INVESTIGATION OF THE D(α, γ) Li⁶ REACTION

by

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April, 1962
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Date April 10, 1962
A search has been made for the radiative capture reaction \( D(\alpha, \gamma)\text{Li}^6 \) at the energy corresponding to the 2.184 Mev level in \( \text{Li}^6 \). The search was carried out using heavy ice targets varying from 100 Kev to 700 Kev thick. The radiative capture reaction was not observed. An upper limit on the resonant capture process was set at \((1.4 \pm 0.6) \times 10^{-31}\text{ cm}^2\).

A gamma radiation peak was observed at 1.64 Mev for runs on \( \text{D}_2\text{O}, \text{H}_2\text{O}, \) and tungsten oxide targets. The cross-section was roughly estimated at \( 4 \times 10^{-29}\text{ cm}^2\). This radiation was attributed to the reaction \( \text{O}^{17}(\alpha, \text{n})\text{Ne}^{20} \).
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>THEORETICAL ASPECTS OF THE D(α, γ)Li⁶ REACTION</td>
<td>3</td>
</tr>
<tr>
<td>III</td>
<td>EXPERIMENTARY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. General Technique</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2. Apparatus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Target Chamber</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>(b) Ice Target Dispensers</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(c) Radiation Detectors</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>3. Target Thickness Measurements</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Theory</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>(b) Procedure</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>(c) Results and Calculations</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>4. Experiments</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>5. Results</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>6. Calculation of an Upper Limit on the D(α, γ)Li⁶ Cross-section</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>BIBLIOGRAPHY</td>
<td>29</td>
</tr>
<tr>
<td>Figure</td>
<td>Subject</td>
<td>Facing Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>1.</td>
<td>Energy Level Diagram of Li$^6$</td>
<td>1</td>
</tr>
<tr>
<td>2.</td>
<td>Target Chamber and Beam Tube Apparatus</td>
<td>9</td>
</tr>
<tr>
<td>3.</td>
<td>Schematic Diagram of the Dispenser System</td>
<td>10</td>
</tr>
<tr>
<td>4.</td>
<td>Circuit Diagram for Large Scintillation Counter</td>
<td>11</td>
</tr>
<tr>
<td>5.</td>
<td>Circuit Diagram for Small Scintillation Counter</td>
<td>12</td>
</tr>
<tr>
<td>6.</td>
<td>Spectrum of Cs$^{137}$ from 2&quot;X 2&quot; Crystal</td>
<td>13</td>
</tr>
<tr>
<td>7.</td>
<td>Spectrum for D(p,$\gamma$)He$^3$ Reaction</td>
<td>18</td>
</tr>
<tr>
<td>8.</td>
<td>Dispenser Calibration Curve</td>
<td>19</td>
</tr>
<tr>
<td>9.</td>
<td>Spectra at 90° for D$_2$O and H$_2$O Targets</td>
<td>21</td>
</tr>
<tr>
<td>10.</td>
<td>Spectra at 0° for D$_2$O and H$_2$O Targets</td>
<td>22</td>
</tr>
<tr>
<td>11.</td>
<td>Spectra for D$<em>2$O Targets with $E</em>{\alpha} = 2.18$ and 2.10 MeV</td>
<td>23</td>
</tr>
<tr>
<td>12.</td>
<td>Difference Between Spectra for $E_{\alpha} = 2.18$ Mev and $E_{\alpha} = 2.10$ Mev on D$_2$O Targets 100 Kev Thick</td>
<td>24</td>
</tr>
<tr>
<td>13.</td>
<td>Spectrum for $E_{\alpha} = 2.18$ Mev on a Tungsten Oxide Target</td>
<td>25</td>
</tr>
<tr>
<td>14.</td>
<td>Low Energy Spectrum for $E_{\alpha} = 2.18$ Mev on D$_2$O Target</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>100 Kev Thick</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Energy Level Diagram of Li\textsuperscript{6}
CHAPTER I  INTRODUCTION

The reaction \( D(\alpha, \gamma)\text{Li}^6 \) can be expected to occur on theoretical grounds although with a very small cross-section. The inelastic scattering of deuterons from \( \text{He}^4 \) carried out by Lauritsen, Huus, and Milleon (1953) and later by Galonsky, Douglas, Haeberli, McEllistrem, and Richards (1955) showed a pronounced resonance at a deuteron energy of 1.069 Mev in the laboratory coordinates. This resonance corresponds to a level of \( \text{Li}^6 \) at 2.184 Mev above the ground state (see Figure 1). From their experimental results the above workers were able to assign to this level angular momentum \( J = 3 \), and even parity. The ground state of \( \text{Li}^6 \) has assignment \( J = 1 \), and even parity. Therefore, at the resonance, the radiative capture reaction \( D(\alpha, \gamma)\text{Li}^6 \) is allowed by electric quadrupole transition. A non-resonant capture process proceeding through electric or magnetic dipole transitions might also be expected. However, calculations by Tombrello (1961) have indicated that at the resonance the non-resonant contribution to the reaction cross-section is at least an order of magnitude smaller than the resonant contribution.

Previous searches for the reaction have been made. Sinclair (1954) carried out a search using 1.055 Mev deuterons on a \( \text{He}^4 \) gas target. No gamma radiation corresponding to this reaction was detected and an upper limit of 0.1 millibarns was set on the cross-section. Tombrello (1961) made another search using deuterium gas as a target and bombarding with 2.14 Mev alpha particles. Again no radiation was observed and an upper limit of 0.2 microbarns was set on the cross-section at the resonant
energy. Using the radiative width determined by the inelastic scattering of electrons by Li$^6$ (Barber, Berthold, et al. (1960)), Tombrello calculated the theoretical total cross-section to be approximately 0.02 microbarns for the resonance capture reaction.

