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The neutron and its properties

Nobel Lecture, December 12, 1935

The idea that there might exist small particles with no electrical charge has been put forward several times. Nernst, for example, suggested that a neutral particle might be formed by a negative electron and an equal positive charge, and that these "neutrons" might possess many of the properties of the ether; while Bragg at one time suggested that the γ -rays emitted by radioactive substances consisted of small neutral particles, which, on breaking up, released a negative electron.

The first suggestion of a neutral particle with the properties of the neutron we now know, was made by Rutherford in 1920. He thought that a proton and an electron might unite in a much more intimate way than they do in the hydrogen atom, and so form a particle of no nett charge and with a mass nearly the same as that of the hydrogen atom. His view was that with such a particle as the first step in the formation of atomic nuclei from the two elementary units in the structure of matter - the proton and the electron - it would be much easier to picture how heavy complex nuclei can be gradually built up from the simpler ones. He pointed out that this neutral particle would have peculiar and interesting properties. It may be of interest to quote his remarks:

"Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope, and it may be impossible to contain it in a sealed vessel. On the other hand, it should enter readily the structure of atoms, and may either unite with the nucleus or be disintegrated by its intense field.

The existence of such atoms seems almost necessary to explain the building up of the nuclei of heavy elements; for unless we suppose the production of charged particles of very high velocities it is difficult to see how any positively charged particle can reach the nucleus of a heavy atom against its intense repulsive field."

Rutherford's conception of closely combined proton and electron was adopted in pictures of nuclear structure developed by Ono (1926), by Fournier and others, but nothing essentially new was added to it.

No experimental evidence for the existence of neutral particles could be obtained for years. Some experiments were made in the Cavendish Laboratory in 1921 by Glasson and by Roberts, hoping to detect the formation of such particles when an electric discharge was passed through hydrogen. Their results were negative.

The possibility that neutral particles might exist was, nevertheless, not lost sight of. I myself made several attempts to detect them - in discharge tubes actuated in different ways, in the disintegration of radioactive substances, and in artificial disintegrations produced by α -particles.* No doubt similar experiments were made in other laboratories, with the same result.

Later, Bothe and Becker showed that γ -radiations were excited in some light elements when bombarded by α -particles. Mr. H. C. Webster, in the Cavendish Laboratory had also been making similar experiments, and he proceeded to examine closely the production of these radiations. The radiation emitted by beryllium showed some rather peculiar features, which were very difficult to explain. I suggested therefore that the radiation might consist of neutral particles and that a test of this hypothesis might be made by passing the radiation into an expansion chamber. Several photographs were taken: some β -particle tracks -presumably recoil electrons - were observed, but nothing unexpected.**

The first real step towards the discovery of the neutron was given by a very beautiful experiment of Mme. and M. Joliot-Curie, who were also investigating the properties of this beryllium radiation. They passed the radiation through a very thin window into an ionization vessel containing air. When paraffin wax or any other matter containing hydrogen was placed in front of the window the ionization in the vessel increased. They showed that this increase was due to the ejection from the wax of protons, moving with very high velocities.

This behaviour of the beryllium radiation was very difficult to explain if it were a quantum radiation. I therefore began immediately the study of this new effect using different methods - the counter, the expansion chamber, and the high-pressure ionization chamber.

It appeared at once that the beryllium radiation could eject particles not

* Cf. Rutherford and Chadwick, *Proc. Cambridge Phil. Soc.*, 25 (1929) 186.

** The failure was partly due to the weakness of the polonium source.

only from paraffin wax but also from other light substances, such as lithium, beryllium, boron, etc., though in these cases the particles had a range of only a few millimetres in air. The experiments showed that the particles are recoil atoms of the element through which the radiation passes, set in motion by the impact of the radiation.

The occurrence of these recoil atoms can be shown most strikingly by means of the expansion chamber. These experiments were carried out by Dr. Feather and Mr. Dee.

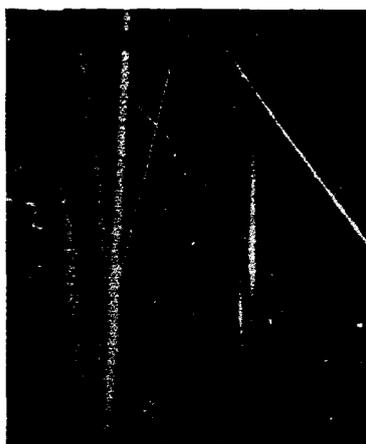


Fig. 1.

