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The Nuclear Photoelectric Effect

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1—Introduction

Some time ago we reported in 'Nature'* the observation of a nuclear photo-effect, the disintegration of the deutron by γ-rays. An effect of γ-rays upon complex nuclei might be expected to occur from analogy with the phenomena of excitation and ionization of atoms by light, and such an effect has been looked for from time to time by various investigators.

A necessary condition to make disintegration possible is that the energy of the γ-ray quantum must be greater than the binding energy of the particle which is to be removed from the nucleus. The most energetic γ-rays which are readily available in sufficient intensity are those of thorium C'', which have an energy $h\nu = 2 \cdot 62 \times 10^6$ electron volts. One can hope, therefore, using these γ-rays, to produce disintegration with the emission of a heavy particle, such as a neutron, proton, etc., only in those nuclei which have a small or negative mass defect, such as the nuclei of deuterium, beryllium, and those radioactive elements which emit α-particles. In fact, only the nuclei of deuterium and beryllium have so far been disintegrated in this way. The disintegration of beryllium by the γ-rays of radium was first reported by Szilard and Chalmers.† No evidence of a photo-electric disintegration amongst the radioactive elements has yet been found.

2—Experiments with Deuterium

The first element to be examined for this nuclear photo-effect was the heavy isotope of hydrogen, deuterium. This was chosen because it was well established that the deuteron has a small mass defect. The disintegration to be expected is

$$_1D^2 + h\nu \rightarrow {_1H^1} + {_0n^1}. \tag{1}$$

If W is the binding energy of the deuteron, the energy available for the proton and neutron will be $h\nu - W$. Unless this energy is very small,

* Chadwick and Goldhaber, 'Nature,' vol. 134, p. 237 (1934).
† 'Nature,' vol. 134, p. 494 (1934).

the kinetic energies of the proton and neutron will be nearly equal since their masses are nearly the same and the momentum of the quantum is small. To establish the reaction (1) completely it is desirable to detect both the proton and the neutron released in the process.

(*a*) *Detection of the " Photo "-protons*—The experimental arrangement for the detection of the protons released from deuterium, which we may for convenience call " photo "-protons, was as follows. An ionization chamber, $4 \times 6 \times 8$ cm in dimension, was filled with heavy hydrogen of about 95% purity to atmospheric pressure. The chamber was connected to a linear valve amplifier and oscillograph in the usual way. A source of radiothorium, equivalent in γ-ray activity as measured through 6 mm of lead to 9 mg of radium, was placed at distances varying from 12 cm to 30 cm from the chamber. Blocks of lead were inserted between the source and the chamber to absorb the soft γ-rays emitted by the source; these would be ineffective in promoting the desired photo-effect while giving rise to a disturbing background due to the ionization produced in the chamber. The oscillograph records showed above the background due to the γ-radiation a number of deflections which could only be due to a heavy ionizing particle. When the heavy hydrogen was replaced by ordinary hydrogen the background remained the same, but very few deflections were observed and their number was not appreciably greater than the natural effect of the chamber, 15 " kicks " per hour on the average. Similarly when the chamber was filled with nitrogen the numbers of kicks observed with and without the radiothorium source were about the same. These observations show that the kicks observed with heavy hydrogen were not produced by the collisions of any neutrons which might perhaps be emitted by the source.* They must be attributed to protons resulting from the splitting of the deuteron by the absorption of a γ-ray quantum.

The kicks were, allowing for the natural effect, all of about the same size; this is to be expected from the reaction (1) since the γ-radiation entering the chamber is mainly of the one energy $h\nu = 2 \cdot 62 \times 10^6$ e.v.† An estimate of the energy of the photo-protons can be deduced from the measurement of the size of the oscillograph kicks. From experiments

* Radioactive sources often emit neutrons produced by the disintegration under α-particle bombardment of light elements, *e.g.*, boron, present in the material or container of the source.

