The ejection of protons from nitrogen on bombardment with \( \alpha \)-particles of short range

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[Plate 19]

Using the expansion-chamber method, ninety proton tracks are obtained from 850 photographs showing the disintegration of nitrogen under bombardment by slow \( \alpha \)-particles. The number of disintegrations decreases as the energy of the \( \alpha \)-particles is reduced, but the photographs show disintegrations occurring for energies less than 1.7 MeV. The angular distribution is approximately isotropic for the protons ejected by \( \alpha \)-particles of energy less than 3 MeV, but there is a marked preponderance at about 90° for the protons ejected by \( \alpha \)-particles of range about 2 cm. in air at N.T.P. Typical photographs are reproduced.

INTRODUCTION

The ejection of protons as a result of the disintegration of nitrogen under bombardment by \( \alpha \)-particles of about 7 cm. range in air at N.T.P. was the first example of artificial disintegration (Rutherford 1919). The scintillation method of detection was used in these early experiments (Rutherford & Chadwick 1922), and it was shown that the number of protons ejected decreased rapidly as the range of the incident \( \alpha \)-particles was reduced. Using the expansion-chamber method (Blackett 1925; Blackett & Lees 1932), the reaction \( ^{14} \text{N} (\alpha, p) ^{17} \text{O} \) was found to occur. In three instances, however, out of a total of thirteen disintegrations, the \( \alpha \)-particle responsible for the disintegration had a range of somewhat less than 3 cm.

By electrical counting methods (Steudel 1932; Pollard 1933) it was next shown that protons were produced when the range of the \( \alpha \)-particles was as low as 2-2 cm. Such slow \( \alpha \)-particles were assumed to enter the nucleus by a resonance process. These results were later confirmed and extended (Stegmann 1935) when two close resonance levels corresponding to \( R_\alpha = 2.2 \) and \( R_\alpha = 2.6 \) cm. were established.

In the present work we have shown that the expansion method reveals that disintegration is produced by \( \alpha \)-particles of much lower ranges. The main aim of the investigation, however, was to form an estimate of the numbers of protons ejected at various angles with respect to the initial direction of the \( \alpha \)-particle.

EXPERIMENTAL DETAILS

The expansion chamber was about 13 cm. in diameter and 1 cm. high. The success of the experiment depended essentially upon the use of an intense source of \( \alpha \)-particles, canalized by a system of slits so as to produce an almost parallel beam of \( \alpha \)-particles of narrow breadth. Rather more than 80% of the \( \alpha \)-particles are situated in a beam which changes in width from 2 mm. at the beginning to 10 mm. at the end
in a total length of about 30 mm. The broader appearance shown in the photographs is due to the presence of a mass of unresolved tracks of α-particles scattered by elastic collisions with nitrogen nuclei, accompanied by a certain amount of ionic diffusion. The source consisted of polonium deposited electrolytically upon a piece of platinum foil; it was situated inside a cylinder which was closed at the end except for a slot 2 mm. wide. The arrangement was introduced into the expansion chamber through a side window, and it was inserted at such a distance that the α-ray tracks were formed centrally in the chamber which was filled with nitrogen gas from a gas cylinder. Because of the intense ionization, very heavy condensation occurred, and it was necessary to make some dozen small subsidiary expansions to clear the chamber between each main expansion. Standard methods of expansion, illumination and stereoscopic photography were used.

RESULTS

In 850 photographs, ninety proton tracks were obtained. The results, as found without corrections except for the reduction of the remaining range $R_\alpha$ to air equivalent at n.t.p., are shown in figure 1, where the ordinate $\theta$ is the angle of ejection of the protons in laboratory co-ordinates and the abscissa represents the corresponding value of $R_\alpha$. Sample photographs are reproduced in figure 4, plate 19.

DISCUSSION OF RESULTS

Perhaps the most striking characteristic of the distribution exhibited in figure 1 is the small number of protons which are ejected in the forward and backward directions, that is, between $\theta = 0$ to $30^\circ$ and $150$ to $180^\circ$. A simple direct count reveals that over 80% are ejected in the angular range $\theta = 30^\circ$ to $\theta = 150^\circ$. Another prominent feature is the large number of points around a value of $R_\alpha = 2$ cm. for which $\theta$ lies between 80 and 100°, indicating a marked preference at this energy for ejection at about 90°. It is interesting to recall that both the disintegration protons recorded by Blackett & Lees for α-particles of this energy were ejected at just such angles. A more detailed analysis of figure 1 indicates further points of interest, some of which can be made with certainty, while others are only probabilities based on prevailing theoretical views of nuclear disintegration.

