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The Existence of a Neutron

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It was shown by bothe and becker that some light elements when bombarded by α–particles of polonium emit radiations which appear to be of the γ-ray type. The element beryllium gave a particularly marked effect of this kind, and later observations by Bothe, by Mme. Curie–Joliot and by Webster showed that the radiation excited in beryllium possessed a penetrating power distinctly greater than that of any γ-radiation yet found from the radioactive elements. In Webster's experiments the intensity of the radiation was measured both by means of the Geiger–Muller tube counter and in a high pressure ionization chamber. He found that the beryllium radiation had an absorption coefficient in lead of about $0 \cdot 22 \ \ \mathrm{cm}^{-1}$ as measured under his experimental conditions. Making the necessary corrections for these conditions, and using the results of Gray and Tarrant to estimate the relative contributions of scattering, photoelectric absorption, and nuclear absorption in the absorption of such penetrating radiation, Webster concluded that the radiation had a quantum energy of about 7×10^6 electron volts. Similarly he found that the radiation from boron bombarded by α-particles of polonium consisted in part of a radiation rather more penetrating than that from beryllium, and he estimated the quantum energy of this component as about 10×10^6 electron volts. These conclusions agree quite well with the supposition that the radiations arise by the capture of the α-particle into the berillium (or boron) nucleus and emission of the surplus energy as a quantum of radiation.

The radiations showed, however, certain peculiarities, and at my request the beryllium radiation was passed into an expansion chamber and several photographs were taken. No unexpected phenomena were observed though, as well be seen later, similar experiments have now revealed some rather striking events. The failure of these early experiments was partly due the weakness of the available source of polonium, and partly to the experimental arrangement, which as it now appears, was not very suitable.

Quite recently, Mme. Curie–Joliot and M. Joliot made the very striking observation that these radiation from berillium and from boron were able to eject protons with considerable velocities from matter containing hydrogen. In their experiments the radiation from beryllium was passed through a thin window into an ionisation vessel containing air at room pressure. When paraffin wax, or other matter containing hydrogen, was placed in front of the window, the ionisation in the vessel was increased, in some cases as much as doubled. The effect appeared to be due to the ejection of protons, and from further experiment they showed that the protons had ranges in air up to about 26 cm, corresponding to a velocity of nearly 3×10^9 cm per second. They suggested that energy was transferred from the beryllium to the proton by a process similar to the Compton effect with electrons, and they estimated that the beryllium radiation had a quantum energy of about 50×10^6 electron volts. The range of the protons ejected by the boron radiation was estimated to be about 8 cm in air, giving on a Compton process an energy of about 35×10^6 electron volts for the effective quantum.[1]

There are two grave difficulties in such an explanation of this phenomenon. Firstly, it is now well established that the frequency of scattering of high energy quanta by electrons is given with fair accuracy by the Klein–Nishina formula, and this formula should also apply to the scattering of quanta by a proton. The observed frequency of the proton scattering is, however, many thousand times greater than that predicted by this formula. Secondly, it is difficult to account for the production of a quantum of 50×10^6 electron volts from the interaction of a beryllium nucleus and an α-particle of kinetic energy of 5×10^6 electron volts. The process which will give the greatest amount of energy available for radiation is the capture of the α-particle by the beryllium nucleus, Be^9, and its incorporation in the nuclear structure to form a carbon nucleus C^{13}. The mass defect of the C^{13} nucleus is known both from data supplied by measurements of the artificial disintegration of boron B^{10} and from observations of the band spectrum of

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[1] Many of the arguments of the subsequent discussion apply equally to both radiations, and the term "beryllium radiation" may often be taken to include the boron radiation.

carbon; it is about 10×10^6 electron volts. The mass defect of Be^9 is not known, but the assumption that it is zero will give a maximum value for the possible change of energy in the reaction $Be + \alpha \rightarrow C^{13} +$ quantum. On this assumption it follows that the energy of the quantum emitted in such a reaction cannot be greater than about 14×10^6 electron volts. It must, of course, be admitted that this argument from mass defects is based on the hypothesis that the nuclei are made as far as possible of α particles; that the Be^9 nucleus constants of 2 α-particles + 1 proton + 1 electron and the C^{13} nucleus of 3 α-particles + 1 proton + 1 electron. So far as the lighter nuclei are concerned, this assumption is supported by the evidence from experiments on artificial disintegration, but is no general proof.

