The Collisions of Neutrons with Nitrogen Nuclei.

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[PLATES 15 AND 16.]

Introduction.

Elsewhere in these ' Proceedings '* experiments are described in which the radiations excited in certain light elements under α-particle bombardment are examined in great detail by means of the valve counter. On the basis of such experiments in the case of beryllium Chadwick† was first led to suggest that the radiation, previously believed to be of the γ-ray type, in fact consisted of particles of zero resultant charge and unit mass. In the present paper a study of this radiation is described, in which the expansion chamber is employed.

Initially visual observations were made with a Shimizu chamber and the production in air of recoil atoms demonstrated.† A more detailed investigation has now been completed in which the usual photographic methods‡ have been employed. Curie and Joliot§ likewise used an expansion chamber in preliminary experiments to establish the ejection of protons from paraffin under the influence of the radiation from beryllium, and later published photographs|| of recoil tracks both of protons and helium nuclei. Similar photographs were published by Rasetti,¶ whilst Auger** has also given examples of the tracks of protons produced in this way. Kirsch and Rieder†† have made more extensive experiments, using visual methods throughout. In certain cases electron tracks also were reported. This aspect of the problem is dealt with by Dee‡‡ in the paper next after this.

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

† ' Nature,' vol. 129, p. 312 (1932).

‡ Photographs were taken with a source of polonium and beryllium in the centre of an expansion chamber by Holoubek in 1927 (' Z. Physik,' vol. 42, p. 704 (1927)) and, with a different arrangement employing smaller solid angles, by Champion in 1931 (see Webster, ' Proc. Roy. Soc.,' A, vol. 136, p. 428 (1932)), but as far as is known no recoil track was observed in either case to originate in the gas.

§ ' C. R. Acad. Sci. Paris,' vol. 194, p. 708 (1932).

|| ' C. R. Acad. Sci. Paris,' vol. 194, p. 876 (1932).

¶ ' Naturwiss.,' vol. 20, p. 252 (1932).

** ' C. R. Acad. Sci. Paris,' vol. 194, p. 877 (1932).

†† ' SitzBer. Akad. Wiss. Wien.' (*in course of publication*). Communication No. 288 (*a*) from the Radium Research Institute of Vienna.

‡‡ 'Proc. Roy. Soc.,' A, vol. 136, p. 727 (1932).

In the experiments to be described the gas chiefly used was nitrogen, and the general results may be stated at once. Recoil tracks of maximum length about 3·5 mm. under standard conditions were obtained with considerable frequency and almost as frequently an entirely new phenomenon was observed, namely, examples of paired tracks having a common origin. These are regarded as evidence for the disintegration of the nitrogen nucleus by the incident radiation*; so interpreted they provide further support for the hypothesis of its neutron (particular) nature. It is of interest to remark that the first evidence for artificial disintegration by α-particles also was obtained in the case of nitrogen,† whilst the only disintegration photographs hitherto published‡ have reference to the same gas. Detailed analysis in the present case shows that when disintegration occurs with capture of the neutron an α-particle is expelled (capture of an α-particle results normally in the expulsion of a proton), but it also suggests that other types of non-capture disintegration occur, in some of which, at least, it is more probable that a proton is emitted. It will be seen, then, that the results are both novel and also of considerable complexity. Further investigation will obviously be required before a complete statement can be made.

General Experimental Arrangement.

The apparatus employed in the present experiment is the same, except for small modifications, as that which the writer has been using during the past 6 months for α-particle track photography, in an attempt to observe certain cases of artificial disintegration. A more detailed description of the automatic expansion chamber and stereoscopic camera system may be reserved until the results of the above-mentioned work are published. It suffices here to give a brief description. The expansion chamber had an internal diameter of 17 cm. and a maximum depth of 5·9 cm. It was illuminated by light from two horizontal quartz mercury lamps placed behind suitably arranged§ cylindrical lenses, and a condenser of 1/20 mfd. charged to about 30 kv. was discharged through the two lamps in parallel immediately after each full expansion.

* Photographs were first taken on February 16 and this general conclusion reached during the following week. A preliminary announcement was made on March 18 by Lord Rutherford in the course of a lecture before the Royal Institution, an abstract of which lecture has since appeared in 'Nature,' vol. 129, p. 457 (1932).

† Rutherford, 'Phil. Mag.,' vol. 37, p. 581 (1919).

‡ Blackett, 'Proc. Roy. Soc.,' A, vol. 107, p. 349 (1925); Harkins and Shadduck, 'Proc. Nat. Acad. Sci.,' vol. 12, p. 707 (1926); Harkins and Schuh, 'Phys. Rev.,' vol. 35, p. 809 (1930); Blackett and Lees, 'Proc. Roy. Soc.,' A, vol. 136, p. 325 (1932).

§ Only the lower three-fifths of the chamber was directly illuminated.

