A 'Nuclear Photo-effect': Disintegration of the Diplon by γ-Rays

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BY analogy with the excitation and ionisation of atoms by light, one might expect that any complex nucleus should be excited or 'ionised', that is, disintegrated, by γ-rays of suitable energy. Disintegration would be much easier to detect than excitation. The necessary condition to make disintegration possible is that the energy of the γ-ray must be greater than the binding energy of the emitted particle. The γ-rays of thorium C″ of $h\nu = 2 \cdot 62 \times 10^6$ electron volts are the most energetic which are available in sufficient intensity, and therefore one might expect to produce disintegration with emission of a heavy particle, such as a neutron, proton, etc., only of those nuclei which have a small or negative mass defect; for example, D^2, Be^9, and the radioactive nuclei which emit α-particles. The emission of a positive or negative electron from a nucleus under the influence of γ-rays would be difficult to detect unless the resulting nucleus were radioactive.

Heavy hydrogen was chosen as the element first to be examined, because the diplon has a small mass defect and also because it is the simplest of all nuclear systems and its properties are as important in nuclear theory as the hydrogen atom is in atomic theory. The disintegration to be expected is

$$_1D^2 + h\nu \rightarrow \,_1H^1 + \,_0n^1 \quad \ldots \ldots \quad (1).$$

Since the momentum of the quantum is small and the masses of the proton and neutron are nearly the same, the available energy, $h\nu - W$, where W is the binding energy of the particles, will be divided nearly equally between the proton and the neutron.

The experiments were as follows. An ionisation chamber was filled with heavy hydrogen of about 95 per cent purity, kindly lent by Dr. Oliphant. The chamber was connected to a linear amplifier and oscillograph in the usual way. When the heavy hydrogen was exposed to the γ-radiation from a source of radiothorium, a number of 'kicks' was recorded by the oscillograph. Tests showed that these kicks must be attributed to protons resulting from the splitting of the diplon. When a radium source of equal γ-ray intensity was employed, very few kicks were observed. From this fact we deduce that the disintegration cannot be produced to any marked degree by γ-rays of energy less than $1 \cdot 8 \times 10^6$ electron volts, for there is a strong line of this energy in the radium C spectrum.

If the nuclear process assumed in (1) is correct, a very reliable estimate of the mass of the neutron can be obtained, for the masses of the atoms of hydrogen and heavy hydrogen are known accurately. They are $1 \cdot 0078$ and $2 \cdot 0136^1$ respectively. Since the diplon is stable and can be disintegrated by a γ-ray of energy $2 \cdot 62 \times 10^6$ electron volts (the strong γ-ray of thorium C″), the mass of the neutron must lie between $1 \cdot 0058$ and $1 \cdot 0086$; if the γ-ray of radium C of $1 \cdot 8 \times 10^6$ electron volts is ineffective, the mass of the neutron must be greater than $1 \cdot 0077$. If the energy of the protons liberated in the disintegration (1) were measured, the mass of the neutron could be fixed very closely. A rough estimate of the energy of the protons was deduced from measurements of the size of the oscillograph kicks in the above experiments. The value obtained was about 250,000 volts. This leads to a binding energy for the diplon of $2 \cdot 1 \times 10^6$ electron volts, and gives a value of $1 \cdot 0081$ for the neutron mass. This estimate of the proton energy is, however, very rough, and for the present we may take for the mass of the neutron the value $1 \cdot 0080$, with extreme errors of $\pm 0 \cdot 0005$.

Previous estimates of the mass of the neutron have been made from considerations of the energy changes in certain nuclear reactions, and values of $1 \cdot 007$ and $1 \cdot 010$ have been derived in this way[2,3]. These estimates, however, depend not only on assumptions concerning the nuclear processes, but also on certain mass-spectrograph measurements, some of which may be in error by about $0 \cdot 001$ mass units. It is of great importance to fix accurately the mass of the neutron and it is hoped to accomplish this by the new method given here.

Experiments are in preparation to observe the disintegration of the diplon in the expansion chamber. These experiments should confirm the nuclear process which has been assumed, and therewith the assumption that the diplon consists of a proton and a neutron. Both the energy of the protons and their angular distribution should also be obtained.

If, as our experiments suggest, the mass defect of the diplon is about 2×10^6 electron volts, it is at once evident why the diplon cannot be disintegrated by the impact of polonium α-particles[4]. When an α-particle collides with a nucleus of mass number M, only a fraction $M/(M + 4)$ of the kinetic energy of the α-particle is available for disintegration, if momentum is to be conserved. In the case of the diplon, therefore, only one third of the kinetic energy of the α-particle is available, and this, for the polonium α-particle, is rather less than $1 \cdot 8 \times 10^6$ electron volts. The more energetic particles of radium C′ should just be able to produce disintegration, and Dunning[5] has in fact observed a small effect when heavy water was enclosed in a radon tube.

