# THE CORPUSCULAR PROPERTIES OF LIGHT

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THE development of the modern conception of light quanta, or photons, began with Planck's ideas concerning heat radiation. Newton indeed had defended the hypothesis of light corpuscles, but the facts which he cited to support this view were later reconciled by Fresnel with the wave theory of light. It was not until new problems were studied, such as the intensity heat radiation and the electrical effects of light, that any real need arose for corpuscles as alternative or supplementary to the wave theory of light.

## Planck's Theory of Heat Radiation

Planck was confronted[1] with the fact that the only theory of emission of radiation from hot bodies to which the classical mechanics and electrodynamics would lead, predicted rays much more intense than are actually observed, and of the wrong color. It is a matter of common experience that as a body gradually becomes hotter it first glows a dull red, then orange, and bright gold and finally white. According to the formula developed from the usual kinetic theory, however, the light emitted should always be of the same blue color, differing only in intensity as the temperature changes. Such a conclusion followed necessarily from the fact that all oscillators in thermal equilibrium with each other should have on the average the same kinetic energy, whatever their natural frequency of oscillation. But the oscillators of higher frequency will be subject to greater acceleration if their kinetic energy is the same, and hence, according to electrodynamical principles, should radiate more energy than those of lower frequency. Thus at all temperatures the theory predicted that the high frequency radiation should be more intense than the low frequency radiation.

Planck saw a possible way of escape from this difficulty if he were to suppose that at low temperatures only the oscillators of low frequencies could emit radiation, whereas at high temperatures those of higher frequencies could also radiate. In order to accomplish this result he introduced the simple assumption that the oscillators in the hot body can emit radiation only in units, or quanta, whose energy is proportional to the frequency of the radiation, i.e.,

$$E = h\nu, \tag{1}$$

where $h$ is the constant of proportionality between the frequency and the the energy $E$ of the unit. With this limitation it is possible for only those

[1] Planck, Verh. d. Deut. Phys. Ges. **2**, 237 (1900). A complete account of Planck's studies of this problem is given in his "Wärmestrahlung" (1915), published by Blackiston's in English translation by Masius.

oscillators which have energy greater than $h\nu$ to emit a unit of radiation. Thus at low temperatures, where the average energy of the oscillators is low, only low frequency rays can be emitted. At higher temperatures the higher frequency oscillators will have enough energy to emit their larger units of radiant energy, and so as the temperature rises the center of gravity of the radiation will shift to higher and higher frequencies. Thus with one bold assumption regarding the unitary nature of the emitted light, Planck was able to arrive at a reasonable explanation of the hitherto insoluble problem of the color of the light emitted by hot bodies.

It would take us too far afield to describe how Planck developed this idea of energy quanta to account quantitatively for the intensity as well as the spectral energy distribution of heat rays. In his hands and those of others the theory has assumed a variety of forms, but it has always retained the essential feature that the rays from the hot body must be emitted in units whose energy is proportional to the frequency. The introduction of this idea has marked the opening of an important epoch in the development of theoretical physics.

## Einstein and the Photoelectric Effect

The units of radiant energy introduced by Planck were not corpuscular. He supposed that the radiation from an oscillator, though having a definite amount of energy, would spread itself through all space after the manner of a spherical electromagnetic wave. It remained for Einstein[2] to introduce the conception of a corpuscular unit of radiation, or photon, in his effort to account for the photoelectric effect.

When Einstein approached this problem it was recognized that the speed with which photoelectrons are ejected from a surface increases with increasing frequency of the light, and it was generally supposed that the number of photoelectrons emitted was proportional to the intensity of the light striking the photoelectric surface. He saw that this proportionality would follow from the assumption that the light which excited the photoelectrons occurs as a stream of particles, each of which would spend its energy in ejecting an electron fron an atom of the photoelectric material. If each of these particles had energy $h\nu$, as might be inferred from Planck's theory of heat radiation, this picture of the process would account also for the increase of speed with higher frequencies. If a certain amount of work $w_0$ is required to remove the electron from the atom, Einstein supposed that all the rest of the photon's energy is spent in giving kinetic energy to the electron, thus deriving his famous photoelectric equation,

$$E_{kin} = h\nu - w_0. \tag{2}$$

It was years before this theory received an adequate test. Experiments by Ladenburg[3] favored the view that the velocity rather than the kinetic energy

[2] A. Einstein, Ann. d. Physik **17**, 145 (1905).

[3] E. Ladenburg, Phys. Zeits. **8**, 590 (1907).

was proportional to the frequency of the incident light, and different results were obtained with different metals. Richardson and Compton[4] and independently Hughes[5] showed that the differences found for different metals were due to their different contact potentials, and to the fact that the value of $w_0$ is different from metal to metal. They were indeed able to show that Einstein's equation was of the right form, and that the constant of proportionality $h$ is approximately the same as Planck's constant. A few years later Millikan,[6] using greater care in securing strictly monochromatic light, was able by means of Einstein's equation to secure from photoelectric measurements one of the best experimental determinations that we have of Planck's constant.

