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THE MAGNETIC ELECTRON.*

BY

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THE evidence brought forward by the speakers who have preceded me has shown that many magnetic phenomena find a satisfactory explanation on the hypothesis that matter contains a large number of minute elementary magnets. The theories of para- and ferro-magnetism as developed by Langevin, Weiss and others, though based upon the hypothesis of such ultimate magnetic particles, make no assumptions concerning their nature. The explanation of diamagnetism, on the other hand, is based upon the view that this effect owes its origin to the circulation of electricity in resistanceless paths. The success of these theories in explaining the principal characteristics of magnetism gives us confidence in the real existence of these magnetic particles. Let us see, therefore, if it is possible to identify these elementary magnets with any of the fundamental divisions of matter.

The original investigations of ferromagnetism which led to the hypothesis of an elementary magnetic particle credited molecules with the properties of small permanent magnets. This view finds some support in the profound effect of heating, mechanical jarring, etc., on the ease of magnetization of iron. The dependence of magnetic permeability upon the chemical condition of a substance suggests the same view. But perhaps the strongest

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argument that has been brought forward in support of the idea of molecular magnets has been the discovery of the Heusler alloys, in which by melting together elements which are only slightly magnetic an alloy with ferromagnetic properties is produced. It is, however, difficult to imagine what mechanism could reasonably give to a group of atoms, such as the chemical molecule, the properties of a single magnetic particle. Moreover, if on magnetization such a group of atoms should actually turn around within a crystal, as the elementary magnets are supposed to do, the resulting change in the positions of the atoms composing the molecule should produce a change in the crystal form; since, as we know, the form of the crystal is dependent upon the arrangement of its component atoms. It is, however, a matter of common observation that a magnetic field effects no such change in the form of a magnetic crystal.

Perhaps the most natural, and certainly the most generally accepted view of the nature of the elementary magnet, is that the revolution of electrons in orbits within the atom give to the atom as a whole the properties of a tiny permanent magnet. Support of this view is found in the quantitative explanation which it affords of the Zeeman effect. It seems but a step from the explanation of this effect to Langevin's explanation of diamagnetism as another result of the induced electronic currents within the atom. On Langevin's view the electronic orbits act as resistanceless circuits in which an external magnetic field induces changes of current. By Lenz's law these induced currents will always be in the direction to give the electronic orbit a magnetic polarity opposite to the applied field, thus accounting for the atom's diamagnetic properties. This theory offers a satisfactory qualitative explanation of diamagnetism, and accounts for the fact that diamagnetism is independent of temperature. But quantitatively it is inadequate. For, in order to explain the magnitude of the observed diamagnetic susceptibility on this view, one must suppose either that the atom possesses a number of electrons equal to several times its atomic number, or the distance between the electrons in the atom must be several times as great as is estimated by more direct methods. Moreover, the experiments of Barnett[1] and J. Q. Stewart[2] show that the ratio of charge to mass of the

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[1] S. J. Barnett, *Phys. Rev.*, **6**, 240 (1915).

[2] J. Q. Stewart, *Phys. Rev.*, **11**, 100 (1918).

elementary magnet, though of the same order of magnitude, is appreciably greater than one would expect if the magnetic moment is due solely to electrons revolving in orbits. But perhaps a more serious difficulty with the usual electron theory of diamagnetism is that the induced change in magnetic moment of the electronic orbit involves also a change in its angular momentum. It is obvious, according to the classical electrical theory, that any electron revolving in an orbit will soon radiate its energy. Any angular momentum induced by an applied magnetic field will, on this theory, therefore, rapidly disappear so that diamagnetism should be merely a transient effect. Let us then assume with Bohr that if each electron has some definite angular momentum such as $h/2\pi$, no radiation occurs. On this view the electrons in the normal atom will all possess the requisite angular momentum, and when an external magnetic field is applied the induced change in angular momentum will put the electrons in an unstable condition. On this view also, therefore, the additional rotational energy induced by an applied magnetic field will not be permanent, but will soon be dissipated. In fact, the theory of atomic structure has yet to be proposed according to which diamagnetism, accounted for by the induced magnetic moment of electrons revolving in orbits, can be more than a transient phenomenon.

