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REPORT
of
COMMITTEE ON EXAMINATION

This is to certify that we the undersigned, as a Committee of the Graduate School, have given Oswald Rognley final oral examination for the degree of Master of Arts. We recommend that the degree of Master of Arts be conferred upon the candidate.

Minneapolis, Minnesota

May 31, 1917

Arthur H. Compton
Chairman

Henry C. Erickson

Anthony Zelensky

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L.W. McKeehan

John T. Tate

REPORT
of
Committee on Thesis

The undersigned, acting as a Committee of
the Graduate School, have read the accompanying
thesis submitted by Oswald Rognley
for the degree of Master of Arts.
They approve it as a thesis meeting the require-
ments of the Graduate School of the University of
Minnesota, and recommend that it be accepted in
partial fulfillment of the requirements for the
degree of Master of Arts.

Arthur H. Compton
Chairman

W. E. Brooke

Henry A. Eisavot

May 30, 1917

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THE EFFECT ON THE INTENSITY OF X-RAY SPECTRUM LINES
OF MAGNETIZING THE REFLECTING CRYSTAL.

A T H E S I S

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL

of the

UNIVERSITY OF MINNESOTA

by

OSWALD ROGNLEY

in partial fulfillment of the requirements for
the degree of

MASTER OF ARTS

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The fact that there seems to be no limit to the divisibility of a magnet, the parts still retaining their magnetic properties, has led physicists to agree that these properties are due to exceedingly small elementary magnets. But what is the nature of the ultimate magnetic particle remains a question. The first theory was that of Weber. According to his theory each molecule of a magnetizable substance is a magnet in a position of equilibrium under the influence of internal elastic forces. These internal forces tend to restore the molecule to its original position when it is moved out of this position by an external field. The theory explains in a satisfactory manner the phenomenon of proportionality between the external magnetizing forces and the intensity of magnetization when the latter is small. It accounts also for saturation, for when the elementary magnets have all been turned the intensity cannot be increased further. To account for hysteresis Wiedemann suggested that the forces opposing the turning of the elementary magnets are of a frictional nature, but this fails to explain magnetization in very weak external magnetic fields. Ewing showed that the phenomena of hysteresis

isis and ferromagnetism may be accounted for by supposing that the only restraints on the molecules are due to the magnetic forces occurring between neighboring molecules. But these theories, however, were unable to account for diamagnetism. Ampere explained this phenomenon by assuming the existence of currents traveling in circular orbits within the molecules. It may be shown that when these currents are placed in an external field, they are so modified by induction that if the resultant magnetic moment was originally zero, the induced currents now set up cause a magnetic field opposing the external field, which accounts for the phenomenon of diamagnetism. If, however, the molecule had originally a magnetic moment different from zero it is turned in such a manner that its own magnetic field approaches coincidence with the external field, thus explaining paramagnetism.

There are many reasons for believing that every atom has a number of negatively charged corpuscles or electrons revolving in orbits about its center. It has been shown by Rowland that the revolution of such a charged particle will cause a magnetic field as if the orbit were a continuous current of electricity as Ampere had assumed.

This is the basis of the electron theory of magnetism which has received its greatest development at the hands of Langevin and Weiss. It may be shown that the effect of an external magnetic field on these revolving electrons is precisely the same as if the orbits were continuous currents of electricity. Thus by electromagnetic induction the magnetic moments of the electron orbits are diminished in the direction of the external field. The result is diamagnetism. If the resultant moment of all the electric orbits in each atom is different from zero, however, the planes of the orbits will be so oriented that their magnetic field will approach coincidence with the external field. This gives the effect of paramagnetism. The intensity of magnetization of the substance depends upon the strength of the external field and upon the rigidity with which the internal forces, electrostatic or otherwise, hold the electron orbits in their normal positions. If the resultant magnetic moments of the atoms are so large that all other interatomic forces are insignificant in comparison, the atoms arrange themselves in a regular order under the influence of a directing external field and ferromag-

netism results.