Accordingly, I made further experiments to examine the properties of the radiation excited in beryllium. It was found that radiation ejects particles not only from hydrogen but from all other light elements which were examined. The experimental results were very difficult to explain on the hypothesis that the beryllium radiation was a quantum radiation, but followed immediately if it were supposed that the radiation consisted of particles of mass nearly equal to that of a proton and with no net charge, or neutron. . . .

OBSERVATION OF RECOIL ATOMS

The properties of the beryllium radiation were first examined by means of the valve counter used in the work on the artificial disintegration by α-particles and described fully there. Briefly, it consists of a small ionisation chamber connected to a valve amplifier. The sudden production of ions in the chamber by the entry of an ionising particle is detected by means of an oscillograph connected in the output circuit of the amplifier. The deflections of the oscillograph were recorded photographically on a film of bromide paper.

The source of polonium was prepared from a solution of radium (D + E + F) by deposition on a disc of silver. The disc had a diameter of 1 cm and was placed close to a disc of pure beryllium of 2 cm diameter, and both were enclosed in a small vessel which could be evacuated

[Fig. 1]. The first ionisation chamber used had an opening of 13 mm covered with aluminium foil of $4 \cdot 5$ cm air equivalent, and a depth of 15

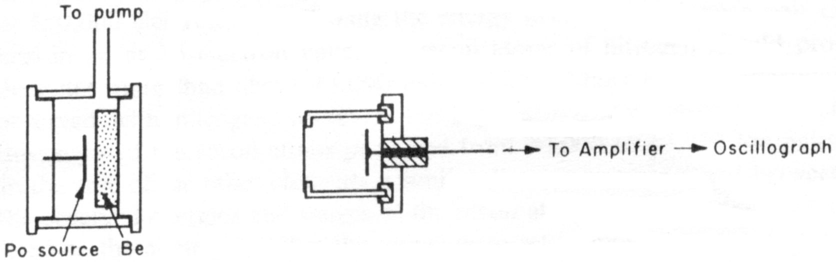

Figure 1:

mm. This chamber had a very low natural effect, giving on the average only about 7 deflections per hour.

When the source vessel was placed in front of the ionisation chamber, the number of deflections immediately increased. For a distance of 3 cm between the beryllium and the counter the number of deflections was nearly 4 per minute. Since the number of deflections remained sensibly the same when thick metal sheets, even as much as 2 cm of lead, were interposed between the source vessel and the counter, it was clear that these deflections were due to penetrating radiation emitted from the beryllium. it will be shown later that the deflections were due atoms of nitrogen set in motion by the impact of the beryllium radiation.

When a sheet of paraffin max about 2 mm thick was interposed in the path of the radiation just in front of the counter, the number of deflections recorded by the oscillograph increased markedly. This increase was due to particles ejected from the paraffin wax so as to pass into the counter.

By placing absorbing screens of aluminium between the wax and the counter the absorption curve shown in [Fig. 2], curve A, was obtained.

From this curve it appears that the particles have a maximum range of just over 40 cm of air, assuming that an Al foil of $1 \cdot 64$ mg. per square centimetre is equivalent to 1 cm of air. By comparing the sizes of the deflections (proportional to the number of ions produced in the chamber) due to these particles with those due to protons of about the same range it was obvious that the particles were protons. From the range–velocity curve for protons we deduce therefore that the maximum velocity imparted to a proton by the beryllium radiation is about $3 \cdot 3 \times 10^9$ cm per second, corresponding to an energy of about $5 \cdot 7 \times 10^6$ electron volts.

The effect of exposing other elements to the beryllium radiation was

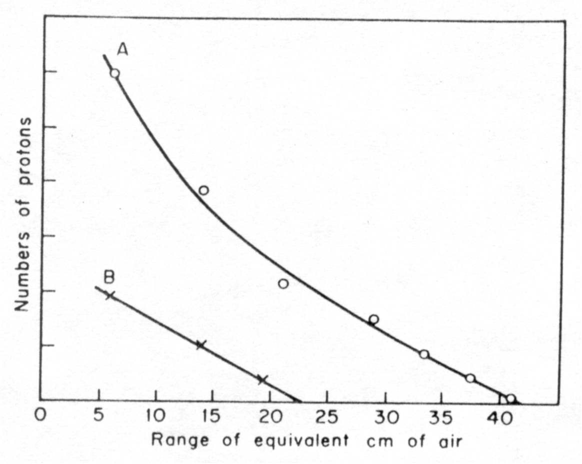

Figure 2:

then investigated. An ionisation chamber was used with an opening covered with a gold foil of $0 \cdot 5$ mm air equivalent. The element to be examined was fixed on a clean brass plate and placed very close to the counter opening. In this way, lithium, beryllium, boron, carbon and nitrogen, as paracyanogen, were tested. In each case the number of deflections observed in the counter increased when the element was bombarded by the beryllium radiation. The ranges of the particles ejected from these elements were quite short, of the order of some millimetres in air. The deflections produced by them were of different sizes, but many of them were large compared with the deflection produced even by a slow proton. The particles therefore have a large ionising power and are probably in each case recoil atoms of the elements. Gases were investigated by filling the ionisation chamber with the required gas by circulation for several minutes. Hydrogen, helium, nitrogen, oxygen, and argon were examined in this way. Again, in each case deflections were observed which were attributed to the production of recoil atoms in the different gases. For a given position of the beryllium source relative to the counter, the number of recoil atoms was roughly the same for each gas. This point will be referred to later. It appears then that the beryllium radiation can impart energy to the atoms of matter through which it passes and that the chance of an energy transfer does not vary widely from one element to another.

It has shown that protons are ejected from paraffin wax with energies up to a maximum of about $5 \cdot 7 \times 10^6$ electron volts. If the ejection be ascribed to a Compton recoil from a quantum of radiation, then the energy of the quantum must be about 55×10^6 electron volts, for the maximum energy which can be given to a mass m by a quantum $h\nu$ is $\frac{2}{2+mc^2/h\nu} \cdot h\nu$. This energies of the recoil atoms produced by this radiation by the same process in other elements can be readily calculated. For example, the nitrogen recoil atoms should have energies up to a maximum of 450,000 electron volts. Taking the energy to form a pair of ions in air as 35 electron volts, the recoil atoms of nitrogen should produce not more than about 13,000 pairs of ions. Many of the deflections observed with nitrogen, however, corresponded to far more ions than this; some of the recoil atoms produced from 30,000 to 40,000 ion pairs. In the case of the other elements a similar discrepancy was noted between the observed energies and ranges of the recoil atoms and the values calculated on the assumption that the atoms were set in motion by recoil from a quantum of 55×10^6 electron volts. The energies of the recoil atoms were estimated from the number of ions produced in the counter, as given by the size of the oscillograph deflections. A sufficiently good measurement of the ranges could be made either by varying the distance between the element and the counter or by interposing thin screens of gold between the element and the counter.

The nitrogen recoil atoms were also examined, in collaboration with Dr. N. Feather, by means of the expansion chamber. The source vessel was placed immediately above an expansion chamber of the Shimizu type, so that a large proportion of the beryllium radiation traversed the chamber. A large number of recoil tracks was observed in the course of a few hours. Their range, estimated by eye, was sometimes as much as 5 or 6 mm, in the chamber, or, correcting for the expansion, about 3 mm in standard air. These visual estimates were confirmed by a preliminary series of experiments by Dr. Feather with a large automatic expansion chamber, in which photographs of the recoil tracks in nitrogen were obtained. Now the ranges of recoil atoms of nitrogen of different velocities have been measured by Blackett and Lees. Using their results we find that the nitrogen recoil atoms produced by the beryllium radiation may have a velocity of at least 4×10^8 cm per second, corresponding to an energy of about $1 \cdot 2 \times 10^6$ electron volts. In order that the nitrogen nucleus should acquire such an energy in a collision with a quantum of radiation, it is necessary to assume that the energy of the quantum should be about 90×10^6 electron volts, if energy and momentum are conserved in the collision. It has been shown that a quantum of 55×10^6 electron volts is sufficient to explain the hydrogen collisions. In general, the experimental results show that if the recoil atoms are to be explained by collision with a quantum, we must assume a larger and larger energy for the quantum as the mass of the struck atom increases.