In the present work a further search has been carried out for the radiative capture reaction D(α, γ)Li$^6$. 
CHAPTER II  THEORETICAL ASPECTS OF THE D(α, γ)Li^6 REACTION

Using Breit-Wigner resonance theory, an estimate of the resonant capture cross-section can be made. The well known Breit-Wigner single level formula gives for the cross-section of a reaction entering the compound state by channel a and decaying through channel b is

$$\sigma(a, b) = (2\ell + 1)\frac{\hbar^2 \chi^2 \Gamma_a \Gamma_b}{(e_a - e_o) + \left(\frac{1}{2}\Gamma\right)^2}$$

where
- $\ell = $ angular momentum of the interacting nuclei
- $\chi = $ wavenumber of the incident nucleus
- $\Gamma_a = $ $\hbar x$ transition probability for formation of compound nucleus through entrance channel
- $\Gamma_b = $ $\hbar x$ transition probability for decay of compound nucleus through exit channel
- $\Gamma = $ total width of the resonance level
- $(e_a - e_o) = $ difference between incident energy and resonant energy in center of mass frame

Similarly, for a reaction entering through channel a and decaying through some other channel c, we may write for the cross-section

$$\sigma(a, c) = (2\ell + 1)\frac{\hbar^2 \chi^2 \Gamma_a \Gamma_c}{(e_a - e_o) + \left(\frac{1}{2}\Gamma\right)^2}$$

The ratio of these cross-sections is given by

$$\frac{\sigma(a, b)}{\sigma(a, c)} = \frac{\Gamma_b}{\Gamma_c}$$
Thus for the reactions $\text{He}^4(d,d)\text{He}^4$ and $\text{He}^4(d,\gamma)\text{Li}^6$ we can write

\[(1) \quad \sigma(d,\gamma) = \sigma(d,d) \frac{\Gamma_\gamma}{\Gamma_d}\]

where
\[
\begin{align*}
\sigma_{dd} &= \text{resonance scattering cross-section} \\
\sigma_{d\gamma} &= \text{resonant capture cross-section} \\
\Gamma_\gamma &= \text{radiative width of the level} \\
\Gamma_d &= \text{scattering width of the level}
\end{align*}
\]

To estimate the value of the resonant capture cross-section from this expression, we substitute for $\sigma_{dd}$ the maximum possible value of the scattering cross-section excluding the contribution due to interference between incoming and outgoing waves. The interference terms introduce a factor 4 into the maximum scattering cross-section, therefore for this estimate we take $\sigma_{dd}$ to be one-quarter of the maximum value for the scattering cross-section. Thus,

\[
\sigma_{dd} = \frac{1}{4} \frac{4\pi}{(2l + 1)} \chi^2
\]

Now

\[
\chi^2 = \frac{\hbar^2}{2m_dE_d}
\]

\[
= \left( \frac{\hbar}{m_ec} \right)^2 \frac{m_e^2c^2}{2m_dE_d}
\]

\[
= \chi_o^2 \frac{m_d}{2m_d} \frac{m_e^2c^2}{E_d}
\]

where
\[
\hbar = \text{Planck's constant} \\
m_d = \text{mass of the deuteron} \\
m_e = \text{mass of the electron} \\
E_d = \text{incident energy of deuteron in center of mass}
\]
\( \chi_0 = \text{Compton wavelength} \)

Therefore

\[
\sigma_{dd} = \frac{\pi \chi_0^2}{2m_d} \frac{m_\alpha^2}{E_d} (2 \ell + 1)
\]

Lauritsen et al. (1953) and Galonsky et al. (1955) have shown that the resonance scattering is a d-wave interaction corresponding to a \( J = 3 \) state of Li\(^6\). Therefore putting \( \ell = 2 \) in equation (2) we get for the resonance scattering cross-section

\[
\sigma_{dd} = \frac{\pi (2.4 \times 10^{-10})^2}{2 \pi} \frac{1}{2 \times 2 \times 1837} \frac{51}{7} (2 \times 2 + 1)
\]

\[= 2.3 \text{ barns} \]

From the data of Galonsky et al. (1955) the total scattering cross-section including Coulomb and interference contributions was estimated assuming symmetry of the differential cross-section about 90 degrees in the center of mass coordinate system. The value of the total scattering cross-section thus obtained was 7.4 barns. This figure compares reasonably well with the value of 9.2 barns obtained from the expression for \( (\sigma_{dd})_{\text{max}} = 4 \pi (2 \ell + 1) \chi^2. \)

The level width for the scattered deuterons was determined experimentally by Lauritsen et al. (1953) to be 35 KeV in the laboratory system. Transforming to center of mass coordinates gives

\[
(\Gamma_d)_{\text{cm}} = (\Gamma_d)_{\text{lab}} \frac{m_\alpha}{m_d + m_\alpha} = \frac{2}{3} (\Gamma_d)_{\text{lab}}
\]

\[= 23 \text{ KeV} \]
The radiative width is given by

$$\Gamma_\gamma = \hbar T_E(\ell)$$

where $T_E(\ell) = \text{the transition probability for electric radiation of multipole order } \ell$

