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Section A.—Mathematical and Physical Sciences.

Bakerian Lecture.—*The Neutron.*

By J. Chadwick, F.R.S.

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§ 1. In an earlier paper* I showed that the radiations excited in certain light elements by the bombardment of α-particles consist, at least in part, of particles which have a mass about the same as that of the proton but which have no electric charge. These particles, called neutrons, have some very interesting properties. Some of the more striking were described in the paper I have mentioned and in those of Dr. Feather† and Mr. Dee‡ which accompanied it. The most obvious properties of the neutron are its ability to set in motion the atoms of matter through which it passes and its great penetrating power. From measurements of the momenta transferred to different atoms the mass of the neutron was estimated and shown to be nearly the same as the mass of the proton, while the penetrating power shows that the neutron can have no nett electric charge. The loss of energy of a neutron in passing through matter is due to the 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 was less than 1 ion pair in 3 metres path, while Massey has calculated that it may be as low as 1 ion pair per 10^5 km. This behaviour is, of course, very different from that of a charged particle such as a proton, which dissipates its energy almost entirely in electron collisions. The contrast between the rate of loss of energy of a proton and a neutron of the same initial velocity is most striking. A proton of velocity 3×10^9 cm./sec. travels about 1 foot in air, while a neutron of the same initial velocity will on the average make a close collision with a nitrogen nucleus only once in 300 to 400 yards'

* Chadwick, 'Proc. Roy. Soc.,' A, vol. 136, p. 692 (1932).

† Feather, *loc. cit.*, p. 709.

‡ Dee, *loc. cit.*, p. 727.

path and it may go a distance of a few miles before losing all its energy. The collision of a neutron with an atomic nucleus, although much more frequent than with an electron, is also a rare event, for the electric field between a neutron and a nucleus is small except at distances of the order of 10^{-12} cm. In such a close collision the neutron will be deflected from its path and the struck nucleus may acquire sufficient energy to produce ions. Thus the nuclei recoiling from encounters with neutrons can be detected by ionization measurements, using an ionization chamber with a sensitive electrometer or with an electrical counting apparatus, or by their ionized tracks when produced in an expansion chamber.

Neutrons can thus be detected only in an indirect way, by the observation of the recoil atoms. For this reason, and also because they are produced as a result of a similar collision process only partly under our control, the study of their properties in detail has proved both difficult and tedious.

The nature and properties of the neutron are of interest not only because of their novelty but because the neutron is probably a very important unit in the structure of matter. It is now generally assumed that atomic nuclei consist of protons and neutrons; then, because the mass of a nucleus is always equal to or greater than twice its charge, there must be more neutrons in matter than there are protons.

In this lecture I shall give a brief survey of our knowledge of the neutron and indicate some directions in which progress has been made recently.

§ 2. *Production of Neutrons.*—Neutrons have been produced so far only by bombarding certain elements by α-particles. The process is assumed to be the capture of the α-particle into the atomic nucleus with the formation of a new nucleus and the release of a neutron. The new nucleus will thus have a nuclear charge two units higher than that of the original nucleus and a mass number three units greater. The yield of neutrons is, of course, very low, and comparable to the yield of protons in the artificial transmutations by the same process. The greatest effect is given by beryllium, where the yield is probably about 30 neutrons for every million α-particles of polonium which fall on a thick layer of beryllium. For the elements of much higher atomic number the yield is very small, probably of the order of 1 or 2 neutrons per million α-particles. The yield can be increased by using bombarding α-particles of greater energy, *e.g.*, using radon and its products as the source of α-particles, but here the γ-radiations from the source may interfere with the detection of neutrons unless suitable precautions are taken. The elements from which neutrons have been obtained are lithium, beryllium, boron, fluorine, neon, sodium, magnesium and aluminium. It is probable that most of the elements of higher atomic number up to argon will give neutrons when α-particles of sufficient energy are used.

It is noteworthy that, with the exceptions of helium, nitrogen, carbon and oxygen, all the light elements up to aluminium give neutrons, while some, *e.g.*, fluorine, give both neutrons and protons. Both results can be related to general rules of nuclear structure.* If a nucleus of mass number A and atomic number Z transforms by capturing an α-particle and emitting a neutron, the new nucleus will have a mass $A + 3$ and an atomic number $Z + 2$. Now all known types of atomic nuclei obey the rule that $A \geqslant 2Z$. If the new nucleus is to be subject to this condition then $A+3 \geqslant 2(Z+2)$ or $A \geqslant 2Z+1$. This condition is not satisfied by He_2^4, C_6^{12}, N_7^{14}, or O_8^{16}, and we should therefore not expect to observe a disintegration of these nuclei with a neutron emission. The application of this condition also forbids the emission of neutrons from B_5^{10}, Ne_{10}^{20} and Mg_{12}^{24}. The neutrons must, therefore, be ascribed to the other isotopes of these elements.

The cases of fluorine and aluminium are interesting because these elements are both pure and yet they emit both protons and neutrons under the bombardment of α-particles. It seems then that the nuclei F^{19} and Al^{27} can disintegrate in either of two ways. For example, the capture of the α-particle may result in the reaction $F_9^{19} + He_2^4 \rightarrow Ne_{10}^{22} + H_1^1$, or in the reaction $F_9^{19} + He_2^4 \rightarrow Na_{11}^{22} + n_0^1$, here forming a sodium isotope of mass 22 which is certainly very rare in nature. If Na^{22} is stable its mass must be less than that of Ne^{22}, for otherwise the capture of a K electron would provoke the change $Na^{22} \rightarrow Ne^{22}$ with a release of energy. It follows that the maximum energy of the neutrons liberated from fluorine should be greater than the maximum energy of the protons. I have not yet been able to test this conclusion, for the yield of neutrons from fluorine is small. If it should prove that the neutrons have a smaller energy than the protons then we must conclude that the Na^{22} nucleus is unstable and transforms into Ne^{22} by capturing an electron, emitting some energy in the form of radiation. A similar argument may be applied to the dual transformation of aluminium which results in the formation of Si^{30} and an otherwise unknown P^{30}.

§ 3. *Boron and Beryllium.*—The production of neutrons from boron and beryllium has been investigated in some detail. These cases are of importance

* The following argument has also been pointed out independently by Dr. Feather in discussions in this laboratory.

because in most experiments with neutrons boron and beryllium have been used as sources.

The element boron consists of two isotopes B^{10} and B^{11}. When boron is bombarded by α-particles both neutrons and protons are emitted. The application* of the arguments used above leads to the conclusion that the protons are emitted in the disintegration of B^{10} and the neutrons from B^{11}. The velocity distribution of the neutrons from boron has not been examined in any detail, but the experimental results are consistent with the supposition that the neutrons liberated from a thin layer of boron by a homogeneous beam of α-particles would consist of a single group of definite velocity. The velocity of the neutron liberated by an α-particle of velocity $1 \cdot 60 \times 10^9$ cm./sec. is about $2 \cdot 53 \times 10^9$ cm./sec. There is no indication of a γ-ray emission connected with the neutrons.†

The dependence of the neutron emission on the velocity of the bombarding α-particles has been examined. The source of α-particles, a silver disk coated with polonium, was placed in an air-tight vessel at a distance of 2·05 cm. from the boron target. The neutrons emitted from the target were detected in an ionization chamber connected to an amplifier and oscillograph. To increase the effect, a sheet of paraffin wax was placed over the front of the ionization chamber. Thus the deflexions of the oscillograph were due partly to nitrogen recoil atoms produced in the air of the chamber itself, and partly to protons ejected from the paraffin wax. Carbon dioxide was then admitted to the source vessel at a pressure of 5 cm., thus reducing the velocity of the α-particles striking the boron target. The number of oscillograph deflexions obtained under these conditions was again counted. In this way, by successive additions of carbon dioxide, the variation of the emission of neutrons was found as the velocity of the impinging α-particles gradually decreased. The results‡ are shown in fig. 1, where the ordinates are the number of oscillograph deflexions observed in 30 minutes and the abscissæ are the maximum ranges of the α-particles incident on the boron, calculated on the assumption that the stopping power of carbon dioxide is 1·53 relative to air. It must be noted that this curve does not necessarily represent the true variation in the number of neutrons emitted as the range of the α-particles is varied. The number of deflexions

* *Cf.* Chadwick, Constable and Pollard, 'Proc. Roy. Soc.,' A, vol. 130, p. 480 (1931).

