SCIENCE

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THE MAGNETIC FIELD OF AN ATOM[1]

THE substance and structure of the atom, the movements of its parts, and its properties, are, perhaps, the most fundamental subjects of modern physical investigation. And although the structure and even the substance of the atom can as yet only be inferred, nevertheless its numerous and varied phenomena not only challenge the theorist, but also, through their manifold checks, afford him at every turn the very best guidance to an approximately correct inference. Among the more important of these phenomena are the actions of atoms in respect to absorption and emission of radiation under various conditions of temperature, pressure, magnetic and electric fields. Crystal forms, chemical reactions and magnetic properties offer additional suggestions and valuable tests.

One of the most interesting inferences concerning the atom is this: that it has a very powerful magnetic field. This inference is supported by a number of investigations of entirely different character which it is proposed in what follows to outline briefly and in approximately their chronological order.

1. The electromagnetic theory of ether vibrations so satisfactorily accounted for many known phenomena and so successfully predicted others, including wireless telegraphy, that it was long ago generally believed that all radiation, including light,

[1] Presented at the symposium on "The Structure of Matter" at a joint meeting of the Sections of Physics and Chemistry of the American Association for the Advancement of Science, The American Physical Society and the American Chemical Society, New York, December 27, 1916.

must have its origin in rapidly oscillating or orbitally moving electric charges whose periods are the same as the periods of the emitted radiation. Further, since spectral lines, except those belonging to bands, were found always to be characteristic of the elements and never of their compounds, it soon became evident that the corresponding radiations are of atomic and not molecular origin. Hence the natural conclusion that the atoms of all elements, for all give line spectra, are either associated with or consist, in part at least, of electric charges undergoing complete periodic changes of distribution or position at the rate obviously found by dividing the velocity of any given radiation by the corresponding wave-length, changes, therefore, in the case of green light, at the rate of some six thousand million million per second. Such numbers, of course, are appalling, but the logic is inexorable.

2. In 1885 Balmer[1] announced his remarkable though empirical series formula as applied to the visible hydrogen lines H_α H_β, H_γ and H_δ; that is

$$\frac{1}{\lambda} = N\left(\frac{1}{2^2} - \frac{1}{n^2}\right), \quad n = 3, 4, 5, \text{etc.},$$

a formula that has since been found to give with great accuracy the wave frequencies of the whole hydrogen series of at least 35 lines. The same general formula, or some modification of it, such as Rydberg's,

$$\frac{1}{\lambda} = N\left(\frac{1}{a^2} - \frac{1}{(n+c)^2}\right),$$

gives with equal accuracy the wave frequencies of the lines of many other series of various elements.

Here, then, was a further important hint in regard to the structure of the atom, but for a long while no one interpreted what it meant.

[1] *Ann. der Phys.*, 25, 80, 1885.

3. In 1897 Lord Rayleigh[2] emphasized the fact that the vibrations producing spectral series hardly could result from ordinary elastic or electric forces of restitution since each of these gives equations involving squares of the frequencies—the displacement being expressed in terms of $\sin t/\lambda$ its acceleration involves the factor $1/\lambda^2$—while the Balmer and similar formulæ that so closely follow the lines as they actually occur contain only first powers of this term.

Although Lord Rayleigh's paper was essentially negative in respect to atomic structure, it nevertheless was an important contribution to this difficult subject in that it rendered well nigh untenable certain theories that appeared then to be more or less generally held, namely, all that compared the atom to an elastic sphere, parallelopiped, or other solid, and those alike that assumed it to be some unknown type of Hertzian oscillator.

4. In the meantime two other important spectroscopic phenomena were announced that at first seemed to render far more difficult any satisfactory interpretation of the atom and its structure. These were, *a*, the pressure displacement of spectrum lines, discovered by Mohler and the author[3] in 1895, and, *b*, the magnetic resolution and dispersion of such lines, discovered by Zeeman[4] in 1896.

5. About this same time investigations on electric discharges through gases, and analogous phenomena, became world wide, initiated mainly by the wonders of the X-rays and largely sustained by the frequent stimuli of new discoveries by Thomson, Rutherford, Madame Curie, and their brilliant associates.