† A small variation in size will arise from the fact that the energy of the proton will vary with its direction of emission relative to the direction of the γ-ray by a noticeable amount, as a simple calculation shows.

in which α-particles of known residual range were admitted into the ionization chamber it was found that an oscillograph deflection of 1 mm on the record corresponded to the production of 1200 ion pairs. The average size of the kicks due to the photo-protons was about 6 mm, corresponding to the production of 7200 ion pairs. Assuming that the amount of energy lost by a proton in producing 1 ion pair is the same as that lost by an α particle, viz., 33 e.v., we find that the energy of the photo-protons in our experiments was about 240,000 e.v. This estimate of the proton energy, although rough, is not likely to be in error by more than 80,000 e.v.

The sum of the kinetic energies of the proton and neutron resulting from the division of the deuteron is thus nearly 500,000 e.v. The binding energy of the deuteron is therefore about $2 \cdot 1 \times 10^6$ e.v. or $0 \cdot 0023$ in mass units.

If the masses of the atoms of hydrogen and deuterium were accurately known we could now fix the mass of the neutron with almost equal precision. Unfortunately, there is still some uncertainty about these masses. During the past few years it has become apparent that there was some discrepancy between the masses of the light atoms as compared in the mass-spectrograph measurements of Aston and Bainbridge and in the data obtained from nuclear transformations. It has been shown by Oliphant, Kempton, and Rutherford,* and by Bethe† that the discrepancies probably arise by the cumulative effect of a small error in the ratio of the masses of $He^4 : O^{16}$. This suggestion seems to be confirmed by direct measurements of Aston.‡ The values derived from disintegration data for the masses of the atoms of hydrogen and deuterium are $1 \cdot 0081$ and $2 \cdot 0142$ respectively. Adopting these values we obtain a value for the mass of the neutron of $1 \cdot 0084$. If, however, we take Aston's recent provisional values, $1 \cdot 0081$ and $2 \cdot 0148$, we obtain a value for the mass of the neutron of $1 \cdot 0090$.

(*b*) *Probability of Disintegration*—The next point of interest is the probability of the " photo "-disintegration. This was measured approximately both in the experiments already described and also in others in which the source of radiation was the active deposit, thorium (B + C). In the latter experiments, a source equivalent in γ-ray activity to $3 \cdot 4$ mg radium was placed 30 cm away from the centre of the chamber. A block of lead 26 mm thick was placed in front of the chamber to absorb the soft

* ' Proc. Roy. Soc.,' A, vol. 150, p. 241 (1935).

† ' Phys. Rev.,' vol. 47, p. 634 (1935).

‡ ' Nature,' vol. 135, p. 541 (1935).

γ-rays. Thus the number of γ-ray quanta of $h\nu = 2 \cdot 6 \times 10^6$ e.v. passing through the chamber was about 8×10^4 per minute, per sq cm of surface. The number of kicks due to the photo-protons liberated under these conditions was about 30 per hour. The volume of the chamber was about 190 cc, and thus the number of deuterons was 10^{22}. We find, therefore, that the cross-section for disintegration of the deuteron by a γ-ray of $2 \cdot 62 \times 10^6$ e.v. is about $6 \cdot 6 \times 10^{-28}$ sq cm. The average value for this cross-section obtained from this and the previous experiments was about 5×10^{-28} sq cm with a possible error of a factor of 2.*

The effects of the γ-rays of radium in producing the photo-disintegration was also examined. A radium source of 7 mg was used and the numbers of kicks observed when the ionization chamber filled with deuterium was exposed alternately to this radium source and the radiothorium source of 9 mg were counted. With the radiothorium source 107 kicks per hour were obtained, compared with 20 kicks per hour with the radium source, while the natural effect to be deducted was 15 per hour. It is clear that the radium γ-rays are much less effective than those of radiothorium. This is indeed only to be expected if the binding energy of the deuterium is as high as $2 \cdot 1 \times 10^6$ e.v. for in the γ-ray spectrum of radium (B + C) there are only a few weak lines with energies greater than this. The excess of 5 kicks per hour over the natural effect shown in the radium experiments is barely outside the statistical error of the observations, but, as we shall show later, a detectable effect is in fact produced by the γ-rays of radium.