The axes of the two lenses of the camera were equally inclined to the vertical, and included a stereoscopic angle of 8° 54′, the magnification of the photographs, taken on a single length of standard ciné negative and each occupying the full width of the film, being about 0·17. In order to increase the effective solid angle of irradiation a circular hole 2 cm. in diameter was made centrally in the glass roof of the chamber and the metal source container inserted as shown to scale in fig. 1. The cylindrical walls of the source container introduced an

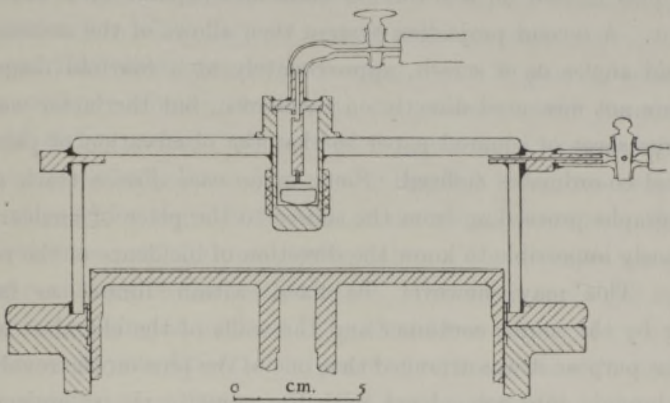

FIG. 1.

absorption of 0·75 gm. per square centimetre of brass in the path of the radiation and an additional absorber of lead to the extent of 2·74 gm. per square centimetre was disposed as indicated. The lower end of the source container was closed by a plug of brass 1 cm. thick. In this way it was ensured that any characteristic X-radiation produced by α-particle excitation in the metal parts of the interior of the container (or soft γ-rays if a small amount of radium D were present in the source) should be reduced to a completely negligible intensity in the chamber itself. This precaution was necessary on account of the comparatively large number of short electron tracks produced by such a radiation. Under the experimental conditions some of these tracks would almost certainly have been mistaken for the tracks of recoil atoms produced at too late a stage for the best photography. Furthermore, absorbers of the total thickness used are known to have practically no effect on the nuclear radiation from beryllium. A piece of beryllium of 5·7 mm. maximum thickness and freshly cut upper surface 1·7 sq. cm. in area* rested at the bottom of the source container and the polonium source (that used in Dr. Chadwick's experiments) was

* I am indebted to Professor Kapitza for this material.

supported 2–3 mm. above. Throughout the experiments the pressure of air in the source container was maintained at 1–2 cm. of mercury, to prevent both undue oxidation of the silver-polonium surface and also needless reduction in velocity of the α-particles incident on the beryllium.

Measurement of the photographs was effected by the method of Nuttall and Williams.* In this method† the film is replaced in the camera, the real image of any track is reconstructed by stereoscopic re-projection and explored by means of pins carried on a revolving table and capable of a wide range of adjustment. A second projection system then allows of the measurement of lengths and angles on a screen, approximately at a fourfold magnification. Angles were not measured directly on the screen, but the latter was covered with a large sheet of squared paper so that the observation of pairs of two-dimensional co-ordinates sufficed. Since in no case does a track appear on the photographs proceeding from the source to the place of nuclear collision, it is obviously impossible to know the direction of incidence of the responsible radiation. This may, however, be fixed within limits, so far as the scattering by the source container and the walls of the chamber will allow, and for this purpose it was arranged that one of the pins on the revolving table could be brought into coincidence with the point in the re-projected image corresponding to the centre of the upper surface of the beryllium in the chamber itself. A knowledge of the distance of this point from the point of collision in any case fixes the corresponding maximum uncertainty in the initial direction.

Altogether 1740 pairs of photographs were taken, the rate of working being generally maintained at about two photographs per minute.

Preliminary Experiments.

The original valve counter experiments of Chadwick showed that under the influence of the nuclear radiation from beryllium sudden bursts of ionisation, many of them representing the production of 3–4 . 10^4 pairs of ions, occurred in a small volume of air, of about 2 cm. maximum linear dimension, at atmospheric pressure. Observations with the Shimizu expansion chamber afforded strong

* 'Proc. Phys. Soc.,' vol. 42, p. 212 (1930).

† The apparatus used was that constructed by Williams and Terroux, 'Proc. Roy. Soc.,' A, vol. 126, p. 289 (1930), and employed in subsequent researches in the Cavendish Laboratory by Terroux, 'Proc. Roy. Soc.,' A, vol. 131, p. 90 (1931); Richardson, 'Proc. Roy. Soc.,' A, vol. 133, p. 367 (1931); and Terroux and Alexander, 'Proc. Camb. Phil. Soc.,' vol. 28, p. 115 (1932).

confirmation of the view that these electrical effects, which on any hypothesis pointed to the transformation of 1–1·5 . 10^6 electron volts of energy in a single process, were in fact due to the production of recoil atoms of nitrogen or oxygen with about this amount of energy. If this energy were in any way transferred to the atoms of the gas any other hypothesis would have been untenable almost from the beginning. It was the object of the detailed investigations with the larger chamber to examine the agreement above mentioned on a more definitely quantitative basis and generally to explore other possible types of nuclear interaction which the new type of radiation might show.

To this end four short runs, each covering about 70 pairs of photographs, were taken with air initially at atmospheric pressure in the chamber. Two hundred and eighty pairs of photographs* contained 12 examples of recoil tracks, the longest of which was 3·22 mm. in length.† Four tracks showed the projection of particles from the surface of the source container. It is most probable that these particles were protons, since a film of water was generally found to be condensed on the metal surface. One track in the gas more than 5 mm. long and making an angle of 76° with the line joining the centre of the upper surface of the beryllium to the point of collision was with considerable probability ascribed to a proton projected from a molecule of water vapour present in the gas. In addition to these recoil tracks five cases of paired tracks were found. These were regarded as evidence of a new type of artificial disintegration, as has already been indicated. It therefore became highly desirable to replace the air in the chamber by some single gas and so concentrate attention upon a more definite investigation.‡

The Experiments with Nitrogen.

Air was removed from the expansion chamber and nitrogen, from a cylinder, admitted until the composition by volume of the permanent gases present was

* The photographic film, four lengths of about 10 feet each, was developed in the laboratory. One of these afterwards proved useless for measurement owing to a shrinkage of about 0·2 per cent., caused by too long a period of washing.

