



LXXV. An atomic model with a magnetic core

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TABLE III.

$$\gamma = \cdot 3649_3; \quad k_0 = 5 \cdot 0500; \quad a = -2 \cdot 5000.$$

i	$\lambda_{i \text{ calc.}}$	$\lambda_{\text{obs.}}$	Δ
1	$\cdot 6499$	(1) $\cdot 6563 \text{ H}\alpha$	-64
2	$\cdot 4909$	(2) $\cdot 4861 \text{ } \beta$	$+48$
3	$\cdot 4363$	(3) $\cdot 4341 \text{ } \gamma$	$+22$
4	$\cdot 4107$	(4) $\cdot 4102 \text{ } \delta$	$+5$
6	$\cdot 3881$	(6) $\cdot 3889 \text{ } \zeta$	-8
8	$\cdot 3789$	(8) $\cdot 3798 \text{ } \theta$	-9
12	$\cdot 3715$	(12) $\cdot 3722 \text{ } \mu$	-7
16	$\cdot 3687$	(16) $\cdot 3692 \text{ } \pi$	-5
21	$\cdot 3672$	(21) $\cdot 3674 \text{ } \phi$	-2
28	$\cdot 3662_2$	(28) $\cdot 3662_1 \text{ H}_{30}$	$+0 \cdot 1$
29	$\cdot 3661_3$	(29) $\cdot 3661_2 \text{ H}_{31}$	$+0 \cdot 1$
\vdots	\vdots		
∞	$\cdot 3649_3$	$\lambda_B = \cdot 3646_1$	$+3 \cdot 2$

the greatest Δ of Table III. to one or a few Å.U. only; but before deciding on the introduction of two new constants, by using formula (3) with $\kappa=2$, I shall not spare further efforts to succeed with the simpler dispersion law (3a). The results of my further calculations, together with some general consequences of the proposed theory, will be reported in a later publication.

London, April 8, 1915.

LXXV. *An Atomic Model with a Magnetic Core.* By H. STANLEY ALLEN, M.A., D.Sc., Senior Lecturer in Physics at University of London, King's College*.

IN spite of their limitations models have been of great service in the development of physical theories. The two models illustrating the structure of the atom that have attracted most attention are those that have been suggested by Sir J. J. Thomson and Sir E. Rutherford respectively. Thomson's atom consists of a sphere containing a uniform volume distribution of positive electricity, in which a certain number of negatively electrified corpuscles are distributed. In Rutherford's atom there is a central

* Communicated by the Author.

nucleus of small dimensions carrying a positive charge, and this nucleus is surrounded by electrons in orbital motion. According to Nicholson coplanar rings of electrons are not possible in such a case, and the model can neither be of the "planetary" nor of the "Saturnian" type; but, provided the electrons are in one plane, can only possess a single ring of electrons.

In these models only the electrostatic forces due to the positively charged portion of the atom are taken into account. It has been pointed out by the present writer* that it may be necessary to consider not only electrostatic but also magnetic forces in the immediate vicinity of the atom. According to this view the atom would consist of a magnetic core which is electrically charged, surrounded by electrons in orbital motion. Whether it is possible for the electrons to form concentric rings in this case is a point deserving the attention of mathematicians; experimentally such rings appear to have sufficient stability to allow them to be directly observed as in the striking cases recorded by Birkeland†. In these experiments photographs were taken of the discharge through a large vacuum-tube with a magnetized sphere as cathode. Rings were formed round this globe resembling the rings of Saturn, in some cases as many as three distinct rings could be observed.

The Scattering of the Alpha Rays.

The scattering of alpha rays by atoms of matter has afforded results from which Rutherford has formed an estimate of the size of the nucleus. In the theory of scattering which he has proposed only electrostatic forces are considered. In this case the scattering depends on the inverse fourth power of the velocity of the α particle. If we consider an α particle moving in the equatorial plane of a simple magnet, it appears that the scattering would depend on the inverse square of the velocity. In the general case of a charged particle projected in any direction in a combined magnetic and electrostatic field, it is probable that some intermediate law would be obeyed. The experiments of Geiger and Marsden‡ agree moderately well with the

* 'Nature,' vol. xcii. p. 630 (1914).

