THE RICE INSTITUTE

DISINTEGRATION OF OXYGEN BY FAST NEUTRONS

by

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I. INTRODUCTION

1.1 General Introduction

Measurement of the cross section for various neutron-induced reactions over continuous energy regions allows systematic compilation of data on nuclear energy levels and comparative intensities of competing reactions and provides useful cross section values. Much present-day work in neutron physics is devoted to such measurements.

1.2 Scope of the Present Work

The disintegration of $^16O$ by neutrons has been studied at bombarding energies up to 4.2 MeV by Seitz and Huber (1) in Switzerland using $^16O$ in a slow ionization chamber. Walton, Clement and Boreli (2) at Wisconsin, using $^16O$ in a proportional counter, measured the $^16O(n,\alpha)^13C$ cross section for neutrons in the energy range from 4.0 to 5.2 MeV, obtaining a value of 180 mb. at the resonance which they reported at 5.03 MeV.

The present measurements began at 5.0 MeV, allowing a comparison of results with those of the Wisconsin group. At this time the range of measurement
has been extended to 8.75 MeV. At these energies the only energetically possible neutron reaction in $^0_{16}$ which leads to charged particle emission is $^0_{16}(n,\alpha)c^{13}$.

II. EXPERIMENTAL METHOD

2.1 General Considerations

The unique properties of the neutron as a tool for investigating the properties of nuclei arise from the fact that it has no charge. One of these properties is of particular significance in the present work: the passage of neutrons through matter does not result directly in ionization, ion production arising only as a secondary consequence of interactions with nuclei.

Thus, in a nuclear reaction induced by neutron bombardment, ionization in the target medium depends upon the charged reaction products, i.e. the recoiling final nucleus and emitted charged particles. Although the details of the ionization are not well understood, it is found that the ionization produced by charged particles in passing through a gas is approximately proportional to the energy loss of the particles in the gas.$^3$

These considerations define the directly measurable quantity in the present experiment: the
ionization appearing as the result of the passage of a neutron of known energy into a gas is approximately proportional to the energy involved in a specific interaction, in particular the Q-value plus the bombarding energy in the case of a nuclear reaction which leads to charged particle emission. There exist the possibilities of simultaneous reactions or successive interactions by reaction products but in the usual experimental set-up these are so rare as to be negligible.

2.2 Experimental Apparatus

a. Ionization Chamber

The measurement of the ionization resulting from disintegrations was accomplished with a grid-shielded fast ionization chamber. This apparatus and its associated circuits have been described by Gabbard et al\(^4\).

Two factors which limit resolution in such a chamber are:

1) recombination of electrons with positive ions, and
2) attachment of electrons to neutral atoms or molecules, forming negative ions.

In each case the result is that less electrons are available for the fast collection process, resulting in diminution of the pulse.

Oxygen has particularly bad characteristics in regard to electron attachment. Spectroscopic carbon dioxide, for which the attachment coefficient is nearly
zero(5), was used in the ionization chamber.

When disintegrations occur within the sensitive volume of the chamber, full size pulses result only if the reaction products are stopped within the sensitive volume. If a particle track ends on the high voltage electrode or grid or outside the sensitive volume, the result is a diminished pulse which does not appear in the peak corresponding to the reaction. This "wall effect" can be minimized by operating the chamber at high pressures. At the necessary pressure CO$_2$ did not yield good resolution, so the favorable and well known characteristics of a carbon dioxide - argon mixture were utilized.

It was desirable to use the greatest amount of carbon dioxide compatible with good resolution, in order to obtain a high counting rate. The optimum filling for the pertinent energy range was empirically determined before beginning each run. From 5.0 to 7.2 MeV the filling was 20% carbon dioxide in a total chamber pressure of 2.4 atmospheres. In the energy range from 7.2 to 8.75 MeV, 12% carbon dioxide was included in 2.0 atmospheres.

In filling the chamber the carbon dioxide was first allowed to flow into the evacuated chamber. Then commercial grade argon was condensed in a liquid
air trap and a portion was boiled away and pumped off by
the vacuum pump. The argon was introduced into the
chamber by boiling. Care was used to retain a substantial
portion of residue in the trap. In this way the
percentages of various impurities possibly present in the
argon should have been reduced.

b. Associated Apparatus and Experimental Geometry

Monoenergetic neutrons were obtained from the
D(d,n) reaction by bombarding a deuterium gas target with
deuterons from the Rice Institute 5.5 MeV Van de Graaff
accelerator. The deuterium target was a platinum
cylinder 4.2 cm. long. The gas was separated from the
accelerator vacuum system by 0.65 mg/cm² nickel foil.

The neutron monitor was a shielded long counter
placed with its inner face one meter from the midpoint
of the gas target at 0° to the deuteron beam. Except
for the BF³ counter this long counter was of the Hanson
and McKibben type(6). The BF³ counter was of thin
walled copper, one inch in diameter, with a sensitive
volume twelve inches long, and was not Ceresin coated.

