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RADIATION AND MATTER[1]

WE must congratulate ourselves upon the fact that we have been able to listen to such clear, concise and accurate presentations of the most fundamental problems that lie before pure science to-day. I would like, also, to extend to the speakers our sincere thanks for their efforts in giving us such interesting expositions of these abstruse theories.

It is my privilege to open the discussion on radiation and the structure of matter. Modern theories of radiation are largely concerned with Planck's conception of the radiation of energy in quanta, and with the extraordinary action constant usually denoted by the letter "*h*." I would like to present for your discussion some ideas on the relations between the high frequency vibrations which we observe in general *X*-radiation, and the forces holding the electrons and atoms together, including a physical conception of what this constant "*h*" really means.

Instead of basing the discussion on the conceptions of entropy, and thermo-dynamic probability, I shall start from our recent experiments on general *X*-radiation.

Before we learned from experiments that *X*-rays had definite wave-lengths, people supposed that they had, and that we could calculate their frequencies by the formula kinetic energy equals $h\nu$.

$$\tfrac{1}{2} m v^2 = h\nu. \tag{1}$$

[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.

We have shown, by experiments at Harvard, that this equation is not, in general, true, but that it does hold for particular cases. Mr. Hunt and I investigated the general X-radiation from a Coolidge tube, excited by a high potential constant voltage storage battery, using an X-ray spectrometer, and found that although the effective, or average, frequency does not obey the law represented in the equation (1), the equation does give the maximum frequency obtainable with a given electron energy. Dr. Webster then examined the characteristic X-radiation, and discovered that the kinetic energy of the electrons required to produce the alpha and beta lines of the K series is larger than is represented by equation (1), but that the gamma line (the highest frequency line in this series) approximately obeys the law. It appears, therefore, from our experiments, that equation (1) gives the maximum frequency of the radiation due to an electron's hitting an atom, but does not, in general, mean that the entire amount of the electron's energy is radiated at frequency ν.

I have recently shown that it is not necessary to assume that energy is radiated in quanta "h" in order to deduce equations for the distribution of energy in emission spectra similar to the equations representing black body radiation, so that we are not compelled to believe that because Planck's radiation law fits the facts of black body radiation more or less closely, therefore energy must be radiated in quanta $h\nu$. In attempting to explain why this constant "h" enters into the radiation law and in seeking for a physical conception of the mechanism of radiation, we are not therefore compelled to explain the emission of radiation in quanta $h\nu$, but rather the fact that an electron with a given kinetic energy, when it hits an atom, can produce radiations of frequency up to but not greater than that given by equation (1). This is the fundamental fact that needs explanation.

According to the modern conception of the constitution of matter, an atom possesses a complicated electro-magnetic structure in which the electrons play an important rôle. The electro-magnetic forces in this structure are greater near its center than at the periphery, and therefore the high frequency vibrations of the electrons must be associated with parts of the atom near its center. Hence, the reason why an electron can not produce a high frequency radiation unless it possesses a certain kinetic energy lies in the fact that it does not penetrate far into the atom unless it has a sufficient speed. This presupposes a force of repulsion between the electron and the atom. The theory of atomic structure seems to demand such a force in order to explain why atoms do not collapse; so that we have confirmation of the existence of such forces from two sides: the radiation and the structure of matter.

Before discussing further the nature of this force and the laws it must obey, I would like to present to you a conception of the difference between line spectra and the general, or continuous spectra. The frequencies of the characteristic lines depend upon the nature of the atoms struck by the electrons, whereas the frequencies of the general radiation depend upon the kinetic energy of the electron that does the striking. This suggests that the characteristic lines are due to vibrations of parts of the atoms themselves (of electrons in the atoms, for instance) whereas the general radiation or continuous spectrum is due to the vibrations of the electrons that hit the atoms.

The question now arises "How can an electron vibrate with all possible frequency so as to give a continuous spectrum?" The electron moves in the strong electromagnetic field of the atom, and when an electron moves in a strong magnetic field, it follows a spiral path around a line of force. This motion in a spiral path radiates energy with a frequency that depends on the strength of the field, and is therefore variable. It is easily shown that in a case where the spiral is tightly wound around a line of magnetic force, the frequency is given by the equation

$$\nu = \frac{H}{2\pi}\frac{e}{m}. \qquad (2)$$

From this equation it appears that the frequency is independent of the velocity of the electron and of the radius of the spiral and that it is practically proportional to the strength of the magnetic field; and since H varies continuously, the frequency can have all possible values (up to a maximum), which gives the radiation the character of a continuous spectrum.

Let us combine this conception of general X-radiation with the experimental fact that the maximum frequency due to the impact of an electron against an atom is given by equation (1). Suppose the electron to be traveling very nearly along the line of force coming from a very great distance, where its velocity is v and let x be its distance from any fixed point at the time t; let F be the total force acting on the electron in the direction of the weaker magnetic field. Then we can show easily that

$$F = \frac{h}{2\pi}\cdot\frac{e}{m}\cdot\frac{\partial H}{\partial x}. \qquad (3)$$

We find, therefore, that a force of repulsion acting on the electron, the magnitude of which is represented by equation (3), will explain why an electron of given kinetic energy can not produce radiation higher than that given by equation (1).

A force such as that represented by equation (3) should hold an electron in equilibrium at a distance somewhat smaller than 10^{-8} from an atomic nucleus, if the nucleus had a charge e and the magnetic moment attributed to atoms and magnetons. Such a force would play an important rôle in determining the size and compressibility of atoms, the conduction of heat and specific heats, and a great variety of phenomena.

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THE RELATIONS OF MAGNETISM TO MOLECULAR STRUCTURE

MAXWELL's classical theory of electricity and magnetism contributes little to our knowledge of molecular structure. For the portion of it which deals with material substances is exhibited in terms of quantities for which the process of definition wipes out structural distinctions. It is only through molecular theories of magnetism that magnetic phenomena may be correlated with molecular structure.

Langevin's theory of magnetism appears to be the soundest attempt to formulate such a theory. He hypothecates the existence in the molecules of every substance of groups of electronic orbits which by virtue of the peculiarities of the structure of the molecules may be so arranged that the resultant magnetic field due to the electronic orbits in a given molecule at points without the molecule may or may not vanish. In the former case the molecule is diamagnetic, in the latter magnetic.

The effect of the application of a magnetic field to a diamagnetic substance is to change the orbital velocity of any electron. This change is in the proper direction to account for the diamagnetic polarity of the substance. Langevin's theory leads to an expression for diamagnetic susceptibility which does not involve the temperature, in agreement with Curie's law for diamagnetism. Numerous exceptions to this law exist, but the exceptions may probably all be taken care of by a slight extension of Langevin's theory as proposed by Oxley.