† Birkeland, *C. R.* vol. cliii. p. 938 (1911).

‡ Geiger & Marsden, *Phil. Mag.* vol. xxv. p. 620 (1913). "Several experiments were made, and in every case the scattering was found to vary at a rate more nearly proportional to the inverse fourth power of the velocity than to any other integral power. Owing to the comparative uncertainty of the values of the velocity for small ranges, however, the error of experiment may be somewhat greater than appears from column V. of the table." The tabulated numbers vary from 22 to 28.

first law, but the point is one of so much importance that it may repay further examination.

The scattering of α rays by the magneton has been discussed by Hicks *, who has calculated a number of trajectories in the equatorial plane similar in character to those investigated by Størmer †. The difficulty of forming an estimate of the amount of scattering is very considerably increased in the general case when the α particle is projected towards a magnetic atom in any direction whatever, but the results obtained by Hicks go to show that scattering of the right order of magnitude can be obtained by postulating a reasonable number of magnetons in the core.

There is no idea of calling in question the mathematical investigations of C. G. Darwin ‡, who dealt with the motion of a charged particle under the action of a central force varying as some power of the distance. The only question at issue is whether the experimental results on scattering are of so decisive a character as to prohibit the introduction of magnetic forces, and to lead with certainty to the conclusion that the nucleus of a heavy atom cannot have a radius much exceeding 10^{-13} cm.

The Size of the Nucleus.

Two arguments only have been advanced in favour of the extremely small diameter assigned to the nucleus of the Rutherford atom. The first is derived from the wide-angle scattering of α particles, and, as we have seen, the argument is inconclusive because no account has been taken of the possibility of a magnetic field being associated with the atom. The second depends on the assumptions that the whole mass of the nucleus is electromagnetic in origin and that this mass arises from a structureless charge of magnitude Ne , where N is the atomic number. Now we know that both α and β particles are derived from the nucleus of radioactive substances, and it is hardly thinkable that these should exist in the nucleus save as discrete particles. We conclude that at least for the elements of high atomic weight the nucleus must possess a structure, though it remains to some extent doubtful whether the two elements, hydrogen and helium, at the beginning of the periodic table, are to be looked upon as possessing a *simple* or a *complex* nucleus. According to the views advanced by Nicholson from a study

* W. M. Hicks, Proc. Roy. Soc. vol. xc. p. 356 (1914).

† Størmer, *Archiv for Matematik*, Christiania, vol. xxviii. p. 36 (1906).

‡ C. G. Darwin, Phil. Mag. vol. xxv. pp. 201-210 (1913).

of nebular and coronal spectra, the nucleus for each of these elements is probably complex. It is only to the simple nucleus that we need attribute the small size necessary to account for the large mass.

The properties of a terrestrial element connected with its atomic number N can be explained just as in the case of the Rutherford atom, if the resultant positive charge of the complex nucleus amount to Ne . In particular Bohr's theory of the hydrogen spectrum remains unaffected if we attribute a complex character to the nucleus, provided the resultant positive charge of the nucleus be $+e$.

The interesting results obtained by Nicholson in his paper on Electromagnetic Inertia and Atomic Weight* appear to the writer to indicate a diameter for the nucleus of an atom of radium or of thorium considerably greater than that formerly assigned. Thus it is suggested in the paper that the α particles in a thorium atom have a mean distance apart comparable with the radius of an electron, 10^{-13} cm. Now as the atom of thorium must contain the equivalent of about 58 α particles, it would appear that the radius of the complex nucleus of thorium must be considerably greater than 10^{-13} cm.

The view to which we are thus led is that the central portion of an ordinary atom may contain α and β particles, or hydrogen nuclei in orbital motion. This motion would give rise to an external magnetic field. But as the velocities in question must presumably be less than that of light, the radius of the *magnetic core* must be greater than that of the simple nucleus of Rutherford, and is perhaps of the order of 10^{-10} cm.

