THE RICE INSTITUTE

THE $^{14}(a,a)^{14}$ AND $^{14}(a,p)^{17}$ REACTIONS FOR
BOMBARDING ENERGIES FROM 3 TO 5 MEV

by

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THE $^1_N(a,a)^1_N$ AND $^1_N(a,p)^1_O$ REACTIONS FOR BOMBARDING ENERGIES FROM 3 TO 5 MEV

I. INTRODUCTION:

The purpose of this work is the investigation of the scattering and reaction resulting from the bombardment of $^1_N$ with alpha particles having energies from 3 to 5 Mev. The $^1_N(a,p)^1_O$ reaction is of some historical interest because it was the first of the laboratory induced nuclear reactions. The original experiments were performed in 1919 by Rutherford. Subsequent work on this reaction has been done by R. R. Roy, using Polonium alpha particles and nuclear plates, by N. P. Heydenberg and G. M. Temmer, using artificially accelerated alpha particles with energies between 1.5 and 3.5 Mev, and others.

The reaction and scattering cross sections give information about the positions and widths of energy levels of the compound nucleus and an analysis of the data by the scattering matrix method as described by J. M. Blatt and L. C. Biedenharn may lead to assignments of total angular momentum and parity to the nuclear energy levels.

When $^1_N$ is bombarded with alpha particles, the following reactions occur below 5 Mev:

$^1_N + He^4 \rightarrow ^1_N + He^4 \quad (1)$

$^1_O + H^1 = 1.198$ Mev \quad (2)$

$^1_O + H^1 = 2.073$ Mev \quad (3)$

The first of these equations corresponds to elastic scattering of alpha particles, the second to a reaction with the protons going
to the ground state of $^0{\ell}^7$, and the third to a reaction with the protons going to the 0.875 Mev state of $^0{\ell}^7$. We have not so far been able to observe this second proton group in our experiment; the yield of protons to the 0.875 Mev state is given by R. R. Roy,\(^1\) who used photographic plates, to be 0.12 of the yield to the ground state of $^0{\ell}^7$.

The analysis of the data is complicated by the large angular momentum of the ground of $^0{\ell}^7$, ( $I = 5/2^+$), because for a given value of the spin and parity of a level in the compound nucleus $^F{\ell}^8$, there are many allowed values of $l_p$, the orbital angular momentum of the outgoing proton.

II. EXPERIMENTAL PROCEDURE:

The Rice Institute 5.5 Mev Van Der Graaff accelerator was used to accelerate singly ionized alpha particles which were then deflected through a 90° angle in a strong magnetic field. The particles then entered the large volume scattering chamber of the Rice Institute. The chamber is described in detail in the theses of C. W. Riech,\(^6\) R. R. Henry,\(^7\) and J. L. Russell, Jr.\(^8\). Briefly, it consists of a large cylindrical chamber which is filled with gas at low pressure. It has two detectors, each of which has a set of defining slits. The detectors can be positioned from the outside of the chamber and the angles measured on circular vernier scales. The detectors are scintillation counters using thin (0.25) Thallium activated Cesium Iodide crystals mounted on 6291 photomultiplier tubes. The chamber is equipped with two Butyl Phthalate manometers which give the pressures of the scattering gas in the chamber and at the first stage in the differential pumping.
tube of the chamber. One side of each manometer is at high vacuum and the other open to the chamber and the first stage in the differential pumping tube respectively. The difference of levels is read with a cathetometer, and the accuracy of the readings is 0.4%. The difference of levels, when multiplied by the density of the Butyl Pthalate, gives the respective pressures.

Each set of slits defines an effective target thickness for the incoming beam of alpha particles. We can compute the target thickness from measurements of slit dimensions and knowledge of the pressure and of the temperature in the chamber. For a pressure of 3.5 cm of oil and at an alpha particle energy of 3 Mev, the target thickness at a laboratory angle of 90° is 5.0 Kev. Figure 1 shows a top view of the scattering chamber and Figure 2 is a schematic of the slit system.

