THE RICE INSTITUTE

THE Ne$^{20}(n,\alpha)$$^{17}$ AND Ne$^{20}(n,\alpha)$$^{17*}$ CROSS SECTIONS
AND ENERGY LEVELS IN Ne$^{21}$

by

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I. INTRODUCTION

When fast neutrons (2.8 to 7.3 Mev) interact with Ne\textsuperscript{20} nuclei there can be three different types of reactions:

1. Elastic scattering which occurs at all energies.
2. Inelastic scattering which takes place only for neutron energies above 1.71 Mev because the lowest excited state of Ne\textsuperscript{20} is 1.63 Mev\textsuperscript{1} above the ground state.
3. The (n,\alpha) reaction which is a 0.603 Mev endoergic process\textsuperscript{2} and is energetically possible for neutron energies above 0.63 Mev. Practically, this reaction is observable only above 1.9 Mev\textsuperscript{3} because of the influence of the Coulomb barrier.\textsuperscript{1}

The elastic scattering has been studied in the energy region from 0.8 to 1.75 Mev.\textsuperscript{4,5}

Using monoenergetic neutrons in the energy range from 1.0 to 3.4 Mev, the (n,\alpha) reaction has been studied by Johnson\textsuperscript{3} and Sikkema.\textsuperscript{6} Flack\textsuperscript{7} has also studied the energy levels in Ne\textsuperscript{21*} (from E* = 10.61 to 12.36 Mev) using monoenergetic neutrons on neon in a grid ionization chamber by analyzing the pulse amplitude spectrum (polonium alpha reference). With continuous neutron sources Gierke\textsuperscript{8}, Ortner\textsuperscript{9}, and others\textsuperscript{10,11} have made measurements of the level energies in Ne\textsuperscript{21*}.
The total cross-section and the differential elastic scattering cross sections in the energy range 1.9 to 3.5 Mev using monoenergetic neutrons have been measured and partially analyzed by Sikkema.\(^1\)

This thesis deals with the measurements of the \((n,\alpha)\) cross section and the energy levels in the compound nucleus \(\text{Ne}^{21*}\) using monoenergetic neutrons (2.8 to 7.3 Mev).

When the \(\text{Ne}^{20}\) nucleus captures a neutron the excited compound nucleus \(\text{Ne}^{21*}\) is formed\(^{11}\) at the excitation energy \(E^* = \frac{\text{Ne}^{20}E_n}{\text{Ne}^{21}} + E_B\) above the ground state where \(E_B = 6.756\) Mev, as calculated from the mass values\(^1,12\), is the binding energy of the neutron above the ground state of \(\text{Ne}^{21}\) and \(E_n\) is the kinetic energy of the neutron in the laboratory.

For decay by alpha particle emission the \(\text{O}^{17}\) residual nucleus is formed in any of its lowest states. The alpha decay may be accompanied by gamma emission, but no attempt was made to detect any gamma rays.

The three lowest levels above the ground state in \(\text{O}^{17}\) are at 0.870, 3.06, and 3.85 Mev\(^{13,14}\) (Figure I). By measuring the energy of the emitted alpha particles, the levels in the residual nucleus \(\text{O}^{17}\) to which the decay took place can be determined. In this manner, the relative cross-sections for \(\text{Ne}^{20}(n,\alpha)\text{O}^{17}\) and \(\text{Ne}^{20}(n,\alpha)\text{O}^{17*}\) were obtained by counting the number of
alpha particles with a particular energy.

The shape of the \((n,\alpha)\) excitation curve shows resonances for the reaction. By measuring the incident neutron energies at resonance, the levels of \(\text{Ne}^{21}\) may be calculated from \(E^* = \frac{20E_{n,R} + E_B}{21}\) where \(E_{n,R}\) is the incident neutron kinetic energy at resonance.