† The lengths of all tracks are expressed in terms of standard air, *i.e.*, dry air at 760 mm. pressure and 15° C.

‡ Above no mention is made of tracks due to α-particle contamination. This occurred throughout the experiments to the extent of about 19 tracks in 200 expansions, but of these at least half appeared to originate in a highly localised spot of radioactive material on the walls of the chamber. Except for the possibility of some of the tracks from the source container being due to this cause it was not difficult to eliminate contamination effects entirely from the final results.

roughly nitrogen 96 per cent., oxygen 4 per cent. (the residual argon amounted to $0 \cdot 15$ per cent.). This small amount of oxygen was retained for the purpose of ensuring more sharply defined tracks than it is possible to obtain in nitrogen of a higher degree of purity.*

Two 100-feet lengths of film were exposed with the chamber so filled, and the films, which together contained 1460 pairs of photographs were developed by Messrs. Kodak, Ltd., Kingsway, London. On examination it was found that there had been registered more than a hundred recoil tracks, about thirty paired disintegration tracks and fifty tracks of particles, probably protons, projected from the surface of the source container. These ratios are in general agreement with those found in the preliminary work, which latter were subject to a much greater statistical error. Electron tracks were found on some of the photographs, but the conditions of photography were not sufficiently good nor the expansion conditions the most suitable for their full investigation. For that reason they were left out of account altogether.†

Measurements were made of the lengths of the recoil tracks and, in addition, whenever it was possible with any degree of accuracy, of the angle between the initial direction of motion of the recoiling nucleus and the most probable direction of incidence of the responsible radiation. The maximum angular uncertainty in this latter direction due to the finite size of the effective source was also determined in each case by the method already described. In the case of the paired disintegration tracks the lengths of the tracks were measured, or a lower limit fixed, in case one or other of the particles was not completely absorbed in the chamber, and the following angles were also determined, namely, ω, the angle between the two visible tracks; γ, the angle between the plane of the visible fork and the most probable direction of incidence of the effective radiation; θ, the angle between this most probable direction and the initial direction of motion of the new nucleus; ϕ, the angle between the most probable direction of incidence and the initial direction of motion of the disintegration particle, and Δ, the angle subtended at the point of collision by half the diameter of the effective source. Then, if there is no error in the measurement of the angles so defined, must

$$\omega = \cos^{-1}\left(\frac{\cos\theta}{\cos\gamma}\right) + \cos^{-1}\left(\frac{\cos\phi}{\cos\gamma}\right),$$

* Blackett, 'Proc. Roy. Soc.,' A, vol. 107, p. 349 (1925).

† In the course of measurement a few of the "recoil" tracks were rejected on the more probable supposition that they were in fact due to slow electrons, being produced either by the δ particles observed by Dee or as branches to fast β-particle tracks which themselves had escaped detection under the poor conditions obtaining.

and this relation* may be used as a test of the accuracy in actual practice attained.

Analysis of the Results.

Recoil Tracks.—Ranges were measured of 109 recoil tracks starting in the gas.† Of these two had lengths greater than could be measured and for two others values of 5·11 and 11·87 mm. were obtained. The distribution with range of the remaining 105 tracks is shown in fig. 2. Fig. 2, *a* gives the direct

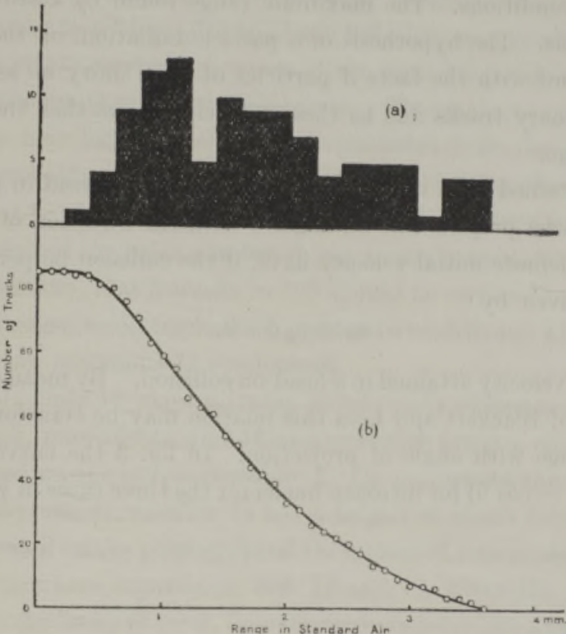

FIG. 2.

distribution, and fig. 2, *b*, the integrated curve, providing a rough comparison with absorption measurements. From either diagram a maximum range of about 3·5 mm. in standard air may be derived. According to the determination of Blackett and Lees‡ this corresponds to a velocity of recoil of $4\cdot72 . 10^8$ cm. per second. As has been pointed out elsewhere this value, taken in conjunction with the corresponding maximum velocity of recoil for hydrogen

* When γ is small we have, approximately, if all angles be measured in degrees,

$$\omega = \theta + \phi - \frac{\gamma^2}{114\cdot6} (\cot \theta + \cot \phi).$$

† This includes nine tracks obtained in the preliminary experiment with air in the chamber.

