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UMI®
A CLOUD-CHAMBER STUDY OF THE
DISINTEGRATION OF OXYGEN AND NITROGEN

by

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A CLOUD-CHAMBER STUDY OF THE
DISINTEGRATION OF OXYGEN AND NITROGEN

1. INTRODUCTION

A study of the disintegration of nitrogen and oxygen when bombarded by neutrons has been made by means of a cloud chamber. By observing the particles produced in the disintegration of the oxygen and nitrogen nuclei, data have been taken on several phenomena; the energy levels of carbon-13, boron-11, nitrogen-15, nitrogen-16, and carbon-14 have been studied; the range-energy relations of boron-11 and carbon-13 have been established over certain portions of their ranges; the relative probabilities of disintegration of the compound nuclei by different modes have been observed. In certain cases the angular distributions of the emitted particles have also been studied.
II GENERAL DESCRIPTION

1. Reactions

The reactions which may occur can be found from the consideration of the energy available and the mass difference of the reacting particles. The energy of the neutron in the center of mass coordinate system must be greater than the $Q_o$ of the reaction. This means that enough kinetic energy must be available to make up any mass deficiency across the reaction.

Referring to mass tables\(^{(1)}\), the following reactions are found to be energetically possible:

For Nitrogen

\[
\mathrm{n} + \mathrm{N}^{14} \rightarrow \mathrm{N}^{15*} \rightarrow \mathrm{C}^{14} + \mathrm{H}_1 + 0.6 \text{ Mev}
\]

\[
\rightarrow \mathrm{C}^{13} + \mathrm{H}_1^2 - 5.3 \text{ Mev}
\]

\[
\rightarrow \mathrm{C}^{12} + \mathrm{H}_1^3 - 4.0 \text{ Mev}
\]

\[
\rightarrow \mathrm{B}^{11} + \mathrm{He}_2^4 - 0.3 \text{ Mev}
\]

\[
\rightarrow \mathrm{Li}^7 + 2\mathrm{He}_2^4 - 8.8 \text{ Mev}
\]

\[
\rightarrow \mathrm{N}^{14} + \mathrm{n} + 0.0 \text{ Mev}
\]
For Oxygen
\[ n + 0^{16} \rightarrow 0^{17} \rightarrow N^{16} + H^{1} \rightarrow 9.9 \text{ Mev} \]
\[ \rightarrow N^{15} + H^{2} \rightarrow 9.9 \text{ Mev} \]
\[ \rightarrow C^{13} + He^{4} \rightarrow 2.3 \text{ Mev} \]
\[ \rightarrow 0^{16} + n + 0.0 \text{ Mev} \]

In each case the residual nucleus may also be left in an excited state which will decay by gamma or particle emission.

2. Apparatus

The general arrangement of apparatus is shown in Figure 1.

The cloud chamber was irradiated by fast monoergic neutrons produced in the Rice Institute Cockroft-Walton accelerator using the deuteron-on-tritium reaction. The target used was tritium absorbed in zirconium, and its preparation has been described elsewhere\(^{(2)}\). It was bombarded by a 140-kev unresolved deuteron beam. The d-t reaction has a resonance at 110 kev with a cross-section of about 7 barns, and is thus a prolific source of neutrons. The Q of the reaction is 17.5 Mev, as can be determined
from a calculation of the masses involved, and the resulting energy of the neutrons taken at right angles to the beam is 14.1 Mev with a negligible spread in energy.

The elements oxygen and nitrogen were used as the filling gases in the cloud chamber. As the condensing vapor in the chamber is normally water or alcohol, or a mixture of these, a study of any gas must include a study of hydrogen, oxygen, and carbon. In this case water was used as the vapor in order to avoid the possibility of carbon disintegrations. The hydrogen present can produce only recoil protons which are easily distinguished from the disintegrations.

The cloud chamber was operated at a pressure a little greater than atmospheric pressure. Measurement of all but the longest tracks (obtained in the disintegration of nitrogen into carbon and hydrogen) was possible at this pressure, although the heavy recoil tracks were generally shorter than desirable for best measurements.

The cloud chamber was expanded approximately once a minute as timed by an electronic circuit. This circuit operated all controls of the accelerator and chamber equipment. Stereographic photographs were taken using one camera and a mirror, and after the film was processed the images were reprojected through the same lens and mirror system for study.
About 1400 pictures were taken and analysed in the study of oxygen; about 3000 pictures have been taken for the nitrogen survey, although only half of these are represented in the present discussion. In each case there were about 1000 usable tracks.

