NEUTRONS FROM THE BOMBARDMENT OF BORON WITH DEUTERONS

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Table of Contents

Introduction---------------------------------1
Targets-----------------------------------2
Apparatus---------------------------------2
Counting Technique------------------------3
Sensitivity of the Counter---------------4
Results----------------------------------6
NEUTRONS FROM THE BOMBARDMENT OF BORON WITH DEUTERONS

The excitation curve for the production of neutrons by deuteron bombardment of boron has been determined over the range of deuteron energies from 0.4 to 0.64 and from 0.85 to 1.65 Mev. A narrow resonance was observed at 1.33 Mev bombarding energy. The half width of this resonance was found to be approximately 25 kev, which is about equal to the target thickness.

Introduction

Bonner and Brubaker\(^1\) determined the energy distribution of neutrons from deuteron bombardment of boron at a bombarding energy of 0.9 Mev. They observed neutrons with Q values\(^2\) of 13.4, 9.0, 6.0, and 3.9 Mev, and relative intensities\(^3\) of 0.36, 0.38, 0.07, and 0.19, and also neutrons with a continuous distribution of energy below 3 Mev. The reactions involved are

\[
\begin{align*}
(1) & \quad 5B^{11} + 1H^2 \rightarrow 6^0^{13} \rightarrow 6^0^{12} + \text{on}^1 \quad Q_0 = 13.8 \text{ Mev} \\
(2) & \quad 5B^{11} + 1H^2 \rightarrow 6^0^{13} \rightarrow 3_2^4 \text{He} \quad + \text{on}^1 \quad Q_0 = 6.4 \text{ Mev} \\
(3) & \quad 5B^{10} + 1H^2 \rightarrow 6^0^{12} \rightarrow 6^0^{11} + \text{on}^1 \quad Q_0 = 6.5 \text{ Mev}
\end{align*}
\]

Reaction (2) is responsible for the continuum. Reaction (1) is the only reaction for which production of the two fastest groups is energetically possible. The two slower groups may be due to B\(^{10}\).
**Targets**

The targets used were made by evaporating fused $\text{B}_2\text{O}_3$ onto thin polished silver disks in a vacuum of $10^{-4}$ to $10^{-5}$ mm of mercury. A helical filament of platinum was used to heat the $\text{B}_2\text{O}_3$. The disks were weighed on a micro-balance before and after coating, and the thicknesses in kev of the targets for 1 Mev deuterons were computed from the difference in these two weights. The difference in weights before and after coating agreed to within 20% in all cases with the expected weight of $\text{B}_2\text{O}_3$ on the disk, as calculated from the solid angle subtended by the disk at the center of the filament. The thickness of the targets was also checked roughly by comparison of their yields with the yield of a thick target. The targets used were approximately 30 kev thick.

The reaction $^{16}_0(d, n)^{17}N$ is not energetically possible over the range of bombarding energies covered, so that neutrons due to oxygen will not be counted.

**Apparatus**

The Rice Institute Van de Graaff generator was used to obtain beams of monoenergetic deuterons. The slit width of the magnetic analyzer was set at 10 kev.

The counter used was a cylindrical proportional counter of 1-7/8 inches inside diameter and 1-15/16 inches sensitive length. The central wire was made of tungsten and was 5 mils in diameter. The outside conductor was made of 1/16" brass. One end was made of 1/8" brass and the other of 1/4" brass.
The counter was filled with five atmospheres of helium, and was operated at 2200 to 2230 volts with an Atomic Instrument Company 204-B Linear Amplifier with a rise time of 0.8 microseconds.

All the data was taken with the counter in the dead ahead position and as close as possible to the target. Its axis was perpendicular to the deuteron beam. It was placed as nearly as possible so that the center of its effective volume fell along the extension of the path to the deuteron beam. The distance from the target to the counter was 1.5 centimeters.

**Counting Technique**

In each run over a range of bombarding energies, points were taken about 25 kev or less apart. For points between 0.85 to 1.65 Mev, at least 4800 neutron counts were taken at each point in each run. Five runs in all were made over the resonance, and a clear peak in the yield curve was observed each time. One of these was a very careful run with closely spaced points.

The background counting rate was checked using a blank silver disk in place of the target. It was found that the number of neutron counts for a given number of integrator counts was essentially proportional to the time. The number of neutron counts per second was determined at seven equally spaced points between 1.0 and 1.7 Mev, and these values were plotted. A smooth curve was drawn through the seven points and extrapolated back to 0.85 Mev. This curve was used for background correction.
It was found that the gamma rays from a 1 milligram radium source were biased out at about 10 volts negative bias. The runs were made with 40 volts negative bias. A check showed that the percentage of background counts could not be materially improved by increasing the bias.

In addition to the runs mentioned above, a single run over the range of energies from 0.4 to 0.64 Mev was made using a singly ionized D$_2$ beam. At least 1850 neutron counts were taken at each point.

**Sensitivity of the Counter**

From the fact that the radium gamma rays were biased out at about 10 volts a rough estimate of the energy of the neutrons biased out at 40 volts can be made.

The gammas are counted by means of the ionization produced by electrons ejected from the walls of the counter. The maximum conversion of kinetic energy of the electron into ionization occurs when the electron stops in the counter. An electron travelling along the longest possible straight line through the effective volume of the counter would pass through about seven mg./cm$^2$ of helium. The extremely low probability of this occurrence is roughly compensated for by the fact that electron tracks curve considerably near the end of the range. Since the mass stopping power of all elements is about the same, the energy dissipated by the electron may be obtained from a range-energy curve for aluminum. This energy is about 0.07 Mev$^4$. Since electrons and alphas expend about the same energy
in producing an ion pair, neutrons producing forward recoils with about four times this energy will be biased out at 40 volts. When a neutron strikes an alpha particle and causes it to recoil in the forward direction the neutron gives $16/25$ of its energy to the alpha. So multiplying $0.07 \times 4 \times (25/16)$ we have the result that neutrons with energies of about 0.4 Mev or less are biased out at 40 volts.

