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Characteristic Röntgen radiation

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I have had some difficulty in deciding what to speak about to-day. Much of my work on characteristic radiation is already comparatively old and may be familiar to many of you, as it has been summarized in such works as the *Jahrbuch der Radioaktivität und Elektronik* and Professor Stark's *Atomdynamik.* I shall therefore choose two, and only two, points which are of more recent interest - firstly, the results of my own experiments which have a bearing on the Quantum Theory of Radiation; secondly, the evidence for another series of characteristic radiations - a *J* series*.

The quantum theory of radiation

Phenomena of scattering - The results of experiments on the scattering of X-rays, which have an obvious bearing on the Quantum Theory of Radiation, may be briefly summarized.

When X-rays traverse matter of any kind, this matter becomes a source of a radiation similar in character to that of the primary radiation falling upon it. A variation in the intensity of this scattered radiation with direction around the primary beam shows slight polarization of the primary radiation proceeding direct from an X-ray tube.

The scattered radiation proceeding in a direction at right angles to that of propagation of the primary radiation is highly polarized in the manner of light scattered from the sky.

The variation in intensity of the scattered radiation with direction relative to the axis of the primary radiation agrees within certain limits very closely with the theoretical distribution as given by the equation

$$I_o = I_{\pi/2} (1 + \cos^2\theta)$$

* References to the original papers by the author will be found in the Bakerian Lecture, 1916, published in *Philosophical Transactions of the Royal Society,* 1917.

an equation readily derived on the orthodox electromagnetic wave theory. These experimental results were looked for as necessarily following from such a theory.

Difficult as the first two results would be to explain on any entity or quantum theory, that is, on any theory assuming radiation itself to exist in definite indivisible bundles or quanta, perhaps the strongest evidence against this is provided by the experimental verification, within limits, of the above equation. The derivation of this equation depends essentially on a steady variation with direction, not of a number of indivisible entities, but of the energy density around a single radiating charge - an electron in this case.

Further, measurement of the energy of radiation scattered furnishes one of the most searching and critical of tests that could be applied to any theory. The writer early concluded that neither atoms, molecules nor gaseous ions were the scattering units, but that these were the constituent electrons in matter, and that in general the number of electrons per atom, for light atoms at any rate, was proportional to the atomic weight.* The fraction of a beam lost by scattering per centimetre of substance traversed was shown by J. J. Thomson to be given by the expression

$$f = \frac{8\pi}{3} N \frac{e^4}{m^2} \mu^2$$

where N is the number per cubic centimetre of particles of charge e and mass m. Applying this to the experimental data, it at first appeared that the number of electrons per atom was several times the atomic weight. As the data available for the values of N, e/m, and e were more accurately determined, the calculated value for the number of electrons per atom became smaller, until with the most recent values the number indicated is one electron per atom of hydrogen, 6 per atom of carbon, 7 per atom of nitrogen, 8 for oxygen, 15 or 16 for sulphur, and so on.

As these conclusions regarding the number of electrons (outer electrons) within the atom have been confirmed by the researches of Rutherford, Bohr and Moseley, it is perfectly legitimate to use the agreement as evidence in support of the theory of radiation upon which it was based. The chances of such an agreement being arrived at accidentally are almost infinitesimal, for, apart from the orthodox theory of electromagnetic radiation, the intensity of scattered radiation might have been anything between - say - one thou-

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* Hydrogen excepted.

sandth part and a thousand times what was experimentally observed. Yet the value experimentally determined in 1904 agrees with the calculated value to a degree of accuracy as close as it is now possible to estimate the pressure of the air upon which the experiments were performed!

This confirmation is very remarkable. The theory on which it is based is the spreading wave theory. It assumes that the scattered radiation is the radiation resulting from the disturbance in electrons while under the influence of the electrostatic field in the primary radiation.

The theory assumes that radiation can take place from these electrons in any quantity whatever, and is not confined to units or quanta; that the radiation is a continuous process not depending on any limiting or critical condition.