3. Measurements

If the two images of a track are reprojected on a sheet, and if the sheet is moved to such a position that the two images coincide, then the single image formed constitutes a true reconstruction of the track in length and in orientation in space. In this case, the white-surfaced disc of the apparatus shown in Figure 2 takes the place of the sheet.

In the disintegration of a nucleus into two particles when struck by a neutron, the resulting particles must lie in a plane with the incident neutron, as can be shown by the application of the conservation of momentum. (This assumes the target nucleus to be at rest.) Therefore, with the arm of the apparatus passing through the position originally occupied by the neutron source, the plane of the disc can be made to coincide with the plane of the two disintegration particles. The arm can be rotated about its own axis, about a vertical axis, and about a horizontal axis. The intersection of these three axes coincides with the original
position of the neutron source. A sliding fit of the arm in its holder allows the disc to be moved in and out. Thus the two images of any forked track can be made to coincide on the white disc.

A direct measurement of the angle between a track and the neutron's path can be made under a fixed index by rotating the disc about its center until one of its reference lines coincides with the track.

This apparatus is, of course, a convenience in the reconstruction of forked tracks, since it can be clamped in any position while length and angle measurements are made. However its more important function is to aid in the discrimination against forks caused by scattered neutrons. A scattered neutron coming from some random direction will not, in general, lie in the plane formed by the assumed neutron path and the two disintegration products, and hence the two stereographic images cannot be made to coincide for both tracks with one setting of the disc.

Another convenience of the apparatus is in the measurement of the angle of the plane of the two tracks with respect to the horizontal. A protractor marked on the arm holder indicates this angle immediately the position of the disc is set.

The lengths of the two tracks and the angle made by each track with respect to the neutron path were measured.
For the longer track these measurements were good, but in the case of a short recoil track it was difficult to estimate the length because of its heavier weight. The length used was the overall length minus the width of the track. The angle measurements of the recoil particles were also subject to some uncertainty because of angular scattering of the particles, and because of the difficulty in estimating the angle. The relative weights of the two tracks in a fork were noted as an aid in the later identification of the type of disintegration. In the reactions emitting a proton, deuteron, or triton, differences in the weights of tracks might be expected—that is the track of the recoil particle might be much heavier. In most cases this was true. For the disintegrations in which an alpha particle is emitted the weights are practically the same. The weight depends on the specific ionization of the particle, which, in turn, depends on the second power of the effective charge of the particle. While the recoil particle here has a nuclear charge of about 6 (for carbon recoil), it is travelling at a low velocity and picks up orbital electrons quickly so that its effective charge over most of its range may be only about 3. Thus the ratio of the specific ionizations might be expected, for carbon and alpha, to be about 2 to 1. (The alpha is completely stripped of electrons at its high velocity over essentially all its range.) Variations in the
cloud chamber may conceal this difference in track weight. The presence of old tracks nearby, differences in temperature at different parts of the chamber, etc., will affect the apparent weight of the track. Thus all tracks cannot be immediately identified by their weights.

For the single recoil tracks due to collisions of the neutrons with oxygen or nitrogen nuclei, measurements of length were made on all tracks lying within a cone of 15 degrees half-angle with the incident neutron path. For oxygen a cone of 10 degrees half-angle was used. This eliminated the necessity for corrections on tracks coming at larger angles. The tracks at larger angles are shorter, making measurements of the length impossible.

Measurements of length only were made on the three tracks of the tridents, but since at least one track was usually in a nearly vertical plane, the measurements were poor.

All the forks were measured regardless of position or orientation. Notes were made on the position of the fork, the quality of the tracks, and whether either track left the chamber.
4. Analysis of Data

The data were first analysed by separating the forks that had no apparent difference in the weights of the two tracks from those which had a difference. The former were then analysed assuming them to be due to an alpha disintegration of the compound nucleus. The measured length of the alpha track was first corrected for the stopping power of the gas and then the alpha energy was found from known range-energy curves\(3\). Using the conservation of momentum, the recoil energy \(E_r\) may be given as

\[
\frac{M_r E_r}{n} = \frac{M_n E_n}{n} + \frac{M_\alpha E_\alpha}{n} - 2\sqrt{\frac{M_n M_\alpha E_n E_\alpha}{n}} \cos \theta
\]

where \(R\) refers to the recoil particle
\(n\) refers to the neutron
\(\alpha\) refers to the alpha particle
\(\theta\) is the angle between the alpha track and the neutron path

The angle of the recoil particle is given by \(\phi\)

\[
\sin^2 \phi = \frac{M_\alpha E_\alpha}{M_n E_n} \sin^2 (\theta + \phi)
\]
In the energy equation the only measured quantities involved in the determination of $E_R$ are the alpha track length and the angle which the alpha particle makes with the neutron path. These are the quantities which are best measured. The masses and the neutron energy are, of course, known.