THE NEUTRON HYPOTHESIS

It is evident that we must either relinquish the application of the conservation of energy and momentum in collisions or adopt another hypothesis about the nature of the radiation. If we suppose that the radiation is not a quantum radiation, but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfer to different masses. In order to explain the great penetrating power of the radiation we must further assume that the particle has no get charge. We may suppose it to consist of a proton and an electron in close combination, the "neutron" discussed by Rutherford in his Bakerian Lecture of 1920.

When such neutrons pass through matter they suffer occasionally close collisions with the atomic nuclei and so give rise to the recoil atoms which are observed. since the mass of the neutron is equal to that of the proton, the recoil atoms produced when the neutrons pass through matter containing hydrogen will have all velocities up to a maximum which is the same as the maximum velocity of the neutrons. The experiments showed that the maximum velocity of the protons ejected from paraffin wax was about $3 \cdot 3 \times 10^9$ cm per second. This is therefore the maximum velocity of the neutrons emitted from beryllium bombarded by α-particles of polonium. From this we can now calculate the maximum energy which can be given by a colliding neutron to other atoms, and we find that the results are in fair agreement with the energies observed in the experiments.For example, a nitrogen atom will acquire in a head–on collision with the neutron of mass 1 and velocity $3 \cdot 3 \times 10^9$ cm per second a velocity of $4 \cdot 4 \times 10^8$ cm per second, corresponding to an energy of $1 \cdot 4 \times 1066$ electron volts, a range of about $3 \cdot 3$ mm in air, and a production of ions of about 40,000 pairs. similarly, an argon atom may acquire an energy of $0 \cdot 54 \times 10^6$ electron volts, and produce about 15,000 ion pairs. Both these values are in good according with experiment. It is possible to prove that the mass of the neutron is roughly equal to that of the proton, by combining the evidence from the hydrogen collisions with that the nitrogen collisions. In the succeeding paper, Feather records experiments in which about 100 tracks of nitrogen recoil atoms have been photographed in the expansion chamber. The measurement of the tracks shown that the maximum range of the recoil atoms is $3 \cdot 5$ mm in air 15○ C and 760 mm pressure, corresponding to a velocity of $4 \cdot 7 \times 10^8$ cm per second according to Blackett and Lees. If M, V be the mass and velocity of the neutron then the maximum velocity given to a hydrogen atom is

$$u_p = \frac{2M}{M+1} \cdot V,$$

and the maximum velocity given to a nitrogen atom is

$$u_n = \frac{2M}{M+14} \cdot V,$$

whence

$$\frac{M+14}{M+1} = \frac{u_p}{u_n} = \frac{3 \cdot 3 \times 10^9}{4 \cdot 7 \times 10^8},$$

and

$$M = 1 \cdot 15.$$

The total error in the estimation of the velocity of the nitrogen recoil atom may easily be about 10 per cent., and it is legitimate to conclude that the mass of the neutron is very nearly the same as the mass of the proton.

We have now to consider the production of the neutrons from beryllium by the bombardment of the α − particles. We must suppose that an α-particle is captured by a Be^9 nucleus with the formation of a carbon C^{12} nucleus and the emission of a neutron. The process is analogous to the well–known artificial disintegrations., but a neutron is emitted instead of a proton. The energy relations of this process cannot be exactly deduced, for the masses of the Be^9 nucleus and the neutron are not known accurately. It is, however, easy to show that such a process fits the experimental facts. We have

$$Be^9 + He^4 + \text{kinetic energy of } \alpha$$
$$= C^{12} + n^1 + \text{kinetic energy of } C^{12} + \text{kinetic energy of } n^1.$$

If we assume that the beryllium nucleus consists of two α-particles and a neutron, then its mass cannot be greater than the sum of the masses of these particles, for the binding energy corresponds to a defect of mass.

The energy equation becomes

$$(8 \cdot 00212 + n^1) + 4 \cdot 00106 + K.E. \text{ of } \alpha > 12 \cdot 0003 + n^1$$
$$+K.E.\ of\ C^{12} + K.E. \text{ of } N^1$$

or

$$K.E.\ of\ n^1 < K.E. \text{ of } \alpha + 0 \cdot 003 - K.E. \text{ of } C^{12}.$$

Since the kinetic energy of the α-particle of polonium is $5 \cdot 25 \times 10^6$ electron volts, it follows that the energy of emission of the neutron cannot be greater than about 8×10^6 electron volts. The velocity of the neutron must therefore be less than $3 \cdot 9 \times 10^9$ cm per second. We have seen that the actual maximum velocity of the neutron is about $3 \cdot 3 \times 10^9$ cm per second, so that the proposed disintegration process is compatible with observation.