Fig. 1 is a photograph taken by Dee, which shows the tracks of protons ejected from gelatine on the roof of the expansion chamber. Fig. 2 shows two photographs taken by Feather, using an expansion chamber filled with nitrogen. Two short dense tracks are seen. Each is due to an atom of nitrogen which has been struck by the radiation. One track (Fig. 2b) shows a short spur, due to collision with a nitrogen atom; the angle between the spurs is 90° , as it should be if the initial track is due to a nitrogen atom.



Fig. 2a.

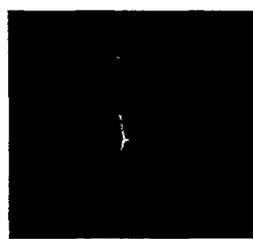


Fig. 2b.

The beryllium radiation thus behaved very differently from a quantum radiation. This property of setting in motion the atoms of matter in its path suggests that the radiation consists of particles.

Let us suppose that the radiation consists of particles of mass M moving with velocities up to a maximum velocity V . Then the maximum velocity which can be imparted to a hydrogen atom, mass 1, by the impart of such a particle will be

$$U_p = \frac{2M}{M+1} V$$

and the maximum velocity imparted to a nitrogen atom will be

$$U_n = \frac{2M}{M+14} V$$

Then

$$\frac{M+14}{M+1} = \frac{U_p}{U_n}$$

The velocities U_p and U_n were found by experiment. The maximum range of the protons ejected from paraffin wax was measured and also the ranges of the recoil atoms produced in an expansion chamber filled with nitrogen. From these ranges the velocities U_p and U_n can be deduced approximately: $U_p = \text{ca. } 3.7 \times 10^9 \text{ cm/sec}$, $U_n = \text{ca. } 4.7 \times 10^8 \text{ cm/sec}$. Thus we find $M = 0.9$.

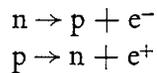
We must conclude that the beryllium radiation does in fact consist of particles, and that these particles have a mass about the same as that of a proton. Now the experiments further showed that these particles can pass easily through thicknesses of matter, e.g. 10 or even 20 cm lead. But a proton of the same velocity as this particle is stopped by a thickness of $\frac{1}{4}$ mm of lead. Since the penetrating power of particles of the same mass and speed depends only on the charge carried by the particle, it was clear that the particle of the beryllium radiation must have a very small charge compared with that of the proton. It was simplest to assume that it has no charge at all. All the properties of the beryllium radiation could be readily explained on this assumption, that the radiation consists of particles of mass 1 and charge 0, or neutrons.

The nature of the neutron

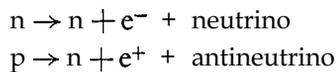
I have already mentioned Rutherford's suggestion that there might exist a neutral particle formed by the close combination of a proton and an electron, and it was at first natural to suppose that the neutron might be such a complex particle. On the other hand, a structure of this kind cannot be fitted into the scheme of the quantum mechanics, in which the hydrogen atom represents the only possible combination of a proton and an electron. Moreover, an argument derived from the spins of the particles is against this view. The statistics and spins of the lighter elements can only be given a consistent description if we assume that the neutron is an elementary particle.

Similar arguments make it difficult to suppose that the proton is a combination of neutron and positive electron. It seems at present useless to discuss whether the neutron and proton are elementary particles or not; it may be that they are two different states of the fundamental heavy particle.

In the present view of the β -transformations of radioactive bodies the hypothesis is made that a neutron in the nucleus may transform into a proton and a negative electron with the emission of the electron, or conversely a proton in the nucleus may transform into a neutron and a positive electron with the emission of the positron. Thus



If spin is to be conserved in this process we must invoke the aid of another particle - Pauli's neutrino; we then write

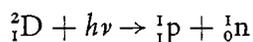


where the neutrino is a particle of very small mass, no charge, and spin $\frac{1}{2}$.

If we knew the masses of the neutron and proton accurately, these considerations would give the mass of the hypothetical neutrino.