In addition to these theories we have Parson's Magneton Theory.¹ Parson assumes that the electron possesses, in addition to its negative charge, the properties of an electric circuit. The radius of the circuit is estimated to be 1.5×10^{-9} cm., which is smaller than the atom, though of the same order of magnitude. This negatively charged ring he calls the "magneton". The magnetons are distributed in a uniform sphere of positive electricity and their number and arrangement determine the various chemical and physical properties of the element.

We may now classify the theories of magnetism into three groups. The first group assumes that the molecule is the fundamental magnet; the second explains magnetism by the effect of rotating electrons in the atoms; the third class of theories makes the ultimate magnetic particle still smaller and assumes it to be the electron itself.

The molecular theory has support in (1) the effect of temperature on the magnetic state; (2) the effect of mechanical jarring on magnetism; (3) the heating effect of rapidly alternating or changing magnetic fields; (4) the

properties of the Heusler alloys. One of the strongest points in favor of the second form of theory in addition to the explanation of magnetic effects, is the simplicity with which it explains the Zeeman effect. Another support of this theory is the phenomena of magnetization by rotation² and the converse effect, rotation by magnetization.³ It appears from these experiments that magnetization is produced by the gyroscopic turning of electronic orbits so as to cause a resultant magnetic moment. But there are facts which are more or less inexplicable by the Langevin-Weis theory. Among these may be mentioned (a) The formation of the ferromagnetic Heusler alloys from copper, manganese and aluminium. (b) The fact that manganese is para- or ferromagnetic according to previous history. (c) The peculiar changes of tin from dia- to paramagnetic state by heating. (d) Some substances may be either dia- or paramagnetic according to the field strength. The magneton theory of Parson seems to be capable of explaining qualitatively the effects of chemical and physical modifications on the magnetic properties of a substance, but the theory has not as yet been subjected to enough quantitative tests to show whether it is completely satisfactory.

Experimental Test of the Theories.

K. T. Compton and Trousdale⁴ performed an experiment with a view to test the first of these theories. They employed the recently developed method of X-ray photography for determining the position of atoms in crystals. The crystals employed were hematite and magnetite, both magnetic and capable of being magnetized to a high intensity. A beam of X-rays was passed through the crystal and the diffraction patterns, determined by the arrangement of the atoms of the crystal, were obtained on photographic plates placed behind the crystals. A photograph was taken of the pattern when the crystal was demagnetized. Then a second one was taken when the crystal was magnetized by means of an electromagnet. Now if the ultimate magnetic particle is the chemical molecule, then the magnetizing of the crystal would turn the molecule and consequently shift the position of the atoms. This would produce a change in the diffraction pattern. In no case did they find that magnetization of the crystals had any influence on the diffraction pattern. This seems to show that the ultimate magnetic particle cannot be the molecule but

must be the atom itself or something intraatomic.

The electron theory of magnetism can be tested in a similar manner if when a crystal is magnetized a change in the arrangement of the electronic orbits within the atom can be detected. By a study of the relative intensity of the different orders of spectra obtained when a beam of X-rays is reflected from a crystal, it has recently been shown that it is possible to form some idea of the distribution of electrons in atoms. A. H. Compton⁵ has deduced the following expression for the reflected energy:

$$E_r = \frac{E_i}{\Delta\theta} \cdot \frac{N^2 \lambda^3}{24} \cdot \frac{1 + \cos^2 2\theta}{4 \sin \theta \cos \theta} \left(\frac{e^2}{mC^2} \right)^2 \times \left\{ \int_a^b F(z) \cos \left(\frac{4\pi z \sin \theta}{\lambda} \right) dz \right\}^2 e^{-B \sin^2 \theta}$$

where E_i is the incident energy, $\Delta\theta$ is the angular aperture of the slit through which the incident beam passes, N is the number of electrons per unit volume of the crystal, λ is the wave length of the X-rays, μ is the absorption coefficient, θ is the glancing angle of incidence, $(1 + \cos^2 2\theta)$ is the polarization factor, C is the velocity of light, e/m has its usual significance, $e^{-B \sin^2 \theta}$ is the factor accounting for the thermal motion of the atoms. The factor inside the squared brackets depends on the arrangement of the electrons in the atomic layers, — $(b - a)$ being the diameter

of an atom and $F(z)$ representing the probability that a given electron shall be at a distance z from the middle of its layer of atoms at any instant.