We can obtain the following expression for the differential cross section in the laboratory system of coordinates, 6

\[\frac{d\sigma}{d\Omega} = \frac{N e \sin \theta}{q G n}\]

where

\[N = \text{number of particles counted}\]
\[e = \text{charge of the alpha particle}\]
\[n = \text{number of target nuclei per unit volume}\]
\[q = \text{charge collected in the Faraday cup}\]
\[\theta = \text{angle of scattering in the laboratory system of coordinates}\]
\[G = \text{geometric factor of the slit system, where } G \text{ is given by}\]

\[G = \frac{A_w}{Rs}\]

and \[A = \text{area of the rear slit}\]
SCHEMATIC OF SLIT SYSTEM (FIG. 2)

- FARADAY CUP
- BEAM
- DETECTOR

Distances:
- S
- W
- R
$w =$ width of the front slit

$s =$ separation distance of the slits

$R =$ distance from the rear slit to the axis of rotation of the detector. The quantities $A$ and $w$ were measured using a traveling microscope, while $s$ and $R$ were measured using a steel ruler. The value obtained for detector #1 for the December experiment was $G_1 = 1.396 \times 10^{-4} \text{ cm}$; for the March experiment, $G_1$ was $1.956 \times 10^{-4} \text{ cm}$; for the #2 detector $G_2$ was $2.069 \times 10^{-4} \text{ cm}$.

A check of the validity of the expression for the differential scattering cross section was obtained from measurements of the scattering of alpha particles by argon. Figure 3 is a plot of the elastic scattering cross section of argon for the energy range of the nitrogen experiments; the experimental points, obtained from the data using the G-factor, agree with the theoretical value at energies of $3.5 \text{ Mev}$ and higher. The discrepancy at the lower energies is due to the state of charge of the alpha particles which will be discussed later.

The transformation of the differential scattering cross section from the laboratory system to the center of mass system of coordinates is given by

$$\sigma_{\text{cm}} = C(\theta) \sigma_{\text{lab}}$$

where

$$C(\theta) = \frac{1 + \frac{M_1}{M_2} \cos \theta}{\left[ 1 + \left( \frac{M_1}{M_2} \right)^2 + 2 \frac{M_1}{M_2} \cos \theta \right]^{3/2}}$$

for elastic scattering.
$A^{40}(\alpha,\alpha)A^{40}$ \( \theta (\text{CM}) = 54.69^\circ \)

- DATA / ASSUMING CHARGE OF INTEGRATED ALPHA PARTICLES = 2e

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CALCULATED CROSS SECTION

---

FIGURE 3
For a reaction,

\[ G(\theta) = (1 - x^2 \sin^2 \theta)^{1/2} \left[ x \cos \theta + (1 - x^2 \sin^2 \theta)^{1/2} \right]^{-2} \]

where

\[ x^2 = \frac{M_1 M_2}{M_2 M_4} \left[ 1 + \frac{M_1 + M_2}{M_2} \frac{Q}{E} \right]^{-1} \]

and \( M_1 \) = mass of the incident particle
\( M_2 \) = mass of the target nucleus
\( M_3 \) = mass of the reaction particle observed at lab. angle \( \theta \)
\( M_4 \) = mass of the residual nucleus
\( E \) = laboratory energy of the incident particle
\( Q \) = energy release of the reaction.

The energy of the alphaparticles as they enter the differential pumping tube is obtained from knowledge of the magnetic field and of the radius of the particle path in the 90° analyzing magnet of the Van Der Graaff accelerator. The magnetic field is determined by a lithium moment magnetometer and the radius by the micrometer slit settings. After entering the differential pumping tube and the chamber, the alpha particles lose energy by collisions with the orbital electrons of the gas. The energy loss is computed in the case of alpha particles on argon from tabulated values of the stopping power,\(^{10}\) and for the case of alpha particles on nitrogen, from the tabulated values of the stopping power of air and Beths's formula for the relative stopping power.\(^{11}\) The following expression was obtained for the energy loss of alpha particles of energy \( E \) in the path between the 90° magnet and the gas target in the chamber:
\[ \Delta E = 1.225 \times 10^{-3} \left[ 17.9 P_0 + 39.3 P_1 \right] \left[ (dE/dx)_E \right] \]