Magnetism.

The views of magnetism that are widely accepted at the present time are those developed by Langevin and by Weiss. An electron in orbital motion may be regarded as equivalent to an elementary magnet. According to the theory of Weiss there is a certain elementary magnet, the magneton, which is common to the atom of a large number of different substances. It was pointed out in a discussion on this theory at a meeting of the German Naturforscherversammlung in 1911, that there may be a connexion between Planck's "universal constant" h and the magnetic moment of the magneton. Nicholson regards this constant as an angular momentum. McLaren† identifies the natural unit of

* Nicholson, Phys. Soc. Lond. Feb. 26, 1915.

† McLaren, 'Nature,' vol. xcii. p. 165 (1913).

angular momentum with the angular momentum of the magneton. According to Bohr's theory* the angular momentum of a "bound" electron is constant and is $\hbar/2\pi$. Conway†, using a different model, obtains the value \hbar/π . Let us suppose that an electron (charge e , mass m) is moving in a circular orbit (radius a) with angular velocity ω . Then its angular momentum is $ma^2\omega$, and the magnetic moment of the equivalent simple magnet is $\frac{1}{2}ea^2\omega$. Thus the magnetic moment is equal to some constant multiplied by he/m . Taking the angular momentum as $\hbar/2\pi$, we obtain $\frac{\hbar}{4\pi} \frac{e}{m} = 92.7 \times 10^{-22}$ E.M.U. as the value of the magnetic moment. This is *exactly* 5 times the magnetic moment of the magneton of Weiss. This numerical relation was first pointed out by Mr. Chalmers‡ at the discussion on Radiation at the Birmingham meeting of the British Association. The magnetic moment of the magneton is found by dividing the magnetic moment of the atom gram 1123.5 by Avogadro's constant. Weiss used the value of this constant found by Perrin, but if we take the more recent value given by Millikan (60.62×10^{22}) we obtain as the magnetic moment of the magneton 18.54×10^{-22} , which is exactly $1/5$ of the number given above.

These commensurable numbers may be of significance in connexion with the structure of the atom. The magneton may arise as a difference effect. The way in which this may come about may be illustrated by a simple model. Suppose we have a uniform sphere of positive electrification of radius A rotating in the same sense as an electron with angular velocity Ω . Outside this, suppose we have a single ring of mean radius a containing n electrons. The remaining negative electrification required to produce a neutral system may be supposed concentrated at the centre without rotation. Then the magnetic moment of the rotating sphere § may be

* Bohr, Phil. Mag. vol. xxvi. p. 1, p. 476 (1913).

† Conway, Phil. Mag. vol. xxvi. p. 1010 (1913).

‡ See 'Nature,' vol. xcii. pp. 630, 687, 713 (1914). The same relation was noticed independently by Dr. Bohr (Richardson, 'The Electron Theory of Matter,' p. 395).

§ This is a particular case of a more general theorem. Since the magnetic moment arising from a charge e moving in a circular orbit of radius a with angular velocity ω is $\frac{1}{2}ea^2\omega$, the magnetic moment arising from a volume distribution of electricity rotating about an axis is $\frac{1}{2}\Sigma \rho dv r^2 \Omega$, where ρ is the electrical density and dv an element of volume. Assuming ρ constant, the magnetic moment

$$= \frac{1}{2} \rho \Omega \Sigma r^2 dv$$

$$= \frac{1}{2} \rho \Omega V k^2$$

$$= \frac{1}{2} E k^2 \Omega,$$

taken as $\frac{1}{3}EA^2\Omega$, where E is the total positive charge, which we shall assume equal to Ne . We have no direct evidence as to the value of $A^2\Omega$, but if, for convenience, we assume that it has the same value as $a^2\omega$ for an electron in the ring, the magnetic moment of the rotating core becomes $\frac{1}{3}Nea^2\omega$. But a magnetic moment of $\frac{1}{2}ea^2\omega$ is equivalent to 5 magnetons. Consequently the magnetic moment of the core is equivalent to $2N$ magnetons. The resultant magnetic moment for the atomic model would be the difference between the $2N$ magnetons of the core and the $5n$ magnetons of the ring. Thus the magneton may be introduced as a unit for measuring magnetic moments without necessitating the existence of a single magneton as an independent entity.