$F(z)$ is the only part of the expression which can be affected by the application of an external magnetic field. If the electron orbits possess a resultant magnetic moment in each atom, then according to the electron theory, the effect of a magnetic field will be to turn the orbits so as to bring this equivalent magnetic doublet in line with the external field. This will affect $F(z)$ and consequently a crystal should show a different intensity of reflection of X-rays for the same incident beam when magnetized and when demagnetized. The magnitude of the effect which is to be expected will now be examined in an approximate manner, after which an experiment will be described in which this effect of magnetization upon the intensity of X-ray reflection was tested for and in which no such effect was observed.

Let

$$\psi = \int_{-a}^{+a} F(x) \cos \frac{2\pi z \sin \theta}{\lambda} dz$$

Suppose all the electrons in an iron atom to be arranged in a ring of radius R , whose plane is inclined at an angle ϕ to that of a layer of atoms. All the electrons will then lie between two planes at distances $R \sin \phi$ and $-R \sin \phi$ from the midplane of the layer of atoms. Suppose the effect of these electrons is the same as if they should be situated in a plane at a distance a and $-a$ from the midplane of the layer, i. e. a is the mean effective value of z in the above formula, then

$$\psi = \cos \frac{4\pi a \sin \phi}{\lambda} \int_{-a}^{+a} F(z) dz = \cos \frac{4\pi a \sin \phi}{\lambda}$$

for $\int_{-a}^{+a} F(z) dz = 1$

Let r be the effective radius of the orbit, then

$$a = r \sin \phi \quad \text{Where } r < R$$

$$\psi^2 = \cos^2 \frac{4\pi a \sin \phi}{\lambda} = \cos^2 (Kr \sin \phi) \quad \text{where}$$

$$K = \frac{4\pi \sin \phi}{\lambda}$$

But we wish to find the rate of change of ψ^2 with respect to a change ϕ i. e. we wish to examine to what extent the

intensity of reflection changes when the electronic orbits are turned through a small angle. Differentiating we have

$$\begin{aligned} -\frac{\partial \psi^2}{\partial \varphi} &= 2 \cos(Kr \sin \varphi) (\sin Kr \sin \varphi) Kr \cos \varphi \\ &= Kr \sin(2Kr \sin \varphi) \cos \varphi \end{aligned}$$

In order to form some idea of the magnitude of this change in ψ^2 for a definite change in φ we will suppose that the effective radius of the orbit is one fourth of the distance between the successive atomic layers in the crystal, and make use of the fundamental equation for X-ray reflection

$$n\lambda = 2D \sin \theta \quad \text{or,}$$

$$D = \frac{n\lambda}{2 \sin \theta}$$

where D is the distance between the layers of atoms in the crystal, n the order of the spectrum, λ the wave length and θ the angle of incidence. Let $D = 4r$ according to the supposition, then

$$Kr = \frac{\sqrt{2}}{2} n$$

$$\frac{\partial \psi^2}{\partial \varphi} = \frac{\pi n \sin(\pi n \sin \varphi) \cos \varphi}{2}$$

Let $n=1$ and $\varphi = \frac{\pi}{4}$

$$\frac{\partial \psi^2}{\partial \varphi} = \frac{\pi}{2} \sin\left(\pi \cdot \frac{1}{\sqrt{2}}\right) \frac{1}{\sqrt{2}} = .88$$