‡ 'Proc. Roy. Soc.,' A, vol. 134, p. 658 (1932).

nuclei as determined by Chadwick, and assuming only the conservation of energy and momentum, provides one important test of any hypothesis concerning the nature of the radiation effective in the collisions. If that radiation consisted of quanta of energy small compared with the proper energy of the nuclei concerned then recoil velocities should to a first approximation be inversely as the masses of the recoiling particles. Nitrogen nuclei of range 3·5 mm. in standard air would correspond to protons of about 4 metres range under similar conditions. The maximum range found by Chadwick is about one-tenth of this. The hypothesis of a particle radiation, on the other hand, is in good accord with the facts if particles of mass unity be assumed. The absence of primary tracks due to these particles shows that they possess no resultant charge.

The data obtained from the recoil tracks may be analysed in greater detail than this. Nuclei projected at an angle θ with the direction of incidence by neutrons of a definite initial velocity have, if the collision be perfectly elastic, velocities v_θ given by

$$v_\theta = v_0 \cos \theta,$$

where v_0 is the velocity attained in a head-on collision. By means of the experimental curve of Blackett and Lees this relation may be transformed into one connecting range with angle of projection. In fig. 3 the curves a, b and c, relate r and $(1 - \cos \theta)$ for nitrogen nuclei for the three cases in which v_0=4·5,

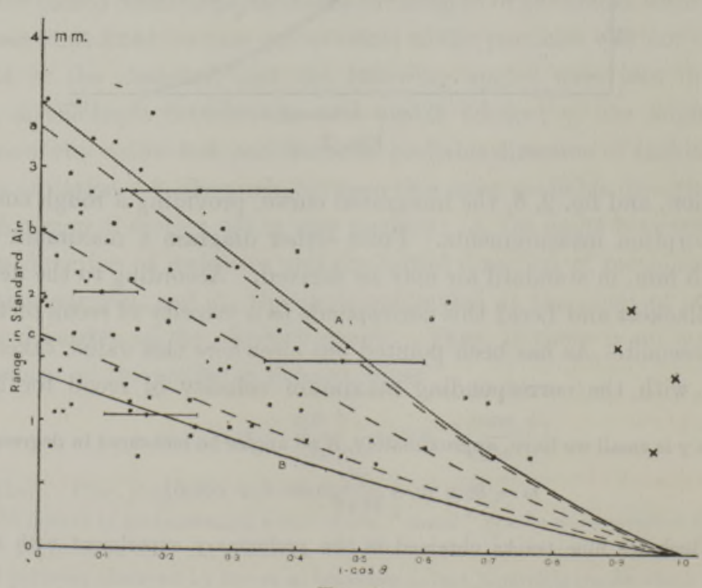

Fig. 3.

$3 \cdot 5$ and $2 \cdot 5 . 10^8$ cm. per second, respectively. The points represent measured values of r and θ for 84 of the recoil tracks included in the distributions of fig. 2. The maximum uncertainty in θ due to the finite size of the effective neutron source is indicated by a horizontal line in a number of representative cases. It is obvious at once that, if elastic collisions be assumed, the incident radiation is not homogeneous. An upper limit of v_0 of $4 \cdot 7 . 10^8$ cm. per second and a lower limit not greater than $2 \cdot 1 . 10^8$ cm. per second* appears to be indicated, curves A and B. The probable range of neutron velocities is therefore seen to extend from $3 \cdot 5$ to about $1 \cdot 6 . 10^9$ cm. per second.

Four of the points marked by crosses at the right-hand side of fig. 3 appear to lie beyond the limits of experimental error. The tracks to which they refer, as well as the four longer tracks already excluded from the distribution of fig. 2, were probably produced by protons ejected from the water vapour in the chamber.† Hydrogen atoms contained in the water vapour constitute about 2 per cent. of the total number of gas atoms present; it seems not unreasonable, therefore, that 8 tracks in 109 should be ascribed to protons since the shortest nitrogen recoil tracks no doubt fail to be detected whilst the longer proton tracks are not similarly overlooked.

Figs. 4 to 11, Plate 15, show nitrogen recoil tracks of progressively smaller apparent length, numbers 14 and 16 the tracks of protons ejected from the water condensed on the source container.‡ On number 14 the tracks of long δ-rays are easily visible, number 16 has a length of about 1 cm. in the gas. Amongst the recoil tracks photographed three showed measurable spurs; two of these cases are here reproduced, figs. 12 and 13, Plate 15. Measurement showed, within the limits of error, that the angle between the forward branches of the fork in these cases was 90°, additional evidence, if that were required, that the recoil tracks themselves were produced by nitrogen nuclei. Finally, photograph number 15 is only of interest from the fact that on one occasion three recoil tracks were obtained at a single expansion.§

* This lower limit might well have been further reduced if measurement of θ had been possible for all the recoil tracks observed. In general the shorter tracks were excluded from the distribution of fig. 3.

† On this assumption, from the measured values of θ for the tracks of length $5 \cdot 11$ and $11 \cdot 87$ mm. above mentioned, neutron velocities of $3 \cdot 12$ and $2 \cdot 14 . 10^9$ cm. per second, respectively, may be deduced.

‡ In all cases the photographs are so arranged that the source is towards the bottom of the picture; on numbers 7, 10 and 16 part of the upper rim of the source container is visible as a circular arc.

§ The third track at the left-hand bottom corner is, however, very faint on this photograph.

The photographs reproduced appear at a magnification of about eight times from the original film; the magnification from the conditions of standard air is about 1·9.