The photoelectric effect is especially prominent with x-rays, for these rays eject photoelectrons from all kinds of substances. The velocities of these x-ray photoelectrons have been measured by means of their curvature in a magnetic field, using the so-called magnetic spectrograph. M. de Broglie[7] showed that even for these very high frequencies Einstein's equation holds, if by $w_0$ we now mean the work required to remove the electron from the $o$ level of the atom. In fact Robinson[8] has applied this equation to his measurements of the speed of x-ray photoelectrons from various substances as a powerful method of studying the energy levels of the different atoms. In a similar way, Ellis,[9] Meitner,[10] Thibaud[11] and others have used equation (2) as a means of determining $\gamma$-ray frequencies from the speed of the secondary $\beta$-rays. Recent measurements of these frequencies by crystal methods[12] show that even for these exceedingly great energies Einstein's law holds. Over a range of kinetic energies corresponding to a drop through potential differences from 1 volt to 2 million volts Einstein's photoelectric equation has thus been verified to within an experimental error of 1 percent. It is thus one of the most adequately tested laws in the realm of physics.

Before these photoelectric experiments had been carried to a successful conclusion, Duane and Hunt[13] observed a closely related phenomenon which is frequently called the inverse photoelectric effect. They found that when an x-ray tube is operated at a constant potential, there is a definite lower limit to the wave-length of the x-rays from the tube, and that this limiting wave-length is inversely proportional to the voltage. This result may be written in the form,

$$Ve = hc/\lambda_{min} = h\nu_{max}, \tag{3}$$

[4] O. W. Richardson and K. T. Compton, Phil. Mag. **24**, 575 (1912).
[5] A. L. Hughes, Phil. Trans. Roy. Soc. **A212**, 205 (1912).
[6] R. A. Millikan, Phys. Rev. **7**, 18 and 355 (1916).
[7] M. de Broglie, J. de Phys. et Radium **2**, 265 (1921).
[8] H. R. Robinson, Phil. Mag. **50**, 241 (1925).
[9] C. D. Ellis, Proc. Roy. Soc. **A100**, 1 (1922); Proc. Camb. Phil. Soc. **22**, 374 (1924), et al.
[10] L. Meitner, Zeits. f. Physik **11**, 35 (1922), et al.
[11] J. Thibaud, Comptes rendus **178**, (1924), et al.
[12] L. T. Steadman, Phys. Rev. **33**, 1069 (1929).
[13] W. Duane and F. L. Hunt, Phys. Rev. **6**, 166 (1915).

where $V$ is the applied potential, and the other letters have their usual significance. Duane and Hunt's quantitative measurements, confirmed and extended by a number of other investigators[14] have shown that the factor of proportionality in this equation is the same quantity $h$ as that which appears in Planck's theory, equation (1). In fact the measurement of this limiting x-ray wave-length is perhaps our best direct method of determining Planck's constant.

The significance of this work will perhaps be more obvious if we imagine the following experiment: Let two x-ray tubes, $A$ and $B$, be placed side by side. Tube $A$ is operated at a constant potential of say 100,000 volts. A cathode electron with a kinetic energy $Ve$ strikes the target of tube $A$ and gives raise to an x-ray of frequency $\nu = Ve/h$. This ray strikes the target of tube $B$ and there ejects a photoelectron whose kinetic energy according to equation(2) is $Ve - w_0$. This means that all of the energy of the cathode electron in tube $A$ has been transmitted to the photoelectron ejected from the target of tube $B$. How is it possible for such a complete transfer of energy to be effected?

A precisely similar difficulty arises in connection with Bohr's picture of radiation and absorption by atoms, which was developed[15] while these studies of the photoelectric effect were going on. According to this picture, radiation is emitted by an atom only when it changes from one state to another having less energy, in which case the frequency is given by the expression,

$$h\nu = \delta E, \tag{4}$$

where $\delta E$ is the loss in energy by the atom. When an atom absorbs energy, it changes from one state to another of higher energy and the frequency of the absorbed radiation is again given by equation (4), where $\delta E$ now means the increase in the energy of the atom. Thus we see again that if one system suddenly radiated an amount of energy $\delta E$, another atomic system, which may be as far away as the earth is from a distant star, may suddenly have its energy increased by the same amount when the radiation reaches it.

The impossibility that an electromagnetic wave whose energy spreads in all directions should effect such a sudden and complete transfer of energy is obvious. It is equally clear that Einstein's photon conception affords a simple and adequate method of making the transfer. There have not been lacking, however, attempts to explain these phenomena without resorting to assumptions departing so completely from the electromagnetic waves of Maxwell.

One such attempt is the accumulation hypothesis, according to which the light energy is gradually accumulated by the atom, and the photoelectron is finally ejected when the accumulated energy exceeds a certain critical value. This process requires the existence of stored energy of all possible amounts within the atom, since the kinetic energy of the ejected photo-

[14] *E. g.*, Duane, Palmer and Chi-Sun-Yeh, J. Opt. Soc. Am. **5,** 376 (1921); E. Wagner, J. d. Rad. Elek. **16,** 212 (1919).