Besides the molecule and the atom we have the other two fundamental divisions of matter, the atomic nucleus and the electron. The sign of the Richardson-Barnett effect indicates that it is negative electricity which is chiefly responsible for magnetic effects, which makes the view that the positive nucleus is the elementary magnet difficult to defend. On the other hand, many of the magnetic properties of matter receive a satisfactory explanation on Parson's hypothesis,[3] that the electron is a continuous ring of negative electricity spinning rapidly about an axis perpendicular to its plane, and therefore possessing a magnetic moment as well as an electric charge. Thus, for example, the fact that such a ring can rotate without radiating enables this hypothesis to account for diamagnetism as a permanent instead of a transient effect. While retaining Parson's view of a magnetic electron of comparatively large size, we may suppose with Nicholson that instead of being a ring of electricity, the electron has a more nearly isotropic form with a strong concentration of electric charge near the centre

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[3] A. L. Parson, Smithsonian Misc. Collections, 1915.

and a diminution of electric density as the radius increases. It is natural to suppose that the mass of such an electron is concentrated principally near its centre and that the ratio of the charge to the mass of its external portions will be greater than that for the electron as whole. While the explanation of the inertia of such a charge of electricity is perhaps not obvious, it is at least consistent with our usual conceptions and it has the advantage of offering an explanation for the large value of e/m observed in Barnett and Stewart's experiments. It also makes possible an explanation of the relatively large induced currents required to account for diamagnetism without introducing the assumption of a prohibitively large radius for the electric charge.

A series of experiments has recently been performed, designed to determine which of these fundamental divisions of matter is identical with the elementary magnet in ferromagnetic substances. The first of these, due to K. T. Compton and E. A. Trousdale,[4] had for its object the detection of any displacement of the atoms of a substance on magnetization. If the elementary magnet consists of a group of atoms such as the chemical molecule, the rotation of this elementary magnet into alignment with an applied external field will cause a displacement of the individual atoms. It is known, however, that the position of the spots on a Laue photograph depends upon the arrangement of the atoms within the crystal employed. If then, such a photograph is taken with a magnetic crystal, the character of the diffraction pattern should change when the direction of magnetization of the crystal is altered. In these experiments, however, no effect of this character was found. The obvious conclusion is that the ultimate magnetic particle does not consist of any group of atoms such as the chemical molecule.

The second of these experiments, performed by Mr. Rognley and myself,[5] was based upon the fact that the intensity of reflection of X-rays from the surface of a crystal depends not only upon the arrangement of the atoms within the crystal, but also upon the distribution of the electrons within the atoms. Let us suppose that the atom acts as a tiny magnet due to the orbital motion of its component electrons. Magnetization of the crystal will orient these atomic magnets and in so doing will change the planes of

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[4] K. T. Compton and E. A. Trousdale, *Phys. Rev.*, **5**, 315 (1915).

[5] A. H. Compton and O. Rognley, *Phys. Rev.*, **16**, 464 (1920).

revolution of the electrons. This change in the electronic distribution should, therefore, affect the intensity of reflection of a beam of X-rays from the crystal's surface. An attempt was made to detect such a change in the intensity of X-ray reflection from a crystal of magnetite when strongly magnetized. Apparatus sufficiently sensitive to detect a change in intensity of less than one per cent. was employed, but magnetization of the crystal failed to produce any measurable effect. The following table shows in the first column the order of the X-ray spectrum line which was being studied; in the second column the calculated ratio of intensity from the magnetized to that from the unmagnetized crystal, supposing the atom to have the Rutherford form; and the third and fourth columns represent the similar ratios as estimated from a cubic form of atom. In the third column it is supposed that the magnetic axis is perpendicular to a cube face, and in the fourth column that the magnetic axis is along the cube diagonal. According to experiment the value of these ratios was always unity, at least within one per cent. It is clear that none of the types of atoms considered could be oriented by a magnetic field without producing a noticeable effect. In fact, it is difficult to imagine any form of magnetic atom which would be so nearly isotropic that it would have given no effect in our experiment. It is, therefore, difficult to avoid the conclusion that the elementary magnet is not the atom as a whole.

