34

Researches on the Gyromagnetic Effect of some Ferromagnetic Compounds.*

By

D. P. RAY CHAUDHURI, D.SC.

(*Received for publication, 3rd April, 1935.*)

ABSTRACT.

The ratio of angular momentum to magnetic moment of the elementary carriers of ferromagnetism in a number of ferrites is determined by the resonance method due to Einstein and de Haas. The 'g' value (Landé factor) falls below the orthodox value of 2 for all cases by about 3 p.c. which is outside the limits of experimental error. The result may be explained on the assumption that the l-moment also contributes to ferromagnetism.

1. INTRODUCTION.

An electron of charge e and mass m moving in a circular orbit of radius r about the positive nucleus of an atom, has a magnetic moment $M = \pi n e r^2$ and an angular momentum $J = 2\pi n m r^2$ where n is the number of revolutions per second. The ratio $R = J/M = 2m/e = 1{\cdot}136 . 10^{-7}$.[1] This ratio of angular momentum to magnetic moment also holds in the general case of an elliptic orbit. It has been shown from various sources that the elementary magnets consist of such electrons. A mechanical moment is thus always associated with a magnetic moment, and when the magnetisation of a body is suddenly changed, there will appear an angular momentum in the direction of this change

---

* Read before the Inaugural Meeting of the Indian Physical Society on 29th September, 1934.

[1] With the latest spectroscopic value of e/m.

owing to the electronic magnets tending to turn their axes in the direction of the applied field. Now, according to the law of conservation of angular momentum, the angular momentum of an isolated system always remains constant. A reactional mechanical force, therefore, appears, to compensate for the change in the intrinsic angular momentum, and causes a rotational motion of the body as a whole, provided the molecules are not free to turn owing to the presence of neighbouring molecules.

This rotational motion accompanying sudden change in magnetisation was first predicted by Richardson.[2] He, however, failed to detect the effect experimentally. Einstein and de Haas[3] first succeeded in detecting the effect and confirmed the above ratio for $R = J/M$. Later Beck,[4] finding in it a method of determining e/m and the sign of the rotating electron, made a very careful observation, and found that for iron and nickel the ratio is not $2m/e$, but half the value. Later investigators confirmed Beck's results.

This discrepancy between theoretical and observed values was called the gyromagnetic anomaly, and could not be successfully explained till the advent of the spinning electron. For an electron spinning about its axis and with no orbital motion the ratio is given as m/e. In his attempt to explain the magnetic properties of the ions of the first transition group, Bose[5] suggested that the l-moments of the electrons were inoperative. This exclusion which means that the spin alone is effective in producing magnetic properties, gives the value of the ratio as m/e and thus explains the gyromagnetic anomaly.

It follows from the above result that it is the spin of the electron which plays the role of elementary magnets in ferromagnetics.

---

[2] Richardson, Phys. Rev., Vol. 26, p. 248 (1908).

[3] Einstein and de Haas, Verh. d. Deut. Phys. Gess., Vol. 17, p. 152 (1915); Do., 18, p. 173 (1916).

[4] Beck, Ann. d. Phys., 60, 109 (1919); Phys. Zeit., 20, 490 (1919).

[5] Bose, Zeit. f. Phys., Vol. 43, p. 864 (1927).

On the other hand, all the ferromagnetics on which gyromagnetic test has been made are metallic conductors and possess two kinds of electrons of which the spin can participate in magnetic phenomena. They are the so-called free electrons carrying electric current, and the electrons attached to metallic ions and moving in orbits about the atoms. The question now is which of these two kinds of electrons play the elementary rôle. No decisive answer can be obtained from theoretical points of view.

From Heisenberg's well-known work on the origin of the Weiss molecular field it appears that ferromagnetism is caused by interaction between the spins of valence electrons [6] which also function as conducting electrons in some incomprehensible way. Heisenberg based his calculations on a model corresponding to Heitler and London's model for the hydrogen molecule, in which each electron is at first thought to be bound to a definite atom. Such a model gives a very small probability for electrical conduction. Bloch [7] bases his considerations on the model of Sommerfeld's free electrons, which gives electrical conduction and he finds the conditions under which it is possible for such a model to give rise to ferromagnetism. A necessary but not sufficient condition for this is that the electrostatic energy of the electrons shall exceed the null-point energy. When there is one free electron eq per atom, the atom-rest forming a closed configuration, and when the temperature is below the critical degeneracy temperature, the above condition requires that the side of the unit cell $a > 0{\cdot}6.\ 10^{-7}$ cm. This is not fulfilled for the alkali metals, which are not ferromagnetic. Bloch shows that it is quite possible for free electrons to give rise to ferromagnetism. Stoner,[8] however, shows that if ferromagnetism were due to free electrons, the Curie point would

---

[6] Heisenberg considers the electrons to be in S states: Zeit. f. Phys., Vol. 49, p. 619 (1928).

[7] Bloch, Zeit. f. Phys., Vol. 52, p. 555 (1928).

[8] Stoner, Proc. Leeds. Phil. Soc., Vol. 2, p. 50 (1930).

have to be higher than the critical temperature of Sommerfeld's conduction theory, and this would require absurdly high temperatures.

Dorfman [9] at one time tried to prove that the magnetic electrons are the conducting electrons, while Ghosh [10] showed that all conducting electrons are not magnetic. Dorfman arrived at his conclusion by studying the magnitude of the sudden change at Curie point of the electrical specific heat of nickel ; but, as shown later by Stoner [11] his results are marred by an error in sign, which invalidates the whole conclusion.[12] Others [13] showed that for nickel there is a sudden change in the secondary emission of electrons at the Curie point.[14] All these facts make one inclined to think that "free" electrons play an important rôle in ferromagnetic phenomena. But from the theory of metallic states developed by Bloch, Peierls, Brillouin, Wilson and others [15] it is clear that too sharp a distinction cannot be made between "free" electrons and electrons in atoms or ions in the metal. We have mentioned that Heisenberg's theory requires the interacting electrons to be in S states. But Van Vleck [16] shows that in order that Heisenberg's considerations may apply it is only necessary to suppose that the orbital moment of the electrons in question has been quenched.

Dorfman and Jaanus, Zeit. f. Phys., Vol. 54, p. 277 (1929).

[10] Ghosh, Zeit. f. Phys., Vol. 68, p. 566 (1931).