The widths in \(\text{Ne}^{21}\) can be calculated from the \((n,\alpha)\) reaction by \(\Gamma_{\text{obs}} = \left[\Gamma_{\text{exp}}^2 - (\Delta E)^2\right]^{\frac{1}{2}}\). \(\Gamma_{\text{exp}}\) is the experimental width at the half height of a resonance and \((\Delta E)_{\text{n}}\) is the total estimated neutron energy spread for this experiment, due to proton beam spread, target thickness, and the angular variation of the neutron energy.
II. EXPERIMENTAL APPARATUS

A. General

For the measurement of the $\text{Ne}^{20}(n,\alpha)\text{O}^{17}$ or $\text{O}^{17}\*$ cross sections a grid ionization chamber filled at about 4 atmospheres pressure of spectroscopic neon was used. The chamber consisted of a cathode (A), a fine wire grid (B), a collection plate (C), and a guard ring (D) housed in and insulated from a large steel cylindrical can (E) (Figure III).

The electrical pulses from the chamber were fed into a Cascode pre-amplifier and then into a linear amplifier. From the amplifier the pulses went to a 20 channel analyzer.

The ionization chamber was built following a design described by Buneman.\textsuperscript{15}

The neutrons passed into the active volume of the chamber where they interacted with the neon nuclei producing alpha particles by the reactions $\text{Ne}^{20}(n,\alpha)\text{O}^{17}$ or $\text{O}^{17}\*$. The recoil nuclei and the alpha particles produced pulses which could be detected and amplified. However, no attempt was made to detect the recoils.

The alpha particles in being slowed down ionized the neon gas releasing electrons which were attracted to the collection plate forming pulses. The amplitudes of the pulses were independent of where the alpha
particles were created because of the effect of the grid but were almost directly proportional to the alpha particle energy. However some alpha particles passed out of the active volume of the chamber before they were stopped, and a wall loss correction factor was taken into account.

It was important that the grid shield the collection plate from the active volume while not collecting any of the pulse forming electrons. This was achieved by choosing: (notation as in reference 15).

\[ d = \text{distance between centers of grid wires} = 0.91 \text{ cm.} \]
\[ h = (a-t) = \text{distance from cathode to grid wires} = 6.42 \text{ cm.} \]
\[ (p-t) = \text{distance from grid wires to collection plate} = 1.55 \text{ cm.} \]
\[ r = \text{radius of grid wires} = 5 \text{ mils} = 0.00635 \text{ cm.} \]
\[ t = \text{fictitious conducting wall thickness of grid} = 2.79 \times 10^{-4} \text{ cm.} \]
\[ R = \text{radius of the chamber} = 4.5 \text{ cm.} \]

These geometrical parameters used with the voltage at the grid, \( V_G \), being roughly one-third of the voltage applied to the cathode showed that the percentage of the electrical field lines that ended on the collector and not on the grid was approximately 93\% and that, for \( \rho = \frac{2\pi r}{d} = 0.44 \), the percentage of electrons reaching the collector was about 97\%. These calculations were based on the grid ionization chamber theory as presented by Bunemann.\(^{15}\)
The ionization chamber was placed at distances of 30 or 40 cm. from the neutron source, and directly behind it at 100 cm. a Long Counter was positioned. The Long Counter was used to monitor the neutron flux.

The Long Counter was constructed according to the design of Hansen and McKibben. It consisted of a BF$_3$ cylindrical proportional counter embedded in a cylindrical piece of paraffin. The neutrons entered the paraffin, were slowed down, and were counted in the BF$_3$ counter.

The efficiency of the Long Counter was nearly constant for neutron energies from 2 to 7 Mev. As will be mentioned later, the slow change in the Long Counter efficiency was incorporated in the cross section calculations.

Since the number of neutrons per steradian versus the Long Counter count rate was known, the Long Counter was also used to establish the absolute neutron flux inside the ionization chamber. The neutron scattering away from the Long Counter by the 1/4" steel wall (E, Figure III) was measured by comparing the Long Counter counting rates with and without the ionization chamber in position.

The pulses from the Long Counter were fed in series to a cathode-follower pre-amplifier, a linear amplifier, and a scalar recorder.
B. Usual Operating Conditions

The ionization chamber was filled with spectroscopic neon gas (90.8% Ne$^{20}$, 0.26% Ne$^{21}$, and 8.9% Ne$^{22}$) at pressures ranging from 3.12 to 4.26 atmospheres. Argon was added to the neon for the work done from $E_n = 5.8$ to 7.4 Mev in an attempt to improve the resolution. The total pressure was then 5.07 atmospheres with 22.8% argon. For all experiments, the alpha particle ranges in the ionization chamber were from 0.3 to 1.4 cm.

