Faraday and the Quantum.

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IN the third volume of his "Experimental Researches in Electricity" Faraday returns again and yet again to the discussion of lines of magnetic force and of their physical existence. The first paper in the volume bears the suggestive title, "On the Magnetisation of Light and the Illumination of Magnetic Lines of Force." He defines the latter by saying: "By *line of magnetic force*, or *magnetic line of force*, or *magnetic curve*, I mean that exercise of magnetic force which is exerted in the lines usually called magnetic curves, and which equally exist as passing from or to magnetic poles, or forming concentric circles round an electric current." He then goes on to describe his discovery of the magnetic rotation of the plane of polarisation, a phenomenon which Lord Kelvin regarded as a demonstration of the reality of Ampère's explanation of the ultimate nature of magnetism. In the celebrated letter to Richard Phillips, published in the *Philosophical Magazine* for May, 1846, under the title, "Thoughts on Ray-vibrations," Faraday writes:—

The view which I am so bold as to put forward considers, therefore, radiation as a high species of vibration in the lines of force which are known to connect particles, and also masses, of matter together. It endeavours to dismiss the æther, but not the vibration.

Again in 1852 he says:—

Having applied the term *line of magnetic force* to an abstract idea, which I believe represents accurately the nature, condition, direction, and comparative amount of the magnetic forces, without reference to any physical condition of the force, I have now applied the term *physical line of force* to include the further idea of their physical nature. The first set of lines I affirm upon the evidence of strict experiment. The second set of lines I advocate, chiefly with a view of stating the question of their existence.

This question he regards as "both important and likely to be answered ultimately in the affirmative."

The quantum theory seems to supply the affirmative answer anticipated by Faraday. It has long been recognised that this theory requires a certain atomicity in nature which may be represented either by Planck's constant h , or by some combination of h with other fundamental constants. Planck's constant, which has the value 6.558×10^{-27} erg sec., may be looked upon as a quantum of action, but it is perhaps simpler to regard it, in accordance with the suggestion of J. W. Nicholson, as an angular momentum. The first indication that the quantum may be essentially magnetic appears in the work of S. B. McLaren, who, in a letter to NATURE (vol. 92, p. 165, 1913), identified the natural unit of angular momentum, $h/2\pi$, used by Bohr, with the angular

momentum of the magneton. "Rejecting entirely the idea of magnetic or electric substance, the magneton may be regarded as an inner limiting surface of the æther, formed like an anchor-ring. The tubes of electric induction which terminate on its surface give it an electric charge; the magnetic tubes linked through its aperture make it a permanent magnet." It may be shown from ordinary electrodynamic considerations that the angular momentum of such a system is equal to $Ne/2\pi$, where N is the number of magnetic tubes threading the magneton, and e is the electrostatic charge. According to the quantum theory, the angular momentum must be $nh/2\pi$, where n is an integer, and we may have a one-quantum magneton, a two-quantum magneton, and so on. Identifying these two expressions for the angular momentum, we find

$$Ne = nh,$$

or

$$N = n(h/e).$$

Thus it is seen that the number of tubes of magnetic induction passing through the aperture of the magneton is equal to an integer, n , multiplied by the constant factor h/e . If we suppose that the charge of the magneton is equal to the electron charge 4.774×10^{-10} E.S.U., we find for h/e , which defines what must be the *fundamental* unit magnetic tube, the value 1.374×10^{-17} E.S.U. or 4.120×10^{-7} E.M.U. Consequently one C.G.S. magnetic tube contains nearly two and a half million (2.43×10^6) *quantum tubes*. The electrokinetic energy of the unit tube is $\frac{1}{2}h\nu$, where ν is the frequency of revolution.

A magneton theory of the structure of the atom has been developed with great ingenuity by A. L. Parson, but his theory has not met with acceptance, partly because it employs the notion of a sphere of positive electricity in place of a positive nucleus, but mainly because it is not based on the atomic numbers of Moseley which are now generally accepted as representing accurately the number of electrons in the neutral atom outside the nucleus. Ultimately it may prove necessary to adopt some form of the magneton hypothesis, which seems well adapted to explain magnetic properties, and, by admitting the possibility of stationary electrons, as in the Lewis-Langmuir theory, chemical properties also. But at the present time the results obtained from the Bohr-Sommerfeld theory of spectral frequencies seem to demand electrons which are moving in certain orbits. As pointed out in these columns by Dr. Norman Campbell (NATURE, vol. 106, p. 408, 1920), the difference between the two views may be purely formal.