[11] Stoner, Nature, p. 125, 1930.

[12] Nevertheless, the significance of Dorfman's work seems still to be shrouded in mystery. Thomson Effect cannot be understood by an elementary hypothesis of a specific heat of electricity, as has been done by both Dorfman and Stoner. The facts are much more complex, and a detailed theory in Lorentz or Sommerfeld's form requires a very minute consideration of a number of factors. (See N. H. Frank, Zeit. f. Phys., 63, 604, 1930). It is found difficult to establish a relation between Thomson effect and specific heat of electrons. (See L. Brillouin, Report of the Solvay Congress, 1981. Gauthier Villars p. 267.)

[13] Tartakowsky and Kudr jawzewa, Zeit. f. Phys., Vol. 75, p. 137, (1932).

[14] The facts observed by Dorfman and collaborators may be due to secondary processes connected with changes at Curie point.

[15] Erg. d. ex. Naturwiss., Vol. 11, p. 264 (1932).

Wilson, Proc. Roy. Soc. Vol. 133, p. 458 (1931), and subsequent papers.

[16] Theory of Electric and Magnetic Susceptibilities, p. 324.

The mechanism of this quenching has been explained by him [17] and is due to the effect of an internal asymmetric electrical field. This theory has been applied by Van Vleck and his collaborators [18] to explain the paramagnetic properties of the salts of the iron and rare earth families. Their works in conjunction with other considerations [19] lead us to assume that the electrons of which the interaction is responsible for ferromagnetism are those belonging to the incomplete '*d*' shell of the atoms. Paramagnetic phenomena [20] show that though most of the orbital moment is quenched there is still an amount left. The counterpart of this in ferromagnetic phenomena is claimed to have been observed by Barnett [21] who finds that the '*g*' value for the ferromagnetic elements is less than the ideal value for the spinning electron by amounts varying from 4% for iron to 7% for cobalt. This is in direct contradiction with the results of British physicists [22] who find $g=2$ (the value for the spinning electron) exactly, within very narrow limits of experimental error. Barnett's value may be explained as due to a participation of the *l*-moment in ferromagnetic phenomena. Stoner [23] has put forth evidence to prove that the *l*-moment does participate in ferromagnetic phenomena, at the least near about the Curie point. In consideration of these facts, *viz.*, (*i*) Barnett's low value of '*g*,' and (*ii*) the possibility of participation of an *l*-moment, we have set ourselves to gather as many data as possible for the gyromagnetic ratio of ferromagnetic substances both near to and away from their Curie points. As almost all gyromagnetic measurements have been made on the metals we have started with ferromagnetic

---

[17] *Ibid*, p. 287.

[18] Penney and Schlapp, Phys. Rev., 42, 666 (1932).
Jordahl, Phys. Rev., Vol. 42, p. 901 (1932).

[19] See *e. g.*, Slater, Phys. Rev., 35, 509 (1930) : Stoner, Phil. Mag., 15, 1018 (1933).

[20] Bose, *loc. cit.* : Van Vleck and Collaborators, *loc. cit.*

[21] Barnett, Proc. Amer. Acad., Vol. 66, p. 273 (1931).

[22] See references to Chattock, Bates and Sucksmith : Proc. Roy. Soc. and Phil. Trans.

[23] Stoner, Phil. Mag., Vol. 12, p. 737 (1931).

compounds like Fe_2O_3, Fe_3O_4 and the ferrites, some of which are reported to have low Curie points.

Moreover, the ferromagnetic behaviour of these compounds[24] is different in many respects from that of the metals. They, therefore, offer possibilities of an interesting study.

The following is a description of the gyromagnetic test made on some of these compounds.

2. THEORY OF THE METHOD.

Owing to the rather low magnetic susceptibility of the materials we had to adopt the resonance method of Einstein and de Haas. The substance, contained in a thin-walled cylindrical tube, is axially hung by means of a glass fibre in a strong magnetic field produced by a cylindrical coil. A sudden reversal of the direction of magnetisation produces a torque on the specimen, which shows a slight rotation. There are disturbing forces

---

[24] (*i*) The curves in reduced co ordinates of the spontaneous magnetisation against temperature of different ferromagnetics may be grouped into two classes, one comprising the metals Fe, Co, Ni and the other the compounds magnetite, pyrrhotite, etc.

(*ii*) The paramagnetic moments above the Curie point of the metals are always much higher than the ferromagnetic moments, while for the ferrites they are practically the same. The following figures are given by Mlle. Serres, Thèse, Strasbourg, 1931.

	Fe	Co	Ni	Fe_2O_3	$NiO.Fe_2O_3$	$CuO.Fe_2O_3$
Para-Mom. (in Weiss magnetons)	15·0	10·0	8·0	9	5·2	5·4
Ferro-Mom. (in Weiss magnetons)	11·0	9·0	3·0	10	5·5	5·4

(*iii*) The ferromagnetic Curie point (θ_f) of the first group lies lower than the paramagnetic Curie point (θ_p), while for the second group the two are very close together or θ_p lies lower than θ_f. See Forrer., Jour. de. Phys , Serie 7, 62, 312 (1931.)

	Fe	Ni	$PbO.Fe_2O_3$	$CuO.Fe_2O_3$	$NiO.Fe_2O_3$	$MgO.Fe_2O_3$
θ_f	770°C	357	442	455	590	339
θ_p	810	378	453	438	597	324

The above figures are taken from Serres' work (*loc. cit*). Some θ_f and θ_p values for ferrites are given by the present author in a succeeding paper to appear in the Ind. Jour. Phys.

which often completely mask this effect. To eliminate these and to make measurement of the very small rotation possible a resonance method is employed in which the period of reversal of the current in the magnetising coil coincides with the natural period of torsional oscillation of the specimen. The equation of motion of a suspended system acted on by a couple is

$$I\ddot{\theta}+\nu\dot{\theta}+C\theta=T$$

[where $I=$ moment of inertia of the system;
$\nu=$ a damping factor;
$C=$ torsion constant of the suspension;
$T=$ turning moment

$$=\frac{1}{g}\cdot\frac{2m}{c}\cdot\chi m_o\,\frac{dH}{dt}, \text{ where}$$

$\chi=$mass susceptibility of the specimen.
$m_o=$mass of the specimen.
$H=$strength of the magnetic field.]