Again, I have found that the intensity of the radiation scattered from light elements over considerable ranges varies little with the wavelength of the primary radiation. This is in perfect agreement with the theory based on the assumption of independent action of the electrons. Further experiments have shown that the intensity of scattered radiation from the heavy atoms in which the constituent electrons are more closely packed, increases rapidly and apparently continuously with the wavelength of the radiation, unless this is fairly small. Also, in general, the rate of increase of intensity with wavelength is greater, the heavier the atom from which the scattered radiation proceeds. Such results are, again to be expected on the wave theory when the wavelength becomes comparable with the size of the atom, for there is very close agreement in phase of the radiations set up by neighbouring electrons; ultimately a group of electrons and not an individual electron moves as a whole and becomes the scattering unit. (When the group comprises all the electrons in the atom, the scattering per atom becomes on this theory proportional to the atomic number squared, instead of to the atomic number, when the electrons scatter independently.)

There is thus in the phenomena of scattering, not only no suggestion of a quantum or entity of radiation, or of any discontinuity in the process of radiation involved, but there is some of the strongest positive evidence against any such theory. The results appear conclusive, for the tests which have been applied are the most searching and sensitive. The phenomena observed become meaningless on any quantum or entity theory. This conclusion is true also of absorption, for in the transmission of X-rays, particularly of short wavelength through matter consisting of light elements only, the energy absorbed is practically all re-emitted as scattered radiation. The quantities radiated by each electron are approximately identical with those absorbed. It follows that *this* process of absorption is also a process which takes place in any quantity whatever, and is unlimited by any critical condition.

Characteristic radiation - Each element when traversed by X-rays emits X-radiations characteristic of the element; each characteristic radiation is in-affected by changes in the physical condition or state of chemical combination of the radiating element, and its quality is independent of that of the exciting primary radiation. But only primary radiations of shorter wavelength are able to excite the characteristic X-radiations - an extension of Stokes's fluorescence law.

All the radiations hitherto definitely observed have fallen into three series, the *K, L,* and *M* series (the *M* series was discovered by Siegbahn and his collaborators). There is also strong evidence of a higher frequency series - a *J* series. This will be discussed later. The absorption method of analysing a radiation showed the radiation of the *K* series from a particular element to be so homogeneous, that it was regarded as giving a spectral line, the Kline; but the possibility of the *L* radiation consisting of more than one line was suggested by an obvious heterogeneity in the *L* radiation.

The interference experiments of Bragg, Moseley and others have shown, however, that both the *K* and *L* radiations give spectra consisting of a number of neighbouring lines.

The uniformity in the distribution of the characteristic radiation around the radiating substance, even when the primary beam is polarized, shows that, in contrast with the process of emission of scattered radiation, the emission of a characteristic radiation is absolutely uncontrolled by the primary radiation exciting it. The phenomena of emission is not an immediate consequence of the passage of the primary beam, but arises only indirectly from it; the process is dependent on some critical condition, as evidenced by Stokes' law. Here we see the possibility of the applicability of some kind of quantum theory. The most significant evidence as to the origin of the characteristic radiation comes from the study of the accompanying phenomena of the absorption of the exciting primary radiation and the emission of electrons by the radiating substance in the form of a corpuscular radiation. I have shown that the total absorption of a primary radiation in the substance traversed can be analysed into what are apparently independent absorptions, each - with the exception of that due to the process of scattering - definitely associated with the emission of a characteristic X-radiation. Thus there are the *J, K, L, M* absorptions. Similarly, a corpuscular radiation may be analysed into *J*, K, *L, M* corpuscular radiations, each associated* with the emission of the corresponding characteristic X-radiation.

