THE RICE INSTITUTE

NEUTRON INELASTIC SCATTERING IN CARBON

by

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Index

I. Introduction

II. Experimental Arrangement and Procedures
   A. Inelastic Scattering
   B. Total Cross Section

III. Data Analysis
   A. Neutron Energy Determination
   B. Inelastic Gamma Determination
   C. Inelastic Cross Section Determination
   D. Total Cross Section Determination

IV. Results and Interpretations

V. Bibliography

VI. Acknowledgments
I. Introduction

To obtain a satisfactory theory for nuclei, one must be able to predict the various energy levels and the behavior of these levels in nuclei. One way to obtain information concerning the energy levels of a nucleus is to bombard the nucleus with neutrons over an energy range and to observe experimentally the behavior of the inelastic cross section. It is rather difficult to measure the inelastically scattered neutrons directly; however, in nuclei with widely spaced energy levels, it is profitable to measure the gamma rays produced from the inelastic collisions. Carbon is an element well suited in this respect as the first level in $^{12}\text{C}$ is $4.43\text{ MEV}$, and the second level at $7.65\text{ MEV}$ would not be excited up to $8.28\text{ MEV}$ neutron energies. Investigations$^{2,3,4,16}$ have been previously made with $14\text{ MEV}$ neutrons. In this experiment, using a sodium iodide crystal, the $4.43\text{ MEV}$ gamma ray resulting from the inelastic scattering of neutrons in $^{12}\text{C}$ was observed over the neutron energy range from $4.70$ to $7.97\text{ MEV}$. A calculation of the inelastic cross section was made from this data. The total cross section of carbon was measured from $7.35$ to $7.97\text{ MEV}$ neutron energy, as this data is not available from the literature.
II. Experimental Arrangement and Procedures

The neutron source used in these experiments was the neutron yield from the reaction:

\[(1) \; ^1H^2 + ^1H^2 \rightarrow ^2He^3 + n^1 + 3.28 \text{ MEV}\]

The deuteron beam from the Rice Institute 6.0 MEV Van de Graaff was used in conjunction with a deuterium gas target.

A. Inelastic Scattering

The experimental arrangement is as shown in Figure 1 and the following is a detailed explanation. The nickel foil was 2.58 mg/cm² in thickness. The target container was stainless steel and usually filled to a pressure of 10 inches of mercury. The iron shield was calculated to remove 97% of the initial neutron beam, and the lead shield was calculated to remove 97% of the gamma rays originating in the iron. The 1" diameter by 1" long Harshaw packaged sodium iodide crystal used in conjunction with a Dumont 6292 photomultiplier tube gave a 17:1 peak to valley ratio and a resolution of less than 9% for the 0.67 MEV gamma ray from Cs¹³⁷. The carbon scatterer was made from a piece of Hanford graphite which is relatively pure carbon. The preamplifier output was fed to a linear amplifier and from there to a five channel pulse height analyzer.

The amplifier gain was adjusted so that the pulses from the 4.43 MEV gamma ray gave a peak counting rate in a channel.
EXPERIMENTAL ARRANGEMENT FOR INELASTIC SCATTERING

FIGURE 1

SCATTERER
PREAMP
PHOTOMULTIPLIER
ALUMINUM CLAMP
LEAD SHIELD
IRON SHIELD
CRYSTAL
GAS TARGET HOLDER
NICKEL FOIL
BEAM

SCALE 6"
near the center of the five channels used. The highest channel was set, for the extreme bombarding energy ranges, to record pulses of approximately 6.0 MeV in energy. For a given analyzer magnet current, or proton resonance signal, the number of counts in all five channels was recorded for a given number of beam integrator counts, the latter number usually being 500 counts on the medium integrator scale. This was done with the scatterer in position and with the scatterer out of position. The differences in the number of counts for these two cases in any channel recording the 4.43 MeV gamma ray pulse is thus a measure of the inelastically produced gamma rays.
B. Total Cross Section

The total cross section experimental arrangement is as shown in Figure II. The target arrangement was the same as described above. The scatterer used was made from the same graphite which was used in the above experiment and was in the form of a cylinder 5 cm. in length with a 1.58 cm. diameter. The plastic crystal containing hydrogen was in the form of a sphere of 6.5 mm, diameter. The material was supplied by Nuclear Enterprises Ltd. and machined at Rice. The crystal size is such that the maximum converted light energy for an electron passing completely through the crystal is less than the recoil proton converted light energy formed by neutrons in the 7 to 8 MEV energy range. The 1 cm. length of carbon on the end of the target was used to eliminate or reduce the possibility of two high energy electrons being produced in the target during a time interval equal to the time resolution of the crystal. If this did occur, the pulse produced would be sufficiently large to be mistaken for a proton recoil pulse. By using this piece of carbon, the cross section at 6.94 MEV was found to be 6% lower than the cross section obtained when it was not used.

