism results very much as in the theory of Voigt already presented; and on account of the slight diminution of this angular momentum in the magnetic field and on account of the rotation of the magneton about the other axes brought about or modified by the thermal agitation in accordance with the law of equipartition, diamagnetism results and is superposed upon the paramagnetism.

This diamagnetism does not appear in Langevin's theory, because instead of a permanently rotating magneton he assumed a permanent magnet without angular momentum about the axis except as produced by thermal collisions. Langevin, however, assumed that Weber's diamagnetism was superposed upon the paramagnetism, and this corresponds in part to the diamagnetism of Gans's theory.

Returning to the results of Gans's statistical treatment for the case of the magneton in permanent rotation about a unique axis, we find that the susceptibility is a function of both field strength and temperature. It may even be positive at lower intensities or temperatures, and negative at higher.

Isothermals for different temperatures θ between the susceptibility G and the magnetic intensity h are shown in Fig. 6, and isodynamics for different intensities h between the susceptibility G and the temperature θ are shown in Fig. 7. Thus while diamagnetism may exist without paramagnetism, paramagnetism is always accompanied by diamagnetism, as on all other theories. In weak fields and at low temperatures the paramagnetism may prevail; but as the temperature and field strength increase it goes over into diamagnetism.

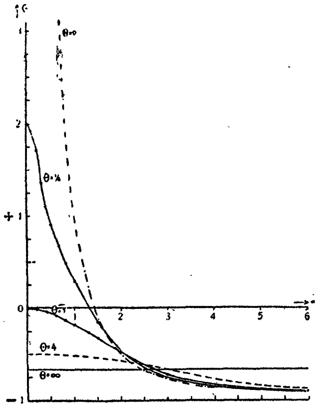

FIG. 6.

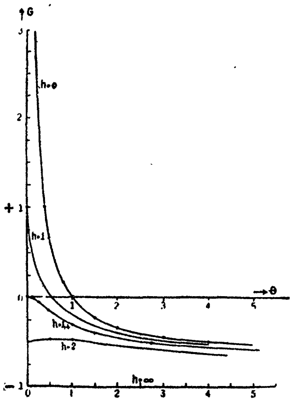

FIG. 7.

A transition from paramagnetic to diamagnetic susceptibility, whatever may be the explanation, has been observed by Weber and Overbeck[13] in the case of copper-zinc alloys, and by Honda in the case of indium. Weber and Overbeck, who have taken great precautions and believe their alloys free from iron, have called the phenomenon *metamagnetism.* The downward trend of paramagnetic susceptibility with increase of field strength is apparent in some of the curves obtained by Honda.

For weak fields at low temperatures, but with H/T finite, Gans's formula approaches that of Langevin as a limit. Here the paramagnetic rotations are prominent in comparison with diamagnetic thermal rotations about the other axes. As the field intensity approaches zero with finite values of the temperature the susceptibility approaches a limit which is the sum of two terms, a paramagnetic term identical with that of Langevin and a diamagnetic term independent of the temperature like that of Weber.

The theory of Gans thus covers a wide range of cases, but so far has been applied in detail to but few. By taking account of the molecular field, and by applying the quantum theory, although not in the most thorough way, he has more recently extended his theory to cover more accurately the paramagnetism exhibited by dense bodies and at low temperatures.[14] In a similar way the quantum theory has been set into the theory of Langevin by Oesterhuis[15] and Keesom[16]; and it has been thoroughly applied, for the case of rotation with one degree of freedom, by Weyssenhoff,[17] and for the case of rotation with two degrees of freedom by Reiche[18] and by Rotzajn,[19] to the system of elementary magnets, without permanent angular momentum, assumed by Langevin. These theories are thus not electron theories, like that of Gans. They reduce to the theory of Langevin at high temperatures when equipartition exists, and the rigorous theories agree well with experimental results obtained at low temperatures, where Langevin's theory completely fails. The next step should be the rigorous application of the quantum theory to the case in which the magneton has a permanent angular momentum, with gyroscopic properties, as required by the electron theory.

