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ON THE INTERACTION BETWEEN RADIATION AND ELECTRONS

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ABSTRACT

In the production of recoil electrons we have an example of the action of radiation on free electrons, whereas the photoelectric effect with x-rays is an example of the action of radiation on a pair of positive and negative charges. In both effects experiment indicates that the whole momentum absorbed from the radiation is imparted to the electron that is set in motion by the radiation, showing that the duration of the action of the radiation is short compared with the natural period of the electron in the atom. It is assumed that the action is sensibly instantaneous. In contrast with the prediction of Lorentz's force equation, which would predict an impulse imparted to an isolated electron almost in the direction of the electric vector, the experiments show that the preferred direction of motion of the recoil electrons is perpendicular to the electric vector. An impulse on a free electron in the direction of the electric vector would not be consistent with the conservation of momentum. The photo-electrons on the other hand have the electric vector of the incident wave as their preferred direction of motion (neglecting radiation pressure), though the experiments show that the impulse imparted to the electron by the radiation may make a considerable angle with the electric vector. In this case the conservation of linear momentum permits motion in any direction, since equal and opposite impulses are applied to the positive and negative parts of the atom by the electric vector; but the conservation of the angular momentum of the system requires that the impulse shall be imparted in a direction determined by the instantaneous position of the electron in the atom. The experiments of Auger and Bubb are consistent with this requirement, but indicate that Lorentz's force equation is only statistically valid in defining the direction of the action of the electric vector on the photo-electron.

WE MAY distinguish between the actions of radiation upon electrons in which the electrons are ejected from the matter traversed and those in which the electrons affected remain in the matter. In the first group are the photoelectric effect and the production of recoil electrons, or as we may call it, the recoil effect. The motions of these electrons after leaving the matter may be studied, and the information which such a study affords regarding the mode of action of the radiation is the chief subject of this paper. Included in the second group of actions is the production of excited atoms by the absorption of radiation, an action which is doubtless similar in character to the photoelectric effect, and such phenomena as the exciting of high frequency currents in conductors by electric waves, and the polarization of dielectric media when traversed by electric waves. It is not possible in phenomena of the latter type to observe the motions of the individual electrons, but our large scale measurements are consistent with the view that each electron in the medium is subject to the force per unit charge

$$F = E + [vH]/c, \tag{1}$$

given by Lorentz's force equation.

The number of recoil and photo-electrons. The experiments indicate that when x-rays traverse different elements, the number of recoil electrons ejected is proportional to the number of electrons traversed by the rays,[1] except that for soft x-rays a correction must be applied for the electrons which are bound to tightly in the atom to be ejected by the recoil process.[2] This proportionality suggests strongly that the action is one in which the radiation and the electrons only are concerned, the positive part of the atom playing no essential part. That is, the recoil effect seems to be the action of radiation on electrons which are effectively *free.*

In support of this suggestion we may point out: 1. The recoil electrons have been identified with those which scatter x-rays,[3] and according to the classical electron theory the scattering process is one in which we can consider the electrons alone, without taking into account the positive part of the atom. 2. It is found that the energy and momentum of the system photon plus electron are conserved, within a rather small experimental error,[4] without taking into account any action on the positive part of the atom.

The photoelectric action of x-rays is, however, apparently an action between radiation and a pair of associated positive and negative charges. Experiments such as those of de Broglie with the magnetic spectrograph[5] show that the large majority of the photo-electrons ejected by x-rays come from the K energy level of the atom, supporting the view that it is these photo-electrons which have received the energy "truly absorbed" from the x-ray beam. Owen's observation[6] that the true absorption of x-rays per atom is proportional to the fourth power of the atomic number, and Moore's observation[7] that the number of photo-electrons is likewise proportional to its fourth power, when interpreted in terms of Moseley's law, means that the probability that a photo-electron ejected from the K shell of an atom traversed by x-rays is approximately proportional to the square of the energy required to remove a K electron from the atom. That is to say, the photoelectric effect becomes a very improbable event for loosely bound electrons, and for free electrons should not occur at all.