To obtain the per cent change in ψ^2 we divide this by the value of ψ^2 . i. e. by $\cos^2(Kr \sin \varphi) = \cos^2\left(\frac{\pi}{2} n \sin \varphi\right)$
 $= \cos^2 \frac{\pi}{2} \cdot \frac{1}{\sqrt{2}} = .199$

$$\frac{\partial \psi^2}{\partial \varphi} \div .199 = \frac{.88}{.199} = .44 \text{ per radian change in } \varphi$$

Per degree change in φ this would be $\frac{.44}{57.3} = 7.7$ per cent

For $n=3$, i. e. the third order spectrum, and taking $\varphi = \sin^{-1} 1/6$ for convenience, we find this percentage change to be 9.30. Per degree change in φ this becomes 16.2 per cent. That is, the intensity of reflection changes at the rate of 7.7 per cent per degree change in orientation of the electronic orbits in the first case and at the rate of 16.2 per cent per degree in the second. This was on the

assumption that all the electrons are in a single ring.

If we assume that of the 26 supposed electrons in the iron atom, 25 are in the center and one is in the ring, then

$$\psi = \frac{25\psi_1 + \psi_2}{26} = \frac{25}{26} + \frac{1}{26} \cos\left(\frac{\pi}{2} n \sin \varphi\right)$$

ψ_1 being that part of ψ which is due to the electrons in the atomic plane itself and ψ_2 that part which is due to the electron in the ring.

$$\psi^2 = \left(\frac{25}{26}\right)^2 + \frac{5.0}{(26)^2} \cos\left(\frac{\pi}{2} n \sin \varphi\right) + \text{small term}$$

$$-\frac{\partial \psi^2}{\partial \varphi} = \frac{5.0}{(26)^2} \sin\left(\frac{\pi}{2} n \sin \varphi\right) \frac{\pi}{2} n \cos \varphi$$

For $n=1$ and $\varphi = \frac{\pi}{6}$ as observed case

$$\frac{\partial \psi^2}{\partial \varphi} \div \psi^2 = .07 \text{ per radian} = .12 \text{ percent per degree.}$$

For $n=3$ and $\varphi = \sin^{-1} \frac{1}{3}$

$$\frac{\partial \psi^2}{\partial \varphi} \div \psi^2 = .33 \text{ per radian} = .57 \text{ percent per degree}$$

change = φ

These are only approximations to the change expected in the intensity, and are worked out for very special cases. But they serve to show that it is reasonable to expect an appreciable change on the application of a magnetic field to the crystal, provided of course that the electron orbits turn appreciably under such a field. According to Weiss' theory a ferromagnetic substance approaches saturation only when the axes of the elementary magnets all point in about the same direction, that is, the maximum intensity of magnetization is reached only when the magnetic axes of the electronic orbits are parallel to the external field. H. du Bois^d has investigated the intensity of magnetization of various substances for different field strengths. His method was an optical one based on Kerr's phenomenon. He found that the saturation intensity for magnetite is about 350 units and that this saturation is reached in a field of from 1000 to 1500 gauss'. The field strength used in the present experiment was 1800 gauss' and consequently saturation was insured. It is accordingly very probable that there was an appreciable change in the orientation of the electronic orbits in the magnetite used in this experiment.

Arrangement of Apparatus.

The arrangement of the apparatus is shown diagrammatically in the figure. X-rays from the anticathode of a Coolidge tube pass thru slits S and S' and are received in ionization chambers D and D' after reflection from crystals C and C'. The outside of the ionization chamber D is connected to one pole of a battery of 240 volts, while chamber D' is connected to the other. The middle of the battery is grounded so that the two ionization chambers are charged each to 120 volts but in opposite directions. The electrodes w and w' of the ionization chambers are connected to the same pair of quadrants of a highly sensitive electrometer while the other pair of quadrants is grounded. Crystal C' is of rock salt and is so set upon the crystal table as to give the maximum reflection into the ionization chamber. Crystal C is of magnetite and is fastened to one pole of an electromagnet. Crystal and magnet are fixed on the crystal table which is geared so as to move with one half the angular velocity of the arm carrying the ionization chamber. Thus when the spectrometer table is rotated by means of the screw Y, the crystal

turns so that the ionization chamber is always in position to receive the reflected beam of X-rays. This makes it convenient to find the positions of the reflection maxima. In the path of each of the beams of X-rays is placed an aluminium absorbing wedge which is moved by screws G and G'. This enables the varying of the intensity of either beam.