The results obtained from a study of the energy of the primary beam absorbed, of the energy of the characteristic radiation emitted, and of the corpuscular radiation emitted, are very significant. In certain substances - bromine and probably substances of high atomic weight - nearly all the energy of the primary beam absorbed in association with the emission of *K* characteristic radiation is re-emitted partly as characteristic X-radiation of the *K* series, and partly as corpuscular radiation of the *K* series. Not only this, but there is a definite relation between the intensity of the *K* radiation and the number of electrons emitted in the associated corpuscular radiation. For various wavelengths of the primary radiation it appears that the number of quanta of *K* fluorescent radiation per *K* electron emitted is approximately 1. The numbers actually obtained are 1.09, 0.95, 0.85, 0.81, 0.90. The maximum variation of 19% from unity is exceedingly small, considering the number and nature of the experimental determinations involved. Apart from the quantum theory, the range of possible values is so enormous, in comparison with the variation observed, that the emission of one quantum of characteristic X-radiation for each electron in the associated corpuscular radiation must be regarded as an experimentally established fact. If the two *K* secondary radiations, the corpuscular and the characteristic X-radiations, together accounted for the whole of the *K* energy absorbed, we should have of the energy of the primary beam absorbed (*K* absorption) the fraction $n/(n+n_k)$, re-emitted as *K* corpuscular radiation, and fraction $n_k/(n+n_k)$, re-emitted as *K* fluorescent X-radiation, where n and n_k are the frequencies of the primary and the characteristic radiation respectively. As a matter of fact, when n is slightly greater than n_k, the two secondary radiations together account for about 88% of the primary radiation. As n increases the two energies of fluorescent and corpuscular radiations remain approximately complementary, the energy of the former diminishing while that of the other increases. There is indeed very close agreement between the fractions observed and those given by the above expressions. It may be, however, that one quantum of *L* radiation, in addition to one quantum of *L* radiation, is emitted for each *K* electron ejected. There is even closer agreement between the observed and the calculated values, based on this assumption. Whatever the process of radiation may be, there can be little doubt that

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* Probably in the case of *T* radiation.

characteristic radiation is emitted in quanta by those atoms merely from which an electron has been ejected.

The same energy relations, however, show us that absorption is not in quanta of primary radiation. Each absorbing atom, that is each atom which ultimately emits an electron, absorbs the energy of one quantum of primary radiation plus the energy of one quantum of characteristic radiation, which is $(1 + n_k/n)$ quanta of primary radiation. This may be anything from 1 to 2 quanta. All the evidence suggests that the characteristic radiation is emitted immediately after the ejection of the electron from the atom.

Summarizing, we may say that all the available evidence shows that X-radiation may be, and is, emitted by electrons, probably in certain cases by groups of electrons, or even atoms - as a continuous process and in any quantity whatever. It is frequently emitted in quantities almost infinitesimal in comparison with a quantum. It is, however, emitted in quanta from atoms, when certain critical conditions resulting in the ejection of certain electrons are reached, the process of radiation then taking place in a perfectly definite manner, involving the radiation of a definite amount of energy which is proportional to the frequency of vibration (Planck's Law: $E = hn$).

Absorption, too, normally takes place in very minute quantities - very small in comparison with a quantum. But in certain processes, which usually account for nearly the whole absorption, the radiation is absorbed in quantities greater than a quantum of the primary radiation, quantities varying with the conditions from one to two quanta approximately. There is no evidence of absorption of X-radiation in whole quanta, though the conditions are frequently such as to give an approximation to this.

All this evidence seems to indicate that a quantum of radiation in the sense in which it has frequently been used, i.e. as an indivisible bundle of radiation energy, does not exist. The process of radiation may be, and is, continuous - at any rate within limits extending to far smaller quantities than the quantum. The quantum is a unit of atomic energy which must be absorbed in order to change the configuration of the atom, and is radiated when that configuration returns to its original state. It thus of necessity appears in certain processes of absorption and radiation.