Both the above calculations were carried out by one setting of a simple mechanical momentum triangle calibrated in Mev energy units. The momentum of the neutron, being a constant, formed the base of the triangle and was laid out on a heavy sheet bakelite base. The momenta of the particles involved were set on lucite arms which pivoted, one at each end of the base line. A protractor was inscribed at each end of the base line.

The calculated recoil angle was then plotted against the measured recoil angle and the calculated energy plotted
against the measured track length. In the first case, a
deviation of seven degrees was set as the arbitrary limit
of acceptance of forks.

In addition, the calculated recoil energy was required
to lie on the appropriate range - energy curve within cer-
tain arbitrary limits.
III DISCUSSION OF RESULTS

1. Range - Energy Relations

The calculated recoil energy was plotted against the measured track length.

Several factors contribute to the buckshot appearance of the data shown for boron-11 in Figure 3. Straggling of the recoil particle will cause a spread in track lengths. Errors in the alpha energy and errors in the measurement of the angle the alpha track makes with respect to the neutron's path will lead to incorrect energies. In addition, if a reaction is improperly identified, the corresponding point may fall off the range - energy curve. A few forks due to scattered neutrons may also contribute to the scatter of points.

In forks where the recoil track is quite short it is sometimes difficult to be sure if the two tracks are really coplaner with the neutron beam. Also one of the tracks may have been scattered so close to the point of origin that no deflection is visible and yet the tracks may still be, or appear to be, coplaner.

A range - energy curve was found by plotting the most probable energy for given range intervals. In some parts of the curve, (for example towards the high end) where there
were too few tracks involved to afford a most probable value of energy, an average value was used.

Figures 4 and 5 show these final range-energy curves for boron-11 and carbon-13. Figure 6 shows these curves together with those of protons, alphas, and early data of Blackett's\(^{(4)}\) for oxygen and nitrogen.

In the passage of a heavy nucleus through matter, the specific ionization depends on the velocity and charge of the particle. As the particle slows down due to loss of energy in collisions, it will spend more time in the vicinity of atoms it is passing and will have a greater probability of interacting. As a result the specific ionization versus residual range curve (Bragg Curve) shows a rise towards the end of its range. When its velocity becomes comparable to the effective velocities of its orbital electrons it will begin to pick up electrons to fill these unfilled orbits. As a result, the specific ionization, which depends on the square of the charge, will rapidly fall off to zero.

This peak occurs for a proton about 1 mm from the end of its range and for an alpha at about 3 mm from the end of its range. For the boron we may expect the peak to occur at about 1.1 or 1.2 cms from the end, and for carbon, at about 2 cms from the end. This assumes the peak to occur when the velocity of the particle equals the effective ve-
Locity of the most tightly-bound electron.

If we plot the specific ionization - range curve for boron we see that this maximum is reached at about 1.2 cms of range.

The carbon specific ionization - range curve shows that the peak is apparently being approached but much nearer the end of the range than would be expected. Further data with longer range values would be necessary to locate the peak of the curve correctly.

Assuming the specific ionization for particles of the same velocity to be dependent only on the charge, we can make an estimate of the effective charge by comparison with the specific ionization of a proton of the same velocity. For the boron particle of energy 6 Mev this effective charge is 4.0. For a carbon particle of energy 5 Mev it is 3.8.

By taking the ratio of ranges of two of these particles for a given velocity, and assuming this to be proportional to the ratio of the masses and inversely proportional to some power 'n' of the nuclear charges, a value of 'n' can be determined. This is, of course, 2 for any two particles travelling with velocities much greater than their orbital electron velocities— for example, for alphas and protons in the Mev range. For low velocity particles Bohr[5] gives a theoretical ratio of 2/3. Blackett[6] gives a ratio of 1/2.
As found here, the ratio for a boron and an alpha particle increases with velocity from about 1.0 to 1.2. Between carbon and boron the ratio varies from about .5 to .6. Blackett's oxygen and nitrogen data give 'n' equal to 1/2--almost constant over the velocity range considered. These values are seen to be consistent. Synthetic range-energy curves may be made for particles of other mass and charge numbers using a suitable value of this exponent.