† The γ-rays of energy about 3×10^6 electron volts emitted from boron bombarded by α-particles are connected with the proton emission from B^{10}.

‡ Similar results have been obtained by Curie and Joliot, 'C. R. Acad. Sci. Paris,' vol. 196, p. 397 (1933).

observed in the chamber will depend not only on the number of neutrons but also upon their velocity; the probability of a collision between a neutron and a nitrogen atom in the chamber or a proton in the paraffin wax depends on the velocity of the neutron, and further, the slower the neutron the less is the energy of the recoil atoms and therefore the greater the chance that some of them will not give a measurable deflexion of the oscillograph. It is not possible at present to estimate the influence of these effects and to deduce from the observations of fig. 1 the true curve showing the variation in the emission of neutrons with the range of the bombarding α-particles.

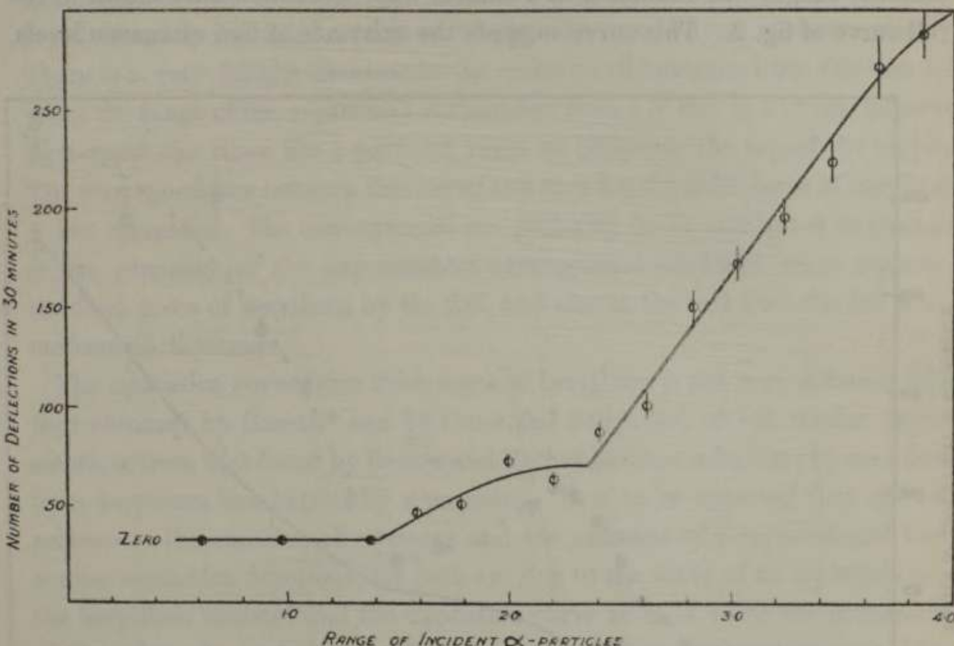

Fig. 1.

It appears from fig. 1 that no neutrons are liberated until the range of the α-particles is about 1·4 cm. of air. As the range of the α-particles is increased the emission of neutrons rises to a stationary value and then increases rapidly as the range of the α-particles is increased from about 2·4 cm. up to the maximum of 3·86 cm. This suggests that the α-particles of 1·4 cm. range enter the boron nucleus through a resonance level, and those of 2·4 cm. and greater range enter through and over the top of the potential barrier. The corresponding energies are $2 \cdot 4 \times 10^6$ electron volts for the resonance level, and about $3 \cdot 7 \times 10^6$ electron volts for the top of the potential barrier (or rather the point at which the α-particles begin to penetrate appreciably).

Since the velocity of the neutron liberated from boron by an α-particle of given velocity is known, the velocity distribution of the neutrons emitted from a thick layer of boron bombarded by polonium α-particles can now be deduced. The resonance level will give a group of neutrons of velocity about $1 \cdot 07 \times 10^9$ cm./sec., and penetration over the barrier will give neutrons with a continuous distribution of velocity between $1 \cdot 9$ and $2 \cdot 53 \times 10^9$ cm./sec. The corresponding energies are $0 \cdot 6 \times 10^6$ volts for the resonance group and $1 \cdot 9$ and $3 \cdot 35 \times 10^6$ volts for the continuous distribution.

The excitation of neutrons from a thick layer of beryllium by α-particles of different ranges was examined in a similar way, with the result shown in the full curve of fig. 2. This curve suggests the existence of two resonance levels,

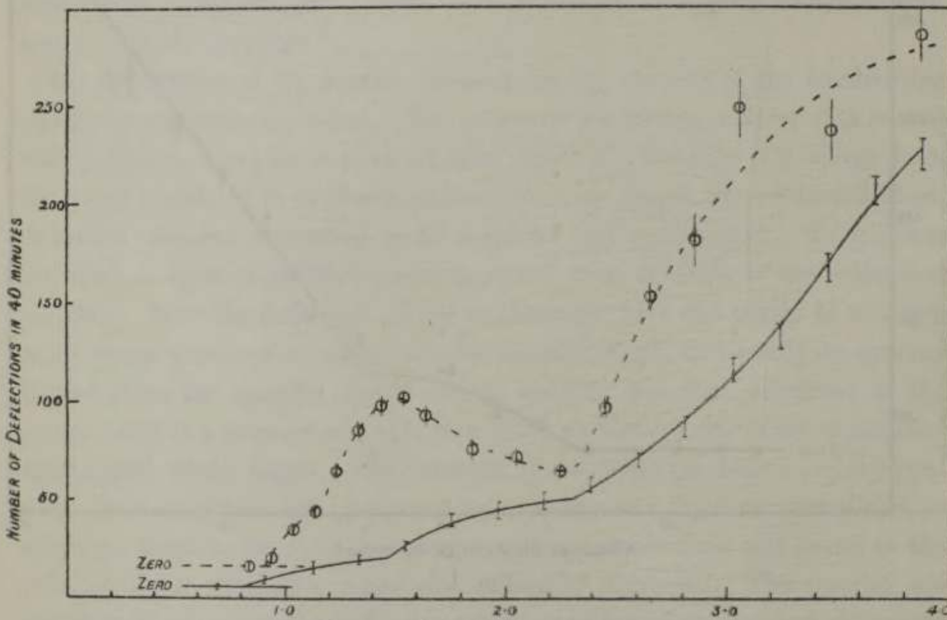

Fig. 2.

the first, through which α-particles of $0 \cdot 80$ cm. range can enter the beryllium nucleus, and the second, through which α-particles of $1 \cdot 46$ cm. range enter. A rapid increase in the emission of neutrons takes place when the range of the α-particles is increased beyond $2 \cdot 25$ cm. This is taken to correspond to the penetration through and over the top of the potential barrier. The energies of the resonance levels are about $1 \cdot 4 \times 10^6$ and $2 \cdot 5 \times 10^6$ electron volts, and penetration through the top of the barrier begins at about $3 \cdot 5 \times 10^6$

electron volts. As we should expect, the height of the potential barrier of beryllium is slightly less than that of boron.

