

LXV. *On Atoms of Action, Electricity, and Light.*
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THE number of optical phenomena which seem to demand some form of corpuscular or photon theory of light are small compared with the number of those which are well explicable in terms of the classical uniform wave theory of light.

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When we recall to mind the very complicated and beautiful effects due to the passage of polarized light through crystals, some of which, such as conical refraction, were predicted in advance, and notice that all of these have been explained in terms of the normal wave theory as well as those of diffraction and interference generally, we see that this theory is not lightly to be discarded.

On the other hand, the phenomena which seem to require the photon or corpuscular theory are, first, the photoelectric effects, second, the ionization of gases, third, the distribution of energy in the black body spectrum, and, lastly, probably such effects as the Compton.

All the theories of light which assume propagation of vibrations along lines of force as discrete entities in various forms labour under the same difficulty as a corpuscular or photon theory, in that they can give no satisfactory explanation of the fundamental fact of interference presented at every step in optical phenomena.

On the other hand, it seems clear that some kind of atomicity is associated with radiation. In all parts of nature we see this atomicity evident, by which we mean that the entities considered are not indefinitely divisible in quantity, but that there is an ultimate minimum amount which loses its identity when divided beyond a certain point. We have that atomicity in matter complex and simple; also in electricity, with its ultimate atoms, protons, and electrons.

Again, the success of Planck's formula for the energy density of black body radiation at various frequencies shows that the dynamical quantity called Action, or the time-integral of energy, has a curious atomic structure, and that the atom of Action is Planck's constant denoted by h . With great diffidence I suggest, then, that this h should be called 1 Planck, just as the unit of electric quantity is called 1 electron.

The peculiarity of both these quantities, action and electric charge, is that they are invariant, or the numerical value of them is the same to all observers no matter how the observers are moving with respect to them. This is not the case for mass, energy, or momentum. The other notable invariant is the velocity of light.

Hence we have three fundamental quantities which are all invariant, viz., the velocity of light (c), the electron or unit of electric charge (e), and the Planck or unit of action (h).

In all those phenomena in which radiation enters or leaves a material atom in exchange for an electron which also at the same time leaves or enters the atom the exchange is conducted on the principle that the product of the radiant

energy so entering or leaving the atom multiplied by the periodic time of its vibration must be equal to the unit of action or to h or else an integer multiple of it.

The apparent atomicity of light may be therefore only a consequence of the atomicity of action and also of electricity.

It is impossible to understand how energy could travel through space in discrete separate bundles or parcels, yet unassociated with atomic matter of some kind, yet nevertheless its entrance into or exit from matter may be accomplished in gushes or quanta which have definite amount, corresponding to the fact that the electric charge entering or leaving can only do so in integer multiples of the atom of electric quantity or the electron.

Moreover, radiation has intrinsically a certain kind of atomicity, in that it repeats its cycle of operations in a definite time, viz., the periodic time of the oscillation.

We have no exact knowledge as yet of the mechanism by which radiation causes an emission of an electron from an atom.

It is not a process of resonance, but takes place instantly by a sort of explosion under certain conditions.

It may perhaps be accomplished as follows:—On the solar system theory of the structure of material atoms the orbital electrons are held on their orbits by the electric attraction between them and the nucleus.

If a wave of radiation passes through the atom it may happen that the electric force of that wave in some position or at some time neutralizes or reduces the electric force holding an electron in its orbit, and it is then flung out to a larger orbit or released entirely from the atom. To do this a certain energy must be given to the electron.

The case is similar to that of a bullet or projectile shot straight up from the earth. If the initial velocity given to the bullet is less than a certain amount it will fall back on the earth. If that velocity (v) is such that $v^2 = 2gR$, where R is the radius of the earth and g the acceleration of gravity at the surface, then the bullet will just escape from the earth. That velocity v corresponds to an initial kinetic energy

$$\frac{1}{2}mv^2 = mgR = Wh,$$

where W is the weight of the bullet at the earth's surface. If more energy than this is imparted it is utilized in increasing the velocity of the bullet.