Disintegration Tracks.—Measurements were made on 32 examples (including certain border-line cases) of paired disintegration tracks photographed in the course of the experiments.* On 12 occasions both the new nucleus and the disintegration particle had been completely absorbed in the chamber, in the 20 remaining cases it was impossible to do more than fix a lower limit to the length of one or other of the tracks. The immediate data which the measurements provided showed fairly conclusively that more than one type of disintegration was in fact being observed. In less than one-half of the cases did the plane of the visible fork contain a possible direction of incidence of the primary (unscattered) radiation. This condition of coplanarity, which is impossible unless $\gamma < \Delta$ (p. 714), must necessarily be fulfilled if disintegration takes place with capture of the incident particle. The remaining cases for which $\gamma > \Delta$ obviously represent nuclear disintegration without capture of the neutron. In these latter cases, as will appear, it is much more difficult from the measurements alone to determine with certainty the exact details of the process involved.

As regards the (presumably) capture cases the following possibilities were numerically explored† :—

(i) $N^{14} + n^1 \rightarrow C^{14} + H^1$.

(ii) $N^{14} + n^1 \rightarrow C^{13} + H^2$.

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

From the range-velocity curve of Blackett and Lees (*loc. cit.*) for nitrogen recoil atoms similar curves were constructed for the recoil atoms B^{10} (this curve will be employed later), B^{11} and C^{12} (which are indistinguishable for the purpose in hand; that for C^{12} will be employed later), C^{13} (this curve is practically identical with that for N^{14}) and C^{14}. The empirical relation

$$r = kmz^{-\frac{1}{2}} f(v),$$

first suggested by Blackett,‡ was here used. Range velocity curves for protons

* In this number are included four cases occurring in the preliminary work with air in the chamber. A fifth such case, fig. 17, Plate 16, was found on the short length of film which had to be rejected (*vide sup.*).

† The symbol n^1 has been employed to represent a neutron of unit mass.

‡ 'Proc. Roy. Soc.,' A, vol. 107, p. 349 (1925).

and α-particles were taken from the latest results of Blackett* in the one case and from those of Briggs† and of Blackett and Lees in the other. Finally, the curve for the recoil atoms H^2 was obtained from the proton curve by the use of the empirical formula above quoted. Using these curves, and assuming in turn each of the possibilities (i) to (iii) mentioned above, the momenta of the new nucleus and the disintegration particle, respectively, were evaluated (where this was possible) for each case. In this way, from the different pairs of possible values, employing the measured value of ω, the resultant final momentum was determined in magnitude and direction. A consistent interpretation of any case was regarded as having been reached only when two conditions had been fulfilled. It was necessary that the magnitude of the resultant momentum should be a possible one for the momentum of the incident neutron—the permissible range of values had already been deduced from the recoil track measurements—and the direction of that resultant an admissible direction of incidence. When it was found impossible in any case to fulfil these conditions on the basis of one or other of the three possibilities, that case was included for consideration with the remaining cases more obviously incapable of explanation on the assumption of artificial disintegration with capture. On the other hand, when these conditions had been fulfilled, not only the general features of the process, but also the energy changes involved could be determined from the measurements. For, initial and final momenta and the masses of the particles being known, it becomes a simple matter to calculate the amount of energy released in the disintegration.

Twelve cases of capture were recognised with a fair degree of certainty. It proved possible to explain them all on the assumption that the disintegration particle was an α-particle and the new nucleus so formed a boron nucleus of mass 11. Whilst this explanation covered all the cases, one or other of the remaining possibilities appeared as a considerably less probable alternative in a small fraction of them. As an example of the general method of numerical investigation the following case may be cited.

Serial number XI 531 (ii), fig. 25, Plate 16. Length of track of new nucleus: 1·93 mm. in standard air. Length of track of disintegration particle: 7·32 mm. ω, 128·0°, γ, 4·4°, θ, 63·5°, $\phi = 65{\cdot}4°$, Δ, 7·9°. Test of accuracy of measurement of angles

$$\cos^{-1}\left(\frac{\cos\theta}{\cos\gamma}\right) + \cos^{-1}\left(\frac{\cos\phi}{\cos\gamma}\right) = 128{\cdot}7°.$$

* 'Proc. Roy. Soc.,' A, vol. 135, p. 132 (1932).

† 'Proc. Roy. Soc.,' A, vol. 114, p. 341 (1927).

(*a*) On assumption (i) above—

Velocity of new nucleus, C^{14} : $2 \cdot 62 \, . \, 10^8$ cm. per second.

Velocity of disintegration particle, H^1 : $8 \cdot 76 \, . \, 10^8$ cm. per second.

Velocity of incident neutron (calculated) : $3 \cdot 21 \, . \, 10^9$ cm. per second—possible.

Calculated value of θ : $12 \cdot 4°$—quite impossible.

(*b*) On assumption (ii) above—

Calculated value of θ : $20 \cdot 4°$—equally impossible.

(*c*) On assumption (iii) above—

Velocity of new nucleus, B^{11} : $2 \cdot 98 \, . \, 10^8$ cm. per second.

Velocity of disintegration particle, He^4 : $7 \cdot 84 \, . \, 10^8$ cm. per second.

Velocity of incident neutron (calculated) : $2 \cdot 82 \, . \, 10^9$ cm. per second—possible.

Calculated value of θ : $61 \cdot 3°$—possible.

Possibility (iii) being assumed correct—

Energy of incident neutron : $4 \cdot 13 \, . \, 10^6$ electron volts.

Energy of new nucleus : $0 \cdot 51 \, . \, 10^6$ electron volts.

Energy of disintegration particle : $1 \cdot 28 \, . \, 10^6$ electron volts.*

Kinetic energy absorbed in the disintegration process $2 \cdot 34 \, . \, 10^6$ electron volts.

The energy change was found not to be constant from one case to another. Table I exhibits this aspect of the results. The velocity of the incident neutron, V, in units of 10^9 cm. per second, and the absorption of energy W, in units of 10^6 electron volts, are given for the 12 capture cases found.