2. Excitation Energies

The amount of energy which is transferred in the reaction into the structure of the nucleus--the excitation energy--can be calculated from consideration of the energies involved. Knowing the masses of the four particles involved, the \( Q \) value for the ground state--the energy released in the reaction--can be calculated. Then from the measured kinetic energies of the reacting nuclei the \( Q \) of the particular reaction can be found. This is the sum of the kinetic energies of the product nuclei minus the sum of the kinetic energies of initial nuclei.

\[
Q = (E_\alpha + E_r) - E_n
\]

The difference between these \( Q \) values is then the energy of
excitation of the residual nucleus.

\[ E_x = Q_o - Q \]

(For alpha reactions this assumes that there is no level in the alpha which can be excited.) The plot of the number of forks in which the recoil nucleus is left with a certain amount of excitation energy versus that excitation energy then gives the position of energy levels in the residual nucleus by the resonances in the curve. The excitation curves for boron-11 and carbon-13 in which alphas have been emitted, for carbon-14 and nitrogen-16 in which protons have been emitted, and for nitrogen-15 and carbon-13 in which deuterons have been emitted are shown in Figures 7, 8, 9, and 10.

Carbon-13 (Figure 7)

The \( Q_o \) for the reaction

\[ n + ^{16}O \rightarrow ^{13}C + \alpha \]

is -2.3 Mev. Thus with a neutron kinetic energy of 14.1 Mev we can expect to find the residual carbon-13 nucleus excited to energies approaching 11 Mev. (About 1 Mev energy is necessary for the motion of the center of mass.) The
energy of the alpha emitted is low when the nucleus is left highly excited (about 1 Mev at 9 Mev excitation), and the penetrability of the alpha drops to a low value. As a result we will expect the number of disintegrations to drop off as the excitation increases. This is seen to be the case. Tabled below are the excitation energies corresponding to the potential barrier peaks for alphas of various values of angular momenta.

<table>
<thead>
<tr>
<th>( \ell )</th>
<th>( E_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.9</td>
</tr>
<tr>
<td>1</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>6.6</td>
</tr>
<tr>
<td>3</td>
<td>5.3</td>
</tr>
<tr>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

It is seen that below 8 Mev excitation the \( \ell = 0 \) alphas pass out unhindered by any barrier. For the lowest three peaks, in fact, alphas with \( \ell = 4 \) or 5 can be emitted with energies greater than the barrier top.

Levels as reported by Rotblatt\(^7\) are indicated in Figure 7 by dotted lines. It is seen that the present data
are in general agreement. Towards the high end of the histogram the levels are closely spaced, and as a result are not resolved. Some of the background in that region probably arises from the alpha decay of the excited oxygen-16 formed by the inelastic scattering of the neutrons.

More recently Buechner\(^8\) reports the lowest two levels to be at 3.083 and 3.677 Mev—in slightly better agreement with this data. In the present data there is no indication of a level near 1 Mev, as reported by others\(^9\). This present study includes the possibility of the level's being one of high angular momentum which might not be excited by the low-energy charged particles used in other experiments where the level was not found. Neither Rotblatt nor Buechner found it. Rotblatt attributes the apparent finding of a level here to possible oxygen contamination in the targets used.

The peak at 3.6 Mev has a narrow width and would appear to be due to a single level rather than to the two reported by Rotblatt. The 3.9 level is very weak, if present at all. Buechner also found this peak to be very weak.

**Boron-11**

Figure 8 is a histogram showing the number of disintegrations of the excited intermediate nucleus of nitrogen-15
into boron-11 plus an alpha for different amounts of excitation of the boron.

The $Q_o$ for this reaction is $-0.3$ Mev. Thus we can expect to find the boron left excited to energies approaching 12.8 Mev. Known levels as reported by Van Patter et al.(10) from a study of the boron-10 (dp) reaction are indicated by dotted lines in Figure 8, and it is apparent that there is satisfactory agreement.