The existence of the resonance levels in beryllium was confirmed by observing the neutron emission from a thin foil of beryllium. This was prepared by evaporating *in vacuo* a small piece of pure beryllium and allowing some of the vaporized metal to condense on a cooled copper disk. The thin layer of beryllium thus obtained was not quite uniform in thickness, but it was suitable for the present purpose. The thick piece of beryllium used in the previous experiment was replaced by this thin foil, and the observations were repeated. The results are given in the dotted curve of fig. 2. The first resonance level is only vaguely indicated in this curve, but the second level is shown clearly. There is a very definite decrease in the emission of neutrons from the thin foil when the range of the α-particles is increased from 1·6 cm. to 2·2 cm. followed by a rapid rise when the α-particles begin to penetrate the top of the barrier. The correspondence between this curve and that for the thick layer of beryllium is not complete. The discrepancies are probably to be attributed to changes in the geometry of the experimental arrangement produced when replacing the thick piece of beryllium by the foil, and also to the fact that the foil is not uniform in thickness.

The excitation curve for a thick layer of beryllium is not very different from that obtained by Rasetti* and by Curie and Joliot (*loc. cit.*) in similar experiments, or from that found by Becker and Bothe† for the excitation of γ-rays from from beryllium bombarded by α-particles. It is to be expected that the two processes—the emission of neutrons and the emission of γ-rays—should have similar excitation functions, for both are due to the entry of an α-particle into the beryllium nucleus, and the excitation curve gives in effect the probability of the entry of α-particles of different ranges. These two processes are, however, more intimately connected. Becker and Bothe found that the energy of the γ-ray is independent of the energy of the incident α-particle and may be greater than it and they pointed out that this means that the emission of the γ-ray is not an independent process; it is probably related to the neutron emission in a manner similar to that in which the γ-rays from B^{10} are related to the emission of two groups of protons. On this view, we should expect to find two groups of neutrons emitted from a thin foil of beryllium bombarded by a homogeneous beam of α-particles. Some observations suggest that this

* 'Z. Physik,' vol. 78, p. 165 (1932).
† 'Z. Physik,' vol. 76, p. 421 (1932).

is so. Curie, Joliot, and Savel* found that the protons ejected from paraffin wax by the neutrons from a thick piece of beryllium bombarded by polonium α-particles consist mainly of a group with maximum range about 28 cm. in air and a weaker group of maximum range about 70 cm. This indicates that the main group of neutrons has a maximum velocity of about $2 \cdot 9 \times 10^9$ cm./sec. and that there is also a small number of neutrons with velocities up to about $3 \cdot 8 \times 10^9$ cm./sec. Without further evidence it is not possible to decide how these groups are excited.

In my experiments I have examined the neutrons emitted from a thick layer of beryllium and from the thin foil. The neutrons passed through a sheet of paraffin wax placed just in front of the face of the ionization chamber. The ranges of the protons ejected by the neutrons from the wax were measured by observing the diminution in the number of protons as absorbing foils of aluminium were interposed between the wax and the ionization chamber. The protons due to the neutrons from the thin foil of beryllium consisted mainly of a group with a fairly well defined range of 23 cm. to 24 cm. in air, fig. 3. There were protons present with ranges much greater than this but

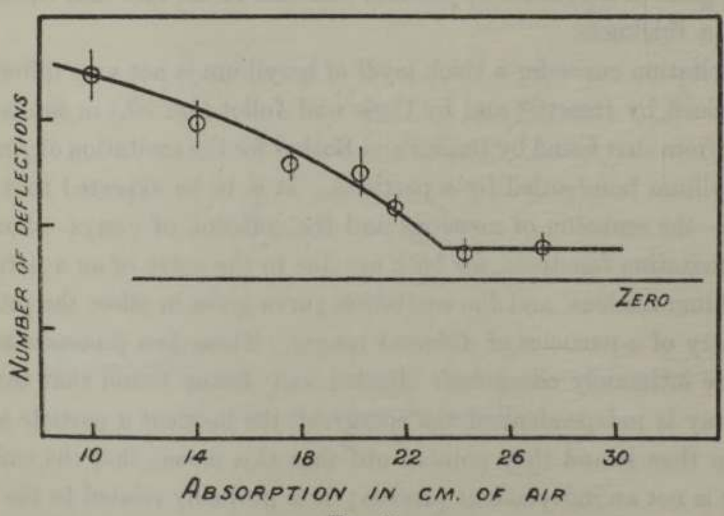

FIG. 3.

their number was very small. Some indication was obtained that the maximum range was at least 100 cm. in air, but the difference between the number of oscillograph deflexions with and without the wax was so small that the range of these fast protons could not be fixed.

* 'C. A. Acad. Sci. Paris,' vol. 194, p. 2208 (1932).

The results using a thick layer of beryllium showed again the presence of a group of protons of 24 cm. range, and also a group of about 65 cm. to 75 cm. range, with a very doubtful indication of the presence of protons of still greater range.

The conclusions to be drawn from these experiments are not very definite. It is, however, certain that the neutrons liberated from beryllium by polonium α-particles of velocity $1 \cdot 6 \times 10^9$ cm./sec. consist of at least two groups; the slower and more intense group has a velocity of $2 \cdot 8 \times 10^9$ cm./sec. (energy $4 \cdot 1 \times 10^6$ electron volts) and the faster group a velocity perhaps greater than 4×10^9 cm./sec. (energy greater than 8×10^6 electron volts). It remains to be seen how these results can be fitted into the disintegration process. I assume that the reaction is

$$Be_4{}^9 + He_2{}^4 \rightarrow C_6{}^{12} + n_0{}^1.$$

The masses of all the nuclei concerned are now known with reasonable accuracy; Bainbridge's measurement gives $Be^9 = 9 \cdot 0132$; from Aston's measurements, $He^4 = 4 \cdot 00106$ and $C^{12} = 12 \cdot 0003$; and the mass of the neutron is $1 \cdot 0067$ (see § 4). Assuming that energy and momentum are conserved, the velocity and energy of the neutron liberated by an α-particle of polonium (velocity $= 1 \cdot 60 \times 10^9$ cm./sec., energy $= 5 \cdot 3 \times 10^6$ electron volts) can be calculated. Its velocity is $4 \cdot 77 \times 10^9$ cm./sec. and energy $11 \cdot 9 \times 10^6$ electron volts. These values are much greater than any found in the experiments described above. Neutrons of this velocity would eject protons with ranges up to about 150 cm. in air, while the greatest ranges found for the protons experimentally is 70 cm., with, however, indications of ranges greater than 100 cm. Some evidence of the presence of neutrons of high energy has been obtained from the examination of oscillograph records of the deflexions due to recoil atoms produced in an ionization chamber. The size of a deflexion is proportional, at least approximately, to the energy of the recoil atom, and therefore, for a given atom, proportional to the energy of the colliding neutron. Neutrons from the thin beryllium foil bombarded by polonium α-particles of full range were passed into an airtight ionization chamber, which was filled in turn with nitrogen, oxygen, and argon. For each gas a large number of oscillograph deflexions was photographed, using the oscillograph at a convenient sensitivity. The examination of the records for all three gases showed very clearly a strong and well defined group of recoil atoms which was attributed to the effect of the group of neutrons of energy about 4×10^6 electron volts, and in addition a much weaker group containing recoil atoms of high energy.