It is not intended that this model should do more than serve as a crude illustration of the structure of an atom, for there can now be little doubt as to the complex character of the core at least in the case of the heavier elements. In particular a spherical or spheroidal distribution is not an essential feature of the proposed atomic model. It may be that all parts of the core must move in one plane. There are obvious outstanding difficulties such as the way in which the parts of the core hold together so as to form a stable system. Passing over these difficulties, the resultant magnetic moment of the atom with a spherical core would be either the sum or the difference of $2N$ and $5n$ magnetons, according to the relative directions of rotation of the core and the ring.

It would seem that the diamagnetic properties of such an atom would depend mainly on the ring, if a is much larger than A . For the expression for the magnetic susceptibility would consist of a series of terms of which the most important would be $k = -\frac{ne^2a^2}{4m}$.

Pascal* has shown that the molecular susceptibility of a large number of chemical compounds can be calculated by

where V is the total volume, k the radius of gyration for a uniform distribution of mass, and E the total charge of the rotating system.

Thus both for a sphere and for a spheroid rotating about an axis of symmetry, the magnetic moment is $\frac{1}{3}EA^2\Omega$.

We may note here that if the electrical distribution is associated with a proportional distribution of mass, the total mass being \mathcal{M} , the angular momentum is $\mathcal{M}k^2\Omega$. If we assume that this is a multiple of $\hbar/2\pi$, say $\tau\hbar/2\pi$, the magnetic moment may be written $\frac{E}{\mathcal{M}} \times \frac{\tau\hbar}{4\pi}$.

* Pascal, *C. R.* vol. clii. pp. 862-865, 1010-1012 (1911).

adding together the appropriate multiples of the atomic susceptibilities and a constant term depending on the structure of the molecule. Further, he has shown that the elements chlorine, bromine, iodine, and fluorine (and some others) contain a common aliquot part in the specific susceptibility. Certain compounds of the halogens show less susceptibility than would be expected from the additive law. This *diminution* can be expressed in terms of the same aliquot part, whose value is 0.2468×10^{-7} . If we identify this quantity with the effect of a single electron in the ring, we are led to the conclusion that the radius of the ring is about the same for the elements in question, and that its value is of the order of magnitude to be expected.

The difficulties connected with the explanation of paramagnetic properties are, of course, left untouched by these suggestions. No one has as yet explained how the orbits become tilted when under the influence of an external magnetic field. We may note that a similar difficulty is found in connexion with Ritz's theory of the Zeeman effect, which is attributed to a precessional motion of the elementary magnet, no explanation being forthcoming of the way in which the precessional motion is set up.

The Quantum Theory of Spectral Series.

The success of Bohr's theory in explaining the ordinary Balmer's series in the spectrum of hydrogen, and especially in obtaining close agreement between the observed and the calculated values of Rydberg's constant, raises a strong presumption in its favour. The essential feature of the theory is the emission of exactly one quantum of energy as monochromatic radiation in the passage between one steady state of motion and another. This leads directly to an expression for the frequency, ν , as the difference between two "sequences," the form of the expression being

$$\nu = \frac{\nu_0}{D_2^2} - \frac{\nu_0}{D_1^2}.$$

When, however, an attempt is made to apply the theory to the spectral series of elements other than hydrogen, serious difficulties are encountered. These have been discussed by Nicholson* with special reference to the spectra of helium and of lithium. In the first place, it is necessary to suppose that every electron concerned in the emission of radiation emits one quantum, instead of supposing that one quantum

* Phil. Mag. vol. xxvii. pp. 541-564, vol. xxviii. pp. 10-103 (1914).

only is emitted in passing from one state to another. This is required both for ordinary spectra and for X-ray spectra. In the second place, it appears necessary to assume that there is no force between bound electrons, so that any one of these electrons is independent of the others. This supposition may be related to Sir J. J. Thomson's conception of tubes of force. A bound electron may have the tube (or tubes) of force originating from it attached to the nucleus, and if all the electrons in question are connected to the nucleus in this way, they cannot exert force on one another.