(a) The distribution at $\theta = 90^\circ$

First, between $\theta = 80^\circ$ and $\theta = 100^\circ$, the error $\delta R_\alpha$ due to the finite thickness of the beam is very small. It may therefore be concluded that the values of $R_\alpha$ and $\theta$ as shown in figure 1 are truly representative of the facts. In figure 2a is shown the variation of yield with change in $R_\alpha$. No disintegrations are observed until $R_\alpha = 0.8$ cm. At this range protons begin to be found. Between $R_\alpha = 1.0$ and 1.4 cm. only one disintegration occurred. At greater ranges the number increased again, reaching a second maximum at about $R_\alpha = 2.1$ cm. Beyond this range the number falls rapidly.
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Figure 1
The existence of a resonance level at \( R_\alpha = 2.2 \text{ cm.} \) has already been established by other workers. In particular, Stegmann pointed out that if disintegration occurred for \( R_\alpha < 2.1 \text{ cm.} \) it must be of quite low intensity. There cannot be any doubt that our photographs show disintegrations occurring at much lower range than this. The distribution shown in figure 2a suggests strongly the existence of a resonance level in the neighbourhood of \( R_\alpha = 0.9 \text{ cm.} \), and this is substantiated by consideration of the combined distribution at \( \theta = 70^\circ \) and \( \theta = 110^\circ \) as shown in figure 2b. The distribution for the total angular range \( \theta = 60^\circ \) to \( \theta = 120^\circ \) is shown in figure 2c.

![Figure 2](http://rspa.royalsocietypublishing.org/)

**Figure 2.** a, \( \theta = 90^\circ \); b, \( \theta = 70^\circ \) and \( 110^\circ \); c, \( \theta = 60^\circ \) to \( 120^\circ \).

There is, however, no essential disagreement with Stegmann's results, either in the position or in the intensity of the resonance levels. First with regard to position we cannot guarantee our absolute range to within 10%, and we therefore identify our resonance level at 2.1 cm. with that found by Stegmann at 2.2 cm. Both finite thickness of the polonium deposit and possible foreign matter on the source surface
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could reduce the effective range of the $\alpha$-particles by this amount. As for intensity, Stegmann’s observations were made largely in the region of $90^\circ$ where the relative reduction in intensity proceeding from the 2-2 cm. level to lower levels is most marked. Our numbers are so small that statistical fluctuations alone would prevent much reliance being placed on quantitative estimates. To this must be added the uncertainty in $\theta$ which could amount to $\pm 5^\circ$. Then, for example, the proton recorded in the 1 cm. group as having $\theta = 82^\circ$ might possibly have $\theta < 80^\circ$; such an alteration would reduce our estimated relative intensity by 30 %.

Referring to figure 2c, the resonance group at 2-1 cm. is too broad and too asymmetrical to be attributed to a single level. Stegmann has shown that two definite levels occur at $R_\alpha = 2-2$ and 2-6 cm. respectively. We interpret the breadth of the larger group in figure 2c to imply the existence of at least one and possibly two or three levels between $R_\alpha = 1-4$ and 2-1 cm. Until more data are available, however, not much importance can be attached to particular figures for these levels intermediate between those at 0-9 and 2-1 cm. respectively.

(b) The distribution between $\theta = 80$ to 60$^\circ$ and 100 to 120$^\circ$

Since the possible error $\delta R_\alpha$ becomes progressively larger at other angles of ejection of the proton, being proportional to $b \cot \theta$, where $b$ is the breadth of the beam, the interpretation of our results becomes more uncertain at angles other than 90$^\circ$. The information which has been obtained under the unambiguous conditions of $\theta = 90^\circ$ acts as a valuable guide to the behaviour under less favourable conditions. The inference already made that resonance levels, if they exist at all between $R_\alpha = 1-1$ and 1-4 cm., must be of quite low intensity, allows us to assign a considerable number of protons to the 1 cm. group for small values of $R_\alpha$. One cannot, of course, rule out the possibility that some of these may correspond to even lower energy levels where $R_\alpha < 0-9$ cm. However, the number of protons ejected from such possible levels is presumably not large, for existing nuclear theory suggests that the separation of the energy levels becomes progressively greater at lower energies, and consequently the energy of the $\alpha$-particle responsible for the disintegration would be very small indeed. The large thickness of the potential barrier for such small values of $E_\alpha$ would be likely to make the probability of penetration of the nucleus by the $\alpha$-particle a rare process.