Probable 3 series of radiation

Recent investigations have led me to the conclusion that a characteristic radiation of higher frequency than the *K* radiation (forming a *J* series in the various elements) is probably emitted by each of the light elements. For experiments on (1) the absorption of X-rays, (2) the ionization of gases by X-rays, and (3) the intensity of corpuscular (electronic) radiation from plates exposed to X-rays, all show that a decrease in the wavelength of the primary X-radiation is accompanied by a sudden increase in the particular effect measured - an increase such as has invariably been found to accompany the emission of a characteristic X-radiation, and such as has hitherto not been observed except in association with such emission.

There is also close agreement between the values of the critical wavelengths found by the three methods.

Further, as with the phenomena accompanying *K, L* or *M* characteristic radiation, an increase in the atomic weight of the element is accompanied by a decrease in the critical wavelength in that element.

Direct evidence of the emission of] characteristic radiations has proved to be less easily obtained than appeared probable from preliminary experiments. Certain experimental results appeared to indicate that, though the *J* radiations might not be separable from the body of scattered radiation, their existence could readily be demonstrated. They have, however, proved more elusive than early experiments led us to believe. Experiments at present in progress are being gradually improved, and will, we hope, succeed in providing the direct evidence for which we are looking. It should, however, be pointed out that the evidence obtained from experiments on the *K* characteristic radiation would lead us to expect only a very weak characteristic radiation from these light elements, for of the energy of a primary beam absorbed in association with the emission of a particular *K* fluorescent characteristic radiation - i.e. *K* absorption - the fraction transformed into that characteristic X-radiation becomes rapidly smaller, as the atomic weight of the element decreases, so that even of the << *K* absorption>> only a very small fraction appears as *K* characteristic radiation from these light elements. Thus the fraction *K* radiation (energy)/ *K* absorption (energy) at its maximum value in copper is about 40%, in iron 30%, in chromium 20%. There is every indication of it becoming very small indeed in the lightest elements. In addition, the <<absorption>> in these light elements is only a small fraction of the absorption by scattering - say of the order of magnitude of 15%.

Consequently, from aluminium, oxygen, nitrogen and carbon we might reasonably expect the energy of the fluorescent radiation to be something much less than 3% - 15% of 2% - of the energy of the scattered radiation; how much less it would be impossible to predict, but the probability is however, that it is less than 1%. We are, however, reasoning from our experience of << *K* radiations a: this might be regarded as unsafe ground if it did not find confirmation in our experimental results, obtained in investigations of *J* radiations.

Duane and others have been unable to detect any *J* characteristic radiation excited in *aluminium* when bombarded by cathode rays. This may mean either that the] characteristic radiation is very weak in comparison with the heterogeneous X-radiation produced in aluminium - for it must be remembered that by analogy with the other characteristic radiations, *J* radiation is produced only in association with the emission of J electrons, and these may be very few or difficult to displace - or it may just possibly indicate that *J* radiation cannot be excited at all or only in the most exceptional cases by the impact of cathode particles. This is not at all unlikely, if the *J* electrons are closely bound with other electrons, positive and negative, as they may be in a nucleus. For the cathode particle may come under the influence of this minute system as a whole and be deflected by it, without ever coming into such intimate relationship with any constituent electron as to disturb its stability. Thus it is quite conceivable that the negative and positive components of such a system are influenced separately by X-radiation, and that equilibrium is disturbed and] electrons are ejected and succeeded by the emission of *J* characteristic X-radiation; whereas an electron of the corpuscular radiation is unable to produce the necessary displacement of the] electron. Further experiments alone can decide this point.

One important feature of the discovery of a *J* series of characteristic X-radiations lies in the fact that there is no room for it in Bohr's theory of radiation as applied to *K* and *L* radiations. It may, however, be that a *J* radiation is emitted by electrons in a system of different kind, as for instance in the nucleus itself instead of outside it. But the association of other phenomena - an association similar to that observed with *K* and *L* characteristic radiations - suggests a close similarity in the whole process involved. Experiments on this subject are at present in progress.