Among the many important results of

[2] *Phil. Mag.*, 44, 356, 1897.

[3] *Astrophys. Jr.*, 3, 114, 1896.

[4] *Phil. Mag.*, 43, 226, 1897.

these numerous investigations are the discoveries that negative electricity occurs in multiples of a perfectly definite and accurately measurable unit; that this unit, the negative electron, perhaps in large numbers, is at least an integral part of all atoms; that electrons often are ejected from an atom; that when ejected they leave with enormous velocities; that when in motion they possess inertia; and that this inertia increases with the velocity.

Naturally such discoveries suggested the Saturnian and other similar atomic models, several of which have been elaborately discussed.

6. In 1906 the author[5] computed the possible magnetic field of a Saturnian atom and found in this field a vera causa, perhaps an adequate cause, of the hitherto unexplained pressure shift of spectral lines. A simple presentation of the argument is as follows:

Assuming Thomson's Saturnian atom of revolving rings of electrons, it seems probable that the wave frequency of the radiation emitted by any one of the rings of a given atom may be a simple multiple of its orbital frequency. Any bunching, for instance, of the electrons, however temporary, would produce radiation whose frequency was the same as that of the complete orbital revolutions. But this revolution of rings of electrons, presumably around a common axis, constitutes so many circular electric currents which obviously produce solenoidal magnetic fields, and themselves are subject to inductive effects.

Now it has been shown by Langevin[6] that in the case of a ring of electrons any forced change in the magnetic flux merely alters the orbital speed without changing the radius. Hence the self induction remains constant and if E be the induced electromotive force, then

$$E = L\frac{di}{dt} + Ri,$$

in which L is the self-induction, R the ohmic resistance and i the strength of the current. But in the case of an atomic ring of electrons $E = dN/dt =$ rate of change of magnetic flux through the ring, and $R = O$, presumably.

Hence

$$\frac{dN}{dt} = L\frac{di}{dt},$$

and

$$di = \frac{dN}{L}.$$

That is, the induced current in the ring is directly proportional to the change in the magnetic flux through it. Furthermore, the induced current is permanent instead of momentary as in ordinary circuits, so long as the change in N is permanent.

In this connection it is interesting to note that Kamerlingh Onnes[7] has recently shown by a series of brilliant experiments that an induced current may last for hours with but little reduction (less than 1 per cent. per hour) in a lead wire solenoid at very low temperatures.

Now, from the Zeeman effect it is obvious that radiating atoms are acted upon by an external magnetic field, and, therefore the inference is immediate that these atoms themselves possess magnetic fields of their own—*they could not otherwise be acted upon by a magnetic force.* Also, since the the kind and magnitude of the Zeeman effect is independent of temperature, as shown by both radiation and absorption, it follows that the atomic field must also be independent of temperature.

Further, as magnetic fields are known always to exist in connection with electric currents, and not certainly known ever to be due to any other cause, and as moving electrons constitute the only known electric

[5] *Astrophys. Jr.*, 23, 233, 1906.

[6] *Journal de Physique*, 4, 678, 1905.

[7] *Nature*, 93, 481, 1914.

current, it therefore will be assumed that the atom's magnetic field is due to orbitally revolving rings of electrons, subject to temporary bunchings or other disturbances, possibly the shift of an electron from one ring to another, that render the ring so disturbed, or the shifting electron, radiative during the brief interval in which equilibrium is being regained.

Let v be the velocity of light, λ the wavelength of the emitted radiation, ω the angular velocity of the electrons as seen from the center of the orbit, S the average strength of the enclosed magnetic field, K a constant and n a whole number, perhaps unity. Then

$$\frac{v}{\lambda} = \frac{n\omega}{2\pi} = KS. \qquad (1)$$

Hence

$$\mp \frac{vd\lambda}{\lambda^2} = \pm KdS. \qquad (2)$$

From (1) and (2)

$$\mp \frac{d\lambda}{\lambda} = \pm \frac{dS}{S}.$$

But dS is added to the fields of some atoms and subtracted from the fields of others by the application of an external magnetic field of strength H to any mass of gas. Hence

$$\mp \frac{d\lambda}{\lambda} = \frac{H}{S}.$$

By substituting H for dS in (2) we get

$$\frac{d\lambda}{H\lambda^2} = \frac{K}{v}, \text{ a constant.}$$

But this is the well-known Zeeman law, and therefore it appears that the assumed simple structure of the atom must at least crudely resemble its actual structure.