The current-time form of the magnetising current is not sinusoidal, but can be repesented by

$$H=\sum_{n=1}^{n=\propto} H_o \operatorname{Sin} n\omega t.$$

As the measurements are taken at resonance, it is easy to show that only the fundamental is effective, which for a perfect square wave has the magnitude

$$\frac{4}{\pi}H_o \operatorname{Sin}\omega t.$$

$$\therefore\quad T=\frac{1}{g}\cdot\frac{2m}{e}\cdot\chi m_o\frac{4}{\pi}\cdot H_o\,\omega\cos\omega t.$$

The resonance amplitude

$$\theta_M=\frac{4}{\pi}\cdot\frac{2m}{e}\cdot\frac{1}{g}\,\frac{\chi m_o H_o}{\nu}$$

But
$$\nu=\frac{2I\lambda}{t}$$

where λ = logarithmic decrement, being given by $\lambda = \log_e \frac{a_1}{a_2}$, where a_1 and a_2 are two successive amplitudes in the same direction ; and t = time period of oscillation of the system.

The method, therefore, consists in measuring the resonance amplitude when the disturbing forces have been reduced to a minimum.

3. ARRANGEMENT AND APPARATUS.

The experimental arrangement is very nearly the same as that used by Sucksmith.[25]

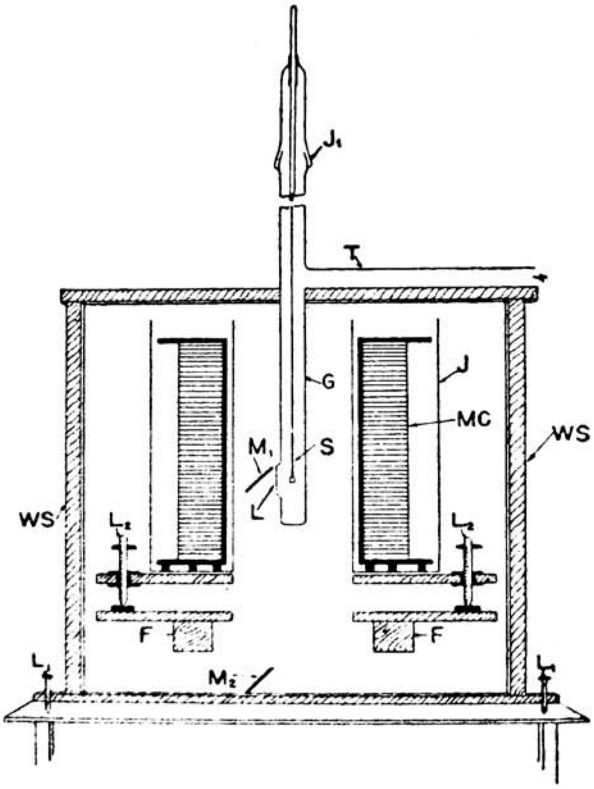

FIG. 1.

---

[25] Sucksmith, Proc. Roy. Soc.(A), Vol. 128, p. 276 (1930).

(i) *Magnetic Field.*

The magnetic field is produced by a cylindrical coil MC (Fig. 1) of 26 layers with a total of 3,341 turns of No. 14 S.W.G. double cotton covered copper wire wound on a brass former. The mean diameter of the coil is about 23 cm. and the length about 30 cm. Field produced at the centre is 110·0 gauss per ampere. The coil was surrounded by a jacket J of thin brass sheet and was kept cool by circulating oil around it. Current was taken from a storage battery of 144 volts, each unit of which had a capacity of 150 ampere-hours.

(ii) *Preparation of the Material.*

Fe_3O_4—Welo's method[26] of preparation was used. To a solution of $FeSO_4.7\,H_2O$ was added a solution of NaOH and KNO_3 of given concentration. The green precipitate was allowed to stand for 24 hours when it became black. It was carefully washed, dried and powdered. Analysis gave 98·5% of Fe_3O_4.

Fe_2O_3—Heating the above compound at 220°C in a stream of oxygen for 12 hours converted it into ferromagnetic Fe_2O_3. Analysis gave 99·3% of Fe_2O_3.

$NiO.Fe_2O_3$—To a solution containing equimolecular proportions of $NiCl_2$ and $FeCl_3$ was added a solution containing requisite quantity of NaOH in boiling. The precipitate was washed, dried and heated to a high temperature to get a ferromagnetic of sufficient intensity.

The ferrites of Mn, Cu, Co and Zn were prepared by the dry method. The metallic oxide and paramagnetic ferric oxide were taken in requisite proportions and heated in an electric furnace to about 1000°C. in a platinum vessel for about 20 hours.

The material under test was finely powdered in an agate mortar, after which a part was taken for susceptibility measurement, while another was used to fill a very thin-walled glass

---

[26] Welo, Phil. Mag., Vol. 50, p. 399 (1925).

tube of length about 6 cm. and diameters varying between 1·4 and 2·2 mm. The thickness of the walls was from ·04 to ·06 mm. This glass tube filled with the material forms the specimen to be tested.

(*iii*) *Suspension.*

This offered a problem; but finally Chattock and Bates'[27] method was adopted. V's (V, Fig. 2) and hooks (H, Fig. 2) of glass, as shown in the figures, were prepared. This preparation offered some difficulty as the usual method of bending over heated platinum wires proved unsuitable for the rather thicker V's and hooks which was necessary for the purpose. After some practice it was found possible to make good specimens by careful manipulation over a small flame. The junction (S, Fig. 2) between the V and hook was filled with shellac. The arms of the V were inside the tube (T). The suspending glass fibre was attached with shellac. At the top the fibre was fixed at two places at a distance of about 2 cm, the lower one of which was melted to enable the fibre to keep taught under the weight of the specimen.

FIG. 2.

---

[27] Phil. Trans., 223, 257 (1923).

A thin mirror (2 mm. × 3 mm.) (M, Fig. 2) was attached to the bottom of the glass tube containing the material. The incident light reached the mirror from the bottom of the coil by reflection at two mirrors (M_1 and M_2, Fig. 1) inclined at 45°, and went out the same way. The source of light was a 6 volt 25 watt lamp producing an intense illumination. A thin wire stretched before the source was focussed on a ground glass scale by means of a lens (L, Fig. 1) attached to the wall of the wider glass tube (G, Fig. 1) containing the specimen. The distance between scale and mirror was over one metre.