A further test of the neutron hypothesis was obtained by examining the radiation emitted from beryllium in the opposite direction to the bombarding α-particles. The source vessel [Fig. 1] was reversed so that a sheet of paraffin wax in front of the counter was exposed to the "backward" radiation from the beryllium. The maximum range of the protons ejected from the wax was determined as before, by counting the numbers of protons observed through different thickness of aluminium interposed between the wax and the counter. The absorption curve obtained is shown in curve B, [Fig. 74–2]. The maximum of the protons was about 22 cm in air, corresponding to a velocity of about $2 \cdot 74 \times 10^9$ cm per second. Since the polonium source was only about 2 mm away from the beryllium, this velocity should be compared with that of the neutrons emitted not at 180 degrees but at an angle not much greater than 90° to the direction of the incident α-particles. A simple calculation shows that the velocity of the neutron emitted at 90° when an α-particle of full range is captured by a beryllium nucleus should be $2 \cdot 77 \times 10^9$ cm per second, taking the velocity of the neutron emitted at 0 degree in the same process as $3 \cdot 3 \times 10^9$ cm per second. The velocity found in the above experiment should be less than this, for the angle of emission is slightly greater than 90 degrees. The agreement with calculation is as good as can be expected from such measurements.

THE NATURE OF THE NEUTRON

It has been shown that the origin of the radiation from beryllium bombarded by α-particles and the behaviour of the radiation, so far as its interaction with atomic nuclei is concerned, receive a simple explantation on the assumption that the radiation consists of particles of mass nearly equal to that of the proton which have no charge. The simplest hypothesis one can make about the nature of the particle is to suppose that it consists of a proton and an electron in close combination, giving a net charge 0 and a mass which should be slightly less than the mass of the hydrogen atom. This hypothesis is supposed by an examination of the evidence which can be obtained about the mass of the neutron.

As we have seen, a rough estimate of the mass of the neutron was obtained from measurements of its collisions with hydrogen and nitrogen atoms, but such measurements cannot be made with sufficient accuracy for the present purpose. We must turn to a consideration of the energy relations in a process in which a neutron is liberated from an atomic nucleus; if the masses of the atomic nuclei concerned in the process are accurately known, a good estimate of the mass of the neutron can be deduced. The mass of the beryllium nucleus has, however, not yet been measured, and, as was shown [earlier], only general conclusions can be drawn from this reaction. Fortunately, there remains the case of boron. It was stated in [the first section] that boron bombarded by α-particles of polonium also emits a radiation which ejects protons from materials containing hydrogen. Further examination showed that this radiation behaves in all respects like that from beryllium, and it must therefore be assumed to consist of neutrons. It is probable that the neutrons are emitted from the isotope B^{11}, for we know that the isotope B^{10} disintegrates with the emission of a proton. The process of disintegration will then be

$$B^{11} + He^4 \rightarrow N^{14} + n^1.$$

The masses of B^{11} and N^{14} are known from Aston's measurements, and the further data required for the deduction of the mass of the neutron can be obtained by experiment.

In the source vessel of [Fig. 1] the beryllium was replaced by a target of powdered boron, deposited on a graphite plate. The range of the protons ejected by the boron radiation was measured in the same way as with the beryllium radiation. The effects observed were much smaller than with beryllium, and it was difficult to measure the range of the protons accurately. The maximum range was about 16 cm in air, corresponding to a velocity of $2 \cdot 5 \times 10^9$ cm per second. This then is the maximum velocity of the neutron liberated from boron by an α-particle of polonium of velocity $1 \cdot 59 \times 10^9$ cm per second assuming that momentum is conserved in the collision, the velocity of the recoiling N^{14} nucleus can be calculated, and we then know the kinetic energies of all particles concerned in the disintegration process. The energy equation of the process is

$$\text{Mass of } B^{11} + \text{mass of } He^4 + K.E. \text{ of } He^4$$

$$= \text{mass of } N^{14} + \text{mass of } n^{1} + K.E. \text{ of } N^{14} K.E. \; of \; n^{1}.$$