[15] N. Bohr, Phil. Mag. **26,** 1,476 and 857 (1913).

electron may have any value, depending upon the frequency of the radiation which traverses its parent atom. Furthermore this energy must remain stored for indefinitely long periods of time, for otherwise emission of photoelectrons would not occur at once upon exposure to the light—time would be required for the atom to accumulate sufficient energy. We are thus led to imagine an atom which may possess any energy whatever, and whose energy may gradually increase as radiation is absorbed. Such a picture is wholly inconsistent with Bohr's idea of an atom with definite stationary states and which changes only suddenly from one such state to another. It is true that recent developments in quantum mechanics have led us to revise considerably Bohr's conception of electron orbits; but this hypothesis of stationary states seems more firmly established than ever, and continues to be the fundamental principle of spectral analysis. We thus find it difficult to consider seriously an accumulation hypothesis which would mean atoms having all possible amounts of energy.

There is another apparently fatal difficulty with this explanation of the photoelectric effect, in that it fails to account for the direction in which the photoelectrons are emitted. Experiments by Wilson[16] Bubb[17] and others[18] have shown that the most probable direction in which a photoelectron is ejected from an atom by x-rays is nearly that of the electric vector of the incident wave, but with an appreciable average forward component to its motion. This forward component is about equal to the momentum $h\nu/c$ of the incident photon, as would be expected if the electron suddenly absorbs a photon of energy $h\nu$ and escapes before any appreciable impulse has been transferred to the atom.[19] On the other hand, if the energy is gradually accumulated by the electron, the forward impulse received from the radiation would be transferred to the whole atom, and no reason appears for the strong forward component to the photoelectron's motion. Thus the accumulation hypothesis does not seem to be tenable.

If the atom cannot gradually accumulate energy, since a spherical electromagnetic wave cannot give up its whole energy to a single atom, the occurrence of photoelectrons with the energy $h\nu$ means that we must either give up our old view that light comes in spherical waves or abandon the doctrine of the conservation of energy. Bohr, Kramers and Slater[20] at one time preferred to assume that energy is not conserved when an individual photoelectron is produced. They supposed that on the average the energy appearing in the photoelectrons is equal to that absorbed from the radiation, but under

[16] C. T. R. Wilson, Proc. Roy. Soc. **A104,** 1 (1923).

[17] F. W. Bubb, Phys. Rev. **23,** 137 (1924).

[18] *E.g.,* Auger, Comptes rendus **178,** 1535 (1924); D. H. Loughridge, Phys. Rev. **26,** 697 (1925); F. Kirchner, Zeits. f. Physik **27,** 285 (1926); E. J. Williams, Nature **121,** 134 (1928).

[19] The average forward component is found in certain recent experiments to approach a value $9/5\times h/\lambda$, where $h/\lambda$ is the momentum of the photon. This value has been derived on the basis of wave mechanics (cf. A. Sommerfeld "Atombau Ergänzungsband" 1929 p. 222, and E. J. Williams, Nature **123,** 565, (1929).

[20] N. Bohr, H. A. Kramers and J. C. Slater, Phil. Mag. **47,** 785 (1924).

the stimulus of the incident waves any particular electron might suddenly escape at high speed without any corresponding loss in energy by the remainder of the system. That is, the conservation of energy, and similarly the conservation of momentum, would become statistical laws. The authors of this theory assume that, though the rays are propagated as spherical waves the motion of the photoelectrons would be the same as if they were ejected by photons. It has thus been difficult to devise a photoelectric experiment which would distinguish between this "virtual radiation" hypothesis and that of photons. The degree of success that has attended the application of the photon hypothesis to the motion of photoelectrons has however come directly from the application of the conservation principles to the individual action of a photon on an electron. The power of these principles as applied to this case is surprising if the assumption is correct that they are only statistically valid.

## Quantum Phenomena Associated with the Scattering of X-Rays

We have seen that Einstein's hypothesis of corpuscular units of radiant energy gives a satisfactory account of the photoelectric effect. As Jeans has significantly remarked, however, Einstein invented the photon hypothesis just to account for this one effect, and it is not surprising that it should account for it well. In order to carry any great weight the hypothesis should also be found applicable to some phenomena of widely different character. Just such phenomena have recently been found associated with the scattering of x-rays—the change in wave-length of the scattered rays, and the recoil electrons associated with them.

The earliest experiments on secondary x-rays and $\gamma$-rays showed a difference in the penetrating power of the primary and the secondary rays. Barkla[21] and his collaborators showed that the secondary rays from the heavy elements consisted largely of fluorescence radiations characteristic of the radiator, and that it was the presence of these softer rays which was chiefly responsible for the great absorption of the secondary rays. When later experiments showed a measureable difference in penetration even for light elements such as carbon, from which no fluorescence radiation appears, it was natural to ascribe this difference to a new type of fluorescence radiation, similar to the $K$ and $L$ types, but of shorter wave-length.[22] Careful absorption measurements[23] failed however, to reveal any critical absorption limit for these assumed "$J$" radiations similar to those corresponding to the fluorescence $K$ and $L$ radiations. Moreover, direct spectroscopic observations[24] failed to reveal the existence of any spectrum lines under conditions with which the supposed $J$ rays should appear. It thus became evident that the softening of the secondary x-rays from the lighter elements was due to a different

[21] C. G. Barkla and C. A. Sadler, Phil. Mag. **16,** 550 (1908).