The maximum energy associated with this group was roughly three times the maximum energy of the short group, that is, about 12×10^6 electron volts. The separation of the recoil atoms into these two groups is to some extent confirmed by an estimate of the number of ions corresponding to the oscillograph deflexions, from which the energies of the recoil atoms can be deduced. This estimation is, however, indirect and somewhat uncertain. With these reservations, the experiments provide fair evidence for the emission of neutrons of energies up to about 12×10^6 electron volts. Some evidence has also been obtained by Feather, who has measured the ranges of recoil atoms of nitrogen, oxygen, and carbon produced in an expansion chamber. He has observed several tracks which lead to values of the neutron energy of about 10×10^6 electron volts. Feather's evidence is more direct and more trustworthy than that just given, but further data are needed before the maximum energy of the neutrons can be definitely ascertained.

I shall suppose for the present that the energy of the faster group of neutrons emitted from beryllium does in fact agree with that calculated on the hypothesis that the disintegration process is $Be^9 + He^4 \rightarrow C^{12} + n^1$ and that energy and momentum are conserved. On this view a thin foil of beryllium bombarded by α-particles of velocity $1 \cdot 60 \times 10^9$ cm./sec. should emit a strong group of neutrons with velocity $2 \cdot 8 \times 10^9$ cm./sec. and a weak group of velocity $4 \cdot 7 \times 10^9$ cm./sec., and a γ-radiation of high energy, which is intimately connected with the emission of the neutrons.

These facts can be given a descriptive explanation in terms of the following picture of the disintegration process. Assume that the beryllium nucleus consists of an α-particle with 2 protons and 3 neutrons. For some reason the formation of another α-particle by the further condensation of 2 protons and 2 neutrons cannot take place (or rather the chance of condensation is very small. When it occurs the beryllium nucleus may break up into two α-particles and a neutron). The capture of an α-particle by the beryllium nucleus provokes the condensation, and usually the nuclear change takes place with the emission of a γ-ray and a neutron. This neutron will belong to the group of lower velocity found experimentally. Sometimes, however, all the energy may be taken by the neutron, and this reaction will correspond to the emission of the group of neutrons of high velocity. On this view we get a residual nucleus, C^{12}, consisting of three α-particles, and two groups of neutrons which should differ in energy by about the energy of the γ-ray (allowance must be made for the energy of the recoiling C^{12} nucleus). Taking the velocities given above for the two groups of neutrons, the energy of the γ-ray should be 7×10^6 electron volts. This is much higher than the value 5×10^6 electron volts deduced by Becker and Bothe from their measurements of the ranges in aluminium of the secondary electrons produced by this γ-radiation. On the other hand, the measurements of the absorption coefficient of the radiation suggest an energy rather higher than 5 million volts; and there is no doubt, from expansion chamber observations, that the radiation does produce some secondary electrons of greater energy than 5 million volts. Thus Auger observed one β-ray track due to this radiation which had an energy of $6 \cdot 5 \times 10^6$ electron volts, while out of 150 electron tracks measured by Blackett, Occhialini and myself, 10 had energies between 5 and 7×10^6 volts. Unless these were due to the penetrating radiation, there must be some γ-radiation emitted from beryllium with an energy of about the required amount. On the other hand, the analysis of the tracks suggests that a large fraction of the γ-radiation has an energy of about 5×10^6 volts. The evidence about the energy of the γ-rays emitted from beryllium is unsatisfactory, but it is not definitely against the proposed scheme of disintegration.

It is now possible to describe the velocity spectrum of the neutrons emitted from a thick layer of beryllium bombarded by polonium α-particles. Each resonance level will give rise to two homogeneous groups of neutrons, the slower group being much stronger than the faster. The groups from the first level will have velocities of about 1×10^9 cm./sec. and $3 \cdot 92 \times 10^9$ cm./sec., or energies of about $0 \cdot 5 \times 10^6$ electron volts and about $8 \cdot 0 \times 10^6$ electron volts.* The groups from the second level will have velocities of about $1 \cdot 68 \times 10^9$ cm./sec. and $4 \cdot 18 \times 10^9$ cm./sec., corresponding to energies about $1 \cdot 47 \times 10^6$ electron volts and $9 \cdot 1 \times 10^6$ electron volts respectively. Since general penetration through the top of the potential barrier begins when the α-particle has a range of $2 \cdot 25$ cm., there will be a group of neutrons with velocities between $2 \cdot 16 \times 10^9$ and $2 \cdot 8 \times 10^9$ cm./sec., or energies between $2 \cdot 5$ and $4 \cdot 1 \times 10^6$ electron volts, and a weaker group with velocities between $4 \cdot 4 \times 10^9$ and $4 \cdot 77 \times 10^9$ cm./sec., and energies between $10 \cdot 1$ and $11 \cdot 9 \times 10^6$ electron volts. The neutron emission from a thick layer of beryllium is thus relatively complicated. The majority of the neutrons are contained in the slow groups and the velocities given for these should be fairly accurate. It must be remembered that there is little direct evidence for the velocities given for the faster groups. The values are obtained on the assumptions that the disintegration proceeds in a certain way and that energy is conserved. The

* The group of neutrons of velocity about $3 \cdot 8 \times 10^9$ cm./sec. observed from a thick layer of beryllium may correspond to this weak resonance group.

picture of the disintegration process adopted here can be tested in two ways—by a search for the group of very fast neutrons and by measurement of the energy of the γ-radiation. The evidence now available on these points is inconclusive.

It is possible that either or both the assumptions made above are untrue. It may be that the capture of an α-particle by the beryllium nucleus results in a complete breakdown of the nucleus, with the emission of three α-particles, a neutron, and a γ-radiation. There seems, however, no reason to expect in such a process that the neutrons would be emitted in two definite groups as appears to be the case. It is perhaps possible that both processes take place, sometimes a C^{12} nucleus being formed and sometimes three α-particles; one might then be able to account not only for the presence of the γ-ray of energy about 7×10^6 volts, but also for that of about 5×10^6 volts which is suggested by Becker and Bothe's measurements.

In none of the examples of artificial transmutation so far examined, has there been any reason to suspect that energy is not conserved; in some cases it is certain that energy is conserved within narrow limits. If it should fail in this particular case, one might be tempted to suppose that the missing energy is taken away by some yet undetected particle. A suggestion has, indeed, been made at various times that neutral particles of very small mass may exist, and it has been revived recently to overcome the difficulty of explaining the continuous distribution of energy among the β-rays expelled from a radioactive body. The emission of such a particle would be very difficult to detect in any cases of artificial transmutations owing to their infrequent occurrence, and the most favourable opportunity of finding it appears to be offered by a radioactive β-ray disintegration. About two years ago Mr. Tarrant kindly made some measurements for me to search for this neutral radiation in the emission from radium E, but we were unable to find any evidence of it. Mr. Lea and I have recently made a stricter examination with the same result. We conclude from our experiments that if a neutral radiation is emitted from radium E to compensate for the energy distribution of the β-rays, it must consist of particles of small mass and of such small magnetic moment that a particle cannot produce more than 1 pair of ions in 100 miles of path in air.