It is, however, desirable to consider whether

the theory of Bohr, like the magneton theory points to the existence of discrete magnetic tubes. In 1916 A. L. Bernoulli came to the conclusion that when an electron is in movement in a uniform molecular magnetic field the number of lines of force cut by the radius vector at each revolution is one and the same universal constant. In a paper read before the Royal Society of Edinburgh in November, 1920, the present writer attempted to show that, without any restriction as to the uniformity of the magnetic field, when any number of point charges are revolving round an axis with a common angular velocity, the number of magnetic tubes passing through the stationary circular orbits is equal to an integral number of times the constant h/e . Recently an attempt has been made to extend the result to the more general case of an electron revolving round the positive nucleus in an elliptic orbit. It has been shown independently by Sommerfeld and by W. Wilson that the size and shape of the ellipse depend upon two integers n and n' , the first introduced by the application of the quantum theory to the angular motion, the second by the application of the theory to the radial motion. The sum of these two integers determines the value of Bohr's W , the total energy of the system with the negative sign prefixed. Making certain plausible assumptions, it appears that the total number of quantum magnetic tubes passing through the elliptic orbit is simply this sum, $n+n'$. This result is obtained by employing the generalised form of the quantum theory first put forward by W. Wilson and used with such success by Sommerfeld and others.

On this theory the mean value of the kinetic energy corresponding to a particular degree of freedom is equal to $\frac{1}{2}nh\nu$, where the mean value is taken over the period, $1/\nu$, corresponding to the co-ordinate under consideration. It is now assumed that this mean energy may be identified with electrokinetic energy. The periodic motion of an electric charge e in an orbit with high frequency ν is regarded as equivalent to a current $e\nu$, and the electrokinetic energy may then be written $\frac{1}{2}Nev$, where N is the number of magnetic tubes passing through the actual orbit, but corresponding to the particular co-ordinate in question. Equating the two expressions for the energy, we find at once

$$N = n(h/e).$$

It must, of course, be admitted that we do not get out of the equations more than we put into them, so that the assumptions made above virtually imply the existence of discrete tubes of magnetic induction. It is to be noted that we are concerned twice over with the process of taking a time average of a certain quantity, first in evaluating the mean kinetic energy, and secondly in evaluating the electrokinetic energy and assuming the moving charge as equivalent to a current $e\nu$. In the words of Dr. Norman Campbell,

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"Classical dynamics, it is clear, is only 'statistical'; what are the principles of the elements of the statistical group is the main problem of the physics of the future." The suggestion now made is that the quantum tube is the element referred to.

The physical existence of Faraday's magnetic tubes conforms in many respects to the mode of representation suggested by Sir Joseph Larmor: "One or more electrons constrained to move round a channel would be like an amperian current. It is not unlikely that constraint of this kind will have to be introduced into molecular models to give an account of paramagnetism and ferromagnetism—namely, structure in space or atom involving channels more or less definite for the electrons to circulate in." On the present view such channels or partitions would be provided in consequence of the discrete nature of the tubes of magnetic induction, which would determine the radius of the permissible orbit which an electron describes about the nucleus and account for the property of rigidity.

Sir Oliver Lodge, in a recent paper (*Phil. Mag.*, vol. 41, p. 942, 1921), writes as follows:—"Magnetic lines are always closed curves; there is no known way of generating them; they always pre-exist, though they may be of atomic or molecular magnitude, and in a magnetic field are opened out so as to enclose a perceptible area. This is generally admitted to be the process of magnetisation, and when the magnetism ceases the lines shrink up into infinitesimal, or practically infinitesimal, orbits again. That the quantum is associated with these ultimate magnetic units is exceedingly likely."

If we accept the existence of quantum magnetic tubes, many questions of great interest suggest themselves. What happens in the emission or absorption of radiation? Does radiation imply the separation or ejection of a quantum tube from an atomic system, and absorption the incorporation of an external tube? Then, again, how are electrostatic forces to be regarded? Sir Joseph Thomson has pictured a magnetic field as due to the motion of electrostatic tubes. It would, of course, be possible to reverse the process and regard an electrostatic field as set up by moving magnetic tubes. In a suggestive communication to the British Association at Edinburgh Prof. Whittaker discussed the properties of tubes of force in four dimensions, and pointed out that such a tube, which would satisfy all the requirements of the relativity theory, would involve *both* the electric and the magnetic vector. Further, in the four-dimensional world it is action, not energy, which is conserved, so that the field appears open for a direct application of the quantum principle. The experimental physicist may feel somewhat appalled at the prospect of such a solution of his difficulties, but it may yet be necessary to invoke a four-dimensional tube of force as the unit brick from which a universe may be constructed.