Perhaps it may be necessary to suppose that a bound electron has both the ends of the double tube of force belonging to it attached to a definite part of the core in such a way that the attraction on the electron is proportional to e^2 instead of to $(Ne)^2$.

A further difficulty in applying the theory of Bohr to actual series lies in the fact that the denominator of a sequence contains terms which are not simple integers. Thus in Rydberg's formula we have $m + \mu$ where m is an integer, μ a fraction, in the formula of Moggendorf and Hicks we have $m + \mu + \alpha/m$, in the formula of Ritz $m + \mu + \beta/m^2$. Nicholson * has shown that the theory in its original form is insufficient to account for such additional terms when electrostatic forces only are considered. The development which I have given †, supposing the electron to be under the action of magnetic forces, yields a formula containing a term of the form B/m^2 , where B is proportional to the magnetic moment of the core, but does not account for the fractional part μ . In attempting to apply this formula to actual elements, it is found that in general the value of β obtained by Ritz is much too large to be due to a small number of magnetons. Further, in the case of hydrogen, if we suppose the fractional part due to a term of the form B/m^2 , it is necessary to assume different values for B in the two sequences, implying the existence of two types of state in the core. This suggested that the core itself might be intimately concerned in the emission of radiation, and that the term in μ , and perhaps also terms such as α/m and β/m^2 , might depend upon the angular momentum of the core.

This line of thought, associating the constants in the formula with the core of the atom, may be supported by

* *Loc. cit.*

† *Phil. Mag.* vol. xxix. pp. 40-49, 140-143 (1915).

several recorded results. According to Hicks * both μ and α depend on the atomic weight or atomic volume of the element, α/μ being a pure number and equal to 0.21520. Birge † points out that the coefficients in the formula of Ritz increase with increasing atomic weight, being proportional to the atomic volume in the case of sodium, potassium, rubidium, and caesium.

Several investigators have drawn attention to relations between frequencies and atomic weights, Ramage and Marshall Watts in particular having obtained relationships involving the square of the atomic weight. This of course implies that the constants in the spectral formulæ depend upon the atomic weight of the element in question.

Hicks finds that the change necessary in the value of μ to account for the observed differences in the frequencies of doublets and triplets can be expressed in terms of a quantity which he calls the 'oun' depending on the square of the atomic weight.

Further arguments may be drawn from the "combination principle of Ritz." The formula of Ritz may be written

$$n = A - \frac{N}{[m + \mu + \beta(A - n)]^2},$$

which is usually abbreviated as

$$n = A - (m, \mu, \beta).$$

The values of μ and of β differ in different "sequences," and Ritz shows that frequencies corresponding to definite lines can be obtained by taking the difference between various sequences.

In the case of a principal sequence μ may have two values μ_1 and μ_2 , the corresponding values of β being β_1 and β_2 . Ritz proves that other lines may be obtained by taking $(m, \mu_1 - \mu_2, \beta_1 - \beta_2)$ as a sequence. In the case of the triplets of the alkaline earths, differences such as $\beta_1 - \beta_2$ for the principal series are the same as the corresponding differences calculated from the diffuse series, so that evidence of a new combination exists here.

According to the simple form of the theory put forward in my former paper, β is proportional to the magnetic moment of the core. From this point of view, it is not difficult to understand how we can get combinations such as $\beta_1 - \beta_2$, regarding the core as composed of positively and negatively electrified particles in orbital motion.

* Hicks, Phil. Trans. vol. ccx. p. 85 (1910); vol. ccxii. p. 33 (1912); vol. ccxiii. p. 323 (1913).

† Birge, Astrophys. Journ. vol. xxxii. p. 112 (1910).

But the significant point is that accompanying $\beta_1 - \beta_2$, we have $\mu_1 - \mu_2$, suggesting that the quantity μ also depends on the revolution of parts of the core in such a way that the effects can be combined by simple addition or subtraction.