The masses are $B^{14} = 11 \cdot 00825 \pm 0 \cdot 0016$; $He^{4} = 4 \cdot 00106 \pm 0 \cdot 0006$; $N^{14} = 14 \cdot 0042 \pm 0 \cdot 0028$. The kinetic energies in mass units are α − particle $= 0 \cdot 00565$; neutron $= 0 \cdot 0035$; and nitrogen nucleus $= 0 \cdot 00061$. We find therefore that the mass of the neutron is $1 \cdot 0067$. The errors quoted for the mass measurements are those given by Aston. They are the maximum errors which can be allowed in his measurements, and the probable error may be taken as about one– quarter of these. Allowing for the errors in the mass measurements it appears that the mass of the neutron cannot be less than $1 \cdot 003$, and that it probably lies between $1 \cdot 005$ and $1 \cdot 008$.

Such a value for the mass of the neutron is to be expected if the neutron consists of a proton and an electron, and it lends strong support to this view. Since the sum of the masses of the proton and electron is $1 \cdot 0078$, the binding energy, or mass defect, of the neutron is about 1 to 2 million electron volts. This is quite a reasonable value. We may suppose that the proton and electron from a small dipole, or we may take the more attractive picture of a proton embedded in an electron. On either view, we may expect the "radius" of the neutron to be a few times 10^{-13} cm

THE PASSAGE OF THE NEUTRON THROUGH MATTER

The electrical field of a neutron of this kind will clearly be extremely small except at very small distances of the order of 10^{-12} cm In its passage through matter the neutron will be deflected unless it suffers an intimate collision with a nucleus. The potential of a neutron in the field of a nucleus may be represented roughly by [Fig. 3]. The radius of the collision area for sensible deflection of the neutron will be little greater than the radius of the nucleus. Further, the neutron should be able to penetrate the nucleus easily, and it may be that the scattering of the neutrons will be largely due to the internal field of the nucleus, or, in other words, that the scattered neutrons are mainly those which have penetrated the potential barrier. On these views we should expect the collision of a neutron with a nucleus to occur very seldom, and that the scattering will be roughly equal in all directions, at least as compared with the Coulomb scattering of a charged particle.

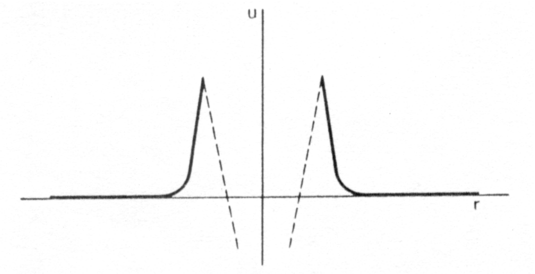

Figure 3:

These conclusions were confirmed in the following way. The source vessel, with Be target, was placed rather more than 1 inch from the face of a closed counter filled with air. [Fig. 1]. The number of deflections, or the number of nitrogen recoil atoms produced in the chamber, was observed for a certain time. The number observed was 190 per hour, after allowing for the natural effect. A block of lead 1 inch thick was then introduced between the source vessel and the counter. The number of deflections fell to 166 per hour. Since the number of recoil atoms produced must be proportional to the number of neutrons passing through the counter, these observations show that 13 per cent. of the neutrons had been absorbed or scattered in passing through 1 inch of lead.

Suppose that a neutron which passes within a distance p from the centre of the lead nucleus is scattered and removed from the beam. Then the fraction removed from the beam in passing through a thickness t of lead will be $\pi p^2 nt$, where n is the number of lead atoms per unit volume. Hence $\pi p^2 nt = 0 \cdot 13$, and $p = 7 \times 10^{-13}$ cm. This value for the collision radius with lead seems perhaps rather small, but it is not unreasonable. We may compare it with the radii of the radioactive nuclei calculated from the disintegration constants by Gamow and Houtermans, viz., about 7×10^{-13} cm.

Similar experiments were made in which the neutron radiation was passed through blocks of brass and carbon. The values of p deduced in the same way were 6×10^{-13} cm and $3 \cdot 5 \times 10^{-13}$ cm respectively.