Our experiments give a value of about 10^{-28} sq. cm. for the cross-section for disintegration of a diplon by a γ-ray of $2 \cdot 62 \times 10^6$ electron volts. In a paper to be published shortly, H. Bethe and R. Peierls have calculated this cross-section,

assuming the interaction forces between a proton and a neutron which are given by the considerations developed by Heisenberg, Majorana and Wigner. They have obtained the transition probability in the usual quantum-mechanical way, and their result gives a value for the cross-section of the same order as the experimental value, but rather greater, if we take the mass of the neutron as 1·0080. If, however, we take the experimental value for the cross-section, the calculations lead to a neutron mass of 1·0085, which seems rather high. Thus the agreement of theory with experiment may be called satisfactory but not complete.

One further point may be mentioned. Some experiments of Lea[6] have shown that paraffin wax bombarded by neutrons emits a hard γ-radiation greater in intensity and in quantum energy than when carbon alone is bombarded. The explanation suggested was that, in the collisions of neutrons and protons, the particles sometimes combine to form a diplon, with the emission of a γ-ray. This process is the reverse of the one considered here. Now if we assume detailed balancing of all processes occurring in a thermodynamical equilibrium between diplons, protons, neutrons and radiation, we can calculate, without any special assumption about interaction forces, the relative probabilities of the reaction (1) and the reverse process. Using our experimental value for the cross-section for reaction (1), we can calculate the cross-section for the capture of neutrons by protons for the case when the neutrons have a kinetic energy $2(h\nu - W) = 1\cdot0 \times 10^6$ electron volts in a co-ordinate system in which the proton is at rest before the collision. In this special case the cross-section σ_c for capture (into the ground state of the diplon—we neglect possible higher states) is much smaller than the cross-section σ_p for the 'photo-effect'. It is unlikely that σ_c will be very much greater for the faster neutrons concerned in Lea's experiments. It therefore seems very difficult to explain the observations of Lea as due to the capture of neutrons by protons, for this effect should be extremely small. A satisfactory explanation is not easy to find and further experiments seem desirable.

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[2] J. Chadwick, *Proc. Roy. Soc.*, A, **142**, 1 ; 1933.
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[4] Rutherford and A. E. Kempton, *Proc. Roy. Soc.*, A, **143**, 724; 1934.
[5] *Phys. Rev.*, **45**, 586 ; 1934.
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Ancient Indian Iron

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IT appears certain that iron was known in India at a very early date. Mention of its production in ancient writings puts the earliest time of production earlier than 1,000 B.C. According to Herodotus[1], the Indian contingent of the army of Xerxes were using iron for military purposes about 500 B.C. The description of iron surgical instruments in an ancient medical work, the excavation of iron weapons from burial sites and the presence to this day of masses of iron like the pillars of Delhi and Dhar all indicate that the production of iron steadily increased as the centuries passed.

The methods of production and qualities of Indian iron and steel seem to have early excited the curiosity of the British conquerors and in 1795, Dr. George Pearson[2] published a paper on a kind of steel named 'wootz', then being manufactured in Bombay. The methods of analysis and examination then available only allowed the vague conclusions that the metal was very hard, had about 0·03 per cent carbon, and was believed to have been produced by direct reduction of the ore. Dr. Buchanan's "Travels in the South of India", published in 1807, describes the native Indian processes for iron and steel production then employed, which were believed to be those handed down from previous ages. Numerous other investigations have been made since that time, which increase in thoroughness as methods of examination have improved.

THE DELHI PILLAR

The Delhi pillar has constantly aroused interest. Sir Alexander Cunningham, in the "Archæological Survey of India", published during the years 1862–65, reported the pillar as a solid shaft of wrought iron, upwards of sixteen inches in diameter and twenty-two feet in length ; he mentions the curious yellow colour of the upper part of the shaft, which at one time caused the belief that the pillar was of bronze. This appearance has been commented upon by many observers since that time. Inscriptions made on the pillar are said still to be perfectly clear and sharp, and these have allowed the approximate date of its erection to be fixed as A.D. 310.

There seems little doubt that the pillar was built up by welding together discs of iron ; it is said that the marks of welding can still plainly be seen[3]. Sir Robert Hadfield examined a small specimen of the pillar in 1911 and afterwards was able to make a fairly detailed investigation of a larger piece[4]. The analysis showed the composition C, 0·08 ; Si, 0·046 ; Mn, 0 ; P, 0·114 ; N, 0·032 ; Fe, 99·72 ; Cu and other elements, 0·034. Hadfield described the iron as an excellent type of wrought iron entirely free from inclusions, being better from the point of view of homogeneity and purity than the best modern Swedish charcoal irons. The structure was found to consist of large grains of ferrite with a very small portion of cementite, sometimes located in the grain boundaries and