(*iv*) *Mounting.*

The specimen was mounted in a glass tube (G, Fig. 1) of $1\frac{1}{4}''$ inner diameter, closed at both ends and provided with a ground joint (J_1, Fig. 1) which helped in the repeated taking off and examination of the specimen (S, Fig. 1) and could also give the specimen a slight rotation when necessary. A side tube (T, Fig. 1) below the ground joint was connected with a pump. The whole thing was mounted on an wooden stand (WS, Fig. 1) provided with levelling screws (L_1, Fig. 1) and the stand placed on an isolated pillar (P, Fig. 1) whose foundation was 12 feet deep. A wooden frame (F, Fig. 1) spanned the pillar, and on this was placed the magnetising coil, which was provided with levelling screws (L_2, Fig. 1).

(*v*) *System for producing Resonance.*

The pendulum of an electrical clock was removed and replaced by one (P, Fig. 3) with adjustable time period. The range of variation obtained was from 1·6 to 3·0 secs. A stiff wire (W) attached to the pendulum rod just closed a circuit when the pendulum was at rest, by contact with a cup of mercury (M), the cup being placed on a stand provided with levelling screws. For one-half the period the circuit was closed.

and for the other half open. The current in this circuit actuated an electromagnet (E M) which again closed another relay circuit by drawing a piece of soft iron (I) attached to one arm of a polarising relay. When the electromagnet was not in action, the loaded arm closed another circuit by contact with a mercury pool.

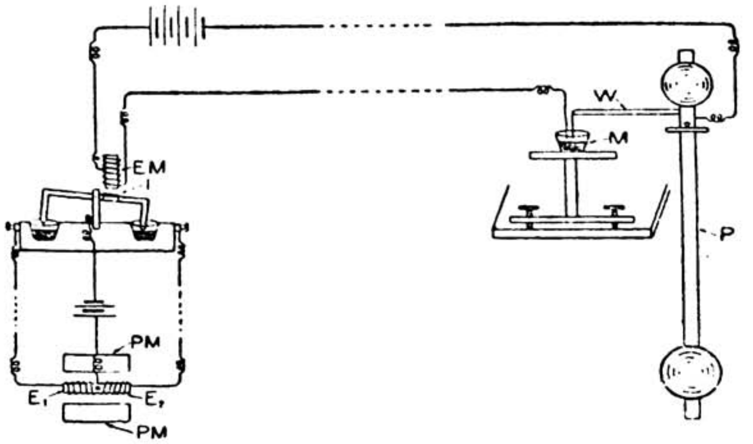

FIG. 3.

These two circuits on their parts actuated two electromagnets (E_1, E_2, Figs. 3 and 4) placed in the field of a strong permanent magnet (PM, Fig. 4). These were so made and mounted that while one exerted a clockwise turning couple on a horizontal rod (R, Fig. 4) which carried them both, the other exerted an opposite one. To this rod was attached the rocker (C) of a commutator whose conductors (C_1, C_2) were cross-connected. The commutator was of a special design there being two channels (L_1, L_2), $9'' \times 1'' \times 1''$ in the place of the usual four mercury cups, and served the purpose of reversing the current in the magnetising coil. This arrangement for producing resonance is essentially the same as used by Sucksmith. Later on the relay was done away with, and the current worked by the pendulum actuated an electromagnet which turned the rocker of the commutator against the pull of a spring. To minimise sparking all the mercury surfaces were covered with light oil and sometimes with glycerine and in all the circuits the minimum potential applied. It was found that with these precautions all the contacts worked regularly for the period necessary.

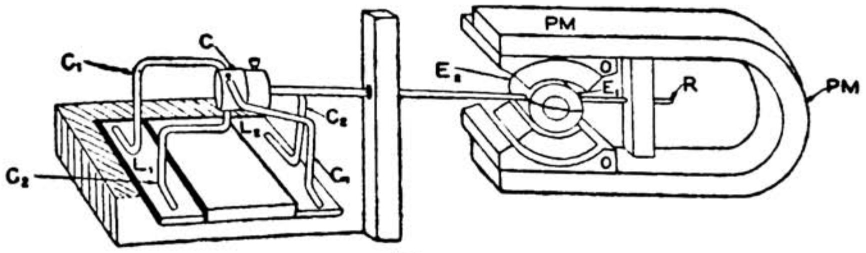

FIG. 4.

To test how far the synchronisation has been perfect a mirror and a long focus lens was attached to the pendulum rod, which served to reflect and focus the light from a distant source on the same scale on which the light from the mirror of specimen under test fell. This spot of light moved with the motion of the pendulum and synchronisation could be tested easily.

4. DISTURBING EFFECTS.

There are disturbing effects whose magnitudes may be hundred to thousand times greater than the effect to be measured, or even more. Their nature as also the method of elimination are given below.

(*i*) *Error due to Earth's Field* :

The earth's magnetic field has three components :

(*i*) The north-south horizontal component.
(*ii*) The east-west horizontal component.
(*iii*) The vertical component.

The compensations are more difficult than they appear to be, because the earth's field is continually varying both in direction and magnitude and because the work had to be done in a building which contains iron and, therefore, disturbs the uniformity of the field.

The first harmonics of the vertical and horizontal magnetic moments of the specimen may be assumed to be

$$M_v = M' \sin \omega t, \quad M_h = M'' \sin (\omega t - \alpha)$$

(*a*) The induced horizontal component of the magnetisation of the specimen may be acted on by the earth's horizontal component H_e and produce an axial torque whose magnitude is given by

$$T_h = CH_e, \; M_h = C' \sin (\omega t - \alpha)$$

If the torsion head is turned through 180° this torque is reversed.

(*b*) The specimen may have a permanent horizontal magnetic moment ${}_pM_h$ which when acted on by the earth's horizontal field produces a steady displacement of zero.

(c) The earth's vertical component may produce mangetostrictive torques of which we shall speak later on.

(*ii*) *Errors due to Horizontal Component of the Field of the Magnetising Coil :*

(*d*) ${}_pM_h$ *{see (b) above} may be acted on by it and produce* a torque which will nearly be in phase with M_v, and we may put it as

$$T_c = C'' \sin (\omega t + \beta)$$

where β is small. This may be eliminated by turning the torsion head through 180° when the torque is reversed. It is often of considerable magnitude and special care has to be taken to reduce both the magnitudes, ${}_pM_h$ and the horizontal component of the field coil.