This conclusion is confirmed by the fact that if a free electron takes all the energy of the photon which it absorbs it must acquire more momentum than that possessed by the photon, so that the energy and momentum of the system photon plus electron cannot both be conserved in the photoelectric process.[8] The motion of the atomic core must also be considered to make conservation possible.

[1] A. H. Compton and A. W. Simon, Phys. Rev. **25,** 306 (1925).

[2] J. M. Nuttall and E. J. Williams, Manchester Memoirs **70,** 1 (1926).

[3] C. T. R. Wilson, Proc. Roy. Soc. **A104,** 1 (1923); A. H. Compton and J. C. Hubbard, Phys. Rev. **23,** 439 (1924).

[4] A. H. Compton and A. W. Simon, Phys. Rev. **26,** 289 (1925).

[5] M. de Broglie, Jour. de physique **2,** 265 (1921).

[6] E. A. Owen, Proc. Roy. Soc. **A94,** 522 (1918).

[7] H. Moore, Proc. Roy. Soc. **A91,** 337 (1915).

[8] Cf. the writer's "X-Rays and Electrons," p. 265, note 1.

Short duration of the recoil and photoelectric actions. Statistical studies of the motion of recoil and photo-electrons by the cloud expansion method have indicated that in both cases the forward momentum of the electron is on the average approximately equal to the momentum of the incident quantum.* The predominant motion of the recoil electrons is forward, though the experiments support the theory in showing a transverse component resulting from the deflection of the motion of the scattered photon.[1] For the photo-electrons the predominant motion is transverse, though, on the average, with a forward component which is stronger for the shorter wave-lengths as is indicated in the three curves of figure 1, representing data due to Auger.[9]

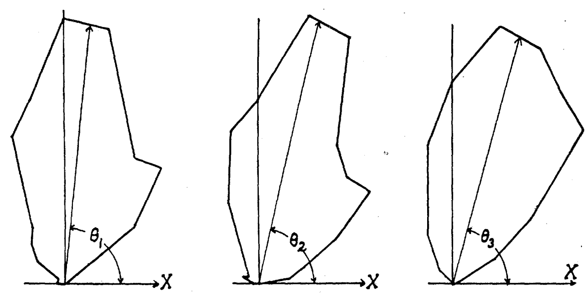

Fig. 1. Longitudinal distribution of photo-electrons for x-rays of three different wave-lengths, according to Auger. A photo-electron ejected at the angle θ has a forward momentum equal to that of the incident photon.

If the experimental result is correct that the recoil and photo-electrons retain all the forward impulse imparted by the photon, it means that the impulse has been imparted in a time short compared with the natural period of the electron in its parent atom. For if the duration were longer than this, most of the impulse would be transferred from the electron to the more massive parent atom. This means that the duration of the impulse due to the photon is also short compared with the period of the associated wave. Thus the action of the radiation on the electron cannot be an oscillatory one with the frequency of the wave associated with the photon. The experiments are on the other hand consistent with the view that both the recoil and the photo-electrons are ejected by sensibly instantaneous impulses from

[9] P. Auger, J. de phys. et rad. **6,** 205 (1925).

[10] F. Kirchner, Ann. d. Physik. **81,** 1113 (1926).

* Since this was written, experiments by Loughridge (Phys. Rev. **30,** 1927) have been published which show a forward component to the photo-electrons' motion which seems to be greater than that predicted by equation (2). Williams, in experiments as yet unpublished, finds that the forward component is almost twice as great as that predicted by this theory. These results indicate that the mechanism of interaction between the photon and the atom must be more complex than that here postulated. The fact that the forward momentum is found to be of the same order of magnitude as that of the incident photon, however, suggests that the momentum of the photon is acquired by the photo-electron, while an additional forward impulse is imparted by the atom. Thus these more recent experiments also support the view that the photo-electron acquires both the energy and the momentum of the photon.

the photons. It is in fact difficult to imagine any other type of action which would not impart to the positive core of the atom some of the forward momentum of the photon.