where \( \Delta E \) is in Kev, \( P_0 \) and \( P_1 \) are the chamber and first stage pressures in cm of oil respectively and \( dE/dx \) is expressed in Kev-cm\(^2\)/mg. In the December experiment the pressure in the chamber was approximately 5 cm of oil so that the energy loss was of \( 135 \pm 14 \) Kev at 2.8 Mev and \( 87 \pm 9 \) Kev at 4.9 Mev. In the January experiment, the pressure was reduced to 3.8 cm of oil so that the maximum energy loss was of \( 85 \pm 9 \) Kev at alpha energy of 3.8 Mev. The accuracy of the above expression was estimated to be of ten per cent. This determined the energy at 2.8 Mev to 0.5% and 4.9 Mev to 0.2%.

The number of alpha particles incident upon the gas target was determined by charge integration in the Faraday cup. Before entering the Faraday cup, the alpha particles go through an aluminum foil of 0.76 cm air equivalent thickness, which strips the orbital electrons from the alpha particles and leaves most of the alpha particles doubly ionized. However, some of the alpha particles have a zero net charge or are singly ionized. The state of charge of the alpha particles cannot be calculated but was determined by measuring the Rutherford scattering of alpha particles on argon. From the ratio of the expected value of the Rutherford scattering to the experimental value obtained assuming the state of charge of the alpha particles to be 2e, we can obtain the average charge of the alpha as a function of the bombarding energy. The results are shown in Figure 4. It can be seen that the correction is negligible above 3.5 Mev but is of the order of ten per cent at 2.7 Mev. The scattering cross sections and reaction cross
sections obtained at alpha bombarding energy of less than 3.5 Mev were corrected using the average charge per alpha particle as given in Figure 4, because it is only at alpha energies below 3.5 Mev that the charge of the alpha particles appear to differ appreciably from the value 2e.

We were able to observe both the scattering and reaction products at the same time at the backward angle and on the same detector.

Figure 5 is a typical pulse height distribution on the 20-channel analyser. The energies of the alpha particles is of 1.2 Mev and that of the protons of 0.8 Mev. The alpha particles are well separated from the protons, the protons in this particular instance belonging to the ground state of the group. The separation of the alphas from the protons in the same crystal, in this case Thallium activated Cesium Iodide, comes from the fact that the alpha particles and the protons exhaust the luminiscence centers along their path in the crystal; the greater range of the protons, although they have less energy than the alpha particles, therefore results in a higher pulse. This explains the separation of the proton group from the alpha group in Figure 5.

The charge integration was performed by discharging a capacitor previously charged to a known potential. The beam current from the Faraday cup is used to discharge the capacitor down to zero voltage, at which point a relay is made to close, terminating the measurement. The capacitor used was calibrated by the A. C. bridge method against a standard capacitor. The value obtained for the capacity was 10.19 microfarads. The capacitor was also calibrated in somewhat the same manner as it was used for the charge integration. Having determined
STATE OF CHARGE OF INTEGRATED ALPHA PARTICLES

FIGURE 4

E(LAB), MEV

-2.0e
-1.8e
-1.6e

2.5  30  35  40  45  50  55
ALPHA PARTICLES

$E_{\text{LAB}} = 3.11 \text{ MEV}$

$\theta_{\text{CM}} = 168^\circ 24'$

FIGURE 5
the time taken for the potential to decay from a value $V_0$ to a value $V_1$ with a large resistance $R$ connected across the capacitor, the capacity was calculated from the relation:

$$t = RC \ln \frac{V_0}{V_1}$$

The value of the capacity obtained in this way was 10.40 microfarads, in good agreement with the bridge value.