[22] C. G. Barkla and Miss White, Phil. Mag. **34,** 270 (1917); J. Laub, Ann. d. Physik **46,** 785 (1915); J. A. Crowther, Phil. Mag. **42,** 719 (1921).

[23] Richtmyer and Grant, Phys. Rev. **15,** 547 (1920).

[24] Duane and Shimizu, Phys. Rev. **13,** 288 (1919); **14,** 389 (1919).

kind of process from the softening of the secondary rays from heavy elements where fluorescence x-rays are present.

According to the usual electron theory of x-ray scattering, the primary waves set the electrons into forced oscillation, and they, because of their accelerations, reradiate x-rays in all directions. It is thus obvious that the scattered rays will be of the same frequency as the primary rays which set the electrons in motion. A series of skillfully devised absorption experiments, performed by J. A. Gray,[25] showed however that both in the case of x-rays and $\gamma$-rays an increase in wave-length accompanies the scattering of the rays by light elements. When spectroscopic studies were made[26] they likewise revealed lines in the spectrum of the scattered rays corresponding to those in the primary beam, but with each line displaced slightly toward the longer wave-lengths. These spectra had the advantage over the absorption measurements of affording a quantitative determination of the change in wave-length, which gave a basis for its theoretical interpretation.

The photon conception gives a simple interpretation of this phenomenon. If we suppose that each x-ray photon is deflected by a single electron the electron will recoil from the impact. That is, part of the photon's energy is spent in setting the electron in motion, so the photon has less energy after deflection than before. The problem is very similar to that of the elastic collision of a light ball with a heavy one. If we assume that the energy and momentum are conserved in the process we can calculate the loss in energy and hence the increase in wave-length of a photon which is scattered at an angle $\phi$ with the primary ray. We thus find[27] for the increase in wave-length,

$$\delta\lambda = \frac{h}{mc}(1-\cos\phi), \tag{5}$$

where $h$ is again Planck's constant, $m$ is the mass of the electron and $c$ is the velocity of light. The electron at the same time recoils from the photon at an angle $\theta$ given by,

$$\cot\theta = -(1+\alpha)\tan\tfrac{1}{2}\phi, \tag{6}$$

where $\alpha = h/mc\lambda$, and the kinetic energy of the recoiling electron is

$$E_{kin} = h\nu\frac{2\alpha\cos^2\theta}{(1+\alpha)^2-\alpha^2\cos^2\theta}\,. \tag{7}$$

Until very recently the experiments showed just two lines in the spectrum of the scattered rays corresponding to each line of the primary ray. Of these lines one, the "unmodified line," is of very nearly the same wave-length as the primary ray, whereas the second, or "modified line," though apparently somewhat broadened, has its center of gravity shifted by ap-

[25] J. A. Gray, Phil. Mag. **26**, 611 (1913); J. Frank. Inst. Nov. 1920, p. 643.
[26] A. H. Compton, Bull. Nat. Res. Coun. No. 20 (1922); Phys. Rev. **22**, 409 (1923).
[27] A. H. Compton, Phys. Rev. **22**, 483 (1923); P. Debye, Phys. Zeits. **24**, 161 (1923).

proximately the amount predicted by equation (5). According to experiments by Kallman and Mark[28] and by Sharp[29] the agreement between the theoretical and the observed shift is precise to within a small fraction of 1 percent.

Within the last year Davis and Mitchell,[30] using their high resolving power double crystal spectrometer, have found that the "unmodified line" has a complex structure, with one line the same wave-length as the primary rays and with a group of other lines each of whose frequencies differs from that of the primary beam by approximately the limiting frequency of some energy level in the normal atom. Thus there is a line whose frequency is given approximately by the relation,

$$h\nu'' = h\nu - h\nu_k \tag{8}$$

where $\nu$ is the primary frequency and $h\nu_K$ is the energy of the $K$ energy level Such lines may be accounted for by supposing that the incident photon spends enough energy upon the atom to release a $K$ electron (or to transfer it to an outside orbit) and then escapes from the atom with its remaining energy. The process is thus analogous to the photoelectric effect, where, however, the photon instead of the electron escapes with the energy remaining after the electron has been removed from its original orbit. These lines seem to be the x-ray analogues of the Raman lines, which had been discovered[31] a few months earlier in the visible spectrum.

Very recent experiments by Davis and Purks[32] have shown a similar fine structure in the modified line. Such a structure is consistent with the photon conception of the scattering process, and had indeed been predicted on this basis by the writer[33] using certain assumtions regarding the action of the photon on bound electrons. The experiments of Sharp[29] and DuMond,[34] however, seem to indicate a broad and almost structureless modified line, which would seem to be in disagreement with the results of Davis and Purks. The spectra obtained by the latter investigators also show a change in wave-length which is almost 10 percent less than that predicted by equation (5), a result difficult to reconcile with the observations of other recent experiments. It is important to settle these differences in the detailed experimental results, because they are of significance regarding the manner in which a photon acts upon an electron bound within an atom. There is in these experiments, however, no evidence of a disagreement with the basic corpuscular theory from which equation (5) was derived.