(*e*) The alternating field acting on the induced horizontal moment produces a torque of twice the natural frequency.

(*iii*) *Errors due to Inequality of Half-cycles of the Magnetising Current.*

(*f*) When the two half cycles are unequal there is a residual torque on the specimen of the same frequency. This may have any phase relation with the gyromagnetic torque, and may be written

$$T' = K \sin (\omega t + \gamma)$$

(*iv*) *Effects due to Magnetostriction, etc.*

Since the change in dimension due to magnetostriction is independent of the direction of magnetisation, no magnetostrictive torque of the same period as that of the first harmonic of the magnetisation can arise if the two half cycles of magnetisation are exactly similar. When the half cycles are dissimilar or when there is a residual vertical magnetic moment there will be an elongation with a first harmonic of the period of the magnetisation. The error due to the presence of a residual vertical moment may be eliminated by working with fields capable of producing saturation.

5. ELIMINATION OF ERRORS.

(*i*) *Error due to Earth's Horizontal Field.*

The specimen usually had a horizontal magnetic moment which caused a lot of trouble, and required the greatest attention. To eliminate the action of the earth's field, it was neutralised by a current flowing through two rectangular coils 3′ × 2′ at a distance apart of about 20″. The coils had 32 turns each and required a current of about ·54 ampere for neutralisation. The degree of perfectness of neutralisation was tested by a small magnet suspended by a silk fibre. As the east-west component of the field was small it could be neutralised by a slight rotation of the coils. While working it was found that the direction of the field underwent small changes at times. Instead of altering the position of the rectangular coils it was found more convenient to add two coils of 5 turns each placed parallel to the magnetic meridian at a distance of 22″. Current through this coil could be adjusted to perfect neutralisation.[28]

(ii) *Error due to Horizontal Component of the Magnetising Coil.*

The magnetising coil was provided with three levelling screws with which the field could be adjusted to the vertical. But as long as the horizontal moment of the specimen was appreciable the disturbance due to even a very small horizontal field was great. It was, therefore, imperative to bring down the

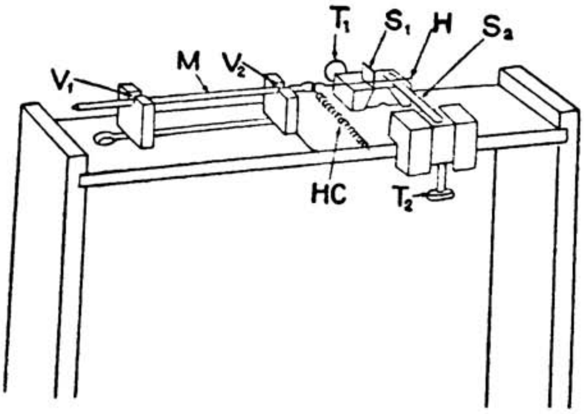

FIG. 5.

---

[28] As the earth's magnetic field underwent changes both in magnitude and direction it was useless to work with a value of the neutralising field obtained at any one time. But the knowledge of such a value is essential as indicating the order of such values. The actual procedure adopted was to vary the north-south component of the neutralising field till a minimum value is obtained for the resonance amplitude, and with that value of the field to vary the strength of the east-west component till a second minimum for the resonance amplitude is observed.

horizontal moment of the specimen to the lowest value possible. This was done as follows :[29]

The specimen (M) was laid down on two metal V grooves (V_1, V_2, Fig. 5). To the base on which these V's stood were attached two steel strips (S_1, S_2) one of which could be moved horizontally and the other vertically by means of two screws (T_1), (T_2) with a small pitch (32 turns to the inch). To the heads of these screws were attached arms about five inches long (not shown in the figure), so that the steel edges could be adjusted to a few thousandths of a millimetre. After the specimen is laid on the grooves, the screws are adjusted so that the steel edges just touch the hook (H) to which the specimen is attached. There is a small heating coil (H C) below the point where the hook is attached to the V. A small current is sent which is sufficient to soften the shellac in the joint. The screws are moved by small amounts at a time after the shellac has softened. This moves the point of suspension relative to the specimen. After the shellac has solidified the specimen is taken and suspended in a horizontal magnetic field of about 60 gauss supplied by a vertical coil which could be rotated about a vertical axis. The magnitude and direction of the horizontal moment of the specimen could be judged from the direction and degree of deflection resulting.[30] The adjustment

---

[29] The method is similar to that used by Chattock and Bates, (Phil. Trans., 223, 257, 1922).

The presence of a horizontal moment is due to the magnetic axis of the specimen not coinciding with the axis of suspension. The procedure adopted is to make them identical.

The magnetic axis is generally not identical with the geometrical axis. The correction for horizontal moment, therefore, raises the moment of inertia of the specimen. This may be seen from the calculated and observed values of the moment of inertia for the specimen.

[30] Whenever such a horizontal magnetic field is applied the necessary co-ercive field is also subsequently applied to eliminate the effect of the first field. The magnitude of the co-ercive field depends on (i) nature of the substance, (ii) density of packing and (iii) the intensity of the field first applied. The correct value for the co-ercive field is determined while making the susceptibility measurements.

By co-ercive field is here meant the reverse field which after application and removal leaves zero residual moment.

is to be carried to such a degree that for two positions of the coil inclined at 90° to each other there is practically no deflection of the specimen. This requires that the specimen should always be laid down in the identical position relative to the V's and the steel strips. To ensure this the mirror attached to the specimen is always made to reflect the light from a distant source at a definite spot both being fixed relative to the V's.

It is found that for zero horizontal moment of the specimen the geometrical asymmetry is not generally appreciably large.

(iii) *Asymmetry in the Alternating Current.*

It is necessary that the duration of the current in the coil in both directions shall be the same, as any want of symmetry will have the frequency of the pendulum and will make itself felt at resonance. To check this the current through the coil was passed through a voltameter and the gas liberated at the two electrodes was collected. When the current was symmetrical the volumes of the gas in the two tubes were the same. In practice it was found that such a method took time. The water voltameter was, therefore, removed and replaced by a siphon recorder. The current while passing through one of the small electromagnets of the recorder, pulled a piece of soft iron to which was attached a nib. The continuous line left on the recording paper was thus marked by transverse lines corresponding to the reversals in the current. The adjustment was made by means of levelling screws with which the mercury cup (M, Fig. 3) in which dipped the rod from the pendulum, was provided. This mercury surface was also covered with oil.