The ionization chamber was placed with its
symmetry axis perpendicular to the deuteron beam at 0°
and at a center-to-center distance of 40 cm. from the
gas target.

The pulse height spectra were recorded on a

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III. DATA AND RESULTS

3.1 General Characteristics of the Pulse Height Spectra

Pulse height spectra obtained at neutron energies of 7.17, 7.96, and 8.72 MeV are displayed in Figs. 1, 2, and 3.

The large number of counts in the low channels is due to the effects of nuclei recoiling from scattering events, electronic noise, and protons from the Al$^{27}(n,p)$Mg$^{27}$ reaction in the plates of the ion chamber. Knowledge of the exact nature of these effects, or at least of the shape of their composite spectrum, is necessary for accurate analysis of those peaks which occur in these lower channels. This analysis has not yet been completed.

Such analysis presents a formidable problem for several reasons. First of all, the recoil pulses are inevitable in this type of measurement, so they must be corrected for, rather than eliminated. However, angular distribution data on elastic neutron scattering from O$^{16}$ and C$^{12}$ is not presently available over wide energy regions. Electronic noise effects appear significant only in the very low channels, and are not of great importance in the analysis.
$E_n = 7.17\text{ MeV}$

Fig. 1 Pulse height spectrum from neutron bombardment of CO$_2$-A mixture at 7.17 MeV.
Fig. 2 Pulse height spectrum from neutron bombardment of CO₂-A mixture at 7.96 MeV.
Fig. 3 Pulse height spectrum from neutron bombardment of $^{12}$CO$_2$-$^4$He mixture at 8.72 MeV.

$E_n = 8.72$ MeV
Two approaches to the $\text{Al}^{27}(n,p)$ problem are being tried. Runs have been made with the chamber filled with krypton at the same stopping power as the experimental carbon dioxide - argon mixture. No disintegrations in krypton were observed, therefore no energy calibration point was available. The spectrum consisted of a large number of counts in low channels, tailing monotonically off toward the high channels. This is due presumably to electronic noise and $\text{Al}^{27}(n,p)$. Attempts to fit this spectrum to the other data have not been successful. The other approach was to change the material of the chamber plates to brass with a veneer of gold foil 0.01 inch thick. At this writing the chamber has not been tested with these plates.

Other background effects which also tend to accumulate in the lower channels are:

1) the "wall effect" discussed above, and
2) disintegrations occurring between the grid and the collector plate.

These effects would be expected to yield a relatively flat spectrum of pulses corresponding to each reaction group. Indeed, it was observed (see Figs. 1, 2, and 3) that the $\text{O}^{16}(n,\alpha)$ peak has a basically flat tail on the low side.

The small peaks which appear on this tail (e.g.
at channel 100 in Fig. 1 are due to \((n,\alpha)\) disintegrations of \(A^{40}\) which lead to excited states of \(S^{37}\). These reactions have been studied separately and reported by Davis et al.\(^{(7)}\). The Q-value for the reaction \(A^{40}(n,\alpha)S^{37}\) was found to be \(-2.5\) MeV, and peaks due to this disintegration were not resolved from \(O^{16}(n,\alpha)C^{13}\).

In Fig. 2, a peak due to the reaction \(C^{12}(n,\alpha)Be^{9}\) appears at channel 54. The structure in channels 40 - 50 corresponds in energy to \((n,\alpha)\) disintegrations of \(O^{16}\) leading to the 3.68 and 3.85 MeV states of \(C^{13}\) and also includes the pulses of maximum energy \(O^{16}\) recoils from elastic neutron scattering.

The slightly poorer resolution (9\% vice 8\%) of the \(O^{16}(n,\alpha)\) peak in Fig. 2 is attributed to the fact that \(A^{40}(n,\alpha)\) disintegrations make up about 12\% of the counts in the peak at this energy, altering the shape of the composite peak.

At higher energies a peak is observed corresponding to the reaction \(A^{40}(n,p)C^{40}\). In Fig. 3 this peak appears at channel 36.

It appears evident from Fig. 3 that the sum of oxygen disintegrations which proceed to excited states of \(C^{13}\) are comparable in intensity to the ground state group. This is the case for neutron energies above 8.5 MeV.

3.2 Data Analysis

In the analysis of a particular pulse height
spectrum such as Fig. 1, the first step was to obtain an energy vs. pulse height calibration. This was done in the case of Fig. 1 by identifying the peak at about channel 124 as due to the reaction \( {^0\text{He}}(n,\alpha) {^4\text{He}} \). The Q-value for this reaction is \(-2.20 \text{ MeV}^{(8)}\). Thus a pulse falling in channel 124 was taken to be equivalent to an energy loss in the chamber of \( 7.17 - 2.20 = 4.97 \text{ MeV} \). Linearity of the pulse height vs. energy relation was assumed. The zero pulse height channel of the analyzer was determined by means of a test pulser on the analyzer which provided two pulse sizes differing by a factor of two.