[28] H. Kallman and H. Mark, Naturwiss. **13,** 297 (1925).
[29] H. M. Sharp, Phys. Rev. **26,** 691 (1925).
[30] B. Davis and D. P. Mitchell, Phys. Rev. **32,** 331 (1928).
[31] C. V. Raman, Indian J. Phys. **2,** 387 (1928).
[32] B. Davis and H. Purks, Phys. Rev. **34,** 1 (1929).
[33] A. H. Compton, Phys. Rev. **24,** 168 (1924).
[34] J. W. M. DuMond, Phys. Rev. **33,** 643 (1929).

## Recoil Electrons

From the close agreement between the theoretical and the observed wave-lengths of the scattered rays, the recoil electrons predicted by the photon theory of scattering were looked for with some confidence. When this theory was proposed, there was no direct evidence for the existence of such electrons, though indirect evidence suggested[35] that the secondary $\beta$-rays ejected from matter by hard $\gamma$-rays are mostly of this type. Within a few months of their prediction, however, C. T. R. Wilson[36] and W. Bothe[37] independently announced their discovery. The recoil electrons show as short tracks in the cloud expansion photographs, pointed in the direction of the primary beam, mixed among the much longer tracks due to the photo-electrons ejected by the x-rays.

Perhaps the most convincing reason for associating these short tracks with the scattered x-rays comes from a study of their number. Each photo-electron in a cloud photograph represents a quantum of truly absorbed x-ray energy. If the short tracks are due to recoil electrons, each one should represent the scattering of a photon. Thus the ratio $N_r/N_p$ of the number of short tracks to the number of long tracks should be the same as the ratio $\sigma/\tau$ of the scattered to the truly absorbed energy when the x-rays pass through air. The latter ratio is known from absorption measurements, and the former ratio can be determined by counting the tracks on the photographs. The satisfactory agreement between the two ratios for x-rays of different wave-lengths means that on the average there is about one quantum of energy scattered for each short track that is produced.

This result is in itself contrary to the predictions of the classical wave theory, since on this basis all the energy spent on a free electron (except the insignificant effect of radiation pressure) should reappear as scattered x-rays. In these experiments on the contrary, 5 or 10 percent as much energy appears in the motion of the recoil electrons as in the scattered x-rays.

That these short tracks correspond to the recoil electrons predicted by the photon theory of scattering becomes clear from a study of their energies. The energy of an electron which produces a track in an expansion chamber can be calculated from the range of the track. The ranges of the tracks which start in different directions have been studied,[38] using primary x-rays of different wave-lengths, with the result that equation (7) has been satisfactorily verified. A more accurate check on these recoil electron energies has recently been made by Bless,[39] using a magnetic spectrometer, and with results wholly consistent with the theory.

In view of the fact that electrons of the recoil type were unknown when the photon theory of scattering was presented, their existence, and the close

[35] A. H. Compton, Bull. Nat. Res. Coun. No. **20,** p. 27 (1922).

[36] C. T. R. Wilson, Proc. Roy. Soc. **A104,** 1 (1923).

[37] W. Bothe, Zeits. f. Physik **16,** 319 (1923); **20,** 237 (1923).

[38] A. H. Compton and A. W. Simon, Phys. Rev. **25,** 306 (1925); J. M. Nuttall and E. J. Williams, Manchester Memoirs, **70,** 1 (1926).

[39] A. A. Bless, Phys. Rev. **30,** 871 (1927).

agreement with the predictions as to their number, direction and velocity, supply strong evidence in favor of the photon hypothesis.

### Interpretation of these Experiments

It is impossible to account for scattered rays of altered frequency, and for the existence of the recoil electrons, if we assume that x-rays consist of electromagnetic waves in the ordinary sense. Yet some progress has been made on the basis of semi-classical theories. It is an interesting fact that the wave-length of the scattered ray according to equation (5) varies with the angle just as one would expect from a Doppler effect if the rays are scattered from an electron moving in the direction of the primary beam. Moreover, the velocity that must be assigned to the electron in order to give the proper magnitude to the change of wave-length is that which the electron would acquire by radiation pressure if it should absorb a quantum of the incident rays. Several writers[40] have therefore assumed that an electron takes from the incident beam a whole quantum of the incident radiation, and then emits this energy as a spherical wave while moving forward with high velocity. There is, however, the difficulty that this theory predicts recoil electrons all moving in the same direction and with the same velocity. The experiments show, on the other hand, a variety of directions and velocities, with the velocity and direction correlated as demanded by the photon hypothesis. Moreover, the maximum range of the recoil electrons, though in agreement with the predictions of the photon theory, is found[38] to be some four times as great as that predicted by this semi-classical theory.

There is nothing in these experiments, however, which is inconsistent with the idea of virtual oscillators continually scattering virtual radiation. In order to account for the change of wave-length on this view, Bohr, Kramers and Slater assumed[20] that the virtual oscillators scatter as if moving in the direction of the primary beam, accounting for the change in wave-length as a Doppler effect. They then suppose that occasionally an electron, excited by the primary virtual rays, will suddenly move forward as if it had received the momentum of a photon. Though we have seen that the electrons move in a variety of different directions, the theory could easily be extended to include the type of motion that is actually observed. It is difficult, however, to see how such a theory could by itself predict the change in wave-length and the motion of the recoil electrons.