From the known values of H, λ and $d\lambda$ the computed value of S, the average strength of the atomic magnetic field, is of the order of 10^8 gauss.

Similarly from the probable size of the atom, radius $= 10^{-8}$ cm., and the charge of the electron it is easy to calculate the magnetic field at the center of the ring system on any definite assumption of the speed of rotation and number of electrons.

If it is assumed that the period of rotation is the same as that of the emitted radiation, and that N, the number of electrons in the atom, is of the order

$$N = A\ 10^8$$

in which A is the atomic weight, a number many investigators regard as probable, then the computed intensity of the magnetic field at the center of an iron, titanium, or other such atom is of the order of 10^8, roughly 2,000 times the most intense field yet produced between the poles of electromagnets.

Whatever the strengths of these fields, each atom must act inductively on all its neighbors and in turn be acted upon by them, to an extent that for each couple varies approximately as the cube of the distance between their centers. If two atoms in the turmoil of the electric arc, for instance, chance closely to approach with similar poles facing each other their mutual induction will be such as to increase the speed of their electrons, and thus for the instant slightly to shift their spectrum lines to the violet. If, however, they approach with opposite poles facing each other the shift will be to the red. But in the second case the atoms clearly will come closer together, thus producing stronger inductions and greater shifts, than in the first. Hence the net result is a displacement of the maximum intensity of the line to the red.

When the gas pressure about the light source, an electric arc, suppose, is low the distance between neighboring atoms is relatively large and therefore during only a correspondingly small fraction of the time is any given atom under the strong inductive influence of others. During the rest of the time the frequency of its vibration is undisturbed. Hence the spectrum lines given out by rarefied gases, in which an atom is only " occasionally " close to another, are comparatively clean and sharp. With increase of pressure the free path is decreased and the total interval of disturbance lengthened to practically the same fractional extent. If, for instance, the pressure is doubled, temperature remaining constant, the free path is halved, atomic "collisions," total duration of an atom's close proximity to others, and, therefore, quantity of shifted light all are at least doubled. Hence with increase of pressure a spectral line must spread (independent of the Doppler effect) and its maximum intensity shift to the red.

Under very heavy pressures the atoms are always within mutually disturbing distances, and therefore under such conditions their lines gradually merge into a continuous spectrum.

It might seem that atoms with such strong magnetic fields necessarily would cluster into rods and rings, like iron filings in a magnetic field. In short, that at any attainable temperature, a gas consisting of such atoms would collapse into—who knows what?

To test this point consider an extreme case. Let two atoms, each consisting of a single circular ring of 5×10^4 electrons and an equivalent positive nucleus at its center, face each other on a common axis, and let the orbital revolution of their rings have the frequency of yellow light of wavelength $.6\mu$: Find the electric and magnetic forces between them.

The magnetic flux through either ring due to the presence of the other is given by the expression

$$N = \frac{2\pi^2 i r^4}{(r^2 + x^2)^{3/2}},$$

in which i is the strength of the current, r the radius of the ring, and x the distance between the centers. Hence the magnetic force between the rings is found by the equation

$$F_{\text{magnetic}} = 2\pi^2 i^2 r^4 \frac{d}{dx} \frac{1}{(r^2 + x^2)^{3/2}} = \frac{6\pi^2 i^2 r^4 x}{(r^2 + x^2)^{5/2}}.$$

Assume the electronic charge to be 4.774×10^{-10}, Millikan's value, and let $r = 10^{-8}$ cm. Then when

$$x = r,$$
$$F_{\text{magnetic}} = 1.6561 \text{ dynes},$$

$$\begin{array}{cc} 10r & 100r \\ 91.39 \times 10^{-5} \text{ dyne}, & 9.37 \times 10^{-8} \text{ dyne}. \end{array}$$