Bateson(11), studying the same reaction, but using range measurements rather than the more precise magnetic analysis used by Van Patter, finds seven levels, all in good agreement with those of Van Patter except for one group. This group Bateson places at $7.82 \pm .07$ Mev rather than at $7.298 \pm .012$ Mev as given by Van Patter. As pointed out in Van Patter's report, this group found by Bateson coincides with the position of that proton group from the $^16_6(dp)^{17*}$ reaction having a $Q$ value of 1.049 Mev, and may be due to target contamination. A boron group, if present, would not be resolved from the oxygen group. By measurements of proton energy at 0 degrees and 90 degrees Bateson concludes that the group is from boron. Fulbright and Bush(12) have studied the inelastic scattering of protons on natural boron and have also found a level at $7.8 \pm 0.4$ Mev. This level then might correspond to the level found here at 8.0 Mev, but would appear to be a little low.
When more data for this reaction have been collected, the position of this peak may be set more closely.

This peak has as great a width as the doublet at 6.76 and 6.80 Mev, and perhaps arises then from more than one level. These would probably not be resolved, even with further data, but a better estimate might be made as to whether one or more levels is present.

The assignment of the small group at 5.6 Mev to a new level should be delayed until further data is collected and statistics improved. This group was larger when a slightly less stringent range-energy condition was applied as a criterion for using a disintegration. This marked decrease in intensity when certain tracks which lay too far off the range-energy curve were discarded, compared with the smaller decreases noted in groups from the well-established levels at 6.7 and 5.0, makes the assigning of this group to a level at 5.6 Mev doubtful. The very low background inherent in this method of studying a reaction, must, however, be taken into consideration.

The group at 11.8 Mev agrees very well with neutron transmission experiments of Bockelman(13), who found a resonance with a neutron energy of 0.4 Mev. This corresponds to an excited level of 11.8 Mev in the intermediate nucleus. The presence of this relatively large group at 11.8 Mev and the absence of any disintegrations down to 9.4
Mev would indicate that there were no levels in the region in between. The presence of the group at 11.8 Mev indicates that tracks in this region, though short, would be measured if they were present. Normally one expects a larger density of levels at such high excitation energies, and the establishing of their absence would, of course, be of interest.

Nitrogen-15 and Nitrogen-16

The Q_o's of these two reactions are each -9.9 Mev, and the amount of excitation available to the nitrogen nuclei is about 3-1/2 Mev in each case.

In the calculation of the Q_o for the N^{16} + p reaction, the mass of the nitrogen-16 was based on -0.03 Mev as the Q_o of the N^{15}(dp)N^{16} reaction, as found by Strait et al. However, Wyly has found two proton groups in the N^{15}(dp)N^{16} reaction, one with a Q_o of 0.23 ± 0.15 Mev, and the second group corresponding to a level in nitrogen-16 at about 0.3 Mev. Thus depending on what value of the Q_o is assumed, the excitation levels found here will vary upwards by perhaps 0.2 or 0.3 Mev.

The nitrogen-15 and nitrogen-16 were analysed together since separation of the two reactions is difficult. The forks were assumed first to be nitrogen-15 plus a deuteron, and then to be nitrogen-16 plus a proton, and the excitation
curves plotted (Figure 9). The groups were then assigned to the reaction for which they best agreed with known levels\(^{(16)}\), as indicated in Figure 9. If the group is incorrectly assigned a smearing of the peak is observed. There is no known level in nitrogen-15 above the ground state and below 5.28 Mev\(^{(9)}\). This level cannot be excited with the amount of energy available, which simplifies the identification. The extra group, then, is to be assigned to a new level in nitrogen-16 at 2.6 Mev.

**Carbon-12, -13, -14**

The \( Q_o \)'s of these three reactions

\[
\text{n + } \ _{14}^\text{N} \rightarrow \ _{15}^\text{N}^* \rightarrow \ _{12}^\text{C} + \text{t} \\
\rightarrow \ _{13}^\text{C} + \text{d} \\
\rightarrow \ _{14}^\text{C} + \text{p}
\]

which were analysed together for the reason stated above, are -4.0, -5.3, and +0.6 respectively. Thus the residual carbon nuclei can be excited to energies of about 9.3, 8.0, and 14.0 Mev respectively. For low excitations the emitted particle carries away a large amount of energy and will not be stopped in the chamber. Thus only high-lying states can be studied. Furthermore, the levels will, in general, be
closely spaced at this high excitation and will not be easily resolved. In the case of triton emission the first known level$^9$ for carbon-12 at 4.5 Mev will not be recorded since the energy of the triton will be sufficient to carry it out of the chamber. The 9.7 level, on the other hand, cannot be excited with the amount of energy available. Since the only other level indicated, at 7 Mev, is very much in doubt$^{17}$, it is unlikely that the carbon-12 plus triton reaction will be observed and identified. Using the criteria mentioned earlier concerning the recoil angles, and the recoil energy and track length, the forks were assigned to the carbon-13 and carbon-14 reactions, as shown in Figure 10. Disintegrations in which positive identification was impossible are represented in both carbon-13 and carbon-14 excitation curves by shaded squares.