The method consists in balancing the two beams of X-rays against each other. The ionization chamber D' is set so as to receive the reflected beam from crystal C' and chamber D receives that from C. The wedges are then adjusted until the two ionization currents are equal and no deflection is observed on the electrometer scale. First the wedges were calibrated by inserting in the path of one of the beams a lead sector disc, cutting off exactly one half the intensity. It was found that when the sector disc was rotating it was necessary to move the other wedge forward 16 mm. to reestablish the balance between the two ionization currents. Thus a motion of the wedge of 16 mm. cuts off one half the intensity and consequently a motion of the wedge of 1 mm. will cut off approximately 3 per cent of the intensity of the beam. It was also found that after a balance had been obtained, an appreciable de-

flection could be observed by turning the screw G' through 1/3 of a revolution. This gives some idea about the sensitivity of the method. A change in the intensity of beam A of 1 per cent could thus be detected.

After the two ionization currents had been balanced and the tube had been running for about 30 minutes to reach a steady state, the alternating current was turned on in the magnet supporting the crystal C, the resistance in the alternating current circuit being gradually raised so as to demagnetize the crystal completely. When the spot of light on the electrometer scale became steady the switch was thrown, turning on the direct current, thus strongly magnetizing the crystal. There was a slight motion of the electrometer needle due to electrostatic induction effects but no disturbance of the balance was observed. The crystal was then demagnetized by means of the alternating current, again magnetized, etc., the motion of the spot of light being carefully observed between each operation. In no instance was the ionization produced by the beam from the magnetite crystal changed to such a degree as to disturb the balance between the two currents. Since a change of 1 per cent in the intensity of the X-ray beam could easily be

detected it is concluded that the intensity of the reflected X-rays does not change by as much as 1 per cent on magnetizing or demagnetizing the crystal. Supplementary experiments showed that the magnetic field between the crystal and the pole piece of the electromagnet was about 1800 gauss'. This is ample to strongly magnetize the crystal. The same process was applied to each order of reflection up to the fourth, but, ^{even} in the higher orders, no effect was observed.

In the experiment just described the crystal was magnetized in a direction perpendicular to the reflecting face. A similar experiment was performed magnetizing the crystal parallel to the reflecting face. On account of mechanical difficulties only the third order was tested in this case. *The results were negative as before.*