Assuming that the independent particle model holds for low lying nuclear states, Blatt and Weisskopf (1952) give for the value of $T_E(\ell)$ the following expression,

$$T_E(\ell) = \frac{4\sqrt{2}(\ell + 1)}{\ell![(2\ell + 1)!]^{2/3}} \left(\frac{3}{\ell + 3}\right)^2 \left(\frac{\hbar \omega}{197 \text{ MeV}}\right)^{2\ell + 1} R^{2\ell} \times 10^{21}$$

where $R = \text{channel width in fermis}$

$= 4.0 \text{ fermis for best fit to experimental data of Lauritsen et al.}$

For electric quadrupole radiation to the ground state of $\text{Li}^6$, we must put $\ell = 2$. Then

$$T_E(2) = \frac{4\sqrt{2} \times 3}{2(15)^{2/3}} \left(\frac{3}{5}\right)^2 \left(\frac{2.18}{197}\right)^5 \times 4^4 \times 10^{21} \text{ sec}^{-1}$$

$$= 4.5 \times 10^{11} \text{ sec}^{-1}$$

Therefore from equations (1) and (3) we get for the radiative capture cross-section

$$\sigma_{d\gamma} = \sigma_{dd} \frac{\hbar T_E(2)}{\Gamma_d}$$

$$= 2.3 \times 10^{-24} \frac{(0.65 \times 10^{-15})(4.5 \times 10^{11})}{(23 \times 10^3)}$$
\[ \sigma_{d \gamma} = 0.03 \text{ microbarns} \]

This value for the cross-section is probably an overestimate by one or two orders of magnitude, because the maximum possible value of the resonant scattering cross-section was used and because simplifying assumptions used in the derivation of the formula for \( T_E(\ell) \) can introduce as much as several orders of magnitude error on the high side.

Investigation of the \( D(\alpha, \gamma)\text{Li}^6 \) reaction can be carried out using a deuteron beam on \( \text{He}^4 \) targets or by using an alpha particle beam on deuterium targets. The use of an alpha beam is preferable to use of a deuteron beam because the high neutron yield from the reaction \( D(d,n)\text{He}^3 \) greatly increases the background in the radiation detectors. The actual beam available for this experiment was a \( \text{He}^{4+} \) beam.
CHAPTER III  

1. GENERAL TECHNIQUE

Heavy ice was used as the deuterium target. All runs were carried out so as to span the resonance as the resonant reaction was expected to dominate the cross-section. To reach the resonance the center of mass energy of the incident particles must be 0.716 Mev. Thus the required energy for the He$^+$ beam was 2.14 Mev in the laboratory coordinates.

To attempt to measure a reaction cross-section of the order of $10^{-32}$ cm$^2$ great trouble must be taken to reduce the background radiation registered by the counter. This necessitates great cleanliness and freedom from carbon in the beam pipes and on places where the beam hits (due to prolific $^{13}$C($\alpha$,n)$^{16}$O reaction), a beam with no minute D contamination, and heavy counter shielding. With such precautions the counter records primarily radiation proceeding from the target itself. Two methods were used to eliminate from the experimental results the background due to the backing material and due to the oxygen in the ice targets.

In the first method, alternate runs were made on equally thick heavy ice and ordinary ice targets. The difference between the gamma-ray yields obtained from the two runs was attributed to the deuterium in the heavy ice target.

The second method used the fact that the main contribution to the cross-section would be from the resonance capture process. One run was made with the beam energy just above the resonance and a second run was made with the beam energy just below the resonance. The diff-
Figure 2. Target Chamber and Beam Tube Apparatus
ference between the gamma-ray yields obtained would be due to the resonant reaction.

For both the above methods the gamma yield was checked at both 0 degrees and 90 degrees to the incident beam. Most runs were made with the counter at 90 degrees, but the 0 degree yields were checked in case there was a strong angular dependence.

Ice target thicknesses ranging from 700 Kev to 100 Kev were used during the course of the experiment. Targets of the order of 100 Kev thick should be best as they are sufficiently thick to span the resonance ensuring a maximum yield, while keeping the neutron background from the D(d,n)He\(^3\) reaction at a minimum. This reaction is a secondary process arising from deuterons elastically scattered by the incident beam. The importance of keeping the target thickness a minimum is due to the neutron yield from the above reaction increasing as the square of the number of deuterium atoms present in the target. However, because of the kinematics involved, the neutron yield is peaked in the forward direction. Thus, by placing the gamma counter at 90 degrees, the neutron background has little effect.

As the width of the scattering resonance is 35 Kev, the experiments were run with a beam energy 40 Kev above the required 2.14 Mev energy. This ensured that the resonance was spanned within the target.

2. APPARATUS

(a) Target Chamber

The ice target chamber used in the experiment is illustrated in Figure 2. The target backing was a piece of solid gold sheet soldered
Figure 3. Schematic Diagram of the Dispenser System
to a copper plate 7/8 inch by 1 inch and 1/16 inches thick. The copper plate was soldered to a brass tube which was part of a liquid nitrogen cooled reservoir. The target and reservoir unit was electrically insulated from the outer chamber by a lucite spacer. During the runs +90 volts was applied to the target to suppress secondary electron emission. The outer chamber and beam tube were insulated from the bellows by another lucite spacer, thus allowing the current striking the beam tube to be measured. This arrangement was very helpful in the alignment of the chamber along the beam axis.

For the first runs, beam definition was accomplished by placing three gold stops in the path of the beam. To reduce the background due to radiation from these stops, a magnetic quadrupole lens was installed about 4 feet in front of the target. When using the lens, only one pure gold stop 5/16 of an inch in diameter was needed. This stop was placed in front of the bellows to limit any scattered beam hitting the beam tube.