From the above information an energy scale was placed on the spectrum and other reaction peaks identified. Since the results reported here will be concerned only with the ground state group this phase of the analysis will not be discussed further in this thesis.

The total number of counts in each peak was corrected for "wall effect" using Gabbard's semi-empirical curve\(^{(4)}\). The wall loss varied from 8% at 5.0 MeV bombarding energy to 32% at 8.75 MeV.

The sum of the counts in each \( {^0\text{He}}(n,\alpha) \) peak was corrected for \( ^4\text{He}(n,\alpha) \) disintegrations, using the cross sections of Davis et al\(^{(7)}\). This
correction is negligible below 7.3 MeV for the carbon
dioxide - argon filling ratios used. The maximum
correction is 25% of the observed disintegrations at the
8.4 MeV resonance in $^4\text{He}(n,\alpha)$.

The long counter correction for neutrons
produced in the nickel foil, on the beam defining slits,
etc., was determined by counting with no gas in the
deuterium target at several points over the energy range
and interpolating for each data point. The correction
was not linear over the whole region, since it was
observed to be time dependent in each run, due probably
to carbon build-up on the foil and slits.

The long counter efficiency is not flat over
the range of neutron energies used in this experiment.
The data were corrected for relative long counter
efficiency using the curve given by Allen and Henkel\(^{(9)}\).

At deuteron energies above 4.5 MeV spontaneous
deuteron break-up is possible since the energy in the
center of mass exceeds the binding energy of the
deuteron. Thus low energy neutrons would appear and
cause an error in the long counter. This effect was
studied by plotting the number of counts from the long
counter (efficiency corrected) per unit of integrated
beam current as a function of deuteron bombarding energy.
The $D(d,n)$ yield curve is approximately linear for
deuteron energies from 4.5 to 5.5 MeV\(^{(10)}\). The
experimental curve showed a discontinuity of slope at 5.28 MeV. The departure of the curve from the extrapolated lower energy curve was attributed to break-up neutrons. The applied correction varied linearly from zero at 5.28 MeV to 14.3% at 5.53 MeV deuteron energy.

The number of long counter pulses per unit beam current was found to decrease when the chamber was interposed as in the experiment. This was attributed primarily to scattering of neutrons by the stainless steel walls of the pressure vessel. One half of the attenuation was presumed to take place in the wall nearest the neutron source. The applied correction was 6% from 5.0 to 7.2 MeV and 5% from 7.2 to 8.75 MeV.

For each run the absolute neutron flux was determined at one energy by comparing the number of counts from the long counter at the energy with the number obtained when a calibrated PuBe source was placed one meter in front of the long counter for a measured time.

The determination of the absolute cross section was made at that point. The plot of the total number of counts in each peak per corrected count from the long counter was normalized to that point to obtain the
cross section curve.

3.3 Results

A plot of the cross section for the reaction $^6\text{He}(n, α)_{^4}\text{He}$ as a function of neutron energy is given in Fig. 4. From this curve it may be noted that the value determined for the cross section at 5.06 MeV is 190 mb., in good agreement with the Wisconsin value of 180 mb. (2).

The plot shows many resonances, corresponding to energy levels in $^0\text{He}$. In Table I these are tabulated and compared with levels determined from the inverse reaction (11). A resonance corresponding to a level at 9.78 MeV was reported from the inverse reaction but was not resolved in the present work.

The experimental indetermination in neutron energy was approximately 55 kev throughout the range of observation, and the resonances were correspondingly broadened. No correction for this effect has been included in the widths reported in Table I, except to note that certain of the resonances might have intrinsic widths less than the experimental resolution.
Fig. 4  Cross section for the \((n,\alpha)\) disintegration of \(^{16}\text{O}\), including only those reactions proceeding to the ground state of \(^{13}\text{C}\).
<table>
<thead>
<tr>
<th>Neutron energy (MeV)</th>
<th>Resonance width (keV)</th>
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<th>Excitation energy from inverse reaction (see Ref. 11) (MeV)</th>
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<td>--</td>
<td>8.91</td>
<td>8.89</td>
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<tr>
<td>5.13</td>
<td>--</td>
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<td>5.33</td>
<td>$\leq 55$</td>
<td>9.16</td>
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<td>5.38</td>
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<td>7.61</td>
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<td>7.92</td>
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<td>8.23</td>
<td>(not resolved)</td>
<td>11.90</td>
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</tr>
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<td>8.42</td>
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<td>12.07</td>
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<tr>
<td>8.66</td>
<td></td>
<td>12.30</td>
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REFERENCES

3. Rossi and Staub, Ionization Chambers and Counters
6. Hanson and McKibben, Phys. Rev. 102, 1348 (1956).
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