§ 4. *The Mass of the Neutron.*—While observations of the momenta transferred in collisions of a neutron with atomic nuclei are enough to show that the mass of the neutron is about the same as that of the proton, the measurements cannot be made with precision. For an accurate estimate of the mass of the neutron we must use the energy relations in a disintegration in which a neutron is liberated from an atomic nucleus. Assuming that energy and momentum are conserved in the disintegration, the measurement of the kinetic energy of the neutrons liberated by α-particles of known energy is sufficient to give the mass of the neutron if the masses of the nuclei concerned are known. In a previous paper I considered the disintegration

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

The kinetic energy of the neutrons liberated from boron by α-particles of polonium was found by measuring the maximum range of the particles ejected from paraffin wax. Using Aston's measurements of the masses of the nuclei, I obtained a value for the mass of the neutron of 1·0067.

Another value can be deduced from the process

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

The mass of Li^7 is best obtained from the experiments of Cockcroft and Walton on the disintegration of lithium by fast protons. The lithium nucleus captures a proton and breaks up into two α-particles

$$Li^7 + H^1 \rightarrow 2He^4.$$

Cockcroft and Walton found that the range of the α-particles is 8·4 cm. in air, corresponding to an energy of $8 \cdot 7 \times 10^6$ electron volts, when protons of energy 300,000 volts were used. This leads to a mass of 7·0133 for the Li^7 nucleus. Aston's measurements give 4·00106 for the mass of He^4 and 10·01075 for B^{10}. The kinetic energy of the neutrons liberated from Li^7 by the α-particles of polonium (energy 0·00565 in mass units) has not been determined. It is small, perhaps less than $0 \cdot 5 \times 10^6$ volts, for the neutrons are easily absorbed in a few millimetres of lead. If we assume that the neutrons are emitted with zero energy we shall get a maximum value for the mass of the neutron. We find in this way that the mass of the neutron cannot be greater than $1 \cdot 0070 \pm 0 \cdot 0005$. The uncertainty in this estimate arises mainly from the probable error in Aston's measurement of B^{10}.

If we assume that the hydrogen isotope of mass 2 consists of a proton combined with a neutron, we can obtain a minimum estimate for the mass of the neutron, for the sum of the masses of the two particles must be greater than the mass of the combination by an amount corresponding to the binding energy. The mass* of the nucleus of the H^2 isotope is 2·0130. Thus the mass of the neutron must be greater than $2 \cdot 0130 - 1 \cdot 0072$, or

* Bainbridge, 'Phys. Rev.,' vol. 43, p. 103 (1933).

1·0058. The mass of the neutron therefore lies between 1·0058 and 1·0070. Provisionally we may retain the value 1·0067 which I deduced from the boron disintegration.

There can be no doubt that the mass of the neutron is distinctly less than that of the hydrogen atom. This is consistent with the view that the neutron consists of a proton and an electron. The difference in mass, 0·0011, then represents the binding energy of the two particles and corresponds to 1 million electron volts. It may be significant that the change of mass corresponds to a change in the energy of the electron from $+ mc^2$ to $- mc^2$. This argument from the mass is certainly in favour of the complex nature of the neutron but it is by no means conclusive. The most direct proof would be the observation of the splitting of the neutron into a proton and an electron in a nuclear collision, but both calculation and experiment show that this must be a very rare event. As I shall show later, some suggestion that either the neutron or the proton may be complex can be deduced from the collisions of neutrons with protons.

On the other hand, certain arguments can be advanced to support the idea that the neutron is an elementary particle. According to the present scheme of quantum mechanics the hydrogen atom represents the only possible combination of a proton and an electron. However, the binding energy of the particles is greater than the proper mass of the electron and a relativistic mechanics would be required to describe their interaction.

A further argument is based on the spin of the neutron. This is deduced from the spins of the light elements on the assumption (1) that a nucleus is built up as far as possible of α-particles, then of protons and neutrons (no free electrons), (2) that the nuclear spin is given by the vector sum of its components' spins. It then appears that the neutron must have a spin $\frac{1}{2}h/2\pi$ and obey the Fermi statistics. The proton has a spin $\frac{1}{2}h/2\pi$ and obeys Fermi statistics. If the neutron is to be regarded as a proton combined with an electron a spin of 0 and Bose statistics must be ascribed to the electron. This is contrary to the behaviour of a free electron. 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.

A more general argument may be used. If the neutron is a proton and an electron why does not the hydrogen atom transform into a neutron with a release of energy? There is ample evidence to show that such a transformation must be exceedingly rare. This consideration seems to me to argue strongly for the elementary nature of the neutron.

It seems necessary for the present to recognize these difficulties and, while retaining the hypothesis that the neutron is complex for some purposes, to regard it as an elementary unit in the structure of atomic nuclei.

One might perhaps attempt to offer an alternative view, that the proton is the complex particle and regard it as a neutron plus a positive electron. The mass of the proton might perhaps be less than the sum of the masses of the neutron and positive electron, if the mass of the neutron is near the higher limit given above. But the difficulty with the spin remains. We should be forced to assume that the spin of the positive electron is 0, and then the annihilation of the positive electron with the negative becomes difficult to understand.

§ 5. *Collisions of Neutrons with Atomic Nuclei.*—The elastic collisions of a neutron with an atomic nucleus can be briefly described in a general way. Whatever view one takes of the nature of the neutron, its interaction with an atomic nucleus will be very small except at distances of the order of 10^{-12} cm. In its passage through matter the neutron will not be deflected unless it suffers a very intimate collision. One may say that the scattering of the neutrons will be due mainly to the internal field of the nucleus; the cross-section for the collisions will be about the same as the cross-section of the potential barrier of the nucleus, and the distribution of the scattered neutrons will not be markedly anisotropic. As I have shown in a previous paper, this view gives a reasonable account of the scattering of neutrons by heavy nuclei.

This is, of course, only a rough picture of the collision process, but the calculations of Massey* lead to much the same conclusion. Massey assumed that the neutron was a hydrogen atom in a nearly zero quantum state. The field of such a neutron will be similar to that just outside the Bohr orbit of the hydrogen atom but on a much reduced scale. It can be represented by

$$V(r) = e^2\left(\frac{1}{r} + \frac{Z}{a_0}\right)e^{-2Zr/a_0},$$

where Z, the effective nuclear charge, will be very large, and a_0 is the radius of the first Bohr orbit of hydrogen. The "radius" of the neutron will be a_0/Z.

The field of interaction between this neutron and a nucleus of charge Z′ at distances greater than the nuclear radius will be $Z'V(r)$. Now the experiments on the scattering of neutrons by lead show that the collision radius is about the same as the nuclear radius, and from this Massey was able to obtain

* 'Proc. Roy. Soc.,' A, vol. 138, p. 460 (1932).

a lower limit to the value of Z of 25,000. (This gives a maximum value of 2×10^{-13} cm. for the radius of the neutron.)

Applying this result for Z to the collisions of a neutron with the lighter nuclei, he was able to show that the collision radii should be proportional to the nuclear charge. This result does not correspond with experiment, which show that the radius varies slowly from carbon (*ca.* $3 \cdot 5 \times 10^{-13}$ cm.) to argon (*ca.* $5 \cdot 5 \times 10^{-13}$ cm.). He therefore concluded that the collision areas are determined by the internal field of the nucleus, that the external interaction is of such short range that the colliding systems penetrate.