For this to be the case, μ would have to be proportional to the first power of the angular velocity, *i.e.* to the angular momentum or to the magnetic moment of the part of the core with which it is associated. Thus it should be possible to express μ in terms of the magnetic moment, and it might be possible to obtain some relation between μ and β .

Rydberg has suggested that the correct expression for the frequency of a line in a spectral series is some function of $\tau + \mu$, where τ is an integer and μ is fractional. This view has received strong support from Thiele, who maintained that the wave-length was some function of $(\tau + \mu)^2$, where τ could take all integral values, both positive and negative. Nicholson's recent critical investigation of the spectrum of helium shows conclusively that in this case the frequency is a function of $\tau + \mu$.

In Bohr's theory of the hydrogen spectrum, the angular momentum of a bound electron is assumed to be constant and equal to $\tau h/2\pi$. In order to obtain a theory applicable to the spectra of other elements, it appears necessary to assume that the angular momentum of the electron is $(\tau + \mu)h/2\pi$. In order to account for the presence of μ in this expression, we assume that we must include with the angular momentum of the electron that of the core, or more probably that of the part of the core which is specially related to the electron. Thus we make the *total* angular momentum of the electron and the part of the core equal to $\tau h/2\pi$.

$$\text{Then} \quad mr^2\omega \mp I\Omega = \tau h/2\pi.$$

$$\text{So} \quad mr^2\omega = \tau h/2\pi \pm I\Omega \\ = (\tau \pm \mu)h/2\pi,$$

$$\text{where} \quad \mu = 2\pi I\Omega/h.$$

Proceeding on the lines of Bohr's theory we can then obtain Rydberg's equation.

The extension of the principle of the constancy of angular momentum from the electron to the core, receives a measure of support from the work of Bjerrum and others. Bjerrum assumed that the energy or the momentum of a rotating molecule could be expressed in terms of h . The experimental results obtained from the absorption of infra-red radiation by gases are in agreement with the results of his theory.

The supposition that μ corresponds to the angular momentum of only a part of the core was suggested by the numerical values found in spectral series. It is intelligible

from the point of view of tubes of force, for we may suppose that a tube of force with one end on the electron has the other end attached to a certain part of the core which carries an equal charge of opposite sign. The suggested arrangement appears to be in partial agreement with the views of Stark with regard to the structure of the atom.

In order to secure agreement with known facts as to spectral series it is necessary to regard μ as constant for one type of state of motion, but as possessing different values corresponding to the different types of state.

It cannot, of course, be claimed that these suggestions constitute a theory of spectral series, but an attempt has been made to see what modifications may be required in the original assumptions of Bohr in order to obtain a formula such as that of Rydberg for elements other than hydrogen. The introduction of the coefficient μ renders the structure of the atom somewhat indefinite, for μ depends on (at least two) factors both at present unknown. It may, however, be possible from a study of the numerical values of this quantity in the case of particular elements, or elements belonging to the same chemical group, to throw further light on the character of these factors.

Conclusion.

The atomic model which is suggested in the foregoing pages consists of a ring or rings of electrons surrounding a central core, having a radius considerably greater than the nucleus of the Rutherford atom and in consequence capable of producing appreciable magnetic forces in its vicinity. The total charge of the core must be equal to Ne , where N is the atomic number. The magnetic moment of the core arises from the orbital motion of the discrete electrified particles (α particles, β particles, hydrogen nuclei or positive electrons) of which it is composed. The diamagnetic properties of the atom arise mainly from the external electrons revolving in orbits whose radius is of the order 10^{-8} cm. The magneton is regarded not as an independent entity, but as a unit convenient for measuring magnetic moments introduced in consequence of the principle of the constancy of angular momentum.

A consideration of the laws of spectral series suggests that the quantity μ , the 'phase' of the series, is connected with the angular momentum of the particular part of the core specially associated with the external electron concerned in radiation. A further study of the values of this quantity may lead to a more complete knowledge of the structure of the core.