The procedure was to obtain the transmission from the measurement of the neutron beam with the scatterer in and out of position. This was done at least twice at each energy,
FIGURE 2

EXPERIMENTAL ARRANGEMENT FOR TOTAL CROSS SECTION

10 CM

PREAMP

PHOTOMULTIPLIER

CRYSTAL

SCATTERER

GAS TARGET HOLDER

CARBON
with more measurements being taken if the first two did not agree within 2%.
Data Analysis

A. Neutron Energy Determination

The data for neutron energy determinations was taken as analyzer magnet current, and checked by using a nuclear magnetic resonance magnetometer over a portion of the energy range covered. The deuteron energy is known as a function of magnet current from threshold p,n reactions in such elements as lithium and tritium. The deuteron energy may be obtained more precisely at any given point by using the magnetometer, for which the following relation holds:

\[
\text{Frequency} \times \rho = H \rho
\]

where \( H \) is the magnetic field intensity, and \( \rho \) is the orbit radius. \( \rho \) is again determined from threshold p,n reactions; however, due to hysteresis in the magnet and other causes, it is much more accurate to use the magnetometer. The values of \( H \rho \) then correspond to a certain deuteron energy.

The deuteron beam energy was then corrected for loss in the nickel foil and for one half the length of the gas target. The magnitude of these corrections which vary with energy are, for example, 219 and 25 KEV respectively at 3.315 MEV deuteron energy. The neutron energy is then calculated as a function of deuteron energy and the angle between the scatterer and the forward direction of the beam. From energy and momentum considerations the following relationship
is found:

\[
E_N = \frac{E_0}{4} \left\{ \cos^2 \theta + 1 + \frac{2.64 + \cos \theta \sqrt{\cos^2 \theta + 2 + 2 \times \frac{2.64}{E_0}}} {E_0} \right\}
\]

where \( \theta = 5^\circ 37' \). The spread due to the width of the scatterer is 11 KEV at the lowest and 32 KEV at the highest deuteron energies used. The energy spread due to the gas is 78 KEV at the lowest and 34 KEV at the highest deuteron energies used. Therefore, from these two sources of energy spread, at low energies the spread is 89 KEV and at high energies 64 KEV.
B. Inelastic Gamma Ray Determination

For neutron energies below threshold there was very little difference in the number of counts for the scatterer in position or not in position. Specifically, the channel which was used in the calculations and for plotting exhibited no differences which were outside of statistical errors. In the channel which was set to record 6 MEV gamma ray pulses there was less than 5% difference at 7.96 MEV for the scatterer in or out of position.

Above 6.17 MEV neutron energy, the reaction $^{12}\text{C}(n,\alpha)^{9}\text{Be}$ is energetically possible$^{12}$. An upper limit of the cross section for this reaction at 14 MEV is given by Graves and Davis$^2$ as $0.08 \pm 0.02$ barns. The cross section for this reaction in the energy region covered in this experiment is assumed to be small in comparison to the cross section measured.

It is therefore assumed in this experiment that neutrons scattered into the crystal were not producing pulses of sufficient magnitude to affect the results and that there are no competing reactions taking place with neutrons of less than 6.2 MEV, and very few competing reactions in the range of neutron energies of 6.2 - 8 MEV.

Any channel which responds to the 4.43 MEV gamma ray is a measure of the inelastic events taking place in the scatterer. The actual pulse height distribution is rather complex due to

-8-
the different types of interactions occurring in the crystal and the escape of neither, one, or both of the anihilation radiations. The data for the channel which gave the maximum change with the scatterer in and out of position is the data which is used in interpreting the results, and this channel is hereafter referred to as the channel of maximum change.

The data was corrected for the difference in neutron yield per deuteron, using the yield curve as obtained by measurement with the long counter and assuming a flat response of the long counter.
C. Inelastic Cross Section Determination

The absolute inelastic cross section may be determined by comparison of the inelastically produced gamma rays to a known source of gamma rays of the same energy, and using this information in conjunction with the data from channel of maximum change. Comparisons were made with a RaD-Be neutron source which emits $6.0 \pm 0.06^{14} 4.43$ MEV gamma rays from $^{12}$C per neutron. This is the same gamma ray that was measured in this experiment. The number of counts per integrator in the channel of maximum change ($N_{max}$) may be expressed as:

$$N_{max} = \text{Geometrical Factor} \times \text{Crystal Efficiency} \times \frac{\text{Gamma Source Strength}}{\text{Integrator}}$$

The geometrical and crystal efficiency factors were measured directly by the gamma rays originating in the RaD-Be source. The combined factor was $1.123 \times 10^{-3}$ counts per gamma in the channel of maximum change with the source at the position of the center of the scatterer. The source was a distributed source of approximately the same length as the scatterer. The RaD-Be neutron source was calibrated using the long counter at a distance of $42^\circ$ with the Ra-Be neutron source, which in turn was calibrated in 1954 to $\pm 4\%$ by the Bureau of Standards.