TABLE I.

Order	E_1/E_0	E_2/E_0	E_3/E_0
1	1.05	1.000	1.004
2	1.27	0.96	1.03
3	1.48	0.86	1.09
4	1.70	0.51	1.09

Since neither the molecule nor the atom gives a satisfactory explanation of these experiments, the view suggests itself that it is something within the atom, presumably the electron, which is the ultimate magnetic particle. Let us see then if we can find any positive evidence for the existence of an electron with a magnetic moment.

On the basis of the classical dynamics we should expect the electron, whatever its form, to possess thermal energy of rotational motion, equal on the average to that of a molecule or atom at the same temperature. On Planck's more recent quantum hypothesis, however, which is perhaps the more reasonable view, at the absolute zero of temperature each particle of matter—including the electron—should retain an average amount of energy ½hv for each degree of freedom for motion. For a rotating system this corresponds to, an angular momentum of $h/2\pi$. Thus whatever view we adopt, the thermal motions of the electron will give to it an appreciable magnetic moment. For a particle of the small moment of inertia of the electron, the frequency of rotation corresponding to an angular momentum $h/2\pi$ will be exceedingly high, and the corresponding energy ½hv will be large compared with the additional energy which it may acquire due to an increase in temperature. Thus the angular momentum, and hence also the magnetic moment of the electron, will be nearly the same at different temperatures—a property characteristic of the elementary magnets. It is interesting to notice, also, that the magnitude of the magnetic moment of an electron spinning with an angular momentum $h/2\pi$ is of the proper order to account for ferromagnetic properties, being about one-third the magnetic moment of the iron atom.

If an electron with such an angular momentum is to have a peripheral velocity which does not approach that of light, it is necessary that the radius of gyration of the electron shall be greater than 10^{-11} cm. While such an electron is much larger than the spherical electron of Lorentz, recent experiments on the scattering of X-rays and gamma rays indicate the electron's diameter may be even greater than the minimum value thus required to explain magnetic properties. Experiment shows that the scattering of very high frequency radiation is considerably less than theory demands if the electron is supposed to have negligible dimensions. In the case of hard gamma rays, indeed, I have found the scattering at certain angles to fall below 1/1000, the intensity predicted on the usual theory.[6] The only adequate explanation of these experiments seems to be that interference occurs between the rays scattered from the different parts of the same electron. Such an explanation clearly implies that the diameter of the electron is comparable with the wave-length of the radiation employed, which means that the effective radius of the electron is of the order of 10^{-10} cm. Considerations of the size of the electron, therefore,

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[6] A. H. Compton, *Phil. Mag.* (in printer's hands).

support rather than oppose the view that the electron may have an appreciable magnetic moment.

Further evidence that the electron possesses properties other than those of an electric charge of negligible dimensions is afforded by a study of the white X-radiation emitted at the target of an X-ray tube. It was noticed by Kaye that the X-rays emitted in the direction of the cathode ray beam are harder and more intense than those traveling in the opposite direction. The difference in both hardness and intensity of the radiation at different angles is in good accord with the view proposed by D. L. Webster that the particles emitting the radiation are moving in the direction of the cathode-ray beam, giving rise to a Doppler effect. Indeed, it is very difficult to give any other explanation of the difference in wave-length of the radiation in different directions. But, on this view, in order to account for the difference in hardness observed in the case of gamma rays, the radiating particles must have a velocity of about one-half the speed of light. Since the highest known speeds at which atoms travel is only about one-tenth the velocity of light, as observed in the case of alpha particles, the swiftly moving radiators giving rise to this high-frequency X-radiation must therefore be free electrons. If this view is correct, it follows, as Webster has pointed out, that the electron must be a system capable of emitting radiation, and is therefore, not a mere charge of electricity of negligible dimensions. On the present view we may well suppose that the electron is spinning like a gyroscope and on traversing matter is set into mutational oscillations, resulting in the observed radiation.