According to experiment hydrogen and helium are diamagnetic although according to Bohr's models their molecules have strong magnetic moments. This is apparently consistent with the theory of Gans, but inconsistent with the theory of Weber and Langevin. Honda and Okubo,[20] in a part of a paper dealing more generally with the kinetic theory of magnetism, have proposed the following explanation of this diamagnetic effect. Suppose the magnetic axis to be rotating about one of the other axes in a plane parallel to the magnetic intensity. On account of the presence of the field, the velocity of rotation, which would be uniform without the field, is now variable, the motion being more rapid when the moment points in the direction of the field than when it points the other way. Hence the time mean of its directions is opposite to that of the field and the mean effect is diamagnetic. If the magnetic axis is rotating in a plane not parallel to the direction of the field, we must resolve the effect in the direction of the field. Doing this for all the elementary magnets, originally pointing uniformly in all directions, we get a resultant diamagnetic effect. This, however, is only a part of the total effect found in Langevin's theory to be paramagnetic, though it is only implicit in his treatment, unless we assume *permanent* rotations, independent of the temperature, about an axis normal to the magnetic axis. This assumption they have made.

From what we have seen there seems to be no way to account satisfactorily for paramagnetism and ferromagnetism except on the assumption of an elementary magnet which is a permanent electrical whirl, as Ampère assumed; which has also mass, as Weber as-

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[13] *Ann. der Phys.* (4), 46, 1915, p. 677.

[14] *Ann. der Phys.* (4), 50, 1916, p. 163.

[15] *Phys. Zeit.*, 14, 1913, p. 862

[16] *Phys. Zeit.*, 15, 1914, p. 8.

[17] *Ann. der Phys.* (4), 51, 1916, p. 285.

[18] *Ann. der Phys.* (4), 54, 1917, p. 401.

[19] *Ann. der Phys.* (4), 57, 1918, p. 81.

[20] *Phys. Rev.*, 13, 1919, p. 6.

sumed; and which has therefore the dynamical properties of a gyroscope. It will now be shown how these gyroscopic properties have made possible a complete and direct demonstration of the correctness of this theory.

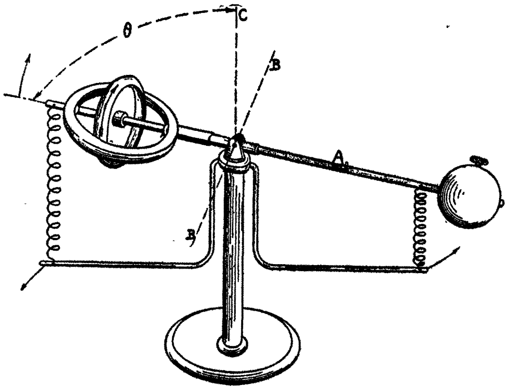

FIG. 8.

In Fig. 8 is shown a gyroscope whose wheel, pivoted in a frame, can be rotated rapidly about its axis A. Except for the action of two springs, the frame and the axis A are free to move in altitude about a horizontal axis B, making an angle θ with the vertical C; and the axis B and the whole instrument can be rotated about the vertical axis C. If the wheel is spun about the axis A, and the instrument then rotated about the vertical C, the wheel tips up or down so as to make the direction of its rotation coincide more nearly with the direction of the impressed rotation about the vertical axis C. If it were not for the springs, the wheel would tip until the axes A and C became coincident. The greater the rotary speed about the vertical the greater is the tip of the wheel. When the wheel's speed about the axis A is zero, no tip occurs.

Now if the magnetic molecule is a gyroscope, it will behave like this wheel. If the body of which it is a part is set into rotation about any axis, the molecule, or magneton, will change its orientation in such a way as to make its direction of rotation coincide more nearly with the direction of the impressed rotation; the coincidence will finally become exact if this is not prevented by the action of the rest of the body. This idea was in the mind of Maxwell in 1861, and has occurred to a number of others since.