This means that the bias reduces the sensitivity for 1 Mev neutrons by a factor of about $(1 - 0.4/1.0) = 0.6$. The bias will not materially affect the sensitivities to the four homogeneous groups of neutrons. These will depend on the cross sections only. The relative sensitivities to 1 Mev neutrons and to the four homogeneous groups are given below.

<table>
<thead>
<tr>
<th>ENERGY (Mev)</th>
<th>CROSS SECTION (Barns)</th>
<th>RELATIVE SENSITIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>3.9</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>6.0</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>9.0</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>13.4</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The cross sections were obtained by use of Staub's and Stephens' curve of the ratio of the cross section of helium to that of hydrogen and the curve given in *The Science and Engineering of Nuclear Power* for the cross section of hydrogen. Staub's and Stephens' curve does not go above 6.0 Mev, but an extrapolation is definitely justified for present purposes.

From the relative sensitivities and the relative intensities
of the four homogeneous groups, and from a comparison of the areas under the humps due to the continuum and to the 3.9 Mev group in the energy distribution curve taken with a helium filled cloud chamber by Bonner and Brubaker, the percentages of counts due to the continuum and the four groups can be calculated. They are

<table>
<thead>
<tr>
<th>Group</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum</td>
<td>66%</td>
</tr>
<tr>
<td>3.9 Mev Group</td>
<td>10%</td>
</tr>
<tr>
<td>6.0 Mev Group</td>
<td>4%</td>
</tr>
<tr>
<td>9.0 Mev Group</td>
<td>12%</td>
</tr>
<tr>
<td>13.4 Mev Group</td>
<td>8%</td>
</tr>
</tbody>
</table>

The ratio of the percentage of counts due to the continuum to the percentage due to the 3.9 Mev group was obtained by multiplying the ratio of the area under the two humps by 0.6. The peak of the continuum hump is at about 1 Mev, and the bias reduces the sensitivity at 1 Mev by a factor of about 0.6. Since the continuum and the two high energy groups are due to $^{11}B$, it appears that even if both of the other groups are due to $^{10}B$, a large majority of the counts are due to $^{11}B$.

**Results**

The excitation curve is shown in figure 1. The energies shown are bombarding energies rather than mean energies in the target. The points between 0.85 and 1.65 Mev are taken from three runs. The first was from 0.85 to 1.62 Mev, the second from 1.04 to 1.65 Mev, and the third was a careful run from 1.20 to 1.36 Mev with closely spaced points. The first and third runs agreed almost perfectly at points where neutrons were counted in both runs. The second gave slightly lower values...
due to the fact that a slightly lower counter voltage was used. This second run was normalized to the first and the two averaged to get all the points on the segment of the curve from 0.85 to 1.65 Mev with the exception of the points from 1.30 to 1.36 Mev. The points between 1.30 and 1.36 Mev, the vicinity of the resonance, were taken from the third run. The points between 0.40 and 0.64 Mev were taken from the single run with the D2 beam mentioned above.

In order to check the possibility of a broad resonance, P/E, where P is the penetrability for l = 0 deuterons and E is the bombarding energy in the center of mass coordinates, has been plotted, along with the excitation curve, against the bombarding energy in laboratory coordinates in figure 2. The ordinates of the two curves are in arbitrary units.

The penetrabilities used are those given by Christy for the penetrability of l = 0 protons. The nuclear radius of Bi11 for deuteron bombardment is only 8% greater than for proton bombardment, so that the penetrabilities for l = 0 deuterons and l = 0 protons will not be much different. At lower bombarding energies the penetrabilities for l ≠ 0 deuterons are very small compared to the penetrability for l = 0. At these energies the P/E curve for l = 0 is a good approximation to the curve for all l. But at higher energies the penetrabilities of the l ≠ 0 deuterons become significant, so that the curve for all l is higher than that for l = 0. The dashed extension of the curve of P/E for l = 0 is probably a good rough approximation
of the all 1 curve, judging from the shapes of the \( l = 0 \) and all 1 curves for other elements.

It can be seen that the ratio of the ordinate of the experimental excitation curve to the ordinate of the P/E curve is everywhere increasing with increasing energy, except near the 1.33 Mev resonance. This ratio has been plotted in figure 3. The dashed portion of this curve represents division of the experimental curve by the dashed P/E curve. The presence of a broad resonance cannot be determined from this curve.

From the height of the resonance at 1.33 Mev and from the fact that a large majority of the counts are probably due to \( B^{11} \) it appears more likely that the resonance is due to \( B^{11} \) than to \( B^{10} \). This would indicate an excited state in \( C^{13} \) at 19.8 Mev. This figure is obtained by adding \( 11/13 (1.33 - 0.015) \) to the energy equivalent of the difference in masses of \( B^{11} \) and \( O^{16} \). The subtraction of 0.015 Mev, half the target thickness, is to get the mean energy of the deuteron in the target. The factor 11/13 converts the energy from laboratory to center of mass coordinates.

The half width of the resonance peak is approximately 25 kev. Since this is about equal to the thickness of the target, it can only be stated that the actual half width is about 25 kev or less. From this and the Heisenberg Uncertainty Principle it follows that the lifetime of the excited state is about \( 10^{-18} \) seconds or greater.

If the resonance were due to \( B^{10} \) it would indicate an excited state in \( O^{12} \) at 26.3 Mev with a lifetime of about \( 10^{-18} \) seconds or greater.
Acknowledgments

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