We may conclude that the photon theory predicts quantitatively and in detail the change of wave-length of the scattered x-rays and the characteristics of the recoil electrons. The virtual radiation theory is probably not inconsistent with these experiments, but is incapable of predicting the results. The classical theory is altogether helpless to deal with these phenomena.

[40] C. R. Bauer, Comptes rendus **177,** 1211 (1923); C. T. R. Wilson, Proc. Roy. Soc. **A104,** 1 (1923); K. Forsterling, Phys. Zeits. **25,** 313 (1924); O. Halpern, Zeits. f. Physik **30,** 153 (1924).

## Experiments with Individual Radiation Quanta

We have seen that while these experiments on the photoelectric effect and on the scattering of x-rays give results which cannot be reconciled with the classical picture of electromagnetic waves, they do not suffice to distinguish between the photon theory and the theory of virtual radiation. The latter theory succeeded in avoiding the difficulties of the classical theory by considering the conservation of energy and momentum as only statistically valid. If experiments can be performed on the interaction of individual photons and electrons, it should be possible to make a direct test of the conservation principles, and to distinguish between the virtual radiation hypothesis and that of photons. Three important experiments of this type have been reported.

(1) *Test for Coincidences with Fluorescence X-Rays.* Bothe has performed an experiment[41] in which fluorescence rays from a thin copper foil are excited by a beam of incident x-rays. Two point counters of the type developed by Geiger are mounted, one on either side of the foil, in each of which an average of 1 photoelectron is recorded for about 20 quanta radiated by the foil. If we assume that the fluorescence radiation is emitted in quanta of energy, but proceed in spherical waves in all directions, there should thus be about 1 chance in 20 that the recording of a photoelectron in one chamber should be simultaneous with the recording of a photoelectron in the other. The experiments showed no coincidences other than those which were explicable by such sources as high speed beta particles which traverse both counting chambers.

This result is in accord with the photon hypothesis. For if a photon of fluorescence radiation produces a $\beta$-ray in one counting chamber it cannot traverse the second chamber. Coincidences should therefore not occur.

According to the virtual radiation hypothesis, however, coincidences should have been observed. For on this view the fluorescence $K$ radiation is emitted by virtual oscillators associated with atoms in which there is a vacancy in the $K$ shell. That is, the copper foil can emit fluorescence $K$ radiation only during the short interval of time following the expulsion of a photoelectron from the $K$ shell, until the shell is again occupied by another electron. This time interval is so short (less than $10^{-15}$ seconds) as to be sensibly instantaneous on the scale of Bothe's experiments. Since on this view the virtual radiation is emitted in spherical waves, the counting chambers on both sides of the foil should be simultaneously affected, and coincident pulses in the two chambers should frequently occur. The results of the experiment are thus contrary to the predictions of the virtual radiation hypothesis.

(2) *Coincidences of Scattered X-Rays and Recoil Electrons.* We have seen according to Bohr, Kramers and Slater's theory, virtual radiation is being continually scattered by matter traversed by x-rays, but only occasionally is a recoil electron emitted. This is in sharp contrast with the photon theory, according to which a recoil electron appears every time a photon is scattered.

[41] W. Bothe, Zeits. f. Physik **37,** 547 (1926).

A crucial test between these two points of view is afforded by an experiment devised and brilliantly performed by Bothe and Geiger.[42] X-rays were passed through hydrogen gas, and the resulting recoil electrons and scattered rays were detected by means of two point counters on opposite sides of the column of gas. The chamber for counting recoil electrons was left open, but a thin sheet of platinum prevented the recoil electrons from entering the chamber for counting the scattered rays. The impulses from the counting chambers were recorded on a moving photographic film.

In observations over a period of five hours 66 coincidences between the impulses due to recoil electrons and the scattered rays were observed. Bothe and Geiger estimated that according to the virtual radiation theory the chance was only 1 in 400,000 that so many coincidences should have occurred. This result is therefore in accord with the predictions of the photon theory, but is directly contrary to the statistical view of the scattering process.

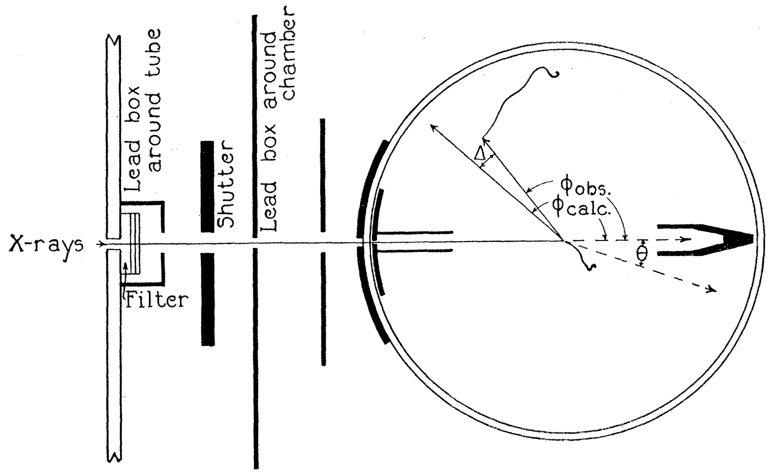


Fig. 1.