The target areas for collision for some light elements were compared by another method. The second ionization chamber was used, which could be field with different gases by circulation. The position of the source vessel was kept fixed relative to the counter, and the number of deflections was observed when the counter was filled in turn with hydrogen, nitrogen, oxygen, and argon. Since the number of neutrons passing through the counter was the same in each case, the number of deflections should be proportional to the target area for collision, neglecting the effect of the material of the counter, and allowing for the fact that argon is monatomic. It was found that nitrogen, oxygen, and argon give about the same number of deflections; the target areas of nitrogen and oxygen are thus roughly equal, and the target area of argon is nearly twice that of these. With hydrogen the measurements were very difficult, for many of the deflections were very small owing to the low ionising power of the proton and the low density of the gas. It seems probable from the results that the target area of hydrogen is about two– thirds that of nitrogen or oxygen, but it may be rather greater than this.

There is yet little information about the angular distribution of the scattered neutrons. In some experiments kindly made for me by Dr.Gray and Mr.Lea, the scattering by lead was compared in the backward and forward directions, using the ionisation in a high pressure chamber to measure the neutrons. They found that the amount of scattering was about that to be expected from the measurements quoted above, and that the intensity per unit solid angle was about the same between 30° to 90° in the forward direction as between 90° to 150° in the backward direction. The scattering by lead is therefore not markedly anisotropic.

Two types of collision may prove to be of peculiar interest, the collision of a neutron with a proton and the collision with an electron. A detailed study of these collisions with an elementary particle is of special interest, for it should provide information about the structure and field of the neutron, whereas the other collisions will depend mainly on the structure of the atomic nuclei. Some preliminary experiments by Mr.Lea, using the pressure chamber to measure the scattering of neutrons by paraffin wax and by liquid hydrogen, suggest that the collision with a proton is more frequent than with other light atoms. This is not in accord with the experiments described above, but the results are at present indecisive. These collisions can be more directly investigated by means of the expansion chamber or by counting methods, and it is hoped to do so shortly.

The collision of a neutron with an electron has been examined in two ways, by the expansion chamber and by the counter. An account of the expansion chamber experiments is given by Mr.Dee in the third paper of this series. Mr.Dee has looked for the general ionisation produced by a large number of neutrons in passing through the expansion chamber, and also for the short electron tracks which should be the result of a very close collision between a neutron and electron. His results show that collisions with electron are extremely rare compared even with those with nitrogen nuclei, and he estimates that a neutron can produce on the average not more than 1 ion pair in passing through 3 metres of air.

In the counter experiments a beam of neutrons was passed through a block of brass, 1 inch thick, and the maximum range of the protons ejected from paraffin wax by the emergent beam was measured. From this range the maximum velocity of the neutrons after travelling through the brass is obtained and it can be compared with the maximum velocity in the incident beam. No change in the velocity of the neutrons due to their passage through the brass could be detected. The accuracy of the experiment is not high, for the estimation of the end of the range of the protons was rather difficult. The results show that the loss of energy of a neutron in passing through 1 inch of brass is not more than about $0 \cdot 4 \times 10^6$ electron volts. A path of 1 inch in brass corresponds as regards electron collisions to a path of nearly 2×10^4 cm of air, so that result would suggest that a neutron loses less than 20 volts per centimetre path in air in electron collisions. This experiment thus lends general support to those with the expansion chamber, though it is of far inferior accuracy. we conclude that the transfer of energy from the neutron to electrons is of very rare occurrence. This is not unexpected. Bohr has shown on quite general ideas that collisions of a neutron with an electron should be very few compared with nuclear collisions. Massey, on plausible assumptions about the field of the neutron, has made a detailed calculation of the loss of energy to electrons, and finds also that it should be small, not more than 1 ion pair metre in air.

GENERAL REMARKS

It is interest to examine whether other elements, besides beryllium and boron, emit neutrons when bombarded by α-particles. So far as experiments have been made, no case comparable with these two has been found. Some evidence was obtained of the emission of neutrons from fluorine and magnesium, but the effects were very small, rather less than 1 per cent. of the effect obtained from beryllium under the same conditions. there is also the possibility that some elements may emit neutrons spontaneously, e.g., potassium, which is known to emit a nuclear β-radiation accompanied by a more penetrating radiation. Again no evidence was found of the presence of neutrons, and and it seems fairly certain that the penetrating type is, as has been assumed, a γ-radiation.