The most interesting collisions of a neutron are those with a proton. The proton should behave as an elementary charge even at very small distances. If there were no other interaction between a proton and a neutron but that given by $V(r)$, the collision radius for these collisions must be less than $1 \cdot 4 \times 10^{-14}$ cm. The disagreement with experiment is startling, for the observed collision radius is about 4 to 5×10^{-13} cm. for neutrons of velocity $2 \cdot 7 \times 10^{9}$ cm./sec. and greater still for slower neutrons. Before proceeding to discuss the reasons for this discrepancy I will state briefly what is known about the neutron-proton collisions.

These collisions have not been studied in much detail owing to experimental difficulties. The most direct method would be to pass a known number of neutrons of definite speed into an expansion chamber filled with hydrogen and to photograph the hydrogen recoil tracks. This would give both the frequency of the collisions and the angular distribution of the struck protons. Unfortunately we have only very indirect methods of estimating the number of neutrons in a beam and the collisions are so infrequent as to make the experiment exceedingly tedious.

Some results on the angular distribution of the protons have been obtained by this method by Auger and Monod-Herzen,* and also by Kurie,† who used a slightly different arrangement. In both experiments the neutrons were obtained by bombarding a thick layer of beryllium by polonium α-particles. The neutrons were therefore heterogeneous, the greater part having speeds below $2 \cdot 8 \times 10^{9}$ cm./sec. In Auger's experiments a large majority of the recoil protons were due to collisions of slow neutrons. The angular distribution of the struck protons was roughly uniform. Kurie confined his attention to the protons produced by the faster neutrons but their distribution with angle was also fairly uniform relative to the centre of mass of the moving system.

* 'C. R. Acad. Sci. Paris,' vol. 196, p. 1102 (1933).

† 'Phys. Rev.,' vol. 43, p. 672 (1933).

Meitner and Phillipp* have used the expansion chamber method to make an estimation of the collision radius. They assumed that 30 neutrons are emitted from a thick foil of beryllium for every 10^6 α-particles of polonium incident upon it, and they measured the time interval in which tracks were recorded in the chamber by an independent experiment with a source emitting a known number of α-particles. Then from the observed frequency of the proton tracks they estimated that the collision radius was not less than 8×10^{-13} cm. From the data given in their account, it would appear that most of the collisions were due to slow neutrons, of velocities around 10^9 cm./sec.

My own experiments, in which electrical counting methods were used, are in general agreement with these. The angular distribution of the protons was measured by counting the number of protons ejected from annular rings of paraffin wax of different apertures. The results, though rough, showed that the distribution with angle of the protons was approximately uniform. Attempts to observe the angular distribution for a reasonably homogeneous beam of neutrons failed, owing to the smallness of the effects.

The collision radius was determined by the method used previously. The neutron source was a thin foil of beryllium of about 5 mm. air equivalent bombarded by polonium α-particles. The neutron beam was therefore fairly homogeneous, the main part consisting of particles of velocity about $2 \cdot 7 \times 10^9$ cm./sec., with a weak group of much higher velocity. The source was fixed in position relative to an ionization chamber connected to an amplifier and oscillograph in the usual way. The chamber could be evacuated and filled with different gases. The number of deflexions was observed when the chamber was filled in turn with hydrogen or a heavier gas, *e.g.*, nitrogen, oxygen, or argon. Each deflexion corresponds to the production of a recoil atom by the collision of a neutron with a nucleus. Since the number of neutrons passing through the chamber was the same in each case, the number of deflexions should be proportional to the collision area of the nucleus concerned. It was found that the number of deflexions in hydrogen was slightly less than the number in nitrogen or oxygen. The collision radius for hydrogen should therefore be rather less than for these nuclei. The collision radius for carbon was estimated by measuring the reduction in number of the deflexions observed in a counter when a thick block of graphite was placed in the path of the neutrons. The value found was about $3 \cdot 5 \times 10^{-13}$ cm. The collision radii of nitrogen and oxygen may be somewhat greater and will be taken as 4×10^{-13} cm.

* 'Naturwiss.,' vol. 20, p. 929 (1932).

The above comparison between hydrogen and nitrogen is subject to a small but uncertain error due to the fact that recoil atoms which make only a few ions will not be counted by the oscillograph. This affects the number of deflexions both in hydrogen and nitrogen. The deflexions in hydrogen are on the whole smaller than those in nitrogen owing to the low ionizing power of the proton and the low density of the gas. On the other hand the energy transfer is smaller in the nitrogen collisions and the more distant collisions may not be recorded. An estimate of the fraction of the hydrogen collisions which were not recorded in pure hydrogen was made from experiments in which mixtures of hydrogen and nitrogen were used in the ionization chamber, but it has not been possible to make a correction for the unrecorded nitrogen collisions. Having regard to this source of error, we may take the collision radius for hydrogen to be about 4 to 5×10^{-13} cm. for neutrons of velocity $2 \cdot 7 \times 10^{9}$ cm./sec.

The same experiment was made with a neutron source consisting of a thick layer of boron bombarded by polonium α-particles. These neutrons would have velocities up to about $2 \cdot 5 \times 10^{9}$ cm./sec. the average being probably rather less than 2×10^{9} cm./sec. The number of deflexions in hydrogen was now about twice the number in nitrogen, suggesting that the collision radius either of hydrogen or nitrogen varies rapidly with the velocity of the neutron. Measurements of the scattering of these slower neutrons in graphite and paraffin wax showed that the variation was to be ascribed mainly to hydrogen. From the comparison with nitrogen a value of 6×10^{-13} cm. was deduced for the hydrogen collision radius, while the comparison between graphite and paraffin wax gave a value of about 7×10^{-13} cm. Some experiments with slower neutrons suggest that the radius for the proton collisions continues to increase as the velocity of the neutron decreases.

In the consideration* of the neutron-proton collisions we thus have to explain the observations that the angular distribution of the struck protons is roughly uniform, and that the collision radius is very large and increases as the velocity of the neutron decreases. If we assume that the hydrogen isotope of mass 2 consists of a proton and a neutron we have a further experimental fact, that the binding energy of this isotope is about 10^{6} volts.

The wave theory of the collisions of two independent particles gives for the collision cross-section

$$Q = \frac{h^2}{\pi M^2 v^2} \Sigma_n (2n + 1) \sin^2 \delta_n,$$

* I am much indebted to Mr. H. S. W. Massey in this discussion of the collisions.

where M is the reduced mass of the system, v the initial relative velocity of the particles, and the δ_n's are phase constants depending on M, v and V(r), the interaction energy of the particles. The angular distribution per unit angle of the particles in a system of co-ordinates in which the centre of mass is at rest is given by

$$I(\theta)\sin\theta = \frac{h^2}{8\pi^2 M^2 v^2}\left|\Sigma_n (e^{2i\delta_n} - 1)(2n+1) P_n(\cos\theta)\right|^2 \sin\theta,$$

where

$$P_0(\cos\theta) = 1, \qquad P_1(\cos\theta) = \cos\theta, \qquad P_2(\cos\theta) = \tfrac{1}{2}(3\cos^2 - 1), \text{ etc.}$$

The fact that the angular distribution is uniform shows that only the spherical harmonic of zero order is important, *i.e.*, the scattering depends mainly on the head-on collisions of the particles. This means that the range of the neutron-proton interaction is small compared with

$$\frac{\text{wave-length}}{2\pi}\left(= \frac{h}{2\pi M v}\right),$$

i.e., the interaction range $\leqslant 10^{-12}$ cm. (This result agrees with the previous calculation of the collisions of neutrons in which the neutron was likened to an atom with an effective nuclear charge of at least 25,000.)