Direction of the impulse imparted to recoil electrons. We have noticed that the predominant motion of the recoil electrons is forward, that is, perpendicular to the electric vector of the incident wave. Recent experiments by Kirchner[10] have shown that even the transverse component of the motion of the recoil electrons is on the average greater in the direction of the magnetic than in that of the electric vector of the incident wave. These results are precisely what we should expect from an application of energy and momentum conservation to the system photon plus electron, if the distribution of the scattered photons is to be in approximate accord with Thomson's classical theory of the distribution of the scattered x-rays. Such a motion of the electrons is however in striking contrast with that predicted by Lorentz's force equation (1). Since the speed of these electrons is at all times small compared with that of light, this equation predicts a motion of the electron almost parallel (or anti-parallel) with the electric vector of the x-ray wave, that is, in a direction perpendicular to the preferred motion of the recoil electrons as shown by the experiments.

Our attention is thus forcibly called to the fact that if the field of an electromagnetic wave acts on a free electron in the manner indicated by Lorentz's equation, the momentum of the system radiation plus electron is not in general conserved in the process. For if the Poynting vector expresses the momentum of the radiation, we find that this momentum is wholly in the direction of propagation of the electromagnetic wave, whereas the impulse imparted to an electron by the electric vector is according to equation (1) perpendicular to the direction of propagation. This means that the electron acquires a transverse momentum which is not balanced by any transverse momentum lost by the radiation. Thus if the momentum is to be conserved, this equation cannot represent the action of radiation on a free electron.

An experimental test of this point is not easy. In experiments with steady or slowly changing electric and magnetic fields, the applied fields are due to the presence of electrically charged or magnetized bodies, which receive the reaction from the force applied to any charge in the field. It is only with radiation fields that the test can be made, since only in this case can the electromagnetic field be considered separate from the charges which give rise to the field. Apparently the only example of the action of radiation on isolated electrons that has been studied experimentally is the production of recoil electrons when x-rays are scattered. In this case, as we have seen, the impulse imparted to the electron by the radiation is in the direction required by the conservation of momentum, which is almost perpendicular to that suggested by the classical force equation.

Direction of the impulse imparted to photo-electrons. When a radiation field acts upon a pair of positive and negative charges, there is no difficulty with the conservation of linear momentum, for the impulses imparted by the electric vector of the radiation to the positive and negative charges will presumably be equal and opposite. From the standpoint of momentum conservation, therefore, it would not be surprising if the greater part of the momentum of the photo-electron were transverse, as suggested by equation (1). We must consider also, however, the conservation of angular momentum.

If the photon acts instantaneously upon a photo-electron, as the experiments suggest, in order that it may impart to the atom all of its energy and at the same time its linear and angular momentum, there is only one definite direction in which the impulse may act. If the angular momentum of the photon is zero, it must not impart any angular momentum to the atom. That is, neglecting the effect of radiation pressure, the impulse imparted to the electron must be along the line joining the electron and the atomic core. If the photon possesses angular momentum, as may be the case with circularly polarized light, the impulse must be in the direction necessary to give this angular momentum to the dissociated atom and electron.

There is thus a single line in the atom on which an electron can lie where the photon can impart to it a photoelectric impulse along the electric vector of the associated wave, and still conserve the angular momentum of the

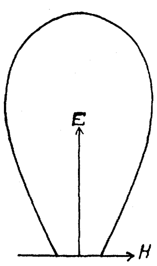

Fig. 2. Lateral distribution of photo-electrons for incompletely polarized x-rays, according to Bubb.

system. If we were to suppose that the impulse must be exactly in the direction of the electric vector, this would mean that if the electron were in any other position in the atom, the photon could not act upon it photoelectrically. A more plausible assumption would seem to be that the photon may act on the electron in any position in the atom, with an impulse in the direction demanded by the conservation of angular momentum, but that the probability that such action shall occur is greater the nearer its direction approaches the electric vector. This assumption would be consistent with the conservation of angular momentum for each individual event, and would be statistically in accord with the force equation.