A liquid nitrogen vapour trap was used between the target chamber and the sidearm of the Van de Graaff generator. The trap consisted of a 1 inch diameter copper tube about 3 inches long through which the beam passed. The tube was cooled by contact with a liquid nitrogen reservoir. Between runs the beam was cut off the target by an electromagnetically operated quartz beam stop.

(b) Ice Target Dispensers

Two dispensers were used in the course of the experiment. Figure 3 is a schematic diagram of the dispenser system. Two removable glass vials were provided, one for heavy water and the other for
Figure 4. Circuit Diagram for the Large Scintillation Counter
ordinary water. A mercury manometer was used to measure the vapour pressure in the dispenser bulb. A full volume of vapour in this dispenser resulted in ice targets which were very thick for 2 Mev alpha particles.

To lay down thinner ice targets, a second dispenser having an oil manometer was used. Octoil Vacuum Pump Fluid with a density of 0.9 gm/cc was the oil used. With this manometer the sensitivity was about fifteen times that of the mercury manometer.

The top glass tube of the dispensers was connected by an O-ring joint to a brass fitting. A fine copper tube connected the fitting to the outer target chamber at a point in line with the target position. The wider tubing at the target chamber connection was filled with spun glass to help diffuse the water vapour evenly over the target backing.

(c) Radiation Detectors

Two scintillation counters were used in the experiment. The counter used in determining the ice target thickness was a Harshaw thallium activated sodium iodide crystal, 2.75 inches in diameter by 4.50 inches long. The crystal was mounted by Harshaw in an aluminum can with a magnesium oxide reflector. The crystal was mounted on a Dumont K1213 photomultiplier tube which has a 2.75 inch diameter photocathode surface. Good optical coupling between the photomultiplier and the crystal was obtained by using Dow Corning 200,000 centistoke Silicone oil.

The preamplifier used with this counter was a cathode follower. The circuit diagram is given in Figure 4. The crystal, photomultiplier, and preamplifier were all mounted in a 4½ inch diameter brass case about
Figure 5. Circuit Diagram for the Small Scintillation Counter
17 inches long. A mu metal shield was mounted around the photomultiplier tube to shield it from the magnetic field of the Van de Graaff generator analyzing magnet.

At the 6.14 Mev energy where this counter was used for this experiment, the crystal has an effective center 5.5 centimeters from the front face of the aluminum container and the efficiency down to the half energy point is 76 percent.

The second scintillation counter, used in observing the radiation from the D(α, ν)Li6 reaction, was a Harshaw thallium activated sodium iodide crystal, 2.00 inches in diameter by 2.00 inches long. The crystal was contained in an aluminum can and was permanently mounted by Harshaw on an RCA 6342A photomultiplier tube. The photomultiplier tube was surrounded by a mu metal shield.

The preamplifier used with this counter was a transistorized current amplifier. The circuit diagram is given in Figure 5. A printed circuit and miniature components were used in building the circuit to make it as compact as possible. The crystal-photomultiplier unit and the preamplifier were mounted in a 3 inch diameter aluminum can about 13 inches long.

This crystal has a very high resolution. Figure 6 shows the spectrum of Cs137 obtained with the counter. The resolution for the cesium peak at 0.662 Mev is 8.1 percent, and for the 2.62 Mev radio-thorium peak the resolution is 6.2 percent. At 1.25 Mev the effective center of the crystal is 2.57 centimeters behind the front face of the aluminum can. The efficiency down to the half energy point is 43.4 percent at 1.25 Mev. The gamma peak detection efficiency for 1.25 Mev gamma radiation is 16 percent.
Figure 6. Spectrum for Cs137 from 2" x 2" Crystal

Counts per Channel

Channel Number

.662 Mev

RESOLUTION = 8.1%
Great care was taken to provide the best possible shielding of the gamma-ray counter used for the D(α, γ) Li^6 reaction. The entire target chamber and counter were surrounded by at least 2 inches of lead. This shielding was very effective in decreasing the background from the Van de Graaff high voltage terminal and from the magnet box.

The output of the scintillation counter preamplifier was fed into the internal amplifier of a 256 channel Nuclear Data Spectrum Analyzer. The signal could also be fed into the Nuclear Data Sidechannel Amplifier which, in conjunction with UBC NPl1 scalers, could monitor the integrated counts over any desired part of the spectrum.

The gamma-ray insensitive neutron counter described by Ssu (1955) was used as a neutron monitor during the experiment.

3. TARGET THICKNESS MEASUREMENTS

(a) Theory

The number of deuterons/cm^2 on the targets, and the target thickness to 2.18 Mev alpha particles were determined from the D(p,γ)He^3 reaction. The absolute cross-section and angular distribution for this reaction had previously been measured by Larson (1957) in this laboratory.

The cross-section for the D(p,γ)He^3 reaction has the following form,

\[ \sigma(\theta) = A \left( \sin^2 \theta + b \right) \ d\omega \]

where A and b are constants. When integrated over all angles, the
total cross-section is given by

\[(5) \quad \sigma_T = 4\pi A \left(\frac{2}{3} + b\right)\]

The constant \(A\) can be related to the observed yield at 90 degrees as follows,

\[(6) \quad N_c(90^\circ) = \varepsilon N_p N_D \omega_{\gamma}^\phi A (1 + b)\]

where

- \(N_D\) = number of deuterons/cm\(^2\)
- \(N_p\) = number of incident protons
- \(N_c(90^\circ)\) = gamma yield at 90\(^\circ\) down to the half energy point of the 6.14 Mev peak
- \(\varepsilon\) = efficiency of the crystal at 6.14 Mev = 0.76
- \(\omega_{\gamma}^\phi\) = solid angle subtended by the crystal at its effective center
  = 0.21 steradians for crystal face 3.2 inches from the target