Table I.

No.	1	2	3	4	5	6	7	8	9	10	11	12
V	2·82	3·26	3·60	3·14	3·45	3·45	2·23	>2·7	2·38	8·49	3·22	~3·5
W	2·34	1·49	2·41	0·63	2·57	0·65	~0·1	~1·0	1·13	3·7	4·5	~ 0

In numbers 1 to 3 both tracks appeared complete, so that the measurements are to that extent the more trustworthy, for the rest one or other particle was

* It may be pointed out that this value for the energy of the disintegration particle is much less than that corresponding to the peak of the potential barrier of B^{11} as against α-particles, $> 3 \cdot 10^6$ electron volts, *cf.* Riezler, 'Proc. Roy. Soc.,' A, vol. 134, p. 154 (1931).

not observed over the full length of its path. Results 4 to 7, however, are regarded as entirely satisfactory; only to the figures given in the last five cases does any real suspicion attach, and even in those the values given for V are entirely possible ones.

For the apparently non-capture cases it was assumed that one or other of the following possibilities must apply :—

(iv) $N^{14} + n^1 \rightarrow C^{13} + H^1 + n^1$.

(v) $N^{14} + n^1 \rightarrow C^{12} + H^2 + n^1$.

(vi) $N^{14} + n^1 \rightarrow B^{10} + He^4 + n^1$.

These were explored, as numbers (i) to (iii) had been, employing the experimental data and the appropriate range velocity curves already referred to.

To reach a decision here, however, was much more difficult than in the former case, for it was no longer possible, employing each assumption in turn, to calculate the momentum of the incident neutron from the data obtained. It became necessary to rely entirely upon the limiting values of the energy change, deduced on the assumption of neutrons of maximum energy, and in many cases rendered still more uncertain on account of a lack of complete knowledge of the energy of the disintegration particle involved. The final conclusion was that no statement could justifiably be made concerning many examples of non-capture disintegration, except that they did not appear to fall in a single class with the rest. The latter, amounting to 6 cases out of 16, are satisfactorily explained on assumption (iv) above, upper limits to the amount of energy absorbed in the process ranging from 3·5 to 0·8 million electron volts, but, if process (vi) is assumed there is a spread of about 10^7 electron volts in the calculated values. We shall assume, therefore, that process (iv) does in fact take place and leave open the possibility that other types of disintegration also occur.

Amongst the 32 cases listed for measurement as presumable examples of disintegration forks there were, in addition to those falling within the broad divisions above made, two cases in each of which the aggregate length of the two components of the visible fork was less than the maximum length found amongst the nitrogen recoil tracks observed. The angles of the forks, however, precluded the possibility that either represented a close collision such as is shown by figs. 12 and 13 of Plate 15, otherwise a branch track would also have been visible. Two possibilities arise: either a recoil atom of nitrogen has made close collision with an atom of argon present in small amount in the gas, or the tracks are due to protons from the water vapour and these have suffered appreciable deflection by the heavier nitrogen nuclei without the production of a visible fork in either case. As a remotely possible alternative to the recoil track explanation is the suggestion that these forks represent a more drastic disintegration process, the production from N^{14} of the two nuclei Be^8 and Li^6, for example, or perhaps more probably, by capture, from N^{15} of Be^8 and Li^7. At this stage, however, it would be unprofitable to pursue further such a suggestion as this.

Examples of the photographs of paired disintegration tracks are collected in Plate 16. The conditions of magnification and the orientation of the photographs are the same as those adopted for the recoil track photographs of Plate 15. Figs. 18, 21 and 25, also showing a recoil track on the same photograph, have been interpreted as due to disintegration with capture, and figs. 19, 22, 24 and 26 as non-capture forks. Figs. 22 and 24 form a stereoscopic pair; mere inspection in this case is sufficient to show that the plane of the fork cannot pass through the source, situated towards the bottom of the photograph. Fig. 17 probably represents non-capture, also, but a final decision in this case was impossible as the length of film on which it occurred had to be rejected.* Fig. 20 is also indefinite, since the fork occurred in a portion of the chamber visible through one of the camera lenses only.

Discussion.

Before entering upon a general discussion of the results of the numerical analysis it will be useful to consider certain features of the experimental method which have a direct bearing upon the interpretation. In the first place this depends to a large extent upon the measurement of angles, but the angles deduced from the photographs will be of value only if they are the true angles involved in the primary collisions. This will not in general be the case if a collision has occurred before the completion of the expansion, and since no mechanical shutter was employed a certain number of " early " tracks were only to be expected. In the extreme cases a very diffuse cloud indicated that the ions had been widely separated by the applied field, cut off just before the end of the expansion, and by diffusion. A few intermediate cases were also detected and excluded from consideration. Nevertheless, other less noticeable cases may well have been overlooked and their inclusion may to some slight extent be responsible for the apparent diversity of explanation which the results require.

In the second place there is the uncertainty caused by the absence of an

* Footnote, p. 713.


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easily detectable track due to the neutron itself. One aspect of this uncertainty has already been discussed, but its extent is not entirely defined merely by considering the upper surface of the beryllium as the effective neutron source. Small angle deflections in nearly 3 mm. of lead might not be very uncommon, whilst particles scattered by surrounding matter and traversing the chamber in random directions cannot altogether be neglected. General considerations indicate that backwards scattering is likely to be most effective from the floor of the chamber, but it is extremely difficult to form a reasonable estimate of the extent to which it might occur. Having mentioned these two difficulties, therefore, we shall proceed on the assumption that the complexity of the results is not chiefly to be attributed to either of them.