The electric force between the two atom models consists of four parts; namely, attraction between each nucleus and its neighbor's ring, repulsion between the nuclei and repulsion beween the rings. The problem of computing this force is not so simple as, at first sight, it is likely to appear. However, a general solution of the problem of the rings (rings of different radii and linear densities) in the form of a converging series has been kindly furnished by Professor R. S. Woodward. A similar solution of the somewhat simpler problem presented by duplicate atom models gives the following total electric forces (repulsions) between them:

$$x = r,$$
$$F_{\text{electric}} = 3578 \times 10^3 \text{ dynes},$$

$$\begin{array}{cc} 10r & 100r \\ 34.186 \text{ dynes}, & 6.45 \times 10^{-8} \text{ dyne}. \end{array}$$

Of course it is not assumed that any such force as that computed for $x = r$, about 3.65 kilograms, actually exists between any two atoms. Neither does it seem probable that atoms can get so close that their centers are separated by only a single atomic radius. However, the calculations appear to prove that the electric forces between any atomic models of the kind here assumed would be more than sufficient to prevent collapse through the interaction of their powerful magnetic fields.

7. In 1907 and again in 1908 Weiss[8] reached the conclusion, through a series of magnetic determinations at various temperatures, that the atomic magnetic field of ferro-magnetic substances is of the order 10^7 gauss.

8. At about the same time, that is, in 1908, Ritz[9] gave an elaborate discussion of a molecular model designed to account for the occurrence of series among spectral lines. He recognized the force of Lord Rayleigh's objection to the assumption of a model in which the electrons vibrated under either mechanical (elastic) or electrical forces, since such forces give equations involving squares of the frequencies. He therefore assumed the electrons to vibrate or describe orbits in planes at right angles to the lines of magnetic fields, under which conditions the reciprocal of the wave-length, $1/\lambda$, is given by the equation

$$\frac{1}{\lambda} = \frac{eH}{mv}$$

in which e is the electronic charge, m the electronic mass, H the magnetic field, and v the velocity of light. Hence for this equation to apply to the spectral region of the average Balmer series H must be of the order of 10^8 gauss.

At the distance r from the adjacent pole of a magnet whose pole strength is μ, and length l,

$$H = \mu \left\{ \frac{1}{r^2} - \frac{1}{(r+l)^2} \right\}$$

and

$$\frac{1}{\lambda} = \frac{\mu e}{mv} \left\{ \frac{1}{r^2} - \frac{1}{(r+l)^2} \right\}.$$

If $l = ns$ and $r = as$

$$\frac{1}{\lambda} = \frac{\mu e}{s^2 mv} \left\{ \frac{1}{a^2} - \frac{1}{(a+n)^2} \right\}, \quad n = 1, 2, 3.$$

If $a = 2$

$$\frac{1}{\lambda} = N \left\{ \frac{1}{2^2} - \frac{1}{(2+n)^2} \right\}$$

which is identical with Balmer's equation for the hydrogen series.

Hence an electron vibrating at the distance $2s$ from such an elementary magnet of length s and proper strength will give the spectrum line H_α. If 2, 3, etc., of these elementary magnets should be placed end on, the electron would emit H , H_γ, etc., respectively.

Ritz does not state what he considers the probable origin of the elementary magnetic field. As above explained, however, it conceivably may be due to the orbital revolution of the electrons themselves. Further, the different magnetic fields demanded by a Balmer series may, perhaps, be provided by a number of concentric rings of electrons, the field abruptly changing on crossing each ring from one to another interspace. This conception obviates the necessity of assuming the magnets to be placed end on, an arrangement that is impossible if the magnetic fields are of electric origin.

In speaking of Ritz's theory, Zeeman[10] says: "Though there is something artificial about this explanation, it is the best we have at the present moment."