(*c*) *The " Photo "-neutrons from Deuterium*—To show the liberation of neutrons from deuterium by the effect of γ-rays we made use in the first experiments of the phenomenon of induced activity. The source of radiothorium was placed in the inner tube of a double-walled glass vessel, the outer tube of which contained heavy water. In the earlier experiments only about 10 cc of water containing about 20% D_2O were available, but later we were able to use about 20 cc of 98% D_2O. A cylinder of silver was placed round the glass vessel and thus exposed to the neutrons liberated from the deuterium. After 2 to 10 minutes' exposure the silver cylinder was removed and placed so as to enclose a Geiger-Müller tube counter which had a wall of copper sufficiently thin to admit β-rays. In some experiments we found it convenient to use a silver-walled counter as detector. Only a small and somewhat uncertain effect was obtained in this way. The source + heavy water + silver

* Owing to an arithmetical error, the value given for this cross-section in the note to ' Nature ' was 1×10^{-28} sq cm.

tube or silver counter were therefore surrounded during the exposure by a large cylinder of paraffin wax. As Fermi and his collaborators have shown* the induced effect produced in silver by neutrons may be largely increased in this way. Under these conditions the silver showed a strong activity which decayed with the known periods of 22 secs and 2·3 min, and the liberation of neutrons from deuterium by the γ-rays of radiothorium was clearly established. We were also able to show, using a source of radon of about 150 millicuries, that the γ-rays of radium (B + C) are able to disintegrate deuterium.

To compare the relative effects of the γ-rays from radiothorium and radium we found it more convenient to use the disintegration effects provoked by slow neutrons rather than the induced radioactivity. When lithium and boron are exposed to slow neutrons the following reactions take place†

$$Li^6 + n^1 \rightarrow He^4 + H^3,$$

$$B^{10} + n^1 \rightarrow Li^7 + He^4.$$

In these reactions the particles are emitted with considerable energy and are therefore readily detectable by their ionization effects. The cross-section for these reactions is very large and thus they afford a very sensitive means of detecting slow neutrons.

The inner surface of an ionization chamber was coated with a thin layer of lithium metal or boron powder and the electrode was connected to a valve amplifier and oscillograph. The capture of a neutron by the lithium or boron was recorded by a kick of the oscillograph due to one of the particles emitted in the disintegration process. In order to reduce the unsteady background due to the presence of γ-rays a block of lead of suitable thickness was interposed between the source and ionization chamber. (The absorption of neutrons in the lead block was small and could be neglected in these experiments.) The whole arrangement, consisting of source + heavy water, lead and ionization chamber, was surrounded by paraffin wax. For convenience we shall use the term " slow neutron intensity " to denote the effect of a neutron source measured in such an arrangement. Using a lithium-coated chamber having a total lithium surface of about 40 sq cm the natural effect—the number of kicks in the absence of the source—was about 40 per hour. With a source of radiothorium of 8 mg γ-ray activity surrounded by 15 cc of

* Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segrè, 'Proc. Roy. Soc.,' A, vol. 149, p. 522 (1935).

† Chadwick and Goldhaber, 'Nature,' vol. 135, p. 65 (1935) ; Amaldi and others, *loc. cit.*; Taylor and Goldhaber, 'Nature,' vol. 135, p. 341 (1935).

heavy water (98%), the number of deflections observed was more than 2000 per hour. To observe the effect of the γ-rays of radium (B + C) a radon source of about 150 millicuries was used, contained in a copper tube of 1 mm inner diameter and 12 mm length.* It was found that the slow neutron intensity of this source was about 1/27 of that for a radiothorium source of equal γ-ray activity. One must not conclude from this observation that the number of photo-neutrons from radiothorium + D is 27 times larger than the number of photo-neutrons from radon + D (for equal γ-ray intensities), since the initial velocities of the neutrons, and hence their mean free paths in paraffin, are different in the two cases. The velocities of the neutrons from radon + D are smaller than those of the neutrons from radiothorium + D and their mean free paths in paraffin will therefore be smaller, so that the number of photo-neutrons from radon + D will be somewhat greater than 1/27 of the number from radiothorium + D.