About all that can be said from this small amount of data is that the reactions do occur and that there are perhaps two or three levels in carbon-14 in the region 12 to 13 Mev.

3. Recoil Nuclei

When the neutron collides with the target nucleus it may be absorbed to form a compound nucleus and then re-emitted with the same amount of energy (elastic scattering)
Figure 11

Nitrogen 14

Oxygen 16

Track length in cm.
or with less kinetic energy (inelastic scattering). If the residual nucleus is left excited, it will decay by either gamma or particle emission. The former will take place if the energy given to the nucleus is insufficient for particle emission. The recoil nitrogen and oxygen particles which were measured will be from those collisions in which the nucleus was either left unexcited or, when excited, decayed by gamma emission. The plot of the number of recoils versus the track length for oxygen and nitrogen is shown in Figure 11. The excitation energy corresponding to any track length can be calculated from simple laws of collision mechanics; some of them are indicated in Figure 11 by dotted lines. Elastic scattering in oxygen corresponds to a track length of .42 cms (this is based on Blackett's range - energy curve for oxygen), and in nitrogen to a track length of .50 cms. It is apparent that the ratio of inelastic to elastic scattering is very high. This might be expected in a general way, since the energy available for excitation is very high and the number of available levels is large. This method is too insensitive to resolve the levels of oxygen and nitrogen, but the presence of some peaks can be noted.
4. Angular Distributions

The angular distributions for the alphas emitted from the 3.1 and 3.7 Mev levels of carbon are shown in Figures 12 and 13. An angular distribution is of interest in that it may give information about the angular momentum of the level concerned.

Applying quantum mechanics, the angular dependent part of the wave function for the emitted particle can be expanded in a series of Legendre polynomials where the order \( l \) of a polynomial indicates the angular momentum concerned. The cross-section for emission of a particle at any angle is proportional to the square of this expansion, and can be written then as a Legendre polynomial series of order \( 2l \). A Legendre polynomial expansion of the experimental distribution will indicate the orders of angular momenta involved where now the order is \( 2l \).

When these experiments were begun, the level at 3.1 was thought to have a large spin, and a study of the angular distribution might have indicated possible values, but since then Butler\(^{(18)}\) has reported the spin to be \( 1/2 \).

The angular distribution in the laboratory coordinate system was first corrected for the geometry of the chamber—that is for tracks which would leave the chamber through the walls or through the top or bottom. These corrections
did not materially change the shape of the curve. The distribution was then corrected to the center of mass coordinate system.

From the distribution shown for this level we see that there is a strong assymetry in the backward direction. This indicates strong interference terms.

Polynomial expansions for orders up to 4 and up to 6 are shown, and we can say that momenta of at least 2 or 3 units are involved. Certainly from the amount of angular momentum which the neutron can bring in, and from the high penetrability of the alphas, there is no reason for not expecting large momenta.

Similarly for the 3.7 Mev level distribution, polynomial expansions using orders up to 4 and up to 6 are shown. The statistics do not allow a precise determination of angular momenta involved, but alphas with at least 3 units of angular momentum are likely present.

5. Relative Disintegration Probabilities

Since the reactions were all produced by the same neutron beam and measured with the same detector, the relative number of tracks found for the different types of reactions will be a measure of the relative probabilities
of disintegration. Certain geometrical corrections must be applied to the number of tracks measured for each reaction. These include a correction for tracks going out of the chamber which varies according to the track length. A correction for solid angle has to be applied to the number of recoils since the recoils measured were limited to a small cone.

This correction is made by considering a spherical distribution in the center of mass system and by calculating the maximum acceptance angle corresponding to 15 degrees for nitrogen, 10 degrees for oxygen. This varies with the Q of the reaction and hence with the length of the recoil track.