The experimental evidence is in complete accord with the latter assumption. It is found that the impulse imparted to the photo-electrons is not always in the same direction, but may occur in a wide variety of directions. This is illustrated by Auger's experiments shown in figure 1. Except for the angle θ, which as we have seen is due to the radiation pressure or momentum of the photon, the most probable direction of emission is that of the electric

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

vector; but many photo-electrons are also observed at other angles. The experiments of Bubb,[11] summarized in Fig. 2, show in a similar manner how the directions of ejection are distributed when polarized x-rays are used. We see here clearly that though the probability is greatest for ejection in the plane of the electric vector, some electrons are ejected at all possible angles. In these experiments the polarization of the x-rays was not complete. A correction for the unpolarized x-rays reduces the probability of emission perpendicular to the electric vector approximately to zero. Even with this correction, however, photo-electrons are observed at all other angles. Both this experiment of Bubb and that of Auger have been confirmed by a number of different investigators.[12]

Attempts have been made[13] to account for the variation in the direction of emission of the photo-electrons as due to the initial motions of the electrons in their orbits; but these have failed to account for the fact that the probability of emission in the different directions is practically the same for all atoms from which the electrons come, whereas the initial motions of the electrons may differ widely for electrons in the different atoms. There does not seem to be any way of accounting for this wide distribution of the directions of emission other than to suppose that the impulse applied to the electron by the radiation is variable in direction.[14] That is, the impulse is not necessarily in the direction of the electric vector; this (neglecting the effect of radiation pressure) is only the most probable direction for the impulse to act.

In the treatment of photoelectric emission from the standpoint of wave mechanics, Wentzel[15] has concluded that the probability of photoelectric ejection at an angle α with the electric vector (neglecting radiation pressure) is proportional to $\cos^2 \alpha$. This is precisely the result to which Auger and Perrin[16] had been led empirically in order to account for Auger's experiments such as those shown in Fig. 1. The distribution of the directions of emission of the photo-electrons is thus of exactly the type which we should expect from considerations of conservation of angular momentum.

In the case of the photo-electric effect with visible or ultra-violet light, the magnitude of the work function required to remove the photo-electrons from the metal suggests that we may be dealing with "conductivity" electrons associated with the whole mass of metal. If this is the case, there should be no difficulty with the conservation of the angular momentum of the system, and we might expect the photo-electrons to be ejected almost exactly in the direction of the electric vector. An experimental test of this point in the case of the selective photoelectric effect would be of great interest.

[12] W. Bothe, Zeits. f. Physik. **26,** 59 (1924); D. H. Loughridge, Phys. Rev. **26,** 697 (1925); F. Kirchner, Zeits. f. Physik. **27,** 385 (1926).

[13] F. W. Bubb, Phil. Mag. **49,** 824 (1925); W. Bothe, Zeits. f. Physik. **26,** 74 (1924).

[14] For a more detailed discussion of this point, see the writer's "X-Rays and Electrons," p. 25 (1926).

[15] G. Wentzel, Zeits. f. Physik. **40,** 574 (1926).

[16] P. Auger and F. Perrin, C. R. **180,** 1742 (1925).

Both in the case of the action of x-rays on isolated electrons (recoil effect) and that of their action on a pair of positive and negative charges (photoelectric effect) we find evidence of radiation pressure, which means a force of the type indicated by the second term of Lorentz's force equation. We find, however, that for isolated electrons there is no evidence that there exists any force associated with the electric field of the x-ray wave. At least the favored direction of recoil is at right angles with the electric field. For an electron associated with a positively charged atom, the first term of equation (1) may be taken to represent the most probable direction in which the electric field will act on the electron. The direction of the photoelectric action in each individual case is however apparently determined by the requirements of the conservation of the angular momentum of the system.

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