When no paraffin wax was used around the source and ionization chamber some effect was still observed, about 1/50 of the effect with paraffin. This effect was shown to be due partly to disintegrations produced by photo-neutrons of the primary energy and partly to disintegrations produced by some slow neutrons. Owing to the smallness of the effect it was not possible to settle definitely how these slow neutrons were produced, but it seems probable that they were due to scattering of photo-neutrons in the heavy water and were not produced by γ-rays of energy very close to the threshold value.

(*d*) *The Angular Distribution of the " Photo " Neutrons*—The probability of the direction of emission of the photo-proton or neutron with respect to the direction of the γ-ray is a point of some importance in the quantum theory of the deuteron. A detailed study of the angular distribution of the protons is possible with the aid of an expansion chamber filled with gas containing deuterium, and this is now in progress. In the meantime, however, we have obtained some rough information about the angular distribution of the neutrons in a plane containing the γ-ray beam by using the arrangement shown in fig. 1.

A cylindrical ionization chamber I of 2 cm diameter, with its inner wall and collecting rod coated with boron powder, was used as the neutron detector. It was enclosed in a block of paraffin wax. The radiothorium source was placed in positions A or B and in both cases observations were made with and without the vessel of heavy water, 3 cm in diameter,

* Such a source was found to emit very few neutrons as compared with radon sources contained in glass tubes.

containing 23 cc of D_2O (98%), at C. The thickness of lead, *a*, was 3·5 cm, and the distances, *b* and *c*, were 7·5 cm and 3 cm respectively. The neutron intensity found with the source at B was about twice as great as with the source at A, showing that more photo-neutrons are emitted in a direction at right angles to the incident γ-ray beam than in the forward direction. The effects observed were too small to allow the geometry of the arrangement to be made more definite, but the result is sufficient to show that the angular distribution of the neutrons is not spherically symmetrical with probably a maximum at right angles to the γ-ray beam.

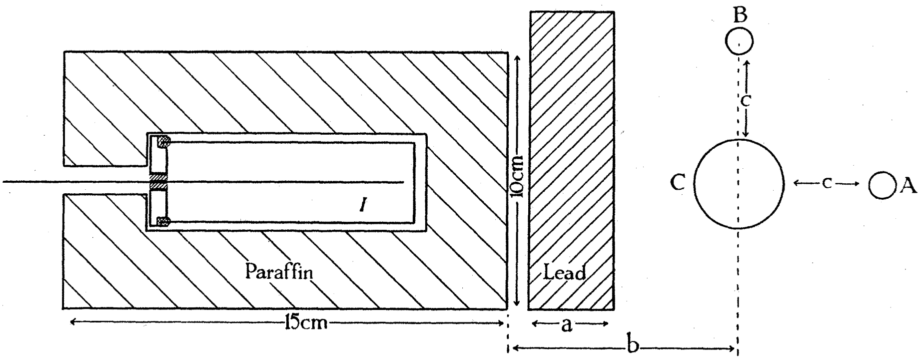

FIG. 1

3—Experiments with Beryllium

(*a*) The disintegration of beryllium by γ-rays was first shown by Szilard and Chalmers.* They used the γ-radiation of radium and observed the photo-neutrons by means of the induced activity produced in iodine. Two processes seem to be possible energetically with the γ-rays used:—

$$Be^9 + h\nu \rightarrow Be^8 + n^1, \tag{2}$$

$$Be^9 + h\nu \rightarrow He^4 + He^4 + n^1. \tag{3}$$

It may be that both reactions take place and that their relative probability depends on the energy of the γ-radiation. The experiments we shall now describe lead indirectly to the conclusion that reaction (2) probably predominates.

In our first experiments to detect the disintegration of beryllium by γ-rays we exposed an ionization chamber, the face of which was covered with a beryllium foil or beryllium powder, to the γ-rays of radium and radio-

* 'Nature,' vol. 134, p. 494 (1934).

thorium. The chamber was connected to a linear amplifier in order to detect the charged particles, whether Be^8 or He^4, resulting from the disintegration. No definite effect was found. This might have been due either to the small probability of the disintegration process or to the small range of the charged particles liberated.