First, note that once again there are practically no disintegrations between $R_\alpha = 1-1$ and 1-4 cm., thus confirming the view already expressed that there are no resonance levels of appreciable intensity in this region. The most significant point is that the number of protons in the lower groups remains independent of the angle between 60 and 120$^\circ$, while the number in the 2-1 cm. group falls by about 50 % as $\theta$ is increased or decreased by 30$^\circ$ from 90$^\circ$.

(c) Angular distribution for other values of $\theta$

The above behaviour is maintained broadly speaking as one proceeds to other angular ranges down to $\theta = 30^\circ$ and up to $\theta = 150^\circ$, and it is therefore concluded that
the marked peak at 90° is characteristic of the highest energy group only. Below 30° one cannot distinguish for all values of \( R_x \) between projected protons due to elastic impact of the \( \alpha \)-particles with the possible hydrogen contamination in the chamber, and ejected protons formed in genuine disintegrations. With water and alcohol vapour present some of these protons at \( \theta < 30° \) may arise from elastic collisions.

![Figure 3](image)

In figure 3b is shown the angular distribution obtained for the protons ejected by \( \alpha \)-particles with \( R_x \) up to 1·6 cm., while figure 3a refers to those with \( R_x = 2·1 \) cm. The essential point revealed is that whereas the distribution for the 2·1 cm. group shows a very marked preference for \( \theta \approx 90° \), with the other groups the distribution is uniform within the rather large statistical error. The inference would appear to be that for the lower groups the disintegration is of an \( S \) type while for the 2·1 cm. group it is of some other type. We might expect the latter, if it is of the \( P \) type, to be proportional to \( \sin^2 \theta \), provided that certain assumptions are made about the angular momentum of the resonance level of the compound nucleus \( F^{18}_6 \). This expression is shown in the full line in figure 3a; the agreement is fairly satisfactory, but the experimental distribution suggests on the whole a rather sharper peak. The apparent too rapid falling away at the largest angles is probably instrumental, for the range of the protons at \( \theta > 130° \) would be short before they impinged on the slit system. However, had there been an appreciable number of these occurrences, some of the protons of such artificially short range would have been observed, whereas in practice none was found.

(d) The energy balance

In all cases the range of the protons exceeded the confines of the expansion chamber. This meant that the range of the proton \( R_p > 5 \) cm., corresponding to a
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proton energy \( E_p > 1.6 \text{ MeV} \). The limitation on the range measurement was unfortunate but unavoidable, since the chamber was originally designed for another purpose. It is, however, fortunate that the protons ejected are not of very short range, otherwise the separation of genuine disintegrations from projected protons due to possible hydrogen contamination would have been difficult. The energies of the two main groups of \( \alpha \)-particles responsible for the disintegrations and with \( R_\alpha = 0.9 \) and 2.1 cm. respectively, are about 1.7 and 3.5 MeV. Hence, taking into account also the energy of recoil of the nucleus, all that can be inferred is that the values of the energy balance \( Q \) are greater than \(-0.1 \) and \(-1.9 \text{ MeV} \) respectively. These values are consistent with those found by other workers.

Unless either the ranges of the ejected protons and the recoil nuclei, or else the \( Q \) values, are known, the transformation of the angular distribution of the protons from laboratory co-ordinates to co-ordinates moving with the centre of mass of the system cannot be effected. We have, however, calculated the corrected distribution on the assumption that \( Q = -1.0 \text{ MeV} \). The effect is to increase \( \theta \) at 90° by about 10% and by a proportionately lesser amount at larger and smaller angles. This merely improves the symmetry of our distribution shown in figure 3a and makes no appreciable difference to our conclusions.

(c) The absolute intensity of the disintegration process

The shutter arrangement which admitted the \( \alpha \)-particles was such that every disintegration which occurred during the sensitive period of the expansion chamber was recorded. Proton tracks which formed before the supersaturation was sufficiently high to cause condensation would show appreciable breadth due to the diffusion of the ions from their points of origin. Inspection of the tracks showed that this occurred in a few per cent of the cases. From observations on diffusion breadth as a function of the age of the tracks and from work on the sensitive period of expansion chambers of various sizes (Blackett 1934; Williams 1939), the effective time during which the proton tracks would be recorded is estimated as about \( \frac{1}{50} \text{ sec} \). The strength of the polonium source was approximately 3 millicuries. Taking into account also the solid angle subtended by the slit at the source, the number of \( \alpha \)-particles entering the chamber per second was estimated as \( 10^7 \). The solid angle in which the disintegrations were recorded was determined from the depth of the light beam and the diameter of the chamber to be about unity. Since ninety disintegrations were found in 850 expansions, the total probability of disintegration when nitrogen is bombarded with \( \alpha \)-particles of energy less than 3.5 MeV is found to be about one in two million. This value is too approximate to be regarded as very much better than expressing an order of magnitude.