It may be the same with the emission of an electron from an atom of a metal. A certain energy is necessary to release

the electron, and any excess is used to give it velocity. It is usual to represent this work as the product of a certain voltage called the ionizing voltage V_0 , and the electron charge in electromagnetic units, q , which is

$$1.6 \times 10^{-20} \text{ E.M.U.}$$

For most of the ordinary metals this voltage is not far from 3.5 volts, though for the very electropositive metals it may be below 2. Thus for sodium it is 1.7 and for platinum 3.9. The product of V_0 and q is then the ionizing energy in ergs, and varies from

$$2.72 \times 10^{-12} \text{ erg to } 6.24 \times 10^{-12} \text{ erg.}$$

The necessary condition, however, is that the action during one period of the radiation T or product of V_0q and T must be 1 unit or 1 Planck ($=h=6.55 \times 10^{-27}$ erg seconds).

Hence the frequency ν must have a value V_0q/h at least, and be not less than 4×10^{14} for the alkali metals and about 10^{15} for the noble metals.

This makes the wave-length for the former about 7500 Å.U., which lies within the visible spectrum, whilst for the noble metals about 3000 Å.U. in the ultra-violet part.

There is, however, one great difficulty which is the chief reason for advocating a corpuscular or photon theory of light which assumes the energy to be concentrated in certain specks or parts of the wave-front and not smoothly distributed. It is as follows:—

It is well known that a photoelectric emission of electrons can occur with an impact of radiation, the surface density of which is so low that the amount captured on the surface of a single atom is far below the known ionizing energy. Thus a surface of potassium or sodium on which light from a single candle falls at a distance of 9 or 10 feet will certainly emit photoelectrons *in vacuo*, yet this radiation is only equivalent to imparting to the surface about 1 erg per cm. sq. per sec. The apparent diameter of a metal atom may be taken as about 2×10^{-8} cm, and its area as about 4×10^{-16} cm.²

Hence if the only energy which can enter the atom is that which is drawn from an area of the wave-front equal to the atomic apparent area it would require an exposure of about a quarter of an hour to such feeble light before the potassium surface could emit electrons. As a matter of fact they are emitted at once. Hence arose the conception of a concentration of light energy in certain spots or specks on the wave-front. This difficulty is mentioned in Norman Campbell's

'Modern Electrical Theory,' 2nd ed. p. 249, as justification for such modified theory.

But there are certain phenomena in connexion with wireless telegraphy which are not as well known to physicists as they should be which show that a material atom may perhaps draw energy from an area of a wave-front of radiation which is hundreds or thousands of times greater than the apparent atomic area. They are as follows:—

As far back as 1906 M. Camille Tissot, then a lieutenant in the French navy, described some quantitative experiments in radio telegraphy of the following kind*.

He constructed a transmitter in which he could measure the energy given out as radiation and by which he could