Solving equation (6) for \(N_D\) and substituting for \(A\) from equation (5) gives

\[(7) \quad N_D = \frac{4\pi N_c(90^\circ)}{\varepsilon N_p \omega_{\gamma}^\phi \sigma_T} \frac{2/3 + b}{1 + b}\]

For proton energies of 1.0 Mev, Larson gives for \(b\) and \(\sigma_T\)

- \(b = 0.0239\)
- \(\sigma_T = 3.24 \times 10^{-30}\) cm\(^2\)

Therefore from equation (7), the number of deuterons/cm\(^2\) on the target
may be calculated from measurements of the gamma yield at 90 degrees.

To calculate the ice target thickness in Kev for 2.18 Mev $\text{He}^{4+}$ particles requires knowledge of the stopping power of the ice. The differential energy loss of a swift heavy charged particle passing through matter is expressed in terms of the stopping cross-section per atom or molecule of the stopping material by the defining equation

$$\epsilon = - \frac{1}{N} \frac{d\epsilon}{dx}$$

where
\[
\epsilon = \text{stopping cross-section/atom (or molecule)}
\]
\[
N = \text{number of stopping atoms/cm}^3
\]

If the rest mass of the particle greatly exceeds the rest mass of an electron, then the mechanism for energy loss is predominantly by inelastic collisions with atomic electrons. The energy transfer from incident heavy particles to atomic electrons results in ionization and excitation of the atoms in the absorber.

Bloch has shown that for ions of velocity large compared to the velocity of the most energetic electrons in the stopping material, the stopping cross-section may be written as

$$\epsilon = \frac{2\pi Z^2 e^4}{E} \frac{m}{m_e} Z \left( \log_e \left( \frac{E}{Z} \right) + \text{constant} \right)$$

where
\[
z e = \text{charge of ion}
\]
\[
m = \text{mass of ion}
\]
\[
m_e = \text{electron mass}
\]
\[
E = \text{energy of ion}
\]
\[
Z = \text{atomic number of stopping material}
\]
From the available experimental data, Whaling (1958) determined a value of the constant in the above equation which best fit the data for each stopping material. He then used the equation to plot the stopping-cross-section versus energy from 10 Mev down to about 1 Mev. This curve was then smoothly joined to a curve through the experimental points in the lower energy region.

To calculate the thickness in Kev of the ice targets used in this experiment, Whaling's curve for the stopping cross-section versus proton energy for \( \text{H}_2\text{O} \) can be used. From this data, the stopping cross-section for alpha particles may be estimated to within \( \pm 20 \) percent as described below. Although the beam used in this experiment was \( \text{He}^{4+} \), the target thickness will be the same as for equal energy alpha particles for all energies above 1.5 Mev. This is because the incident \( \text{He}^{4+} \) ion will be stripped of its remaining electron with negligible energy loss immediately on entering the stopping material. The fraction of \( \text{He}^{4+} \) ions in the stopping material is approximately 90 percent at energies between 2.2 Mev and 1.5 Mev.

The target thickness, \( T \), in energy units is derivable from equation (8)

\[
T = - \int dE = N \int \xi \, dx
\]

For targets \( \leq 700 \) Kev thick, \( \xi \) is approximately constant for 2.2 Mev alpha particles stopped in \( \text{H}_2\text{O} \). Therefore

\[
T = \frac{N D}{2} \xi_\alpha \times 10^{-3} \text{ Kev}
\]

where \( \frac{N D}{2} \) = number of H2O molecules/cm\(^2\) of the target
\[ \epsilon_\alpha = \text{molecular stopping cross-section for alpha particles in } H_2O \]

However, Whaling's table only gives the stopping cross-section of protons, \( \epsilon_p \), in \( H_2O \). Whaling does give the value of the ratio of the stopping cross-sections for alpha particles to that for protons of the same velocity, therefore we can deduce the stopping cross-section for alphas in \( H_2O \) from

\[ T = \frac{N_D}{2} \frac{\epsilon_p}{\epsilon_p} \frac{\epsilon_\alpha}{\epsilon_p} \times 10^{-3} \text{ Kev} \]

where
\[ \frac{\epsilon_\alpha}{\epsilon_p} = \text{ratio of stopping cross-sections} \]
\[ = 4.0 \text{ for 2 Mev alpha particles} \]
\[ \epsilon_p = \text{molecular stopping cross-section for equal velocity protons in } H_2O \]

In practice, an estimate of the target thickness was made by using the value of \( \epsilon_p \) corresponding to the incident \( He^{4+} \) energy. Then the target thickness was recalculated using a new value of \( \epsilon_p \) corresponding to an average value of the incident particle energy throughout the target.

As the stopping power of a material depends only on scattering from atomic electrons, then the stopping power and hence the thickness of \( D_2O \) and \( H_2O \) ice targets will be the same to a very close approximation.

(b) Procedure

The method used was to deposit an ice target, bombard with 1.0 Mev
Figure 7. Spectrum for D(p,γ)He$^3$ Reaction
protons, and measure the yield of $6.14\,\text{Mev}$ gamma radiation at 90 degrees. Then using the known value of the absolute cross-section and angular distribution of the $\text{D}(p,\gamma)\text{He}^3$ reaction, and knowing the efficiency of the scintillation counter, the number of deuterons/cm$^2$ and the target thickness were calculated.