Since the scatterer is almost square; and since most elastic scattering for high energy neutrons is mainly at
small angles, it is reasonable to assume that most neutrons that undergo an elastic collision will still possess sufficient energy to be scattered inelastically. The gamma source strength per integrator may be expressed as follows:

\[ \text{Gamma Source Strength per Integrator} = \frac{N_0 A}{\Delta A} \left( 1 - \epsilon^N \right) \]

where \( N_0 \) = number of incident neutrons per integrator count.

\( A \) = sterradian.

\( \Delta A \) = solid angle of scatterer.

\( N \) = number of atoms, \( \text{cm}^3 \).

\( x \) = thickness of scatterer, \( \text{cm} \).

\( \sigma_i \) = inelastic cross section, \( \text{cm}^2 \).

The number of incident neutrons per sterradian per integrator was measured at the angle of the scatterer with the long counter at a distance of 42" and a neutron energy of 6.94 MEV by comparison to the calibrated Ra-Be neutron source. This was measured to be \( 5.84 \times 10^6 \) neutrons per medium integrator per sterradian. The solid angle of the scatterer was calculated, using the center of the target as the origin, to be 0.0314 sterradians. The inelastic cross section is then 0.216 barns at this energy.

There are several possible sources of error in the above analysis. One source of error would be in the difference in neutron energy spectra for the RaD-Be and Ra-Be neutron sources when comparing them. This effect should not cause a very large error because of the long (42") spacing used.
and the fact that the spectra are not too different.

Another source of error would be the difference in scattering of the 4.43 MEV gamma rays in the scatterer and in the RaD-Be neutron source. The pulse height spectrum for the 4.43 gamma is essentially the same for both the scatterer and the source. Therefore, it is assumed that this effect is small. Another effect occurs when the neutron source is placed in the position of the scatterer. It also emits some low energy gamma rays, and when there are a large number of low energy gammas in the presence of high energy gammas, the gain is effectively decreased. This effect was evident to a slight degree, but since the peak counting rate of a monoenergetic source of gammas, when shifted electronically, varies as a constant over \( \sqrt{\text{pulse height in volts}} \), this effect was lower than 2%.

Taking the sources of error into account and using the limits for calibration, the inelastic cross section should be good to \( \pm 25\% \).
D. Total Cross Section Determination

The total scattering cross section was calculated from the measured transmission by the equation:

\[ I = I_0 \epsilon^{-N \sigma \x} \]

where

- \( I \) = transmitted neutron intensity, scatterer in.
- \( I_0 \) = transmitted neutron intensity, scatterer out.
- \( N \) = nuclei per \( \text{cm}^{-3} \).
- \( \x \) = length of scatterer, cm.
- \( \sigma \) = cross section, \( \text{cm}^2 \).

The cross section was then corrected by the method of Day and Henkel\(^{17} \), for small angle scattering, using the following:

\[ \frac{\Delta \sigma}{\sigma} = 4 \pi \left( \frac{D}{L} \right)^2 \frac{1}{2} \left( \frac{k R + 1}{4 \pi} \right)^2 \]

where

- \( D \) = diameter of scatterer, cm.
- \( L \) = source to scatterer = scatterer to crystal spacing, cm.
- \( k \) = neutron wave number, center of mass coordinate system.
- \( R \) = radius of nucleus, cm.
Results and Interpretations

The curve of the counts in the channel of maximum change for the 4.43 MEV gamma rays versus neutron energy is shown in Figure 3. On this same figure is shown the total cross section from the literature', as well as the total cross section measure in this experiment. The energy levels of $^{13}C$ are also indicated.

The observed threshold of 4.34 MEV neutron energy gives an excitation energy of 4.46 MEV for $^{12}C$. The energy of this level in $^{12}C$ is given as 4.43 MEV by Ajzenberg and Lauritsen'. The threshold is difficult to determine in this experiment because of the scarcity of points taken near threshold and the gradually increasing slope.

In general the energy levels of $^{13}C$ agree with the resonances of the inelastically produced gamma rays in Figure 3. The absolute value of the neutron energy should be correct to ±20 KEV. The relative energy difference over a range of a few hundred kilovolts should be within ±10 KEV. Specifically, the energy difference between the 10.8 and the 11.02 MEV levels is 194 ±10 MEV. The 11.02 and 11.08 MEV levels are accurately known from the Be$^9$ ($\alpha$,n) $^{12}C$ reaction'.