(3) *Directional Emission of Scattered X-Rays.* According to the photon theory, we have a definite relation (equation 6) between the angle at which the photon is scattered and the angle at which the recoil electron is ejected. But according to any form of spreading wave theory, including that of Bohr, Kramers and Slater, the scattered rays may produce effects in any direction whatever, and there should be no correlation between the direction in which a recoil electron proceeds and the direction in which the scattered x-ray produces an effect. A test to see whether such a relation exists has been made,[43] using a cloud expansion apparatus, in the manner shown diagrammatically in Fig. 1. Each recoil electron produces a visible track, and oc-

[42] W. Bothe and H. Geiger, Zeits. f. Physik **26,** 44 (1924); **32,** 639 (1925).
[43] A. H. Compton and A. W. Simon, Phys. Rev. **26,** 289 (1925).

casionally a secondary track is produced by the scattered x-ray before it escapes from the chamber. When but one recoil electron appears on the same plate with the track due to the scattered rays, it is possible to tell at once whether the angles satisfy equation (6). If two or three recoil tracks appear, the measurements on each track can be appropriately weighted.

Of 850 plates taken in the final series of readings, 38 show both recoil tracks and secondary $\beta$-ray tracks. On 18 of these plates the observed angle $\phi$ is within 20 degrees of the angle calculated from the measured value of $\theta$, while the other 20 tracks are distributed at random angles. This ratio 18:20 is about that to be expected for the ratio of the rays scattered by the part of the air from which the recoil tracks could be measured to the stray rays from various sources. There is only about 1 chance in 250 that so many secondary $\beta$-rays should have appeared at the theoretical angle.

This result means that associated with each recoil electron there is scattered x-ray energy sufficient to produce a $\beta$-ray, and proceeding in a direction determined at the moment of ejection of the recoil electron. In other words, the scattered x-rays proceed in directed units of radiant energy.

This result, like those of the previous two experiments, is irreconcilable with the virtual radiation hypothesis of the production of recoil and photo-electrons. On the other hand all of these experiments with individual radiation quanta are in complete accord with the predictions of the photon theory.

## The Paradox of Waves and Particles

Experiments on the photoelectric effect and on scattered x-rays, taken together with these experiments on the individual interactions of radiation and electrons, show therefore that radiation is emitted in units, is propagated in definite directions, and is absorbed again in units of undiminished energy. Light thus has all the essential characteristics of particles. It is well known however that light has the characteristics of waves. The phenomena of reflection, refraction, polarization and interference, which occur with light, can leave no reasonable doubt about its wave properties. How can these two apparently conflicting conceptions be reconciled?

*Electron Waves.* Before attempting to answer this question, let us notice that this dilemma applies not only to radiation, but also to other fundamental fields of physics. When the evidence was growing strong that radiation, which we have always thought of as waves, had the properties of particles, L. de Broglie asked, may it not then be possible that electrons, which we have known as particles, may have the properties of waves? He was able to give a mathematical proof[44] that the dynamics of any particle may be expressed in terms of the propagation of a group of waves. That is, the particle may be replaced by a train of waves—the two, so far as their motion is concerned, may be made mathematically equivalent. The motion of a particle in a straight line is represented by a plane wave. The wave-length is determined by the momentum of the particle. Thus just as the momentum of

[44] L. de Broglie, Phil. Mag. **47,** 446 (1924); Thesis, Paris 1924.

a photon is $h\nu/c = h/\lambda$ so the wave-length of a moving electron is given by $mv = h/\lambda$, or

$$\lambda = h/mv. \tag{9}$$

In C. T. R. Wilson's cloud expansion photographs we have ocular evidence that electrons are very real particles indeed. Nevertheless de Broglie's suggestion that they should act as waves has been subjected to experimental test by Davisson and Germer[45] and later by G. P. Thomson,[46] Rupp,[47] Kikuchi[48] and others.

For ou· present purpose we may describe Thomson's experiment, which is typical of them all. His experiment is analogous to those in which Debye and Scherrer[49] and Hull[50] secured diffraction patterns of x-rays by passing them through powdered crystals placed some distance in front of a photographic plate. Thomson replaced the x-ray beam with a stream of cathode rays (falling through about 30,000 volts potential difference), and the mass of powdered crystals with a sheet of gold leaf. The resulting photographs showed the same kind of diffraction pattern as that obtained when x-rays pass through gold leaf. Indeed from the size of the diffraction rings the wave-length of the cathode rays could be calculated, and was found to be just that predicted by de Broglie's formula (9). If the diffraction of x-rays by crystals proves that they are waves, this diffraction of cathode rays establishes equally the wave characteristics of electrons.

We are thus faced with the fact that the fundamental things in nature, matter and radiation, present to us a dual aspect. In certain ways they act like particles, in others like waves. The experiments tell us that we must seize both horns of the dilemma.