9. Within the past year or two Oxley[11] has shown that the change of magnetic susceptibility on crystallization of some 40 diamagnetic substances examined can be satisfactorily explained on the assumption of molecular magnetic fields of the order of 10^7 gauss. He says in part:

> 1. The change of susceptibility observed on crystallization demands a local molecular field of this order of intensity [10^7 gauss].
>
> 2. The natural double refraction of a crystalline substance as compared with the artificial double refraction which can be induced in a liquid by the strongest magnetic field at our disposal is consistent with the value of the local molecular field implied by (1) for diamagnetic crystalline media.

[8] *Jour. de Phys.*, 6, p. 661, 1907; 7, p. 249, 1908.
[9] *Ann. der Phys.*, 25, 660, 1908.
[10] "Magneto-optics," p. 182, 1913.
[11] *Phil. Trans. Roy. Soc.*, 215, p. 95, 1915.

3. (1) and (2) together imply that the aggregate of the local intensity of magnetization per unit volume of a diamagnetic substance is comparable with the saturation intensity of magnetization of a ferro-magnetic substance.

4. The above results lead to a correct estimate of the energy (potential) associated with the crystalline structure, in virtue of the molecular grouping, as tested by the magnitude of the latent heat.

5. Lastly, unless the forces binding the diamagnetic molecules together were of the order of magnitude stated, we should not be able to detect a departure of the experimental value of the specific heat near the fusion point from the value calculated on Debye's[12] theory [of specific heat]. Every substance investigated by Nernst and Lindemann discloses such a departure.

The above evidence is sufficient to establish the existence of an intense local molecular field of the order 10^7 gauss, if interpreted magnetically, in those diamagnetic crystalline substances (about 40 of which have been investigated) which show a measurable change of χ [specific magnetic susceptibility] on crystallization.

10. Finally, Professor Ernest Merritt, in an address to the American Physical Society in 1915, showed, through the fluorescence bands of uranium salts, interesting evidence of the existence of atomic magnetic fields of the order 10^8 gauss.

Hence, from all the foregoing, which could be greatly elaborated, it seems that there is much and varied evidence in favor of the assumption that atoms have very powerful magnetic fields, due, presumably, to orbital revolutions of electrons.

Of course no one claims that more than a mere beginning has been made in the solution of the problem of the atom, but there is abundant evidence from many sources that this beginning is real.

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KENTUCKY AS AN OIL STATE

AT the present writing (June, 1917) Kentucky stands in the limelight as a prospective oil state. Due to the fact that the Irvine District of Estill County has been extended over a large area together with the greatly renewed activity in the older Kentucky fields, operators are now turning their attention to the state as a whole. This is particularly true of oil men from the Mid-continent Field. So it appears that the latter part of this year and the early months of 1918 will forever settle the question as to the state's potential rank in the production of petroleum and natural gas. Test wells are to be drilled in nearly every county in the state and the most modern applications of petroleum geology are being freely used. Up to the present time most of the "wild cat" work has progressed only to the mapping or leasing state, but the high standing of the companies interested is a good indicator of the developments that undoubtedly will follow.

There are four important geological factors that are always met in the search for new oil fields. When all of them are found to work in harmony great fields, like those of Oklahoma, Kansas and Texas or those of Pennsylvania, Ohio and West Virginia, are the result. Geological "structure," such as anticlines, domes, etc., constitute only one of these factors. A large number of structures do not produce oil or gas. They may or may not produce salt water. Furthermore, they may lie in what would be considered favorable regions. In such cases the detail which may have been expended in mapping them is of no avail. Such conditions result from failure of one or more of the three other factors, namely either (1) there is no open "sand" or other porous medium under the structure to serve as a retainer for oil and gas; or (2) there has never been present any salt water or other water in the sand to serve as a concentrating factor; that is, no gathering of oil and gas from a disseminated state to a commercial body; or (3) there is an absence of petroliferous shale or other fossil-bearing rocks that produce oil in a disseminated form.

Now the future of Kentucky as an oil state depends on the four factors above mentioned: (1) structure, (2) sand, (3) water, (4) original oil. There can be no question about the state

[12] *Ann. der Phys.*, 39, 789, 1912.