The 10.8 MEV level is approximately 100 KEV wide as measured by the total cross section. This is approximately twice the energy resolution of this experiment, which makes
Figure 3
Inelastic gammas - Total cross section - L.A.

Counts \times 10^3 (channel max. change) per 500 integrators

Neutron energy - Mev.

- 10.8 MeV.
- 11.02 MeV
- 11.08 MeV
- 11.64 MeV
- 11.98 MeV
- 12.21 MeV

Total cross section - barns
comparisons of widths difficult. The two levels at 11.02 and 11.08 MEV show up as one peak on the inelastic gamma curve. Evidently there is interference between these two levels in the total cross section curve. The 11.64 level is approximately 200 KEV in width. This level appears much weaker in the inelastic gamma curve; the 11.98 MEV level is evidently very broad and it has a relative high cross section. The 12.21 MEV level shows up on the inelastic gamma curve very prominently.

The total cross section data taken in this experiment from 7.40 to 7.96 MEV neutron agrees well with the Los Alamos data where they overlap. The validity of the highest Los Alamos point seems questionable. It is felt that with a very wide level at 11.98 MEV, and the apparent 200 KEV level at 11.64 MEV, there would be no sharp decrease of the total cross section at this point.

Figure 4 shows the neutron energy region from threshold to 6.0 MEV for the inelastic cross section. The inelastic cross section would vary as some function of $E'$ of $E^{2+1/2}$. An attempt was made to fit the data with the following relation:

\[ \nu_e = 40(E - 4.840)^{1/2} + 106.5 (E - 4.840)^{3/2}. \]

There is reasonable agreement between this curve and the experimental points. The deviation at 5.40 MEV is due to a resonance in the total cross section at this energy.

The first excited state of $^{12}C$ is known to be a $2^+$ state
FIGURE 4

INELASTIC CROSS SECTION - BARNs

40(E - 4.840) \frac{1}{2} + 106.5(E - 4.840) \frac{1}{2}

NEUTRON ENERGY - MEV

4.80  5.00  5.20  5.40  5.60  5.80  5.90
and the ground state is $0^+$. The reaction may be written as:

$$ (9) \quad ^{12}_C + _0^1n \rightarrow ^{13}_C \rightarrow ^{12}_C + _0^1n $$

For $l = 0$ neutrons emitted the total angular momentum would be $3/2$ or $5/2$. This requires the incident neutron to have $l = 2$ as there is no change of parity. For outgoing neutrons of $l = 1$, the total angular momentum is $1/2$, $3/2$, $5/2$, or $7/2$. This requires an incident neutron of $l = 1$ or 3. Table I shows the possibilities for the incident neutron angular momentum for increasing outgoing neutron angular momentum values.

**TABLE I**

<table>
<thead>
<tr>
<th>Angular Momentum Values of Neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outgoing</strong></td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

For 5 to 6 MEV neutrons the transmission coefficient for $l = 2$ is not too different from the transmission coefficients of $l = 0$ and $1$. The outgoing neutron is of low energy for incident neutrons of slightly above threshold. Here the $l$ values make a considerable difference in the transmission coefficient, with the higher $l$ values having lower coefficients. Therefore there is a higher probability
for the first two possibilities listed in Table I, with an incident neutron angular momentum $l = 1$ for the second possibility.

The inelastic cross section is compared to the total cross section in Figure 5. There are no specific values to compare this data with. In general for neutron energies far above threshold, the nonelastic cross section approaches one half the total cross section. At 7.97 MEV the inelastic cross section is $0.38$ times the total cross section. There is some data at 14 MEV bombarding energy available from the literature. Taylor, Lanajo, and Bonner$^{16}$ report a nonelastic cross section of $0.51 \pm 0.08$ barns at 14 MEV. Graves and Davis$^2$ report $0.601 \pm 0.006$ barns for the nonelastic cross section at 14 MEV. Thompson and Risser$^3$ report a cross section of $0.3$ barns at this energy for the production of 4.45 MEV gamma rays. Graves and Rosen$^4$ report an integrated inelastic cross section of $0.52 \pm 0.2$ barns from 0.5 to 12.0 MEV for 14 MEV neutrons. The data of this experiment seems to appear reasonable in view of the meager data for comparison.
Figure 5

- INELASTIC CROSS SECTION
- TOTAL CROSS SECTION - L.A.
- TOTAL CROSS SECTION - RICE

TOTAL CROSS SECTION - BARNS

INELASTIC CROSS SECTION - MILLIBARNS

NEUTRON ENERGY - 5.0 MEV

7.0

7.50

8.00
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