Strong evidence that the electron possesses a magnetic moment is afforded by H. S. Allen's recent explanation of the rotation of the plane of polarization by optically active substances.[7] You will remember in Drude's classical work it is found that optical rotation may be explained if the electrons, when made to oscillate by a passing electric wave, do not move exactly in the plane of the electric vector. He supposes rather that there is a component of motion at right angles to the electric vector and finds that such a motion will account for the observed rotation. Allen shows that the motion perpendicular to the electric vector which Drude assumes is a natural consequence of the view that the electron is magnetic and has an appreciable diameter. It would take us too

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[7] H. S. Allen, *Phil. Mag.*, **40**, 426 (1920).

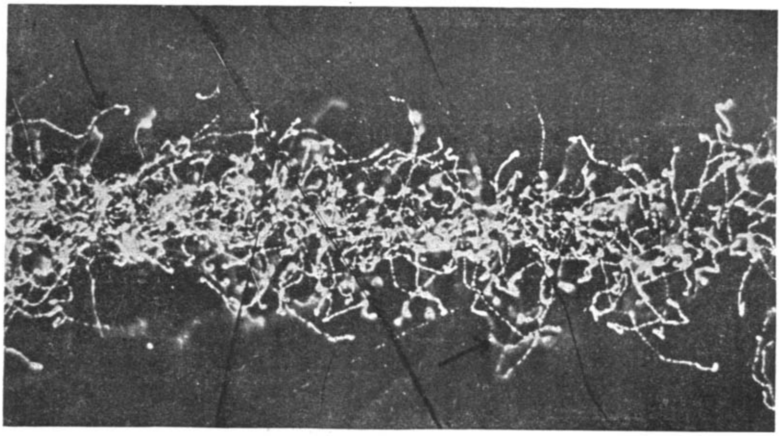
far afield to discuss the details of this work, but the significance of the result is obvious, since it has heretofore been difficult to give a reasonable account of the type of motion postulated by Drude.

Finally, I wish to discuss a phenomenon, first noticed by C. T. R. Wilson and brought to my attention by Mr. Shimizu, which, if its obvious explanation is correct, gives direct evidence that free electrons possess magnetic polarity. Suppose that a magnetic electron is placed in a homogeneous paramagnetic medium. Every part of the medium will be slightly magnetized in the direction of the lines of force, and the magnetic field at the electron due to the magnetic moment of each portion of the medium will have a positive component in the direction of the electron's magnetic axis. Thus the magnetization induced in the surrounding medium will give rise to a magnetic force at the electron in the direction of its own magnetic axis. The case is exactly analogous to placing a bar magnet in a field of iron filings. The iron filings will be magnetized by induction in the direction of the lines of force and if the bar magnet is removed, there still exists a magnetic field where the magnet was because of the magnetization of the surrounding iron filings. If now the electron is in motion, this induced magnetic field will produce the same effect as would an externally applied field of the same intensity. That is, the force due to the magnetic field from the surrounding medium acting on the moving electric charge will make it follow a curved instead of a straight path.

If, because of its gyroscopic action, the axis of the electron does not change its direction, the induced magnetic field will always be in the same direction, and the electron will describe a helical orbit. In any actual medium, composed of discreet particles and therefore not homogeneous on an electronic scale, this spiral motion will be superposed upon an irregular motion due to collisions, and the axis of the electron will not remain fixed in direction. Thus any spiral motion that may appear should be rather broken. A rough calculation, assuming an electron to be projected into air with a speed corresponding to a drop through 10,000 volts, which is about that of the secondary cathode rays produced by ordinary X-rays, and having a magnetic moment corresponding to the angular momentum $h/2\pi$, indicates that the induced magnetic field at the electron should be of the order of 3000 gauss, if the permeability of the medium is that of ordinary air. This field is strong enough to produce a very decided curvature in the electron's path, so in spite of the irregularities in the electron's motion we might hope to observe experimentally the predicted helical tracks.