*A Suggested Solution.* During the last few years there has gradually developed a solution of this puzzle, which though at first rather difficult to grasp seems to be free from logical contradictions and essentially capable of describing the phenomena which our experiments reveal. A mention of some of the names connected with this development will suggest some of the complexities through which the theory has gradually gone. There are L. de Broglie, Duane, Slater, Schrödinger, Heisenberg, Bohr and Dirac, among others, who have contributed to the growth of this explanation.[51] The point of departure of this theory is de Broglie's proof, mentioned above, that the motion of a particle may be expressed in terms of the propagation of a group of waves. In the case of the photon, this wave may be taken as the ordinary

[45] C. J. Davisson and L. H. Germer, Phys. Rev. **30,** 705 (1927).

[46] G. P. Thomson, Proc. Roy Soc. **A117,** 600 (1928); **A119,** 651 (1928).

[47] E. Rupp, Ann. d. Physik **85,** 981 (1928).

[48] S. Kikuchi, Jap. J. of Phys. **5,** 83 (1928).

[49] Debye and Scherrer, Phys. Zeits. **17,** 277 (1916).

[50] A. W. Hull, Phys. Rev. **10,** 661 (1917).

[51] A review of the development of this theory is given in the report of the fifth Solvay Congress, "Electrons et Photons," Brussels, 1928, written chiefly by W. L. Bragg, A. H. Compton, L. de Brogile, E. Schrödinger, W. Heisenberg and N. Bohr.

electromagnetic wave. The wave corresponding to the moving electron is generally called by the name of its inventor, a de Broglie wave.

Consider, for example, the deflection of a photon by an electron on this basis, that is, the scattering of an x-ray.[52] The incident photon is represented by a train of plane electromagnetic waves. The recoiling electron is likewise represented by a train of plane de Broglie waves propagated in the direction of recoil. These electron waves form a kind of grating by which the incident electromagnetic waves are diffracted. The diffracted waves represent in turn the deflected photon. They are increased in wave-length by the diffraction because the grating is receding, resulting in a Doppler effect.

In this solution of the problem we note that before we could determine the direction in which the x-ray was to be deflected, it was necessary to know the direction of recoil of the electron. In this respect the solution is indeterminate; but its indeterminateness corresponds to an indeterminateness in the experiment itself. There is no way of performing the experiment so as to make the electron recoil in a definite direction as a result of an encounter with a photon. It is a beauty of the theory that it is determinate only where the experiment itself is determinate, and leaves arbitrary those parameters which the experiment is incapable of defining.

It is not usually possible to describe the motion of either a beam of light or a beam of electrons without introducing both the concepts of particles and waves. There are certain localized regions in which at a certain moment energy exists, and this may be taken as a definition of what we mean by a particle. But in predicting where these localized positions are to be at a later instant, a consideration of the propagation of the corresponding waves is usually our most satisfactory mode of attack.

Attention should be called to the fact that the electromagnetic waves and the de Broglie waves are according to this theory waves of probability. Consider as an example the diffraction pattern of a beam of light or of electrons, reflected from a ruled grating, and falling on a photographic plate. In the intense portion of the diffraction pattern there is a high probability that a grain of the photographic plate will be affected. In corpuscular language, there is a high probability that a photon or electron, as the case may be, will strike this portion of the plate. Where the diffraction pattern is of zero intensity, the p.obability of a particle striking is zero, and the plate is unaffected. Thus there is high probability that a photon will be present where the "intensity" of an electromagnetic wave is great, and a lesser probability where this "intensity" is smaller.

It is a corollary that the energy of the radiation lies in the photons, and not in the waves. For we mean by energy the ability to do work, and we find that when radiation does anything it acts in particles.

In this connection it may be noted that this wave-mechanics theory does not enable us to locate a photon or an electron definitely except at the

[52] E. Schrödinger, Ann. d. Physik **82,** 257 (1927).

instant at which it interacts with another particle. When it activates a grain on a photographic plate, or ionizes an atom which may be observed in a cloud expansion chamber, we can say that the particle was at that point at the instant of the event. But in between such events the particle can not be definitely located. Some positions are more probable than others, in proportion as the corresponding wave is more intense in these positions. But there is no definite position that can be assigned to the particle in between its actions on other particles. Thus it becomes meaningless to attempt to assign any definite path to a particle. It is like assigning a definite path to a ray of light: the more sharply we try to define it by narrow slits the more widely the ray is spread by diffraction.

Perhaps enough has been said to show that by grasping both horns we have found it possible to overcome the dilemma. Though no simple picture has been invented affording a mechanical model of a light ray, by combining the notions of waves and particles a logically consistent theory has been devised which seems essentially capable of accounting for the properties of light as we know them.

Starting with Planck's epoch-making suggestion that radiation is emitted in discrete units proportional to the frequency, we have thus seen how Einstein was led to suggest corpuscular quanta of radiation or photons in order to account for the photoelectric effect, and how recent experiments with x-rays, especially those with individual x-ray quanta, have seemed to establish this corpuscular hypothesis. Yet we have long known that light has the characteristics of waves. For centuries it has been supposed that the two conceptions are contradictory. Goaded on, however, by the obstinate experiments, we seem to have found a way out. We continue to think of light as propagated as electromagnetic waves; yet the energy of the light is concentrated in particles associated with the waves, and whenever the light does something it does it as particles.