As I have shown, observations of the momenta transferred in collisions of a neutron with atomic nuclei lead to a value of the mass of the neutron but the measurements cannot be made with precision. To obtain an accurate estimate of the neutron mass we must use the energy relations in a disintegration process in which a neutron is liberated from an atomic nucleus. The best

estimate at present is obtained from the disintegration of the deuteron by the photoelectric effect of a γ -ray



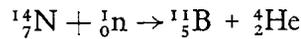
The energy of the protons liberated by a γ -ray quantum of $h\nu = 2.62 \times 10^6$ eV has been measured recently by Feather, Bretscher, and myself. It is 180,000 eV. Thus the total kinetic energy set free is 360,000 eV, giving a binding energy of the deuteron of 2.26×10^6 eV. Using the value of the deuteron mass given by Oliphant, Kempton, and Rutherford, we then obtain a value for the mass of the neutron of 1.0085*. The mass of the hydrogen atom is 1.0081. It would seem therefore that a free neutron should be 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 an electron. On the other hand, an argument from the shape of the γ -ray spectra suggests that the mass of the neutrino is zero. One must await more exact measurements of the masses of hydrogen and deuterium before speculating further on this matter.

Passage of neutrons through matter

The neutron in its passage through matter loses its energy in collisions with the atomic nuclei and not with the electrons. The experiments of Dee showed that the primary ionization along the track of a neutron in air could not be as much as 1 ion pair in 3 metres' path, while Massey has calculated that it may be as low as 1 ion pair in 105 km. This behaviour is very different from that of a charged particle, such as a proton, which dissipates its energy almost entirely in electron collisions. The collision of a neutron with an atomic nucleus, although much more frequent than with an electron, is also a rare event, for the forces between a neutron and a nucleus are very small except at distances of the order of 10^{-12} cm. In a close collision the neutron may be deflected from its path and the struck nucleus may acquire sufficient energy to produce ions. The recoiling nucleus can then be detected either in an ionization chamber or by its track in an expansion chamber. In some of these collisions, however, the neutron enters the nucleus and a disintegration is

* Recent measurements of the mass of deuterium lead to a value of 1.0090 for the mass of the neutron.

produced. Such disintegrations were first observed by Feather in his observations on the passage of neutrons through an expansion chamber filled with nitrogen. An example is shown in Fig. 3. The disintegration process is



Since these early experiments many examples of this type of disintegration have been observed by different workers.

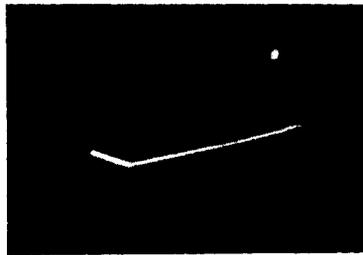
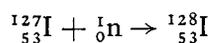
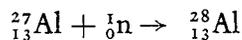
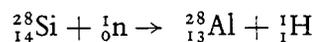
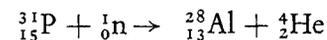


Fig.3.

Fermi and his collaborators have also shown that the phenomenon of artificial radioactivity can be provoked in the great majority of all elements, even in those of large atomic number, by the bombardment of neutrons. They have also shown that neutrons of very small kinetic energy are peculiarly effective in many cases.

In some cases an α -particle is emitted in the disintegration process; in others a proton is emitted; while in others an unstable species of nucleus is formed by the simple capture of the neutron.

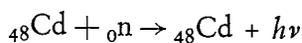
Examples of these types are:



In the cases just cited the nuclei formed in the reaction are unstable, showing the phenomenon of induced activity discovered by Mme. and M. Joliot-Curie, and return to a stable form with the emission of negative electrons.

In the transformations produced in heavy elements by neutrons, the pro-

cess is, with very few exceptions, one of simple capture. The nucleus so formed, an isotope of the original nucleus, is often unstable but not invariably so. For example the reaction



The cadmium isotope formed is stable, but a γ -ray quantum is emitted of energy corresponding to the binding energy of the neutron.

Other cases of this type of transformation are known.

The great effectiveness of the neutron in producing nuclear transmutations is not difficult to explain. In the collisions of a charged particle with a nucleus, the chance of entry is limited by the Coulomb forces between the particle and the nucleus; these impose a minimum distance of approach which increases with the atomic number of the nucleus and soon becomes so large that the chance of the particle entering the nucleus is very small. In the case of collisions of a neutron with a nucleus there is no limitation of this kind. The force between a neutron and a nucleus is inappreciable except at very small distances, when it increases very rapidly and is attractive. Instead of the potential wall in the case of the charged particle, the neutron encounters a potential hole. Thus even neutrons of very small energy can penetrate into a nucleus. Indeed slow neutrons may be enormously more effective than fast neutrons, for they spend a longer time in the nucleus. The calculations of Bethe show that the chance of capture of a neutron may be inversely proportional to its velocity. The possibility of capture will depend on whether the nucleus possesses an unoccupied p-level or a level with azimuthal quantum number $l = 1$.