(iv) *Mechanical Disturbances.*

Traffic in the street often caused a vibratory motion of the specimen to be set up, which was more troublesome while working in vacuum. Though the isolated pillar mounting reduced this effect greatly, it was found that regular working could only be obtained between 1 A.M. and 5 A.M. in the night when all traffic had stopped.

(v) *Heating Effect of the Coil.*

A current of 4 amps. sent through the coil raises the temperature of the bath at the rate of 2°C per hour. A thermocouple inserted at the position occupied by the specimen within the glass tube records a rise of temperature of 0·2°C per hour. It may, therefore, safely be concluded that temperature changes due to heating effect of magnetising current produces no appreciable effect on the specimen.

(vi) *Form of the Magnetising Current.*

This was investigated with an oscillograph. The time taken by the current to change from maximum in one direction to maximum in the other, was a minimum and corresponded to that required by the self-induction of the coil. This duration was less than $\frac{1}{50}$ of the average time period of the specimens used in the experiment. Sucksmith (Proc. Roy. Soc., 128, 276, 1930) has shown that even when this duration is 3·5% of the time period, the departure from square wave form does not introduce a correction in the const. $\frac{4}{\pi}$ (see p. 389) by more than 0·1 %. We, therefore, neglected this correction.

6. PROCEDURE.

The field within the magnetising coil was explored and standardised. The susceptibility of the material is determined for values of the field strength which are to be used as also for different densities of packing. A suitable thin-walled tube having been found, it is filled with the material. The mirror is attached to the bottom as much possibly axially to keep the moment of inertia lowest. To the mirror is attached a very small hook which helps to measure the moment of inertia of the specimen. A suspension fibre is so chosen that the period of torsional oscillation of the specimen falls within the range of periods of which the pendulum is capable, *viz.*, 1·6 to 3·0 secs. in our case. The specimen is suspended in a horizontal magnetic field of 60 gauss and adjusted for zero horizontal moment (see page 399). The moment of inertia of the specimen is determined by loading it with small aluminium discs of known moment of inertia. The correct value of the earth's field neutralising current having been previously obtained, the specimen is put in position and the reflecting mirrors adjusted. The pendulum is then synchronised with the free period of the specimen after fully exhausting the system. The applied field is adjusted to the vertical by means of levelling screws with which the coil is provided. This adjustment is better tested by using a specimen with a horizontal magnetic moment. As long as the coil has a horizontal component the period of oscillation of the specimen with a steady field acting will be different from its natural period. The levelling screws are adjusted till the two periods are the same, the test being made by the pendulum. Accurate centring[31] of the specimen is extremely necessary to avoid pendulum like oscillations of the specimen as a whole as also oscillations about its centre of gravity. When the adjustment is complete the specimen shows no appreciable motion when the current through the coil is put on or reversed. The duration of the current through the coil in either direction is adjusted to be the same by means of levelling screws with which the mercury cup (M, Fig. 3) in the pendulum relay

---

[31] For this purpose the frame carrying the glass tube containing the specimen, was provided with an arrangement by means of which it could be moved in two mutually perpendicular directions. The motion was given by a screw with a big head and a small pitch. (This arrangement has not been shown in the figure.) Thus the axis of suspension of the specimen could be made to coincide with the axis of the magnetising coil. To make the centres of the coil and the specimen coincide the latter was moved up or down with the help of the glass rod from which it was suspended.

circuit is provided. All these adjustments being complete, the pendulum is started and the magnetising current put on. Sufficient time is allowed to pass for the resonance amplitude to attain 98% its maximum value, and the amplitudes noted every half a minute for a run extending from 20 minutes to half an hour. The earth's field neutralising current is slightly altered by small steps at a time (see page 398) and the corresponding resonance amplitude noted. There is a critical value of this current for which the amplitude is a minimum. This critical value is not a fixed one, but changes from day to day and time to time, though the change is slight and lies within ±·01 ampere of the value for perfect neutralisation which has been fixed previous to mounting the specimen. For higher and lower values of the neutralising current the amplitude increased. Variations of temperature from day to day affects the viscosity of the material of the suspension fibre, glass in this case, and the time period of the specimen changes slightly. It is then necessary to alter the period of the pendulum and readjust it. Sometimes this temperature effect causes more trouble, the time period showing a marked change in a period of 2 hours. The most consistent results are obtained on those nights when the temperature shows no sudden and large change. Any possible departure of the field from the vertical is tested by slight alterations of levelling screws of the coil and noting the effect on the amplitude. In all cases the minimum amplitude[32] is sought. After one series of readings the specimen is turned through 180° and another series of readings taken.

When working in vacuum the pump is started after resonance has been obtained at atmospheric pressure. This is

---

[32] The reason for this is that all the disturbing torques are in quadrature with the gyromagnetic torque. The former can, therefore, only increase the amplitude due to the latter alone. *Vide* Sucksmith, Proc. Roy. Soc. 128, 276, 1930.

convenient for the fact that at times there are irregular vibrations at the start, which die away more quickly at higher pressures. At the end of the observations the logarithmic decrement is noted with the field on.

7. MEASUREMENT.

(i) *Field Strength.*

This was measured by means of a ballistic galvanometer which has been standardised by a coil of known dimensions. The exploring coil was wound on a piece of copper rod of about the same diameter as the specimens, *viz.*, 2 mm. and had a length of 6 cm., the same as that of the specimens. This was placed in about the same position as was later on occupied by the specimen. The average value of the field over the specimen was thus obtained, and was 109·4 gauss per ampere. A small coil also explored the field axially. The results are given in the Table.[33]

TABLE.

Distance from the Centre of the Coil.	Field Strength in gauss.
0 cm.	110·0
3 ,,	108·5
5 ,,	105·7
10 ,,	90·4

---

[33] The value of the field at any point as also the average value over the specimen when the latter is placed at the centre of the magnetising coil, may be computed from the known dimensions and the number of turns of the coil. The value thus obtained is about 0·3% higher than the value obtained experimentally. We prefer the latter to the computed value obtained because of the errors introduced by the rather large diameter of the copper wire used (No. 14 S. W. G.).