Although there is certain evidence for the emission of neutrons only in two cases of nuclear transformations, we must nevertheless suppose that the neutron is a common constituent of atomic nuclei. We may then proceed to build up nuclei out of α-particles, and protons, and we are able to avoid the presence of uncombined electrons in a nucleus. This has certain advantages for, as is well known, the electrons in a nucleus have lost some of the properties which they have outside, e.g., their spin and magnetic moment. If the α-particle, the neutron, and the proton are the only units of nuclear structure, we can proceed to calculate the mass defect or binding energy of a nucleus as the difference between the mass of the nucleus and the sum of the masses of the constituent particles. It is, however, by no means certain that the α-particle and the neutron are the only complex particles in the nuclear structure, and therefore the mass defects calculated in this way may be the true binding energies of the nuclei. In this connection it may be noted that the examples of disintegration discussed by Dr. Feather in the next paper are not all of one type, and he suggests that in some cases a particle of mass 2 and charge 1, the hydrogen isotope recently reported by Urey, Brickwedde and Murphy, may be emitted. It is indeed possible that this particle also occurs as a unit of nuclear structure.

It has so far been assumed that the neutron is a complex particle consisting of a proton and an electron. This is the simplest assumption and it is supported by the evidence that the mass of the neutron is about $1 \cdot 006$, just a little less than sum of the masses of a proton and an electron. Such a neutron would appear to be the first step in the combination of the elementary particles towards the formation of a nucleus. It is obvious that this neutron may help us to visualise the building up of more complex structures, but the discussion of these matters will not be pursued further for such speculations, though not idle, are not at the moment very fruitful. It is, of course, possible to suppose that the neutron may be an elementary particle. This view has little to recommend it at present, except the possibility of explaining the statistics of such nuclei as N^{14}.

There remains to discuss the transformations which take place when an α-particle is captured by a beryllium nucleus, Be^9. The evidence given here indicates that the main type of transformation is the formation of a C^{12} nucleus and the emission of a neutron. The experiments of Curie–Joliot and Joliot, of Auger, and of Dee show quite definitely that there is some radiation emitted by beryllium which is able to eject fast electrons in passing through matter. I have made experiments using the Geiger point counter to investigate this radiation and the results suggest that the electrons are produced by a γ-radiation. There are two distinct processes which may give rise to such a radiation. In the first place, we may suppose that the transformation of Be^9 to C^{12} takes place sometimes with the formation of an excited C^{12} nucleus which goes to the ground state with the emission of γ-radiation. This is similar to the transformations which are supposed to occur in some cases of disintegration with proton emission, e.g., $B^{10}4$, F^{19}, Al^{27}, the majority of transformations occur with the formation of an excited nucleus, only in about one–quarter is the final state of the residual nucleus reached in one step. we should then have two groups of neutrons of different energies and a γ-radiation of quantum energy equal to the difference in energy of the neutron groups. The quantum energy of this radiation must be less than maximum energy of the neutrons emitted, about $5 \cdot 7 \times 10^6$ electron volts. In the second place, we may suppose that occasionally the beryllium nucleus changes to a C^{13} nucleus and that the surplus energy is emitted as radiation. In this case the quantum energy of the radiation may be about 10×10^6 electron volts.

It is of interest to note that Webster has observed a soft radiation from beryllium bombarded by polonium α-particles, of energy about 5×10^5 electron volts. This radiation may well be ascribed to the first of the two processes just discussed, and its intensity is of the right order. On the other hand, some of the electrons observed by Curie–Joliot and Joliot had energies of the order of 2 to 10×10^6 volts, and Auger recorded one example of an electron of energy about $6 \cdot 5 \times 10^6$ volts. These electrons may be due to a hard γ-radiation produced by the second type of transformation.[2]

It may be remarked that no electrons of greater energy than the above appear to be present. This is confirmed by an experiment made in this laboratory by Dr. Occhialini. Two tube counters were placed in a horizontal plane and the number of coincidences recorded by them was observed by means of the method devised by Rossi. The beryllium source was then brought up the plane of the counters so that the radiation passed through both counters in turn. No increase in the number of coincidences could be detected. It follows that there are few, if any, $\beta -$ rays produced with energies sufficient to pass through the walls of both counters, a total of 4 mm brass; that is, with energies greater than about 6×10^8 volts. This experiment further shows that the neutrons very rarely produce coincidences in tube counters under the usual conditions of experiment.

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[2] Although the presence of fast electrons can be easily explained in this way, the possibility that some may be due to secondary effects of the neutrons must be lost sight of.