The experimental procedure was as follows. The gold backing on the target plate was cleaned and then the target chamber was pumped to a high vacuum. The target plate was rotated to be perpendicular to the dispenser inlet and was cooled by filling the liquid nitrogen reservoir. The desired pressure of heavy water vapour was admitted to the dispenser bulb through the lower stopcock. The upper taps were then opened allowing the vapour to diffuse through the glass wool plug and spray onto the target where it was frozen into a uniform layer of ice. The target was then rotated until perpendicular to the beam axis, and was bombarded with $1.0\,\text{Mev}$ protons. The gamma yield at 90 degrees was obtained using the larger scintillation counter.

The above procedure was repeated for one, two, and four volumes of heavy water vapour sprayed on the target.

(c) Results and Calculations

The gamma radiation spectrum for the run on 1 volume of heavy water vapour is illustrated in Figure 7. The three peaks observed are the $6.14\,\text{Mev}$ photo-peak from the $\text{D}(p,\gamma)\text{He}^3$ reaction with its associated pair production and pair peaks spaced $1.02\,\text{Mev}$ and $0.51\,\text{Mev}$ respectively below the photo-peak. The integrated beam current used to obtain this spectrum was 2000 microcoulombs with a beam current of 6 microamperes. Using equation (7), the number of deuterons/cm$^2$ was calculated
Figure 8. Dispenser Calibration Curve
as follows,

\[ N_D = \frac{4 \pi \times 16308}{0.76 \times \frac{2000}{1.6 \times 10^{-13}} \times 3.24 \times 10^{-30}} = 0.691 \]

\[ = 2.1 \times 10^{19} \text{ atoms/cm}^2 \]

The target thickness to 2.18 Mev He\(^{4+}\) particles was calculated for this target from equation (10).

\[ T_\alpha = \frac{2.1 \times 10^{19}}{2} \times 13 \times 10^{-15} \times 4.0 \times 10^{-3} \]

\[ = 550 \text{ Kev} \]

For thinner targets the dispenser with the oil manometer was used. The correct manometer reading for the desired target thickness was taken directly from Larson's data, using his dispenser calibration curve which is reproduced in Figure 8. The expression relating the target thickness for 2.18 Mev He\(^{4+}\) particles to that for 340 Kev protons is

\[ T_p = \frac{T_\alpha \xi_p}{\xi_\alpha} = \frac{340 \text{ Kev}}{1/4(2.18) \text{ Mev}} \]

\[ = 0.27 T_\alpha \]

where the values of the stopping cross-sections used were obtained from Whaling (1958).
4. EXPERIMENTS

For the study of the \( D(\alpha, \gamma)Li^6 \) reaction, careful preparation of the target was necessary to minimize the background radiation. The gold backing was very carefully cleaned by etching with 'aqua regia' and boiling in distilled water. The inner chamber and target assembly was baked at 220° F to remove volatile substances. After the target was installed in the outer chamber, the system was pumped to a high vacuum. The target chamber was then rotated and the beam allowed to strike the back of the target plate. The target chamber was aligned and the beam focused so as to get the maximum amount of the beam on the target with the minimum amount on the beam tube and defining stop. The beam was then cut off the target by the electromagnetic beam stop.

A heavy ice target of the desired thickness was deposited on the target plate in the manner described in Section 3 above. The target was turned perpendicular to the beam and a beam of \( He^+ \) particles was allowed to strike the target. To decrease target deterioration the quadrupole lens was used to defocus the beam so that it covered as large an area as possible on the target without striking the beam tube or the defining stop. The beam defocusing was easily accomplished by observing the blue glow from the ice target where the beam was striking.

The target and scintillation counter were carefully shielded and a run on the target was made. After printing out the results from the first run, a second run of equal integrated beam current was usually made on the same target. In this way longer runs could be made on one target while maintaining a check on target deterioration. The above
Figure 9. Spectra at 90° for D₂O and H₂O Targets
procedure was repeated using an equal thickness of ordinary ice as a target.

For these runs the incident He\textsuperscript{4+} energy was 2.18 Mev. As the ice targets used were always thicker than 100 Kev, and the resonance width was expected to be of the order of 70 Kev, running at 2.18 Mev ensured that the resonance was spanned.

A second experimental method used was to run on a heavy ice target at 2.18 Mev, and then on another equally thick ice target at 2.10 Mev. The difference in the yields of these two runs may then be attributed to the resonance.

Calibration spectra were obtained before and after the runs to fix the energy scale. Sources used for calibration were radio-thorium, cesium 137, and sodium 22.

Decreasing the background to a minimum level was the major source of difficulty in the experiment. As the Van de Graaff generator had previously been used with a deuteron beam, it was found necessary to run a proton or He\textsuperscript{4+} beam for several days to remove residual deuterium from the ion source and beam tubes. Replacement of collimating stops by a magnetic quadrupole lens also removed a source of background radiation. Finally, the deuterium bottle was removed from the top terminal of the Van de Graaff generator in case deuterium was leaking into the system through the solenoid valve. At the same time the magnet box assembly was removed and cleaned. The latter two precautions resulted in a decrease by a factor of 2 in the background at the 2.2 Mev gamma energy level.

For most of the runs the beam current on the target was approx-
$E_a = 2.18 \text{ Mev}$

4000 $\mu\text{coulombs}$

Targets 700 Kev Thick

$D_2O$ Ice Target

$H_2O$ Ice Target

Figure 10. Spectra at $0^\circ$ for $D_2O$ and $H_2O$ Targets
imately 4 microamperes and the total integrated beam current per run was 2000 microcoulombs. When two runs were made on the same target the target deterioration was found to be approximately 25 to 30 percent.