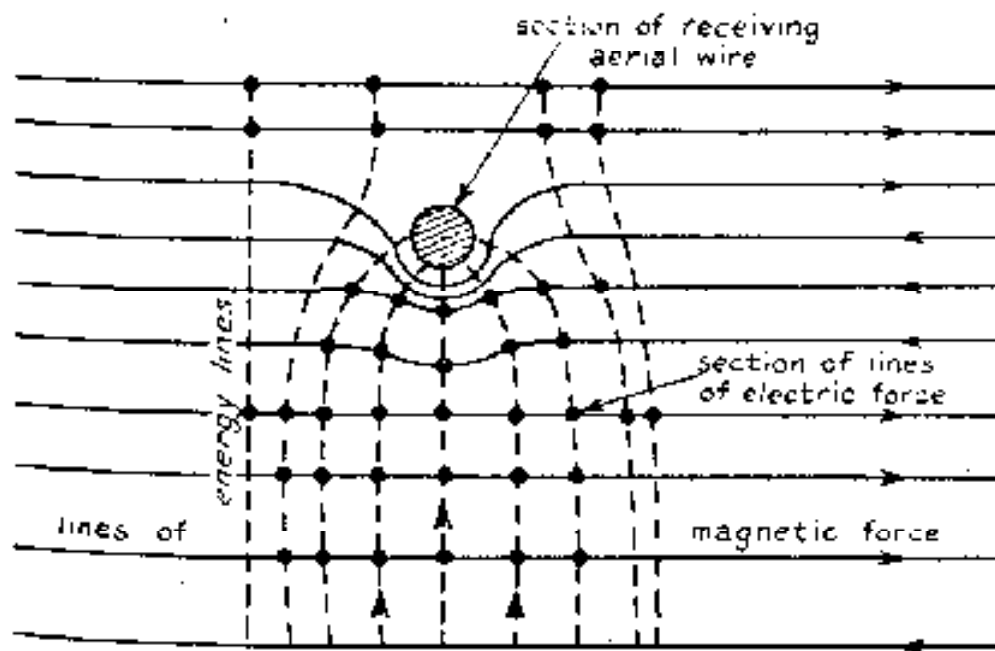


Diagram representing the nature of the electromagnetic field near a receiving aerial in wireless telegraphy.

The dotted lines represent the direction in which the energy is advancing on the aerial.

determine the radiation density at any distance near the earth's surface. He set up a single-wire receiving aerial at a known distance, and measured the radiant energy captured by this wire. If the apparent area of the aerial was A and the energy density of the wave at that point was E and its velocity c , it might have been thought that the aerial would only capture energy per second equal to AEc . Tissot found, however, that it captured several hundred times as much.

* 'Étude de la Résonance des Systèmes d'antennes dans la télégraphie sans fil' (Gauthier-Villars, Paris, 1906), see p. 191.

He says that an aerial wire 3 or 4 mm. wide drew energy from the wave-front spread over an area of 1 or 1.5 metres in width.

Tissot gave no explanation of this fact, but it seems to the writer to be explicable as follows:—Let the small circle in the figure represent the horizontal section of the vertical aerial wire, and let the firm black lines denote the direction of the lines of magnetic force in the advancing electric wave and the small dots the section of the lines of electric force. Then, according to Poynting's Theorem, the lines along which the energy travels are perpendicular to both the lines of magnetic and electric force and are denoted by the dotted lines.

Now, when the lines of magnetic force of the wave come up against the copper aerial wire and cut through it they induce in the aerial wire electric currents which create circular lines of magnetic force round the wire, and these, combining with the magnetic force of the wave, distort the field, as shown in the figure.

It will be seen that the result of the banding of the lines of magnetic force round the aerial is to converge on it the lines of energy, so that the aerial sucks out of the wave-front energy spread over a much wider area, it may be 300 or 400 times wider than the apparent area of the receiving wire.

The suggestion may then be made that the same kind of operation takes place when an electromagnetic wave of radiation passes over an atom of matter. The atom so to speak creates a dimple in the wave-front, and so causes it to absorb energy from an area in the wave-front which may be many thousands of times greater than its own apparent area. Moreover, just as the wireless aerial must have its direction parallel to, or nearly parallel to, the direction of the magnetic vector of the incident wave in order that it may absorb energy, so in the case of the material atom there may be some axis or direction in it which must be in a certain position as regards the light vectors of the incident wave if it is to absorb radiation at all.

When it does absorb, the Action law must hold good, viz., that the energy absorbed E , multiplied by the time period T of the wave, must be equal to the Planck unit, or to h , which fixes the limit of the effective wave frequency ν , since it must not be less than E/h .

Hence these two assumptions meet the difficulty that when radiation passes through a gas or falls on a photoelectric surface it is not every atom which is ionized.

The fact that only a certain number of atoms emit electrons

may not be due to the concentration of radiation energy in small spaces on the wave-front, but to the fact that the atom is ionized only when it holds a certain position with regard to the passing wave.