Finally, there is the question of the accuracy attained in the measurement of angles, entirely apart from their identification. In a recent paper Blackett and Lees* have discussed this question in detail and conclude that in the case of disintegration forks, examined by the method of right-angle photography, a probable error of 1° in θ and $0 \cdot 5^\circ$ in ϕ is a reasonable assumption. In the present method somewhat greater errors are to be expected; moreover it is likely that the error in θ is increased more than is the error in ϕ. Probable errors of 3° in the former case and 1° in the latter may be tentatively assumed. Whilst these will not in general make decision between alternative modes of capture disintegration impossible, they will obviously lead to considerable uncertainty in the energy change in any specified case. A probable error of about $0 \cdot 2$ mm. in measured lengths must also be considered.

About 130 cases of interaction between a neutron and a nitrogen nucleus have been observed; of these about 30 resulted in disintegration, more than half of the latter without capture of the neutron. This is very different from the results obtained under α-particle bombardment, where elastic collisions, resulting in measurable spurs in an expansion chamber, outnumber inelastic (disintegration) collisions by a factor of the order of 1000 : 1. Moreover, although the possibility of non-capture disintegration by α-particles has frequently been considered,† unexceptionable evidence for its occurrence has yet to be obtained. The former of these points of difference is certainly to be ascribed to the different extent of the external fields of the two particles, that of the neutron falling off very rapidly to become already inappreciable at a few diameters distance; it is quite possible that further investigation will exhibit the latter difference, also, as a direct result of the same circumstances.‡

* 'Proc. Roy. Soc.,' A, vol. 136, p. 338 (1932).

† Chadwick and Gamow, 'Nature,' vol. 126, p. 54 (1930).

‡ It would hardly arise in this way on the basis of the detailed mechanism suggested by Pollard, 'Proc. Leeds Phil. Soc.,' vol. 2, p. 206 (1931).

A study of the angular distribution of recoil tracks must obviously lead to important data for any theory of the field of the neutron, but hydrogen collisions are so much more suited to this study, owing to the greatly simplified conditions, that this aspect of the problem must be left until the experimental data are available. For the present the distribution shown in fig. 3 may be discussed from another point of view, namely, the process in which neutrons are liberated.

The experiments of Webster* and of Kirsch and Rieder (*loc. cit.*) have shown that whilst the effects observed with beryllium are produced for the most part by α-particles of more than 4 million electron volts energy, yet in some part they are to be attributed to particles of lower energy. They do not become inappreciable until the energy of the incident particles is reduced to about $2 \cdot 6$ million electron volts. Now if neutrons of $6 \cdot 4 \cdot 10^6$ electron volts energy, corresponding to the upper limit of velocity $3 \cdot 5 \cdot 10^9$ cm. per second, are ejected in the forward direction when α-particles of $5 \cdot 3 \cdot 10^6$ electron volts energy are captured, and if the energy released in this process is constant, then when α-particles of $2 \cdot 6 \cdot 10^6$ electron volts are captured the neutrons emitted in the backward direction will have an energy of $2 \cdot 2 \cdot 10^6$ electron volts. Almost all directions of emission are represented in the data of fig. 3 and a lower limit of $1 \cdot 3 \cdot 10^6$ electron volts has been deduced ($v_{\text{min.}} = 1 \cdot 6 \cdot 10^9$ cm. per second) from that distribution. The discrepancy is not outside the limits of error; and if it be divided, and mutually consistent limits, $5 \cdot 8$ and $1 \cdot 7 \cdot 10^6$ electron volts, be assumed, the internal agreement may be regarded as quite satisfactory, whilst the agreement between the upper limit here deduced and that adopted by Chadwick is greatly improved. It may be that the energy change is not constant, the C^{12} nucleus in some cases being left in an excited state, but more extensive and more accurate data than the present would certainly be required in order to establish this result from energy considerations alone.

From the disintegration phenomena, on the other hand, we have more definite proof of a state of higher energy in the case of the boron nucleus B^{11}, the energy of excitation being of the order of $1 \cdot 5 \cdot 10^6$ electron volts.† The capture disintegration here observed is of interest from another point of view

* 'Proc. Roy. Soc.,' A, vol. 136, p. 428 (1932).

† This excess energy is doubtless emitted in the form of γ-radiation in a time negligible compared with the time of description of the recoil track of the new nucleus. The observed direction of the latter will differ from the original direction on this account, but the difference is well within the limits of acuracy of measurement.

also. Curie and Joliot and Chadwick have shown that the anomalous effects found with beryllium are obtained with boron also under α-particle bombardment. If the α-particle is captured in this case, as in the former, when the neutron is liberated it is most probable that the nucleus B^{11} is effective, for otherwise the final result would be N^{13}, hitherto unknown. On the assumption of capture, therefore, we have observed the nuclear reaction

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

to take place both in the forward and reverse directions. In the reverse direction the maximum release of energy found is almost certainly negative, $1 \cdot 5 \,.\, 10^5$ electron volts. In the forward direction, likewise, no release of energy greater than about $-1 \cdot 5 \,.\, 10^6$ electron volts has as yet been detected. There is a discrepancy here which may be due either to the restricted data of Table I or to the difficulty of absorption measurements in the case of a weak proton radiation markedly inhomogeneous in velocity, but at least it indicates that in one case or the other, or in both, capture of the incident particle into the ground level of the final nucleus is a relatively infrequent occurrence.*