We must now examine the significance of the H^2 isotope, assuming it to consist of a proton and a neutron. The potential field between a neutron and a proton is taken as in fig. 4. V(r) is negligible for $r > r_0$. From the fact that an energy level of energy $-E_0$ (= binding energy) exists we can deduce that V(r) must be very great in the region $r < r_0$, for the field has to be so great as to compress a half wave-length into this region. We have found that the wave-length of the incident protons is much greater than r_0 and their energy is of the same order as the binding energy E_0. Thus V(r) must be $\gg E_0$ or E the energy of the incident protons.

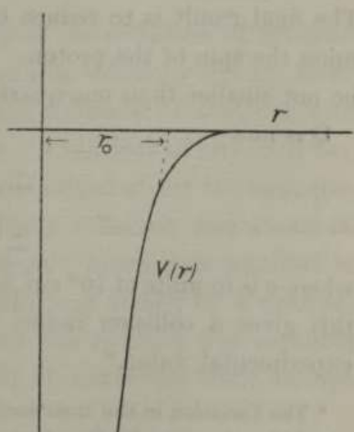

Fig. 4.

The potential field of a proton and a neutron may be roughly likened to a very deep hole of small radius. It can be shown that the effect of this deep hole is to make the wave function describing the collisions of a neutron and a proton nearly a maximum at $r = r_0$ instead of nearly zero, corresponding to a phase shift of nearly $\frac{1}{2}\pi$.

Thus $\delta_0 = \frac{1}{2}\pi$ approximately, and $Q \simeq \frac{h^2}{\pi M^2 v^2}$ about $2 \times 10^{-23} \times v^{-2}$ sq. cm. when v is measured in 10^9 cm./sec.

The collision radius $\simeq 2 \cdot 5 \times 10^{-12}/v$ cm. Since we have taken the maximum value of δ_0 this collision radius is a maximum also. It is most unlikely that δ_0 can be less than $\frac{1}{4}\pi$. A minimum value for the collision radius can therefore be obtained by putting $\delta_0 = \frac{1}{4}\pi$. The minimum collision radius is then $1 \cdot 8 \times 10^{-12}/v$ cm.

This result is in better accord with experiment than the previous one. The cross-section for proton collisions is large and varies with velocity in the way required. On the other hand, the cross-section is now too large. Putting $v = 2 \cdot 7 \times 10^9$ cm./sec. we obtain a collision radius of nearly 10×10^{-13} cm., certainly not less than 7×10^{-13} cm., whereas the observations give rather less than 5×10^{-13} cm. I do not think that the errors in the experiments can cover such a discrepancy, and an explanation must be sought elsewhere.

The explanation is perhaps to be found by introducing some type of exchange interaction between the neutron and proton. For example, if the neutron consists of a proton and an electron another kind of interaction between the proton and the neutron is possible—the change of the electron from the neutron to the proton and the exchange of protons. This interaction is analogous to that between a hydrogen atom and a proton. In effect it introduces a strong repulsive field and a strong attractive field, both of very small radius of action. The final result is to reduce the collision cross-section by a factor depending upon the spin of the proton. If the spin is $\frac{1}{2}h/2\pi$ the cross-sections may now be not smaller than one-quarter of those given above, *i.e.*,

Q is now

$$\simeq \frac{1}{4} \frac{h^2}{\pi M^2 v^2}$$

$$\simeq 5 \times 10^{-24} \times v^{-2} \text{ cm.}^2,$$

where v is in units of 10^9 cm./sec. For neutrons of velocity $2 \cdot 7 \times 10^9$ cm./sec. this gives a collision radius of about 5×10^{-13} cm. in good accord with the experimental value.*

* The variation in the cross-section with the velocity of the neutron appears to be more rapid than is given by the above expression. This can be explained in a more detailed development of the theory. It is worthy of note that this rapid variation of the cross-section for hydrogen collisions accounts in part for the difficulty found in observing fast neutrons by their ejection of protons (§ 3). While the cross-section for collisions with other nuclei also depends on the velocity of the neutron the decrease with increasing speed is not so rapid as for hydrogen. The rapid variation in the cross-section for collision also explains the marked preponderance of short proton tracks in expansion chamber photographs, as observed in the experiments of Auger and of Meitner and Philipp.

It would be premature to conclude definitely that the neutron is a complex particle, for the theory of the collisions is not yet complete and the experimental observations are somewhat uncertain. It seems probable, however, that the experiments can only be explained if there is some kind of exchange interaction between a neutron and a proton. The nature of this interaction may be different from what has been assumed above and it may perhaps not be necessary to conclude that either of the particles is complex. In this discussion the spins of the particles and the effects of any possible magnetic forces have not been considered. These may ultimately prove to be significant in these interactions.

The interaction between a neutron and a proton is of great importance in the theory of nuclear structure. If we assume that the atomic nuclei are built up from protons and neutrons then the binding forces in a nucleus are the interactions proton-proton, neutron-neutron, and proton-neutron. The interaction between two protons should be due to Coulomb forces (neglecting any magnetic forces) and it is clear, from the nature of the nuclear fields, that these forces play only a small part inside a nucleus, certainly in the case of the lighter nuclei. The interaction between two neutrons is probably small in comparison with the others. Thus the interaction between a neutron and a proton is the most significant for the structure of a nucleus and governs its stability.

§ 6. *Disintegration by Neutrons.*—The majority of the collisions of neutrons with atomic nuclei are elastic, but occasionally inelastic collisions occur. These were first observed by Feather when studying the collisions of neutrons with nitrogen with the aid of the expansion chamber. Collisions of any kind are, of course, rare, but in 2000 photographs Feather obtained about 100 examples of recoil tracks of nitrogen obviously due to elastic collisions, and about 30 examples of paired tracks of quite a different type. These were ascribed to a disintegration of the nitrogen nucleus which has been struck by a neutron. In about half the cases observed it appears that the neutron was captured and an α-particle emitted, the final nucleus being therefore the boron isotope of mass 11.

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

This is, of course, the reverse of the process in which a neutron is emitted from boron under the bombardment of α-particles. The mechanism of the disintegration in the other cases is not yet clear. It seems probable that the neutron was not captured and that the ejected particle was a proton. If this view should prove correct, we have here the first example of a transmutation in which the bombarding particle is not captured.

Examples of disintegrations of nitrogen by neutrons have also been obtained by Meitner and Philipp (*loc. cit.*), by Harkins, Gans and Newson,* and by Kurie.†

Feather‡ has also observed paired tracks in oxygen, in about the same proportion to the normal tracks of recoiling oxygen atoms as in nitrogen. In all the collisions observed the neutron was captured and an α-particle emitted, forming a nucleus C^{13}.

$$O^{16} + n^1 \rightarrow C^{13} + He^4.$$

This transmutation is of special interest, for the oxygen nucleus appears to withstand bombardment both by α-particles and by protons.

He has also found a few examples of disintegration when neutrons were passed through an expansion chamber filled mainly with acetylene. Some of these appear to be due to a small impurity of air and only two can be definitely ascribed to the disintegration of carbon. It is obvious from the results so far obtained that inelastic collisions are much less frequent in carbon than in nitrogen or oxygen. This is, indeed, to be expected, for the transition

$$C^{12} + n^1 \rightarrow Be^9 + He^4$$

requires a large amount of energy, about $7\frac{1}{2} \times 10^6$ electron volts, and few of the neutrons from the source used by Feather (beryllium bombarded by α-particles of polonium) possess such an energy. Further, if the views expressed above about the constitution of the Be^9 and C^{12} nuclei are correct the change from C^{12} to Be^9 would be extremely unlikely, for an α-particle in the C^{12} nucleus would have to expand from a condensed system to a looser one.