(f) General conclusions

It does not seem that any complete theoretical calculation has yet been made of the precise angular distribution to be expected for the disintegration protons in the present experiment. In broadest outline, our results show, however, that when the uncorrected data shown in figure 1 are corrected for \((a)\) possible contamination
protons and large probable error in $R_x$ for $\theta < 30^\circ$, (b) the artificial reduction in the number of protons recorded for $\theta > 150^\circ$ due to the experimental arrangement of the slit system, and (c) the transformation of the distribution from laboratory co-ordinates to co-ordinates moving with the centre of mass of the system, then, irrespective of the energy of the incident $\alpha$-particles, the angular distribution of the ejected protons is symmetrical in the forward and backward directions, about a plane at $90^\circ$ to the direction of the incident $\alpha$-particles. Such an angular distribution is to be expected for all energies of the incident $\alpha$-particles, provided one is concerned with resonance disintegrations operating on the type of nuclear model suggested by Bohr. While, however, Bohr’s liquid-drop model may account for this very general feature of the angular distribution, and while it may be best suited to account for the wide range of experimental observations concerning the behaviour of heavy nuclei, particularly as regards interaction with neutrons, for light nuclei some degree of substructure is probably present. The well-known fact that disintegration of nitrogen with the emission of protons occurs at much lower energies of the incident $\alpha$-particles than are necessary for the disintegration with neutron emission, suggests that the protons are closer to the nuclear surface than the neutrons. Without postulating any precise arrangement it therefore appears that when an $\alpha$-particle strikes the nucleus it will in general first impinge on a proton.

If the $\alpha$-particle impinged centrally on the nucleus, the struck proton would have to traverse the nucleus in order to escape. In doing so it would, if not very fast, communicate all its energy to the other nuclear particles. The compound nucleus would therefore exist for an appreciable time, and when final disintegration occurred the direction of ejection of the protons would be expected to be approximately isotropic. This is in agreement with the angular distribution found for the disintegrations produced by $\alpha$-particles at the lowest energies.

Those $\alpha$-particles which impinged off-centre on the nucleus would communicate angular momentum to it. For a semi-rigid nucleus if the speed of rotation, the energy communicated to the struck proton and the force with which this proton is bound to the remainder of the nucleus, are just of the right relationship, one may imagine that the proton does not leave the nucleus until the latter has rotated through an appreciable angle. To explain the angular distribution for the 2.1 cm. group, the most probable value of this angle of rotation would have to be about $90^\circ$. Like all classical nuclear models, the above constitutes only a working approach to the problem, and it appears that ultimately the distribution should be accounted for on the general principles of quantum mechanics (Myers 1938).

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REFERENCES

Myers 1938 *Phys. Rev.* 54, 381.
Rutherford 1919 *Phil. Mag.* 37, 581.
Rutherford & Chadwick 1922 *Phil. Mag.* 44, 417.
Stegmann 1935 *Z. Phys.* 95, 72.
Stoeudel 1932 *Z. Phys.* 77, 139.

DESCRIPTION OF PLATE 19

Certain features are common to all the photographs. At the bottom is the source-holder, and in front of this is the slit system. The beam of $\alpha$-particles is shown as the dense column of condensation emerging from the slit system; it is situated centrally in the expansion chamber. In all cases the ejected proton travels beyond the confines of the chamber. The magnification varies between about 0·5 and 0·75.

**Figure 4.** A proton track is ejected at about 25° to the incident beam of $\alpha$-particles by one of the $\alpha$-particles of short remaining range. The possible error $\delta R_\alpha$ is large, and either the 0·9 cm. or one of the intermediate groups might be the cause of the disintegration.

**Figure 5.** In this disintegration $\theta = 60°$ and the transmutation is clearly due to the 2·1 cm group. The track is inclined to a horizontal plane, for while it begins quite sharply, by the time it reaches the edge of the chamber it has apparently become broadened because of the finite depth of focus of the camera lens.

**Figure 6.** Here $\theta = 85°$ and $R_\alpha = 1·65$ cm.

**Figure 7.** $R_\alpha = 0·5$ cm. and $\theta = 68°$. This has been assigned to the $R_\alpha = 0·9$ cm. group, but it is quite possible that it is an example of disintegration at a still lower energy group.

**Figure 8.** $\theta = 90°$, $R_\alpha = 1·6$ cm.

**Figure 9.** $\theta = 133°$. The stereoscopic pair of photographs gives the mean value of $R_\alpha = 1·2$ cm. with a maximum error of $\pm 0·3$ cm.
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