In cases where a particle (α -particle or proton) is ejected from the nucleus, the possibility of disintegration will depend on whether the particle can escape through the potential barrier. This will be easier the greater the energy set free in the disintegration process. As a rule disintegration by neutrons will take place with absorption of kinetic energy if a proton is released in the transformation, and may take place with release of kinetic energy if one at least of the products is an α -particle. Thus processes in which a proton is emitted can only occur with fast neutrons, even in collisions with elements of low atomic number; while processes in which α -particles are emitted can occur with slow neutrons in elements of low atomic number, but again only with fast neutrons in elements of higher atomic number. If the atomic number is sufficiently high, the neutrons at present at our disposal have insufficient

energy and the particles cannot escape through the potential barrier. Thus with elements of high atomic number, only capture processes are observed, although there may be a few exceptions. There may be, however, special cases in which the particles escape through a resonance level. These would be characterized by the phenomenon that the energy of the escaping particle would be independent of the energy of the incident neutron. These special cases may explain the exceptional disintegrations in which a particle is emitted from a heavy nucleus. They may be of particular interest in giving information about the resonance levels of atomic nuclei.

There is also the possibility of resonance capture of the neutrons, more particularly with very slow neutrons. The capture of neutrons of a certain energy may take place with very great frequency in one species of nucleus while for another neighbouring nucleus the same neutrons may have a long free path. These resonance regions may perhaps be rather broad and therefore comparatively easy to observe experimentally.

The structure of the nucleus

Before the discovery of the neutron we had to assume that the fundamental particles from which an atomic nucleus was built up were the proton and the electron, with the α -particle as a secondary unit. The behaviour of an electron in a space of nuclear dimensions cannot be described on present theory; and other difficulties, e.g. the statistics of the nitrogen nucleus, the peculiarities in the mass defect curve in the region of the heavy elements, also arose. These difficulties are removed if we suppose that the nuclei are built up from protons and neutrons. The forces which determine the stability of a nucleus will then be of three types, the interactions between proton and proton, between proton and neutron, and between neutron and neutron. It is assumed, with Heisenberg and Majorana, that the interaction between neutron and proton is of the exchange type - similar to that between the hydrogen atom and the hydrogen ion - and that the interaction between neutron and neutron is small.

For a nucleus of mass number A and charge Ze we shall have

$$\begin{aligned}N_n + N_p &= A & N_p &= Z \\N_n/N_p &= (A-Z)/Z\end{aligned}$$

The value of N_n/N_p for the most stable nucleus of a given mass number will be determined by the condition that the binding energy is a maximum. The repulsive Coulomb force between the protons tends to diminish the number of protons in a nucleus, while the neutron-proton interaction tends to make $N_n = N_p$, $Z = A/2$; the neutron-neutron interaction is probably very small. Now in existing nuclei $N_p \sim N_n$ and therefore the neutron-proton interaction must be the predominating force in the nucleus. In heavy elements $N_n > N_p$. This relative increase in the number of neutrons may be due either to an attractive force between neutron-neutron, or more probably to the Coulomb forces between proton-proton.

Thus it appears that the interaction between proton and neutron is of the highest significance in nuclear structure and governs the stability of a nucleus. It is most important to obtain all experimental evidence about the nature of this interaction. The information we have at present is very meagre, but I think that it does to some degree support the view that the interaction is of the exchange type. Dr. Feather and I hope to obtain more definite information on this subject by an extensive study of the collisions of neutrons and protons.

Heisenberg's considerations of nuclear structure point very strongly to this exchange interaction. Such an interaction provides an attractive force at large distances between the particles and a repulsive force at very small distances, thus giving the effect of a more or less definite radius of the particles. A system of particles interacting with exchange forces will keep together due to the attraction, but there will be a minimum distance of approach of the particles; thus the system will not collapse together but will have a more or less definite "radius".

The exchange forces between a hydrogen atom and a hydrogen ion are large compared with the forces between neutral atoms; by analogy we explain why the neutron-proton interaction is so much stronger than the proton-proton or neutron-neutron interactions.

By a suitable choice of the exchange forces it is possible to obtain a saturation effect, analogous to the saturation of valency bindings between two atoms, when each neutron is bound to two protons and each proton to two neutrons. Thus two neutrons and two protons form a closed system - the α -particle.

These ideas thus explain the general features of the structure of atomic nuclei and it can be confidently expected that further work on these lines may reveal the elementary laws which govern the structure of matter.