(ii) *Susceptibility of the Substance.*

The B-H curve of the substance was obtained by a magnetometer method and from it the susceptibility for the field strength used was calculated. Details are given in a separate paper.

(iii) *Moment of Inertia.*

This was measured in the usual way by loading the specimen with aluminium discs of known moment of inertia. A number of discs of values of moment of inertia varying from $16{\cdot}14.10^{-4}$ to $31{\cdot}66.10^{-4}$ C.G.S. units were used. These were hung from the hook attached to the specimen by means of very short silk loops so that the axis of rotation passed centrally through the disc perpendicular to its axis. The position of the hook had to be slightly altered to secure this. The time period is a minimum when the adjustment is correct.

The accuracy with which 'I' could be measured is manifested by the fact that with care any one of these discs gave the moment of inertia of any other within 0·5 per cent.

8. DATA.

Results of measurement are given below in a tabulated form. For notations please turn to pp. 389 and 411.

Detailed Data for one successful run.

Material—Copper ferrite. ($CuO.\ Fe_2O_3$)
Date and duration—26th June to 1st July, 1933.
Diameter of glass tube for filling with material :

Diameters in mutually perpendicular directions at

Top.	Middle.	Bottom.	
1·72 mm.	1·70	1·70	mean value 1·71 mm.
1·70 ,,	1·71	1·72	

Thickness of wall = ·04 mm.
Length of tube filled = 6·6 cm.
Weight of material = ·3098. gm.
Density of packing = 2·25 gm/cm^3.
Determination of moment of inertia (I)

Free period = 2·468 secs. (mean of 550 oscillations)

Time period when loaded with aluminium disc (A) = 3·435 secs. } of moment of inertia = $16{\cdot}1_4.10^{-4}$ c.g.s.u.

Time period with disc (B) ($1 = 22{\cdot}3_4.10^{-4}$. c.g.s.u.)
= 3·743 secs.

Time period with disc (C) ($I = 24{\cdot}9_6.10^{-4}$ c.g.s.u.)
= 3·869 secs.

I from (A), (B), (C) respectively = $17{\cdot}2_2.10^{-4}$, $17{\cdot}1_8.10^{-}$ and $17{\cdot}1_2.10^{-4}$

Mean value of $I = 17{\cdot}1_7.10^{-4}$. c.g.s.u.

Actual run :

Free period = 2·468 secs.
Magnetising current at start = 2·303 amps.
" ,, ,, end = 2·302 amps.

Resonance amplitude = 8·19/2 cm.
Resonance amplitude with
specimen turned through 180° = 8·27/2 cm.
Mean Resonance amplitude = 8·23/2 cm.

Logarithmic Decrement (λ).

No. of Oscillations.	Ratio of Amplitudes.	Log a_1/a_2
25	69/40	·009468
25	90/52	·009528
25	112/65	·009452
25	122/71	·009404
25	86/50	·009420
25	138/80	·009468
25	140/81	·009504
25	81/47	·009456
25	93/54	·009444
25	117/68	009426
25	129/75	·009420
25	143/86	·009445
25	126/73	·009464
25	100/58	·009464

Mean value = ·009465.

$\lambda = \cdot009465 \times \log_e 10 = \cdot02180.$

Field strength = 2·303 × 109·4 gauss = 252·2 gauss.

Magnetic susceptibility for this field strength and density of packing 2·25 gm/cm^3 = ·0824.

Scale distance = 130·2 cm.

'*g*' calculated from these data = 1·940.

Here we have not considered the demagnetising factor, which reduces the field by 5 parts in 1000 in this instance. In the data which follow in pages 408-410 the demagnetising factor has different magnitudes in different cases. The total effect is in the direction of reducing the '*g*' value by amounts varying between 1 part in 1000 and 5 parts in 1000 in rare cases.

Substance.	Mass (gm.)	χ	H (gauss.)	t (secs)	D (cm.)	I. 10^4 (C. G. S. U.)	λ	d (cm.)	g	REMARKS.
Fe_3O_4	·2372	·072	226·6	2·229	130·2	21·72	·1161	·64	2·012	Only the damping is varied.
	·2372	·072	226·6	2·229	130·2	21·72	·0328$_2$	2·39	1·936	
	·2372	·072	227·7	2·232	130·2	21·83	·1161	·67	1·924	Do. do.
	·2372	·072	227·7	2·232	130·2	21·83	·0334$_9$	2·28	1·961	
	·1062	·0705	219·1	1·882	105·5	6·26	·1192	·62	2·036	Do. do.
	·1062	·0705	219·1	1·882	105·5	6·26	·0325$_8$	2·30	2·009	
	·2913	·0697	215·2	1·683	130·2	23·02	·0324	1·90	1·954	Do. do.
	·2913	·0697	215·4	1·682	130·2	23·02	·0640$_7$	·95	1·976	
	·1763	·0840	210·0	1·772	130·2	14·4$_2$	·114	·64	1·967	Do. do.
	·1763	·0840	210·4	1·772	130·2	14·4$_2$	·0865	·82	2·032	Other conditions have changed slightly.
	·1763	·0840	210·3	1·773	130·2	14·4$_2$	·0314	2·31	1·986	
Fe_2O_3	·0998	·0825	120·6	1·863	130·2	4·32	·0321	2·57	1·953	Field strength varied.
	·0998	·0837	183·2	1·863	130·2	4·32	·0319$_6$	3·98	1·954	
	·0998	·0840	210·8	1·864	130·2	4·32	·0315$_7$	4·94	1·920	
	·2346	·0840$_5$	228·5	2·414	130·2	22·4$_3$	·114$_8$	·81	1·963	Damping varied.
	·2346	·0840$_5$	229·2	2·4131	130·2	22·4$_3$	·0324	2·90	1·948	