The detection of the neutrons is possible by a variety of means. In some experiments we have made use of the induced activity of silver, in others of the disintegration effects produced in a boron- or lithium-coated ionization chamber. In general the effects are small unless paraffin wax or water is used to slow down the neutrons. Using a similar arrangement to that described in § 2 for the photo-neutrons from deuterium—lithium-coated chamber, source and chamber surrounded by paraffin—we have compared the intensities of the slow neutrons obtained when beryllium is irradiated by radium or radiothorium. The ratio found was about 2 : 1 for sources of equal γ-ray intensity, agreeing with a result of Gentner.* One must not conclude from this result that the effective cross-section for disintegration of beryllium by radon γ-rays is larger than that for disintegration by radiothorium γ-rays, for the neutrons will be liberated with different energies in the two cases and will therefore have different mean free paths in paraffin. Although the difference between the relative effects of radiothorium and radium γ-rays in deuterium and beryllium is very striking, it is not possible to make any certain deduction from the above observations about the dependence of the probability of disintegration with the energy of the γ-ray quantum.

(*b*) *The Threshold Value of Beryllium*—A matter of some interest is the minimum energy of the γ-ray quantum which will disintegrate beryllium. In some preliminary experiments we attempted to obtain some information on this point by interposing lead absorbers between the radon source and the beryllium, and measuring the decrease in the slow neutron intensity as the thickness of lead was increased. The results showed that no rays of energy less than 10^6 e.v. are able to disintegrate beryllium. The threshold value for the energy could not be fixed with any accuracy in this way, for when the geometry of the arrangement was made reasonably definite the effects obtained were rather small.

We therefore proceeded to use the following method to determine the energy necessary to remove a neutron from beryllium. In an ionization chamber filled with either hydrogen or helium the effects due to the recoil atoms produced by impact of the photo-neutrons from radon-Be or radiothorium-Be can be readily observed. We measured the maximum

* 'C.R. Acad. Sci. Paris,' vol. 199, p. 1211 (1934).

energy of the recoil atoms produced in a helium chamber when bombarded by photo-neutrons from radiothorium-Be. With a source of radiothorium the photo-neutrons are almost entirely due to the strong line of $h\nu = 2 \cdot 62 \times 10^6$ e.v., and this source was therefore preferred to a radon source. Helium is in this case more suitable than hydrogen because the maximum range of the recoil atoms, which must be small compared with the dimensions of the chamber, is shorter; moreover, the oscillograph deflections due to the recoil atoms can be compared directly with those produced when α-particles of known range are admitted into the ionization chamber.

The radiothorium source was surrounded by pieces of beryllium metal of a total weight of 450 gm. To reduce the γ-ray background a suitable thickness of lead (from 3 to 6 cm) was interposed between the photo-neutron source and the helium chamber. By plotting a diagram of the number of deflections against their size and allowing for the small natural effect it was found that the maximum deflection was about 10 mm. This corresponded to a maximum energy of the recoil atoms of 580,000 e.v. Since in a collision with a neutron the helium atom receives a maximum of 16/25 of the neutron energy this leads to a maximum energy of the photo-neutrons of about 900,000 e.v. As at the most 8/9 of the kinetic energy of the particles resulting from the disintegration can be acquired by the neutron we obtain for the total surplus energy about 1×10^6 e.v. Since the γ-radiation used has an energy of $2 \cdot 6 \times 10^6$ e.v. this means that an energy of about $1 \cdot 6 \times 10^6$ e.v. is required to remove a neutron from Be^9. This is in general agreement with the experiments of Brasch, Lange, and others,* who found that beryllium can be disintegrated by X-rays of energy less than 2×10^6 e.v., and those of Arzimovitch and Palibin,† who found that X-rays of $1 \cdot 35 \times 10^6$ e.v. were ineffective.