A calibration check was made on the Van de Graaff generator generating voltmeter to be certain that the energy of the incident He\textsuperscript{4+} beam was that read from the meter. The check consisted of running an excitation function over the three principal resonances of fluorine. A proton beam was run on a fluorine target, and excitation functions were obtained for the 0.873 Mev, the 1.381 Mev, and the 1.69 Mev resonance peaks. The generating voltmeter was adjusted so that the errors for these three resonances were less than 0.15 percent. This adjustment was made prior to the final runs on which the results of the experiment were based.

5. RESULTS

Figures 9, 10, and 11 show the spectra on which the results of this search for the D(α, γ)Li\textsuperscript{6} reaction were based. Figures 9 and 10 show the spectra obtained from runs with a 2.18 Mev He\textsuperscript{4+} beam on heavy ice and on ordinary ice at counter angles of 90 degrees and 0 degrees. For these runs the target was approximately 700 kev thick. No radiation peak was observed at 2.184 Mev as expected for the D(α, γ)Li\textsuperscript{6} reaction. However, very prominent peaks were observed at 0.87 Mev and at 1.64 Mev on the spectra from the heavy ice runs. On the runs on ordinary ice the peak at 1.64 Mev was still present with approximately the same integrated yield. The 0.87 Mev peak, although still visible, had a very
Counter at 90°
4000 μcoulombs
Targets 100 Kev Thick

\[ E_\alpha = 2.18 \text{ Mev} \quad \bigcirc \]
\[ E_\alpha = 2.10 \text{ Mev} \quad \bigcirc \]

Figure 11. Spectra for D₂O Targets with \( E_\alpha = 2.18 \text{ Mev} \) and 2.10 Mev
greatly reduced yield.

Figure 11 shows the spectra obtained from runs on identical heavy ice targets with the incident beam energy above and below the required energy for the resonance reaction. For these runs the targets were approximately 100 Kev thick. Figure 12 is a plot of the difference between the two spectra shown in Figure 11. Again no 2.184 Mev peak was observed. Well defined peaks were again present in the spectra at 0.87 Mev and at 1.64 Mev. When the incident beam energy was reduced to 2.10 Mev, the resulting spectrum showed a very much diminished yield for both these peaks.

Varying the incident beam energy over a range of several hundred Kev caused no energy shift of either the 0.87 Mev peak or of the 1.64 Mev peak. This fact indicated that the observed radiations were due to gamma-ray transitions between well defined energy levels.

The 0.87 Mev peak corresponds to radiation from the first excited state of O^{17} to its ground state. As the yield was greatly increased for runs on heavy ice targets as compared to ordinary ice targets, the reaction causing the greatest part of this radiation appears to involve deuterium. Therefore, the 0.87 Mev peak was attributed to the reaction O^{16}(d,p)O^{17}. The protons populate the first excited state of O^{17} which then decays by the 0.87 Mev gamma radiation to the ground state. The deuterons necessary to initiate this reaction would be elastically scattered deuterons from collisions with the incident He^{4+} beam. Consideration of the kinematics involved in an elastic collision shows that the deuterons can have laboratory energies ranging up to about 1.9 Mev, which brings them well above the threshold of the O^{16}(d,p)O^{17} reaction.
Figure 12. Difference Between Spectra for $E_\alpha = 2.18$ Mev and $E_\alpha = 2.10$ Mev on $D_2O$ Targets 100 Kev Thick
The 1.64 Mev radiation peak was tentatively ascribed to the $^{17}(\alpha,n)^{20}Ne^*$ reaction, the $^{17}$ isotope having an abundance of 0.037 percent in natural oxygen. The neutrons would populate the first excited state of $^{20}Ne$ which then decays by gamma radiation to the ground state. To check that the 1.64 Mev peak was due to a reaction involving oxygen, a run was made with a 2.18 Mev $He^{4+}$ beam on a tungsten oxide target. The spectrum obtained is shown in Figure 13. The 1.64 Mev peak was observed as expected. The dotted curve shows where there may be some contribution to the yield due to the 0.87 Mev peak. If this contribution is indeed a small 0.87 Mev peak, it may be due to a small percentage of molecular hydrogen in the beam giving rise to the $^{17}(p,p')^{17}O^*$ reaction. There is also the possibility of the $^{17}(\alpha,\alpha')^{17}O^*$ reaction taking place.

The yields of both the 0.87 Mev peak and the 1.64 Mev peak rise sharply in going from 2.10 Mev to 2.18 Mev excitation energy. The $^{20}(n,\alpha)^{17}Ne$ reaction has strong resonances in this energy region which correspond to energy levels in $^{21}Ne$. Therefore, the increased yields may be due to being close to a resonance in $^{21}Ne$.

In Figures 9 and 10, a small peak was observed in channel 56 which corresponds to 1.92 Mev. This peak was only present in the spectra from runs on heavy ice targets which were very thick. As this peak seems very D sensitive it appears to be due to a knock-on D reaction.

Figure 14 has been included to illustrate the low energy spectrum for 2.18 Mev $He^{4+}$ particles on a heavy ice target. The energy range shown in the figure is from 0.30 Mev to 1.17 Mev. The gamma peaks visible in this figure are the 0.87 Mev peak and 0.51 Mev annihilation radiation.
Figure 15. Spectrum for $E_\gamma = 2.18$ Mev on a Tungsten Oxide Target
6. **CALCULATION OF AN UPPER LIMIT ON THE D(α, γ)Li\(^6\) CROSS-SECTION**

Based on the experimental data obtained during the course of this experiment, an upper limit on the cross-section for the reaction D(α, γ)Li\(^6\) was calculated.