Substance	Mass (gm.)	χ	H (gauss)	t (sec.)	D (cm.)	I. 10^4 (C. G. S. U.)	λ	d (cm.)	g	REMARKS.
$NiO.Fe_2O_3$ (Nickel ferrite.)	·1074	·0381	232·8	2·188	129·4	7·33	$\cdot 0291_3$	1·90	1·923	
	·1074	·0381	232·5	2·192	129·4	7·38	$\cdot 0298_2$	1·82	1·948	Taken down and remounted after fresh adjustment.
	·1074	·0381	234·0	2·180	129·2	7·38	$\cdot 0331_4$	1·63	1·957	Setting on different nights
	·1074	·0381	235·8	2·180	129·7	7·38	$\cdot 0292_5$	1·90	1·924	
	·1061	·0381	246·0	2·082	130·8	6·47	$\cdot 0248_4$	2·49	1·956	
	·1061	·0381	265·2	1·926	130·8	6·52	$\cdot 0239_2$	2·57	1·948	Taken down and remounted after adjustment. Field different.
	·1061	$\cdot 0380_5$	271·4	2·568	130·8	6·58	$\cdot 0236_5$	3·57	1·912	Do.
$2ZnO.3Fe_2O_3$ (Zinc ferrite.)	·1165	·0154	235·2	2·236	132·3	5·08	$\cdot 0257_2$	1·45	1·906	
	·1165	·0153	279·6	1·635	132·3	5·12	$\cdot 0261_5$	1·20	1·942	Do.
	·1165	·0153	278·3	1·623	132·3	5·02	$\cdot 0283_0$	1·13	1·920	Do.
	·3416	·0161	265·3	2·462	131·8	$19·4_2$	$\cdot 0248_2$	1·51	1·921	
	·3416	·0161	273·4	2·348	131·8	$19·2_3$	$\cdot 0286_8$	1·51	1·957	Do.
	·3416	·0161	274·2	2·348	131·8	$19·2_5$	$\cdot 0284_9$	1·54	1·941	Setting on different days.

9. THE ESTIMATION OF PROBABLE ERROR.

(i) *Errors in Reading.*

Measurements of quite a number of different quantities are involved in the determination of g by the method here adopted. They are: the mass of the material (m), the moment of inertia of the specimen (I), time period of oscillation of the specimen (t) the magnetic susceptibility (χ), logarithmic decrement (λ), field strength (H), distance between scale and mirror (D) and the deflection on the scale (d). The probable error in the measurement of each of the above quantities is given below:

	Probable error in %.
m	0·05
I	0·5
t	0·05
χ	0·5
λ	0·5
H	0·1
D	0·1
d	0·2

From the above it follows that even if all the component errors are in the same direction the total probable error is 2·0%. The departure from the mean of the final values of g is, with only one exception (*viz.*, second set of readings in Fe_3O_4), less than this value.

Fe_3O_4 was the substance with which the experiment began, and it was not possible to attain the degree of accuracy as obtained later. This makes itself particularly felt in the small values of 'd' which, for the smallest values, may be in error by as much as 1%. Considering these larger probable errors in 'd'

the total probable error for Fe_3O_4 is placed at 3·0%. For Fe_2O_3 similar considerations lead to a maximum probable error of about 2·5%. For the rest what is said earlier holds good.

For nickel, manganese, copper and zinc ferrites the values obtained for g differ from the orthodox value for the spinning electron by more than the experimental error, the g values obtained being lower than 2. The individual g values for all these ferrites are less than 2 in all cases, while for Fe_3O_4 and Fe_2O_3 only three and one, out of eight readings each, are higher than 2. After duly weighing all the results the author is of opinion that for Fe_3O_4 and Fe_2O_3 also the g values do differ from that of the spinning electron.

(ii) Errors due to Adjustment.

The possibility of a systematic error is discounted by the fact that the sources of error mentioned in pp. 395-97 have been attended to properly and the elimination made by taking the readings in two azimuths by turning the specimen through 180°. The only possible source of error not considered is that due to magnetostrictive effects and non-compensation of the earth's vertical field. The first has a harmonic of the natural frequency of the specimen only when the two half cycles of magnetisation current are unequal. But we have taken special care to make the two cycles equal. The only error may arise from the earth's vertical field ; but this only when there is a residual vertical magnetisation. At no time was the specimens subjected to a vertical field outside the coil except that of the earth. Moreover, we took special care to make the axis of suspension of the specimen pass through the magnetic axis. Under such circumstances it is hard to believe that an error can arise from the earth's vertical field. In addition, nickel ferrite is characterised by a very low value of remanent magnetisation. The possibility of a large permanent vertical magnetisation is in this case, therefore, to be discounted.

10. SUMMARY AND DISCUSSION OF RESULTS.

The results of the above experiments show that the value of the gyromagnetic ratio for the substances investigated, substances which are poor conductors of electricity, is a few per cent smaller than the orthodox value for the spinning electron. This shows that though electron spin supplies the majority of the interaction causing ferromagnetism, there are also other contributing factors to consider. One of them may be a participation of the l-moment (the orbital moment). This is in agreement with the observations of Barnett.

Summary.

(1) The ratio of angular momentum to magnetic moment of the elementary carriers of ferromagnetism in the following substances is determined by the method of resonance due to Einstein and de Haas :

(*i*) Fe_3O_4, (*iii*) $NiO.Fe_2O_3$, (*v*) $MnO.Fe_2O_3$,
(*ii*) Fe_2O_3. (*iv*) $CuO.Fe_2O_3$. (*vi*) $2ZnO.3Fe_2O_3$.

(2) The g and R values with the probable error are given below :—

	g	R	Probable Error.
Fe_3O_4	1·96	$1{\cdot}02\frac{m}{e}$	3%
Fe_2O_3	1·96	1·02 ,,	2·5%
$NiO.Fe_2O_3$	1·94	1·03 ,,	2%
$nO.Fe_2O_3$	1·94	1·03 ,,	2%
$uO.Fe_2O_3$	1·94	1·03 ,,	2%
$nO.3Fe_2O_3$	1·92	1·04 ,,	2%

(3) It is concluded that g is in each case less than 2 (the value for the spinning electron). The difference may be explained as due to participation of an l-moment.

(4) The value of g for all the substances is very nearly the same as that for pure iron as found by Barnett, showing that it is principally the $Fe^{+3}-Fe^{+3}$ interaction that gives most of the ferromagnetism in these cases.

My heartiest thanks are due to Prof. D. M. Bose who kindly suggested this problem, gave me every facility to work in his laboratory, and took a constant interest during its progress.

University College of Science,
92, Upper Circular Road,
Calcutta.