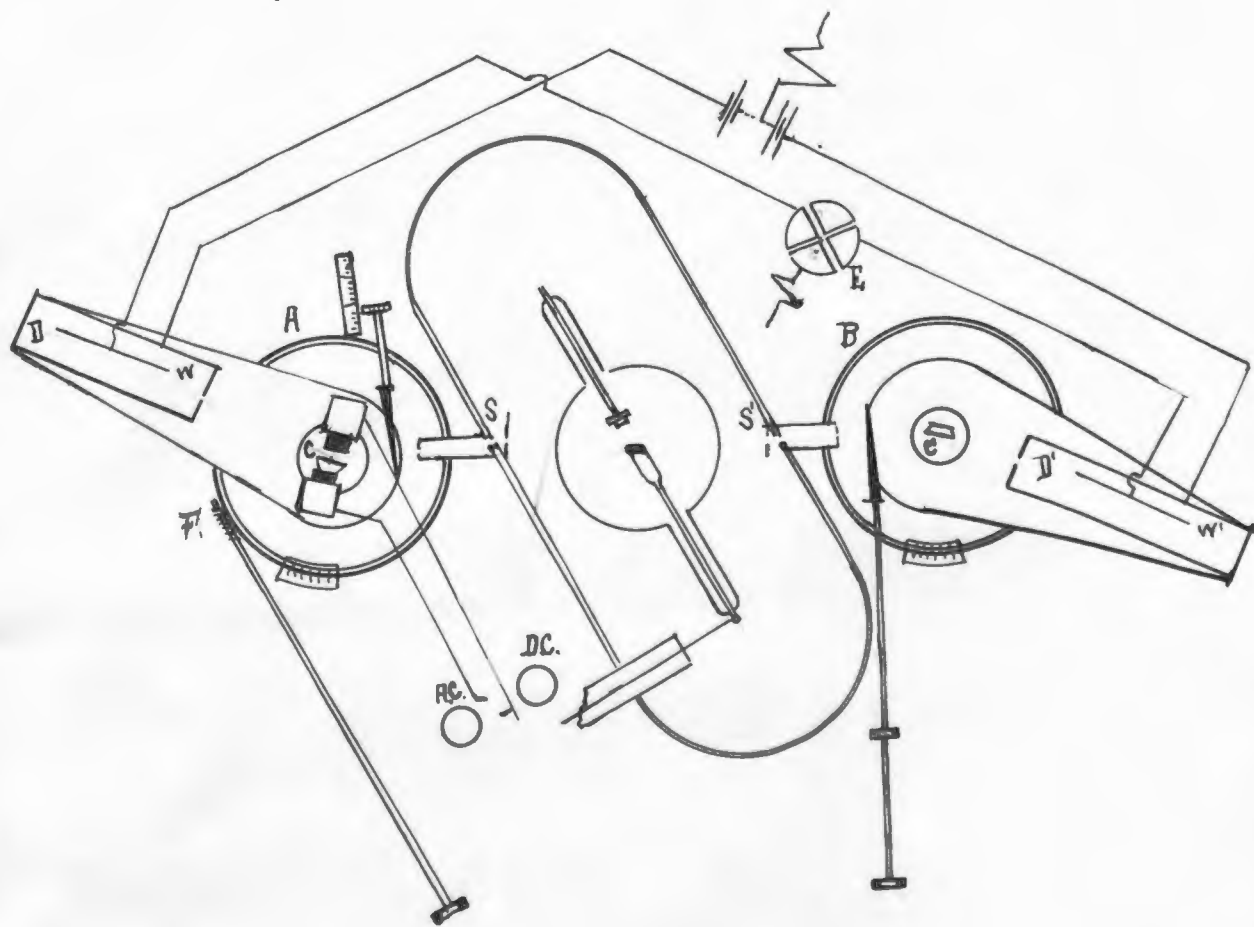
Conclusion.

The results of this experiment do not seem to agree well with the electron theory of magnetism. According to this theory the ultimate magnetic particle is the atom. The atom in a ferromagnetic substance possesses a resultant mag-

netic moment and can consequently not have its electrons distributed isotropically. Thus a turning of the atom will result in a change in the distribution of the electrons in the atomic planes of a crystal. K. T. Compton and Trusdale conclude from their experiment with X-ray photography through a crystal that the ultimate magnetic particle cannot be a molecule or any other group of atoms since the turning of such a group would involve a translational motion of atoms. The present experiment seems to show something of a similar nature with regard to the atom. The atom does not seem to turn, or if it does, it turns to such a slight degree that the electron distribution is not materially changed.

On the other hand, if, as according to the magneton theory, the ultimate magnetic particles are not the atom but the electrons themselves, no effect on the intensity of X-ray reflection would be expected. In this case the elementary magnets would turn but there would be no translation of the electrons, thus no change in distribution.

I wish to acknowledge my indebtedness to Dr. A. H. Compton under whose constant guidance this experiment was performed.



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