So far we have been considering the balance of energy without reference to its wider implications. It becomes necessary now to investigate the bearing of the present results upon the general question of the mass defects of the lighter nuclei. These have generally been calculated on the assumption of a nuclear structure composed of α-particles, protons and electrons in which the number of α-particles is as large as possible. Then Aston's† results lead to the values $(16 \cdot 7 \pm 1 \cdot 6) \,.\, 10^{-3}$ and $(14 \cdot 0 \pm 2 \cdot 8) \,.\, 10^{-3}$ mass units for B^{11} and N^{14}, respectively. This corresponds to a liberation of energy, $2 \cdot 5 \,.\, 10^6$ electron volts in probable amount, in the transition $N^{14} \rightarrow B^{11}$. If the net result is, in fact, the liberation of energy, considerably less than this amount is involved. The discrepancy is not entirely beyond the limits of error in the direct determinations of mass, but it may be pointed out that it would be greatly reduced if a structure composed of α-particles, protons and neutrons were adopted, the binding energy of the neutron being assumed to be of the order of $1\text{–}1 \cdot 5 \,.\, 10^6$ electron volts.

It is much more difficult to explain the non-capture results on the basis of the general assumptions hitherto accepted. The mass defect of C^{13}, calculated

* This is also found in the capture (resonance) disintegration of boron, fluorine and aluminium by α-particles, Chadwick and Constable, 'Proc. Roy. Soc.,' A, vol. 135, p. 48 (1932).

† 'Proc. Roy. Soc.,' A, vol. 115, p. 487 (1927).

from the α-particle disintegration experiments with boron, is probably $4 \cdot 2 \, . \, 10^{-3}$ mass units less than that of N^{14}, so that the absorption of $3 \cdot 9 \, . \, 10^{6}$ electron volts of energy* should be necessary to effect the non-capture disintegration $N^{14} \rightarrow C^{13} + H^{1}$, presumed to occur. Actually about $1 \cdot 5 \, . \, 10^{6}$ electron volts appear to be required. Moreover, the present suggestion of the α-particle-proton-neutron structure does little to remove the difficulty. For the nuclei B^{10}, N^{14} are similar in type ; the difference in mass defect of the two, and therefore the difference $C^{13} \rightarrow N^{14}$, would not be greatly influenced by the change. Finally, if release of energy in certain cases is eventually established it may be necessary to assume, following Gamow,† that the number of α-particles in the nuclear structure is not the maximum possible on merely arithmetical grounds—and it may even be the case that certain of the non-capture disintegrations observed are really of the type $N^{14} \rightarrow C^{12} + H^{2}$, though this assumption would require the further structural unit H^{2} with the consequent additional complication of the problem of the mass defects of nuclei.

At present more extensive data are urgently required. It is the writer's hope to be able to undertake, in the near future, the necessary investigations which will enable us to study as many cases as possible of the artificial disintegration of nuclei under neutron bombardment. The expansion chamber is indispensable for such investigations and it is of interest to point out that the speed with which data may be obtained is limited only by the strength of source available, since the absence of a track due to the neutron itself does not impose any restriction upon the number of particles admitted to the chamber at each expansion. In the present experiments that number was probably of the order of a few thousand.

Summary.

Tracks have been observed in an expansion chamber resulting from elastic and inelastic collisions between neutrons of mass 1 and nitrogen nuclei. The neutrons were obtained from beryllium under α-particle bombardment. They are shown to be emitted with energies distributed over a wide range.

Inelastic collisions resulting in disintegration were found to be of two main types, in the first the neutron is captured and an α-particle liberated, in the second the neutron is not captured. It is probable that a proton is liberated in the second type of collision, although certain indications are found of a further subdivision of this class corresponding to the possible occurrence of

* This figure may be reduced to $3 \, . \, 10^{6}$ electron volts if optical data be adopted.

† "Atomic Nuclei and Radioactivity," p. 112 (1931).

non-capture disintegrations with emission of α-particles or H^2 nuclei, also. The emission of γ-radiation in cases of artificial disintegration appears as a general phenomenon.

A general consideration of the energy changes involved in the various nuclear processes has been undertaken.

The investigations above described would have been altogether impossible but for a generous gift of old radon tubes from Dr. C. F. Burnam and Dr. F. West of the Kelly Hospital, Baltimore, to whom my best thanks are due. I wish to thank Dr. Chadwick, also, for preparing the polonium source from this material and for his continual help and encouragement throughout the course of the experiment. I wish, further, to acknowledge many helpful discussions with Professor Lord Rutherford and, finally, to express my gratitude to the Council of Trinity College for a grant from the Rouse Ball Research Fund towards the cost of the apparatus.

Attempts to Detect the Interaction of Neutrons with Electrons.

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[Plates 17–19.]

§ 1. *Introduction.*

The present paper contains an account of investigations made with a Wilson chamber on the penetrating radiation emitted by beryllium when the latter is bombarded by the α-particles of polonium. Dr. Chadwick* has suggested that this radiation consists of a stream of neutrons of unit mass and maximum velocity $3 \cdot 3 \times 10^9$ cm. per second. The neutrons in their passage through matter collide occasionally with the atomic nuclei and produce recoil atoms of short range and great ionising power. The recoil atoms of nitrogen have been studied in detail by Dr. Feather,† using an automatic expansion chamber, and the lengths of the recoil tracks are in agreement with the neutron hypothesis. It is of special interest to examine the interaction of the neutrons with electrons.

* 'Nature,' vol. 129, p. 312 (1932).

† 'Proc. Roy. Soc.,' A, vol. 136, p. 709 (1932).