The quantum absorption is due to the fact that Action is a more fundamental quantity than energy alone, and is atomic in nature.

Action is measured by the product of energy and time. We do not know why there should be a limit to the divisibility of action and a sort of atom of action denoted by h when dealing with atomic phenomena; but then we do not know either why there should be a limit to the divisibility of electricity and an atom of it called the electron.

The importance of action as a physical quantity may arise from the fact that in the production of physical effects it is not merely energy that counts, but a certain time for its availability or use, and hence their product is fundamental; but why there should be a lower limit to this product we cannot say.

Nevertheless this atomicity furnishes an explanation of the main fact of photoelectric emission and gas ionization, provided we also admit that for reasons above suggested the atom can absorb energy from an area vastly greater than its own apparent area.

The same principles can be used to explain the emission of radiation from an atom which has already been ionized and therefore can take up an electron.

In an incandescent black body there are free electrons moving at various speeds which may be considered to plunge into atoms down to various energy levels, and hence to lose some of their energy.

Some of these electrons enter perhaps only the outer layers of atoms, others plunge more deeply into atoms. In all cases the electrons lose energy. The sudden entrance of the electron into the family circle of the atom causes a violent disturbance of the electric field in it, and the result is to create an electromagnetic impulse which spreads out in space and conveys away the difference of the energies of the electron before and after entrance.

The probability of a feeble or "soft" impact is greater than that of a "hard" or direct or deep impact, because the latter must involve something like a "head on" collision of an electron with an atom, these impacts producing "pulses" of electric force which can, in virtue of Fourier's Integral Theorem, be expanded into continuous spectra of electric vibrations. Those that arise from "soft" collisions would

be equivalent to low temperature spectra, and those from "hard" collisions would be high temperature spectra.

In each of these spectra the energy of various wave-lengths would be distributed in accordance with Wien's Law and be a maximum for some wave-length λ_m , such that $\lambda_m K$ would be a constant = 0.294, where K is absolute temperature. Wien's Law has been demonstrated by thermodynamic reasoning and also from "dimensions" without calling for any assumption of light quanta or photons (see 'The Quantum Theory,' Fritz Reiche, p. 128). Hence we might say that the result of such complex collisions of electrons and atoms would be to yield a radiation equivalent to a vast number of superimposed spectra, very many with small maximum energy near or beyond the red end, a few with large maximum energy near the violet end, and others in between, the resulting integral spectrum having therefore maximum energy corresponding to some definite wave-length.

If we knew the form of graph of each pulse of electric force and the form of the function in Wien's formula which connects radiation energy for each wave-length with the wave-length, it would be possible to determine the energy distribution according to wave-length in the final or resultant spectrum for the incandescent black body.

In default of this knowledge Planck was obliged to proceed by a more tentative or artificial method. He assumed that the radiation took place from ideal Hertzian oscillators which could contain or radiate energy only in an integer number of "quanta" proportional in energy to their frequency, and that the probability of their containing small quanta was greater than their probability of containing large quanta.

Then, assuming that the relation of frequency ν and quantum energy E was $E = h\nu$, where h is some constant, which proved to be of the dimension of action, he was able to arrive at his well-known formula for the energy of radiation at various wave-lengths of a black body. Experiment has shown that it agrees extremely well with the facts over a wide range of temperature; nevertheless it does not give any absolute proof of the existence of these energy quanta in space during the transmission of light.

The ordinary classical theory of radiation cannot, however, account for the existence of a maximum energy radiation at some wave-length intermediate between very long and very short waves which does occur.

It is clear, however, that the basic fact is not the division of radiant energy into "quanta," but the unexpected appearance of an atomic quality in that dynamical quantity we

call Action. This seems to imply that there is an ultimate limit to the divisibility of each of the two factors, energy and time, the product of which gives action and this may be the consequence of a more fundamental atomicity, viz., that neither time nor space is infinitely divisible.