(*c*) *The Disintegration Process*—The above result is consistent with the reaction

$$Be^9 + h\nu \rightarrow Be^8 + n^1. \tag{2}$$

The mass difference between Be^9 and Be^8 obtained from this reaction using our result agrees well with that determined by Oliphant, Kempton, and Rutherford‡ from the reaction

$$Be^9 + H^1 \rightarrow Be^8 + D^2.$$

* Brasch, Lange, Waly, Banks, Chalmers, Szilard, and Hopwood, 'Nature,' vol. 134, p. 880 (1934).

† 'Z. Phys. Sowjet,' vol. 7, p. 245 (1935).

‡ 'Proc. Roy. Soc.,' A, vol. 150, p. 241 (1935).

Other evidence points indirectly to the same process (2). The failure to observe charged recoil atoms in the photo-disintegration of beryllium would be immediately explained, for recoil atoms of Be^8 would be short in range and of small energy. Moreover, if reaction (3) were the disintegration process one would expect to obtain in a three-body reaction some neutrons of small energy.* This does not appear to be the case. Using lithium-and boron- coated ionization chambers without paraffin, we found a small but measurable effect which was not appreciably reduced when a plate of silver 3·5 mm thick was placed between the photoneutron source, either radon-Be or radiothorium-Be, and the chamber. Such a silver plate is sufficient to absorb to a large extent any slow neutrons present. By placing a paraffin block behind the chamber the relative effect of neutrons of small energy would be increased owing to the larger scattering in the paraffin. No appreciable difference, however, could be observed with and without the silver absorber in the primary neutron beam. Absorbers of lithium fluoride and borax were also used with the same negative result. These experiments indicate that the proportion of photo-neutrons of low energy is small.

Assuming that the reaction (2) is correct, which implies that the photoneutrons from beryllium with a radiothorium source are homogeneous in velocity, a lower limit for the probability of the photo-disintegration by these γ-rays can be obtained in the following way. We found that the slow neutron intensities per atom Be or D when a radiothorium source was surrounded by beryllium powder or heavy water—keeping the geometry as far as possible the same—were in the ratio of 1 to 6.† As the mean free path in paraffin of the Be photo-neutrons will be greater than that of the slower D photo-neutrons we conclude that the cross-section for the disintegration of beryllium is greater than one-sixth of the cross-section for deuterium, *i.e.*, $\sigma_{Be} > \frac{1}{6}\sigma_D \sim 10^{-28}$ sq cm using γ-rays of $h\nu = 2 \cdot 62 \times 10^6$ e.v.

(*d*) *Angular Distribution*—The angular distribution of the photoneutrons from beryllium was investigated, using an arrangement similar to that used for the D photo-neutrons and described in § 2 and fig. 1. The vessel with the heavy water was replaced by a beryllium block of 98 gm weight. The block was of irregular shape with a maximum linear

* The term " small energy " here means energies up to a few thousand volts. Some unpublished experiments indicate that neutrons of these energies have still a high probability of disintegrating lithium.

† This ratio depends, of course, to some degree on the geometry of the general arrangement (paraffin, etc.) and on the indicator used for the slow neutrons.

dimension of 6 cm. A radon source of about 150 millicuries was used, and the effects were large enough to allow a better defined geometry than with heavy water. The distances a, b, c, fig. 1, were now $a = 9$ cm, $b = 12$ cm, $c = 7 \cdot 5$ cm. The effects found with the source in positions A and B were equal within the probable error of 15%. Thus the angular distribution of the photo-neutrons from beryllium differs markedly from that found for the photo-neutrons from deuterium.

4—We have given in the course of this paper measurements of the relative effects of the photo-neutrons from deuterium and beryllium under the action of radium and radiothorium γ-rays, as determined by the relative numbers of slow neutrons obtained in a paraffin scatterer. For convenience the results are collected in Table I in which the slow neutron intensities per mg γ-ray activity per nucleus D or Be are given relative to the intensity obtained from radiothorium-D.