These are at present the only known examples of disintegration by neutrons but it is possible that many other elements will be transmuted in this way.

The energy relations in the disintegrations produced by neutrons present some interesting features. The disintegration $B^{11} + He^4 \rightarrow N^{14} + n^1$ takes place with an absorption of kinetic energy of $1 \cdot 4 \times 10^6$ electron volts. We should therefore expect the reverse process to take place with a liberation of energy of this amount. Feather showed that the measurements of 12 examples of this process corresponded in 10 to an absorption of energy, and that the energy change was not always the same. This suggests that the disintegration

* 'Phys. Rev.,' vol. 43, p. 208 (1933).

† 'Phys. Rev.,' vol. 43, p. 771 (1933).

‡ 'Nature,' vol. 130, p. 237 (1932).

takes place usually with the formation of an excited nucleus of B^{11}, the residual energy being emitted in the form of γ radiation. To account for the different energy changes one must suppose that more than one excited state of B^{11} is possible. Similarly, the analysis of the oxygen disintegrations leads to the conclusion that nuclei of C^{13} in different states of excitation may be formed.

In many disintegrations with the emission of protons the reaction takes place usually with the formation of an excited nucleus, but there is no evidence for more than one excited state.* It must be pointed out that the calculated energy changes in the neutron disintegrations are subject to errors arising partly in the actual measurements of the tracks and partly in their interpretation; while it seems certain that the residual nucleus is generally formed in an excited state the evidence for several excited states requires confirmation.

§ 7. *Production of Positive Electrons.*—As I have mentioned in § 3, the radiation excited in beryllium by the bombardment of α-particles consists not only of neutrons but also of a very penetrating γ-radiation, and it is sometimes difficult to decide whether the phenomena observed in experiments in which the beryllium radiation is used are to be ascribed to the neutrons or the γ-rays. The most interesting example of this kind is the production of positive electrons, particles of the same mass as an electron but carrying a positive charge. The first evidence for the existence of positive electrons was given by the experiments of Anderson† and of Blackett and Occhialini‡ on the effects produced in an expansion chamber by the penetrating radiation of the atmosphere. It seemed highly desirable to find some way of producing positive electrons by more ordinary means so that the evidence could be clinched and the properties of the particles studied. Certain observations led Blackett, Occhialini and myself§ to consider the possibility that positive electrons might be produced in the interaction of the beryllium radiations and matter.

A capsule containing a polonium source and a piece of beryllium was placed outside an expansion chamber close to the wall. On the inside of the wall a target of lead, 2·5 cm. square and 2 mm. thick, was placed. This target was thus exposed to the γ-rays and neutrons liberated from the beryllium. Expansion photographs were taken by a stereoscopic pair of cameras. A magnetic field, usually of about 800 gauss, was applied during the expansion; any electrons

* *Note added in proof.*—Recent experiments on the disintegration of aluminium by α-particles give evidence of two excited states of the residual nucleus.

† 'Science,' vol. 76, p. 238 (1932).

‡ 'Proc. Roy. Soc.,' A, vol. 139, p. 699 (1933).

§ Chadwick, Blackett and Occhialini, 'Nature,' vol. 131, p. 473 (1933).

liberated from the target would be bent in the field, the sense of the curvature indicating the sign of their charge and the amount of the curvature the $H\rho$ value. Of the electron tracks observed from the target about 200 were clearly due to negative electrons, but about 70 tracks showed a curvature in the opposite sense. There was a remote possibility that these tracks were due to negative electrons ejected in distant parts of the chamber and bent by the magnetic field so as to end on the lead target. A statistical examination of all the tracks observed in the chamber was strongly in favour of the view that the tracks were due to positive electrons. Definite proof was obtained in the following way. A metal plate was placed across the expansion chamber so as to intercept the path of the particles, and some photographs were obtained in which a positively curved track passed through the plate, remaining in good focus throughout its path. The curvature of the track was less on the target side of the plate than on the further side, showing definitely that the particle travelled from the target and therefore carried a positive charge. In one case, the track had a curvature on the target side of the plate, a sheet of copper 0·25 mm. thick, corresponding to a value of $H\rho = 12{,}700$; on the other side the curvature gave a value $H\rho = 10{,}000$; in another case, in which the plate was a sheet of aluminium 0·33 mm. thick, the corresponding values of $H\rho$ were 5000 and 4000.

The observations of the ionizing power in the gas and loss of energy in the metal plates are consistent with the assumption that the mass and magnitude of the charge of the positive particle are the same as for the negative electron.

Similar observations have been made by Meitner and Philipp* and by Curie and Joliot.† Some results of the latter workers suggest that the production of the positive electrons is, at least mainly, to be ascribed to the γ-radiation from beryllium and not the neutrons.

That a γ-radiation can produce positive electrons has been shown in further experiments‡ we have made, in which the beryllium source was replaced by a very weak source of thorium active deposit, enclosed in a lead block, 1 cm. thick. In these experiments the lead target was bombarded by γ-radiation alone, the strongest component in the radiation being a ray of $h\nu = 2\cdot62 \times 10^6$ electron volts. Expansion photographs were taken as before, with a metal plate across the chamber to indicate the direction of the particles. Among about 1200 tracks of negative electrons, about 50 tracks due to positive

* 'Naturwiss.,' vol. 21, p. 286 (1933).

† 'C. R. Acad. Sci. Paris,' vol. 196, p. 1105 (1933).

‡ Also in experiments by Anderson, 'Science,' vol. 77, p. 432 (1933).

electrons have been observed. These must certainly be ascribed to the action of a γ-radiation, very probably to the strong γ-ray of $h\nu = 2 \cdot 62 \times 10^6$ electron volts. The ratio of positive to negative electrons is much lower than that observed with the beryllium radiations. On the hypothesis, first suggested by Blackett and Occhialini, that a negative and a positive electron may be created simultaneously in some interaction of a γ-ray and the electric field of an atomic nucleus, it is not unlikely that the effect will increase very rapidly with the energy of the γ-ray, as the above observations suggest. The creation of the two electrons will require an energy of $1 \cdot 02 \times 10^6$ electron volts, so that the energy of a positive electron produced by the γ-ray of $h\nu = 2 \cdot 62 \times 10^6$ electron volts should never be greater than $1 \cdot 60 \times 10^6$ electron volts.

The measurements of the energy distribution of the positive electrons are in agreement with this hypothesis of their origin, and in a few cases, both with the thorium active deposit and with the beryllium source, a negative track appeared to be associated with the positive. The evidence, however, is not yet sufficient to decide how the positive electrons are produced.

Some observations have been made using a source of boron exposed to polonium α-particles. The target was thus bombarded by the neutrons liberated in the disintegration of B^{11} and by the γ-radiation accompanying the proton emission from B^{10}. The energy of this γ-radiation is rather less than 3×10^6 electron volts, so that the ratio of the number of positive to the number of negative electrons should have been of the same order as found in the experiments with thorium active deposit, *i.e.*, 1 to 25. Actually the fraction of positive electrons was much higher than this, but the total number of electrons observed in the experiments was small. It seems likely that positive electrons can be produced not only by the action of γ-rays but also by neutrons, but more information is required before a definite decision can be made.