III. EXPERIMENTAL RESULTS:

We have taken five excitation curves and two angular distributions corresponding to energy levels in $F^{18}$. The results appear in Figures 6 through 12. The differential reaction cross section in the laboratory system of coordinates is plotted for laboratory angle of $89^\circ 0'$ in Figure 6 and for laboratory angle of $163^\circ 54'$, in Figure 7. The excitation curves for the case of elastic scattering are all given in the center of mass system of coordinates. Figures 8, 9, and 10 represent the elastic scattering cross section at center of mass angle of $54^\circ 44'$, $90^\circ 0'$, and $168^\circ 24'$ respectively. Figures 11 and 12 represent angular distribution of the protons of the $0^{17}$ ground state group at alpha particles bombarding energies of 3.11 and 3.72 Mev.

From the excitation curves, we are able to make a table of the levels of the compound nucleus, $F^{18}$ with the corresponding value of the alpha particles bombarding energy and the width of the levels in the lab in KeV(Table 1).
$N^{14}(\alpha,p)O^{17}$

$\theta(\text{LAB}) = 89^\circ 0'$

FIGURE 6

$\sigma_p(\text{LAB})$, MILLIBARNS/STERADIAN.

$E(\text{LAB})$, MEV
\[ N_{17}^{17}(\alpha, p) O_{17}^{17} \]
\[ \theta_{(LAB)}=163.54' \]
\[ \text{in millibarns per steradian (LAB)} \]
$^{14}_N(\alpha,\alpha)^{14}_N$

$\theta (\text{cm}) = 90^\circ$
ANGULAR DISTRIBUTION $E = 3.11$ MEV

$N^{14}_{\alpha,p}O^{17}_{\gamma}$

$\theta_{\text{CM}}$

$\theta$ (CM), ARBITRARY UNITS

$Q$ (CM)
ANGULAR DISTRIBUTION $E(\text{LAB})=3.72\text{ MEV}$

$N^{14}(\alpha,p)O^{17}$

$\sigma/\sigma_0 + 1.2 \sigma_2$

DATA

$\theta(\text{CM})$
<table>
<thead>
<tr>
<th>$E_{\text{lab}} \text{ MeV}$</th>
<th>Levels in $^{18} \text{F}$ MeV</th>
<th>$l'$ (lab) keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.09</td>
<td>6.82</td>
<td>95</td>
</tr>
<tr>
<td>3.72</td>
<td>7.30</td>
<td>68</td>
</tr>
<tr>
<td>4.00</td>
<td>7.52</td>
<td>45</td>
</tr>
<tr>
<td>4.05</td>
<td>7.56</td>
<td>80</td>
</tr>
<tr>
<td>4.11</td>
<td>7.61</td>
<td>50</td>
</tr>
<tr>
<td>4.28</td>
<td>7.74</td>
<td>150</td>
</tr>
<tr>
<td>4.50</td>
<td>7.91</td>
<td>38</td>
</tr>
<tr>
<td>4.55</td>
<td>7.95</td>
<td>90</td>
</tr>
</tbody>
</table>
Figure 13 represents the energy levels in $^{13}$F as given by Ajzenberg and Lauritsen (1955)\textsuperscript{12} and the proposed scheme of levels, as given in Table 1.

**IV. INTERPRETATION OF THE ANGULAR DISTRIBUTION DATA:\textsuperscript{13}**

If only a limited range of the orbital angular momentum $l_1$ of the incident particle makes up a reaction, then the angular distribution of the product particle contains no powers of $\cos \theta$ greater than $(\cos \theta)^{2l_1}$. The same limitation applies for the orbital angular momentum of the product particle: if $l_p$ is the largest value of the angular momentum of the product particle, then the highest power of $\cos \theta$ that makes up the distribution is $2l_p$. A similar limitation holds relating to the spin of the level in the compound nucleus: if a resonance corresponds to a level whose total angular momentum is $J$, then the maximum power of $\cos \theta$ in the angular distribution is $2J$.