TABLE I

Source of γ-rays \ Nucleus	D	Be
RdTh	1	1/6
Rn	1/27	1/3

These four sources of neutrons are useful in many experiments in which neutrons of fairly homogeneous or not too high velocity are required. They give neutrons which are not slow in the sense of the "slow" neutrons produced by paraffin scattering but give neutrons of energies from a few 10^4 e.v. for radon-D up to 9×10^5 e.v. for radiothorium-Be. By using neutrons of different energies it may be possible to throw light on the processes which take place in the passage of neutrons through matter. It is interesting in this connection to note that when one of these photo-neutron sources was used no increase in effect could be obtained in a boron-coated chamber by surrounding it with lead; that is, no "slow" neutrons were produced by scattering in lead. On the other hand, we confirmed the result of Amaldi and others (*loc. cit.*) that lead slows down the neutrons from the usual beryllium-radon source. This suggests that these neutrons have not sufficient energy to excite a lead nucleus, for which process an energy of about $1 \cdot 5 \times 10^6$ e.v. seems from Lea's experiments* to be required.

* 'Proc. Roy. Soc.,' A, vol. 150, p. 637 (1935).

5—Search for Photo-effect in other Elements

We have found no evidence of a nuclear photo-disintegration in any other elements.

We have examined the following elements for the emission of charged particles, using a radiothorium source and sometimes also a radon source: lithium, boron, carbon, nitrogen, oxygen, fluorine, neon, aluminium, nickel, copper, zinc, and uranium. With uranium a foil of aluminium of 3 cm air equivalent was placed over the target of uranium oxide in order to prevent the α-particles of uranium from entering the chamber. It was expected that any α-particles emitted under the action of the γ-rays would have greater energy than the natural α-particles and would therefore pass through the aluminium screen. No evidence of such particles could be detected.

The following elements have been examined for the emission of neutrons: lithium, boron, carbon, nitrogen, oxygen, fluorine, magnesium, aluminium, phosphorus, chlorine, potassium, calcium, manganese, copper, zinc, bromine, tin, rhodium, silver, cadmium, tungsten, thallium, lead, bismuth, thorium, and uranium.

6—Discussion

The main importance of the nuclear photo-electric effect is that it gives a means of studying the interaction of electromagnetic radiation and heavy particles. The deuteron is of special interest because this is the simplest of all nuclear systems. As our experiments have shown directly, it consists of a proton and a neutron bound together with an energy of about $2 \cdot 1 \times 10^6$ e.v. The role of the deuteron in nuclear theory thus corresponds to the role of the hydrogen atom in atomic theory. If the forces between the proton and the neutron were known exactly the properties of the deuteron-binding energy, probability of disintegration by γ-rays, etc.—could be calculated. On the assumption that the interaction between a proton and a neutron is very strong at short distances and is confined to a range of the order of 10^{-13} cm, Bethe and Peierls,* and also Massey and Mohr,† have calculated the probability of disintegration of the deuteron by γ-rays. They assume further that the laws of non-relativistic quantum mechanics are valid for the interaction of the proton and neutron with each other and with radiation; the proton is treated as a point charge and it is assumed that there is no

* ' Proc. Roy. Soc.,' A, vol. 148, p. 146 (1935).

† *Ibid.*, vol. 148, p. 206 (1935).

interaction between the neutron and radiation. On this basis Bethe and Peierls obtained an excitation curve for the photo-disintegration of the deuteron in which the cross-section for disintegration is a function of the ratio of the energy of the quantum to the binding energy of the deuteron. The maximum cross-section occurs when the quantum energy $h\nu$ is equal to twice the binding energy W, and is given by

$$\sigma_{\text{max}} = \frac{1}{6} \cdot \frac{he^2}{\text{M}c} \cdot \frac{1}{\text{W}},$$

where $\frac{1}{2}$M is the reduced mass of the proton and neutron. The cross-section for a quantum of energy $h\nu = \gamma \, . \, \text{W}$ is

$$\sigma = 8 \, . \, \frac{(\gamma - 1)^{3/2}}{\gamma^3} \, . \, \sigma_{\text{max}}.$$

The cross-section for disintegration by a given γ-ray is thus completely determined when the binding energy of the deuteron is known. With the value given by the experiments of § 2 (*a*), $\text{W} = 2 \cdot 1 \times 10^6$ e.v., the above formula gives $\sigma = 8 \times 10^{-28}$ sq cm for a γ-ray of $h\nu = 2 \cdot 62 \times 10^6$ e.v. The direct measurement of the cross-section, § 2 (*b*), gave a value for σ of about 5×10^{-28} sq cm with an uncertainty of a factor 2. This is a satisfactory agreement with the theoretical value.