In an ordinary ferromagnetic body in the usual state with which we are familiar only a slight change of orientation can occur on acount of the forces due to adjacent molecules, which perform the function of the springs in the case of our gyroscope. The rotation causes each molecule to contribute a minute angular momentum, and thus also a minute magnetic moment, parallel to the axis of impressed rotation; and thus the body, whose magnetons originally pointed in all directions equally, becomes magnetized along the axis of impressed rotation. If the revolving electrons, or rotating magnetons, are all positive, the body will thus become magnetized in the direction in which it would be magnetized by an electric current flowing around it in the direction of the angular velocity imparted to it. If they are all negative, or if the action on the negative magnetons is preponderant, it will be magnetized in the opposite direction.

If R denotes the ratio of the angular momentum of a magneton, or an electron orbit, to its magnetic moment, it can readily be shown that rotating a magneton or electron orbit about any axis with an impressed velocity N revolutions per second, is equivalent to placing it in a magnetic field with intensity H directed along this axis such that

$$H = R 2\pi N.$$

If the electric density is proportional to the mass density throughout the volume of the magneton this ratio is easily shown to be $R = 2m/e$; so that in this case

$$H = 4\pi \frac{m}{e} N. \qquad (16)$$

If all the magnetons in a body are alike, therefore, rotating it at an angular velocity of N r.p.s. will produce the same intensity of magnetization in it as placing it in a field of strength $4\pi(m/e)N$ gausses.

For negative electrons of the ordinary type $4\pi(m/e) = -7.1 \times 10^{-7}$ e.m.u. according to well-known experiments. Hence, if orbital motions of these electrons are responsible for the magnetism of ferromagnetic substances, rotating them at a velocity of N revolutions per second should magnetize them as would a field of intensity

$$H = -7.1 \times 10^{-7} N \text{ gauss}. \qquad (17)$$

Now in two investigations on cold-rolled steel by a method of electromagnetic induction, a third investigation principally on steel, nickel and cobalt by a magnetometer method, and a fourth investigation on steel, soft iron, cobalt, and Heusler alloy by another magnetometer method, Mrs. Barnett and I have found the above theory verified, except that in place of the number 7.1 we find smaller numbers; in the best work, which appears to be free from any serious systematic error, we find instead of 7.1 numbers about one half as great and even smaller.[21] This work, however, is still in progress.

If these results are correct, we seem to be driven to one of two conclusions: Either negative electrons or magnetons with a value of m/e or R for the motions involved different from that ordinarily accepted are responsible for magnetism; or positive electrons or magnetons, whose rotation we have seen must produce an opposite effect, are also involved. It does not seem impossible that a ring or other type of negative magneton, with R different for the permanent rotary motion from the value obtained from cathode ray experiments and otherwise, should be involved; but the presence of positive electron orbits, or rotating positive magnetons, is also possible, especially in view of the known expulsion of α particles with great velocities from the radioactive substances. Chemical evidence is often quoted in favor of the idea that superficial negative electrons alone are responsible for magnetism; but I do not think this evidence conclusive.

Not long after our first conclusive experiments on magnetization by rotation were communicated to this society, experiments on the converse effect, viz., rotation by magnetization, first suggested by Richardson, were performed by Einstein and deHaas.[22] Magnetizing a bar of iron, in turning the magnetons about until they all rotate in the same direction, produces angular momentum in this direction which must be compensated by an angular momentum within the molecules themselves, or in the bar, or in the magnetizing solenoid. If we assume that the reactions all take place upon the bar we can calculate $4\pi(m/e)$ from the measurable angular momentum communicated to it when magnetized to a given intensity on the assumption that all the magnetons are alike. The result published by Einstein and deHaas agreed closely with the value to be expected on the hypothesis that only the common type of negative electron is involved; but the sign of the effect was not determined with certainty till much later, and errors in the value of the assumed intensity of magnetization and in the experiments themselves undoubtedly exist. The experiments have been repeated with great improvements by Emil Beck,[23] and experiments on the same subject but by a different method had already been made by J. Q. Stewart;[24] both these investigations, on the basis of a single kind of electron and on the assumption made above with reference to the seat of the reaction to the electron momentum, give values of $4\pi(m/e)$ for iron and nickel similar to those which Mrs. Barnett and I have found by the method of magnetization by rotation, into the theory of which no assumptions appear to enter except such as can be justified completely.