The angle in center of mass coordinates is related to the angle in lab coordinates by the expression

\[ \tan \phi_0 = \frac{\sin \phi}{\phi + \cos \phi} \]

p. 99, Schiff(19)

\[ Q = \frac{m + M}{m} E_r - 2 \left( \frac{M}{m} E_n E_r \right)^{\frac{1}{2}} \]

where \[ \gamma^2 = \frac{E}{E + Q} \]

\[ E = \text{energy of the system in center of mass coordinates} \]
\[ m = \text{mass of neutron} \]

\[ M = \text{mass of recoil nucleus} \]

Thus from the track length the recoil energy and hence the \( Q \) can be calculated. From this, and using the first expression, we can calculate the maximum acceptance angle in the center of mass system. For sufficiently high excitation energies (low velocity in center of mass system), all recoils will come out within the limits set and all will be measured. For lower excitation, some recoils will lie outside the cone and will not be counted. The fraction counted may be found from the fraction of the total solid angle subtended by the cone and by assuming an isotropic distribution (c. of m.).

The solid angle used is

\[ 2\pi(1 - \cos \phi) \]

and the fraction counted will be

\[ F = \frac{(1 - \cos \phi)}{2} \]

\[ = \sin^2 \frac{\phi}{2} \]
The recoil distribution was divided into intervals and an average correction applied to the number of tracks in each interval.

The forked tracks measured were limited to those whose planes made an angle of less than 50 degrees with the horizontal. A correction had to be made for this. All tridents were measured and are, of course, easily identified. It is assumed that tracks which are too short to measure will cause a similar fractional loss in all reactions.

Oxygen

The number of recoil tracks measured was 83, of which 3 were likely due to elastic scattering of the neutron. When corrected for solid angle as indicated above, this gives relative probabilities for inelastic scattering to elastic scattering of 1219 to 100, or 12 : 1.

Correcting the total number of recoils for solid angle gives the number of recoils as 1319.

The number of alpha disintegrations measured was 555. Making geometrical corrections for tracks leaving the chamber (50 percent loss for the lowest three levels of carbon-13, 25 percent loss for the top levels), and for the azimuthal angle limit used, we get a corrected number of alpha disintegrations of 1750.

The ratio of the number of reactions in which the
neutron is scattered to the reactions in which an alpha is emitted is 1319 to 1750, or about 1 : 1.3.

The number of hydrogen reactions identified is 48, but one set of tracks which may contribute to this number has yet to be studied, and a relative probability cannot be assigned for these reactions. However, the relative number of proton reactions to deuteron reactions may be estimated from the relative number of tracks measured and identified. This gives a ratio of 34 to 14, or about 2.4 : 1.

Nitrogen

The number of recoil tracks measured was 207, of which perhaps 3 may be assigned as due to elastically scattered neutrons. Making the solid angle corrections as mentioned above, we get a ratio of the relative probabilities of inelastic scattering to elastic scattering of 1347 to 50, or 27 : 1.

Correcting the total number of recoils for solid angle gives 1397.

The number of alphas measured was 221. By applying geometrical corrections as above (assuming an average loss of 40 percent) we get the number of alpha disintegrations to be 664.

The number of tridents was 176.
The relative cross-sections for tridents, alphas, and recoils are, then, 176 to 664 to 1397, or 1 : 4 : 8.

The number of hydrogen reactions is more difficult to establish since the reactions are not easily identified, or, as in the case of the triton reaction, not even measured. However, from the number of disintegrations identified (33 proton, 21 deuteron), we may estimate very roughly the total number of hydrogen reactions to be about 600.
IV SUMMARY

From this cloud-chamber study of the disintegration of oxygen and nitrogen the following data have been obtained:

Excitation curves for boron-11, carbon-13, carbon-14, nitrogen-15, and nitrogen-16 have been taken, and general agreement with known levels has been noted. Possible new levels in boron-11 at 5.6 and 8.0 Mev, and in nitrogen-16 at 2.6 Mev have been indicated.

Range - energy relations have been plotted for carbon-13 and boron-11 in the range of 0 to 1 cm. This covers the range in which the boron picks up its orbital electrons.

The angular distributions of the alphas from the 3.1 and 3.7 Mev levels in carbon-13 have been analysed. A strong assymetry in the backward direction is noted for the 3.1 level group. Angular momenta up to 3 units is indicated.

Values of the relative probabilities for disintegration by different reactions have been calculated on the basis of the number of tracks found.

Typical tracks in the disintegration of nitrogen are shown in the following photographs. The neutrons enter from the top of the page.
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