Below are a few of C. T. R. Wilson's photographs of the tracks of secondary cathode rays and beta particles. In the first figure are seen the tracks of the cathode rays ejected by a comparatively intense beam of X-rays. Let me call your attention particularly to the two tracks marked by arrows. You see here paths in the form of almost perfect helices. Most of the tracks are too irregular and too confused with each other to trace so perfect a spiral form; but you will notice that in almost every case, the track terminates in a close spiral. The tracks can be examined more satisfactorily if we use a photograph showing a smaller number. In the next figure I have called attention particularly to three tracks. It is unfortunate that one cannot show these paths on the screen in three dimensions. Mr. Wilson showed me some remarkable stereoscopic photographs, as yet unpublished, which he obtained of X-rays passing through air. In one of these, showing altogether about 66 complete tracks, all but about 14 seemed to be of a spiral form. Of these fourteen 12 were too irregular to detect with certainty any spiral tendency that might exist, and the remaining two were for the most part straight. But to me

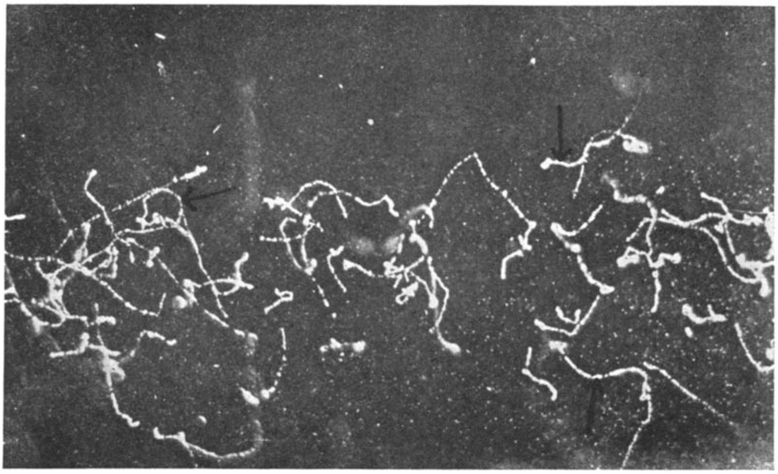
FIG. 1.



there seemed no doubt, nor did there to others who examined them carefully, but that there was a real tendency to spiral motion in the tracks of these secondary cathode particles.

The beta rays from radium show the same consistent curvature. Notice particularly the path shown in Fig. 3 with its almost uniform curvature. If one would calculate the probability of such a curvature on the basis of chance collisions, each as likely to deflect the particle in one direction as in another, this type of path would be declared impossible.

FIG. 2.



Examining again the tracks of the secondary cathode rays, let us see how their form compares with that to be expected for gyroscopic magnetic electrons. In the first place we find that the tracks exhibit a helical curvature of the kind we should anticipate. In the second place the axis of the helix is different for each beta particle, which we should anticipate since each beta particle induces its own magnetic field and the direction of the field is coincident with its own axis. And, finally, we notice changes in the direction of curvature such as might well result from sudden precessions of the electron's gyroscopic axis. If the obvious explanation of these spiral tracks is the correct one, we have here positive evidence for our hypothesis that the electron acts as a tiny magnet as well as an electric charge.

Let us then review the different lines of evidence that have given us information concerning the nature of the elementary magnet. In the first place, the Richardson-Barnett effect shows that magnetism is due chiefly to the circulation of negative electricity whose ratio of charge to mass is not greatly different from that of the electron. In the second place, experiments on the diffraction of X-rays by magnetic crystals indicate that the elementary magnet is not any group of atoms, such as the chemical molecule, nor even the atom itself; but lead rather to the view that it is the electron rotating about its own axis which is responsible for the ferromagnetism. And finally, positive evidence in favor of the hypothesis of some form of magnetic electron is supplied by a consideration of the curvature of the tracks of beta rays through air. May I then conclude that the electron itself, spinning like a tiny gyroscope, is probably the ultimate magnetic particle.

FIG. 3.