If a magneton is sufficiently free it will, as stated above, when rotated about a given axis align itself with its axis completely parallel to the axis of impressed rotation. If in the unit volume there are N magnetons all alike, each with the moment of inertia C and initial angular velocity U about the magnetic axis, and if the effects of collisions and the demagnetizing field are negligible, the intensity of magnetization will be

$$I = \frac{NCe}{2m}(U + \Omega). \qquad (18)$$

The first term is independent of Ω, which is a measure of the intrinsic intensity of rota-

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[21] *Phys. Rev.*, 6, 1915, p. 239; 10, 1917, p. 7; *Proc. American Phys. Soc.* for December, 1920; *Proc. Phil. Soc. of Washington* for October 9, 1920.

[22] *Verh. d. D. Phys. Ges.*, 17, 1915, p. 152.

[23] *Ann. der Phys.* (4), 60, 1919, p. 109.

[24] *Phys. Rev.* (2), 11, 1918, p. 100.

tion, just as, in Voigt's equation, the first term is independent of H. The orientation is here produced by the rotation, but only the time taken to reach a steady state is affected by its magnitude. The second term, here added to the first, corresponds to Voigt's diamagnetic term. Here we have, except for the small second term, saturation for even very small values of Ω.

If collisions are not absent, or if the magnetic fields of adjacent molecules and the demagnetizing field become appreciable, the intensity of magnetization will not reach saturation; but it will increase with Ω, being greater for a given value of Ω the greater the mean interval between collisions, the less their violence, and the weaker the field.

It was suggested by Schuster in 1912 and by Einstein and deHaas in 1915, and earlier by myself, that the behavior of a magnetic molecule as a gyroscope might account for cosmical magnetism, as the direction of the magnetization of the earth and sun bear to the direction of the rotation the relation required by the theory. If the theory is quantitively sufficient, the interior of the earth and sun, as pointed out years ago, must be in a very different state from that of bodies with which we are familiar. If m/e reaches enormous values for magnetons within the earth and sun, which is not probable, or if the magneton density is sufficiently high and the effects of collisions and the molecular and demagnetizing fields at the same time sufficiently small, it is possible that even the small angular velocities of the earth and sun may be sufficient to produce the observed magnetizations.[25]

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SPRING MEETING OF THE EXECUTIVE COMMITTEE

THE executive committee of the council of the association held its regular spring meeting in the Cosmos Club, Washington, D. C., on the afternoon and evening of Sunday, April 24. The following paragraphs summarize items of business that were transacted. The personnel of the executive committee is as follows:

Simon Flexner (chairman), J. McK. Cattell, H. L. Fairchild, L. O. Howard, W. J. Humphreys, B. E. Livingston (permanent secretary of the association), D. T. MacDougal (general secretary of the association), E. H. Moore (president of the association), A. A. Noyes, Herbert Osborn, H. B. Ward. All of the members were present at this meeting, excepting Messrs. Flexner, Moore, and Noyes. The meeting was called at 4.00 P.M.

After the minutes of the last meeting of this committee (Chicago, Dec. 29, 1920) had been read and approved it was voted that the next meeting of the executive committee "shall occur in New York City on the first Sunday after November 1 that shall be convenient to a majority of the members," the exact date to be arranged by the permanent secretary.

It was voted that the action thus far taken by the American Association committee on conservation, be approved and that that committee be authorized to proceed with its plans. (The committee on conservation consists of J. C. Merriam (chairman), H. S. Graves, Barrington Moore, V. E. Shelford and Isaiah Bowman. It held a meeting in New York City on April 9, jointly with corresponding committees of the National Academy of Sciences and the National Research Council, and it was recommended that these three committees form a continuing joint committee on national conservation, representing the three organizations just mentioned, and that this joint committee be authorized to set up an executive and secretarial agency for the active prosecution of its work.)

The executive committee ratified the action taken by the committee on honorary life memberships through the Jane M. Smith fund, in placing the names of the distinguished scientists, J. E. Clark and J. N. Stockwell, recently deceased, on the list of honorary life members of the Association. (Both were ac-

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[25] See papers by Professor S. Chapman and by myself in *Nature*, Nov. 25, 1920, and March 3, 1921.