An asymmetry of the angular distribution as found for the photo-neutrons from deuterium, § 2 (*d*), is to be expected on simple theoretical reasoning. If one assumes that the range of the forces between neutron and proton is small compared with the wave-length of the γ-ray used, namely $4 \cdot 7 \times 10^{-11}$ cm, and that the ground state of the deuteron has an orbital momentum $l = 0$,* then the $\cos^2 \phi$ law should hold for the probability of emission of the photo-protons or neutrons at an angle ϕ with the direction of the electric vector,† neglecting the momentum of the γ-ray.

The apparently spherically symmetrical distribution of the photo-neutrons from beryllium, § 3 (*d*), suggests that the neutron in beryllium is probably bound in a state with orbital momentum $l = 1$.

A few remarks may be made about the mass of the neutron. As we have shown, our experiments fix the binding energy of the deuteron as about $2 \cdot 1 \times 10^6$ e.v. This leads to a value for the mass of the neutron of 1·0084 if we take the value for the deutron mass given by Oliphant, Kempton, and Rutherford, or Bethe, and 1·0090 if we take the new value

* Wigner, ‘Phys. Rev.,’ vol. 43, p. 252 (1933); Bethe and Peierls, *loc. cit.*

† *Cf.* Wentzel, ‘Z. Physik,’ vol. 40, p. 574 (1926); Bethe, ‘Handb. der Physik,’ vol. 24, pt. 1, p. 482 (1933).

of Aston. It seems that the neutron is definitely heavier than the hydrogen atom (1·0081).

It is generally assumed that the neutron and proton behave in many ways like elementary particles but yet can under certain conditions change into each other with the emission of an electron, negative or positive, as the case may be. In order to conserve energy and spin it appears necessary to assume the existence of a neutrino, a particle of small mass, no charge, and spin $\frac{1}{2}$.* If the neutron is definitely heavier than the hydrogen atom, then one must conclude that a free neutron is unstable, *i.e.*, it can change spontaneously into a proton + electron + neutrino, unless the neutrino has a mass of the order of the mass of the electron. These speculations must, however, depend on more exact measurements of the masses of hydrogen and deuterium.

In conclusion we wish to thank here Dr. D. E. Lea for the loan of the amplifier used in the Geiger counter experiments and Professor A. I. Leipunski for his help in some of the observations and for the loan of beryllium. One of us (M. G.) desires to acknowledge the financial assistance received from the International Student Service, London, and Magdalene College, Cambridge.

Summary

An account is given of experiments on the nuclear photo-electric effect. With heavy hydrogen, the reaction

$$D^2 + h\nu \rightarrow H^1 + n^1$$

has been established, both protons and neutrons having been detected. From the energy of the protons released by a γ-ray of $h\nu = 2\cdot62 \times 10^6$ e.v. the binding energy of the deuteron has been determined; it is about $2\cdot1 \times 10^6$ e.v. This fixes the mass of the neutron with respect to the masses of H and D. Using the masses of H and D from disintegration data the mass of the neutron is 1·0084; using Aston's new values, the mass is 1·0090. The neutron appears to be definitely heavier than the hydrogen atom.

The probability of disintegration of the deuteron by γ-rays agrees satisfactorily with theoretical calculations.

* The non-conservation of energy is well known from the β-ray spectra. The non-conservation of spin appears from reactions such as

$$Mg^{24} + n^1 \rightarrow Na^{24} + H^1 \rightarrow Mg^{24} + e + H^1.$$

Experiments with beryllium suggest that the main reaction is

$$Be^9 + h\nu \rightarrow Be^8 + n^1.$$

The energy necessary to remove a neutron from beryllium is about $1 \cdot 6 \times 10^6$ e.v.

Some information about the angular distribution of the photo-neutrons is given for both cases.

No evidence of a nuclear photo-effect has been observed for several other elements which were examined.