Using the data for the runs on heavy ice targets at energies above and below the resonance the following calculation was made. The upper limit on the resonant capture cross-section is given by the following expression.

\[
\sigma_T = \frac{N_\gamma}{\epsilon_{pk} \cdot \epsilon_{D} \cdot N_\alpha}
\]

where

- \(N_\gamma\) = the difference in the yields for the 2.18 Mev and the 2.10 Mev runs summed over the number of channels corresponding to the crystal resolution
- \(\epsilon_{pk}\) = total detection efficiency of the crystal for the gamma peak
- \(N_D\) = number of deuterons/cm\(^2\) in a thickness of the target equal to the resonance width.
- \(N_\alpha\) = number of incident He\(^{4+}\) particles, i.e. integrated beam current.

For these runs the target thickness was 100 Kev to 2.18 Mev He\(^{4+}\) ions. The resonance width is 70 Kev for incident alpha particles. Therefore,

\[
N_D = 2.1 \times 10^{19} \times \frac{100}{550} \times \frac{70}{100} = 2.7 \times 10^{18} \text{ deuterons/cm}^2
\]
Figure 14. Low Energy Spectrum for $E_\alpha = 2.18$ Mev on D$_2$O Target 100 kev Thick
The total detection efficiency for the gamma peak was estimated for the 2.00 inch diameter by 2.00 inch long crystal from the experimentally known value of 16 percent at 1.25 Mev, and from the ratios of the total detection efficiencies at 1.25 Mev and 2.2 Mev, and the ratios of peak to total detection efficiency at 1.25 Mev and 2.2 Mev. These ratios were determined for the crystal size from tables given in the AEC Nuclear Data Tables (1960). The peak detection efficiency at 2.2 Mev is then approximately given by

\[
\left(\varepsilon_{pk}\right)_{2.2} = \left(\varepsilon_{pk}\right)_{1.25} \times \left(\frac{\varepsilon_T}{\varepsilon_T}\right)_{2.2} \times \frac{\left(\frac{\varepsilon_{pk}}{\varepsilon_T}\right)_{2.2}}{\left(\frac{\varepsilon_{pk}}{\varepsilon_T}\right)_{1.25}}
\]

\[
= 0.16 \times 0.85 \times \frac{0.18}{0.26}
\]

\[
= 0.094
\]

Then, for the effective center of the crystal 2.6 centimeters behind the front face, and the front face 1.8 centimeters from the target, the total detection efficiency for the gamma peak is

\[
\varepsilon_{pk} = \left(\varepsilon_{pk}\right)_{2.2} \times \frac{\pi r^2}{4\pi}
\]

\[
= 0.094 \times \frac{\pi (2.54)^2}{4\pi (2.6 + 1.8)^2}
\]

\[
= 0.008
\]

The gamma yield was determined from the spectra in Figure 11 for a crystal resolution of 6.2 percent.

\[
N_\gamma = 192 - 114 = 78
\]
For a run of 4000 microcoulombs integrated beam current

\[ N_\alpha = \frac{4000}{1.6 \times 10^{-13}} \]

Putting these values in equation (11) we get for the upper limit on the resonant capture cross-section

\[ \sigma_T = \frac{78 \times 1.6 \times 10^{-13}}{0.008 \times 2.7 \times 10^{18} \times 4000} \]

\[ = 1.4 \times 10^{-31} \text{ cm}^2 \]

A calculation of the upper limit on the cross-section was also made from the difference in the spectra for the runs on heavy ice and ordinary ice at 2.18 Mev incident energy. The value thus determined was

\[ \sigma_T = 2.6 \times 10^{-31} \text{ cm}^2 \]

The approximate cross-section of the 1.64 Mev peak was also calculated for a 2.18 Mev He\(^{4+}\) beam on a 100 Kev thick target. As the yield for the 1.64 Mev peak is almost identical for the 100 Kev target and the 700 Kev target, it was assumed that the effective layer of \(0^{17}\) was in the top 70 Kev of the target. As \(0^{17}\) comprises 0.037 percent of natural oxygen, the number of \(0^{17}\) atoms in a 70 Kev heavy ice target is

\[ N_{0^{17}} = \frac{1}{2} \times 2.7 \times 10^{18} \times \frac{0.037}{100} \]

\[ = 5 \times 10^{14} \text{ atoms/cm}^2 \]
The total detection efficiency for the 1.64 Mev gamma peak was determined to be 0.010. The integrated number of counts in the peak was 514 for a run of 4000 microcoulombs. Using equation (11) the approximate cross-section for the 1.64 Mev peak was

\[
\sigma = \frac{514 \times 1.6 \times 10^{-13}}{0.010 \times 5 \times 10^{14} \times 4000} \\
= 4.1 \times 10^{-29} \text{ cm}^2
\]

Estimated Errors:
- Counter efficiency ± 10%
- Counting statistics ± 10%
- Current measurements ± 2%
- Target thickness ± 30%
- Number of deuterons/cm² ± 20%

The percentage uncertainty in the upper limit of the resonance capture cross-section is the square root of the sum of the squares of the above uncertainties. This results in a 40 percent uncertainty in the upper limit obtained.

Therefore, the upper limit for the resonance capture cross-section of the D(α, γ)Li⁶ reaction is \((1.4 \pm 0.6) \times 10^{-31} \text{ cm}^2\).
BIBLIOGRAPHY