If the angular distribution is symmetrical about $90^\circ$, then the wave function represents a state of definite parity, either even or odd. This in turn means either that a single state of the compound nucleus is involved in the reaction or that interference, if any, involves states of like parity. At 3.72 Mev the proton angular distribution can be fit by the combination of $P_0(\cos \theta) + 1.2P_2(\cos \theta)$. Since this distribution is symmetrical about $90^\circ$, it indicates a definite parity of the wave function for the reaction, i.e., there is little or no interference from neighboring states of different parity.

Since the highest power of $\cos \theta$ that appears in the 3.72 Mev angular distribution is 2, the state is made up either of $l_\alpha = 1$ or
ENERGY LEVELS IN F\textsuperscript{18} (MEV)

AJZENBERG & LAURITSEN (1955)

PROPOSED LEVEL SCHEME

FIGURE 13
of $l_p = 1$, or else it is a $J = 1$ state. By considering the conservation of angular momentum and of parity in the $N^{14}(\alpha,p)O^{17}$, where the $O^{17}$ is left in the ground state, we can tabulate the possible values of $l_\alpha$ and $l_p$ that can make up the states in $F^{18}$ of given spin and parity.\(^2\)

<table>
<thead>
<tr>
<th>$J$ of $F^{18}$</th>
<th>Parity</th>
<th>$l_\alpha$</th>
<th>$l_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>even</td>
<td>not allowed</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>odd</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>even</td>
<td>0, 2</td>
<td>2, 4</td>
</tr>
<tr>
<td>1</td>
<td>odd</td>
<td>1</td>
<td>1, 3</td>
</tr>
<tr>
<td>2</td>
<td>even</td>
<td>2</td>
<td>0, 2, 4</td>
</tr>
<tr>
<td>2</td>
<td>odd</td>
<td>1, 3</td>
<td>1, 3, 5</td>
</tr>
<tr>
<td>3</td>
<td>even</td>
<td>2, 4</td>
<td>0, 2, 4, 6</td>
</tr>
<tr>
<td>3</td>
<td>odd</td>
<td>3</td>
<td>1, 3, 5</td>
</tr>
</tbody>
</table>

The 3.72 Mev angular distribution of the protons rules out all even parity states except for $J = 1^+$. The $J = 0^-$ possibility is ruled out because it would give an isotropic distribution. The probability of the state having a $J > 3$ was thought small because of the large value of the orbital angular momentum of the alpha particle required to make up such a state. Of the remaining possibilities, i.e., $J$ of $1^+, 1^-$, and $2^-$, the $J = 1^-$ state was investigated by computing a theoretical angular distribution as outlined by Blatt and Biedenharn\(^5\) for the elastically scattered alpha particles. Figure 14 is a plot of that angular distribution with the data points obtained from the excitation
$N^{14}(\alpha,\alpha)N^{14}$

THEORETICAL CURVE ASSUMING $J=1^-$

$\sigma_R/\sigma$

$\Theta$(CM)

$30^\circ$ $60^\circ$ $90^\circ$ $120^\circ$ $150^\circ$

FIGURE 14
curves at the various angles. The results are inconclusive at this point because the theoretical curve of Figure 14 assumes an isolated resonance corresponding to an isolated level in the compound nucleus. Other possibilities for the spin and parity of the state have not yet been investigated. The angular distribution for the 6.82 Mev level is very nearly isotropic. It is tempting to make the assignment $J = 0^-$ for that state. However, in order to be able to make final assignments of spin and parity to these and other states, more data must be taken and all the possibilities investigated.
V. CONCLUSION

In our investigation of the scattering and reaction resulting from the bombardment of $^{14}\text{N}$ with alpha particles, we were able to assign previously unreported levels to $^{18}\text{F}$. We have also restricted the possible values of the spin and parity of the 7.30 Mev level and our isotropic angular distribution of the 6.82 Mev level which agrees with the work of Heydengerg and Temmer, has also restricted the possible value of the parity for that state.
VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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