The high voltage applied to the cathode of the chamber was usually around 2000 volts which gave satisfactory pulse height resolutions. There appeared to be negligible recombination and attachment in the chamber as exhibited by the shape of the pulse height distributions.

Usual energy resolutions were about 12% to 16% (ratio of energy width at peak half height to alpha particle energy). Once a resolution of 6.8% was obtained. From $E_n = 4.4$ to 7.3 Mev the resolution deteriorated to about 20 to 25%. Figure IV is a sample pulse spectrum.

The rise times of the pulses from the ionization chamber as observed at the 20 channel analyzer with a Techtronic 517 Oscilloscope were approximately 4 $\mu$ secs.
III. NEUTRON ENERGY AND ABSOLUTE CROSS SECTION MEASUREMENTS

A. Neutron Energy

The mean energy of the neutrons on the neon gas was determined by the energy of the accelerated particles, the target thickness, and the mean neutron energy over the geometry of the chamber.

The particle beam energy was obtained by taking $^7\text{Li}(p,n)^7\text{Be}$ thresholds and calibrating the frequency of the magnetometer in terms of $E_{\text{Li, thres}} = 1.8811 \pm 5$ MeV. Since magnetic inhomogeneities and particle relativistic energy corrections were treated separately and normalized to zero values at the lithium threshold energy, the particle energy was:

$$E = K f^2 + (\Delta E)_I + (\Delta E)_R$$

where $f$ was the magnetometer frequency, $(\Delta E)_I$ and $(\Delta E)_R$ were the inhomogeneity and relativistic corrections and $K = 1.8811/f^2$ thres.

Values of $(\Delta E)_R$ and $(\Delta E)_I$ as tabulated by R. C. Chapman were used.

A thin tritium (for $E_n = 2.8$ to 4.4 MeV) and a deuterium gas (for $E_n = 4.4$ to 7.3 MeV) target which were made at Rice were used as the neutron sources. The tritium was absorbed in zirconium on a tantalum blank and the half thickness, $(\Delta E)_{p,T} = 15$ Kev, was measured at the proton energy 1 Mev. $(\Delta E)_{p,T}$ was
calculated at higher energies in zirconium from the stopping power of protons on silver.\(^{20}\) Thus the proton energy available for the \(T^3(p,n)He^3\) reaction was:

\[
E_p^* = E_p - (AE)_{p,T}
\]

where \(E_p\) was the proton beam energy.

The deuterium gas target (\(P = 0.267\) atm.) was in a cylinder 1.5" long with a 0.77 mg/cm\(^2\) nickel foil retaining the gas from the Van de Graaff vacuum system. The energy of the neutrons available for \(D(D,n)He^3\) reaction was calculated by

\[
E_n^* = E_D - \left[(\Delta E)_{D,N} + (\Delta E)_{D,D_{1/2}}\right] = E_D - (\Delta E)_{D,T}
\]

where \(E_D\) was the deuteron beam energy and \((\Delta E)_{D,T}\) was the mean energy loss in the nickel foil and the deuterium gas. \((\Delta E)_{D,N}\) was determined first for the nickel foil, \((\Delta E)_{D,D_{1/2}}\), and then after correcting the deuteron energy was computed for the loss at the half length of the \(D_2\) gas cylinder, \((\Delta E)_{D,D_{1/2}}\). The nickel foil energy loss was computed from the curve for protons on copper\(^{30}\) and checked with the curve for protons on nickel.\(^ {21}\) For \(E_D = 4\) to 4.8 Mev the two calculations agreed within 2 Kev. The energy loss in the deuterium gas was calculated from the stopping power given in reference 22.

Since the ionization chamber intercepted a finite solid angle with respect to the neutron sources, the
angular variation of the neutron energy, the differential cross section for the T(p,n)He and D(D,n)He reactions, and the elastic and inelastic neutron cross sections for iron had to be considered. Since the center of the ionization chamber was 30 or 40 cm. from the neutron source while the beam area was ~1.5 cm², a point source was assumed. Because the elastic scattering in iron is strongly peaked in the forward direction and is ~100 times larger than inelastic scattering, it was assumed that the neutrons were scattered by the iron at zero degrees.

With these assumptions the mean angle at which the neutrons entered the active volume of ionization chamber was:

\[ \bar{\theta} = \frac{\int_0^{2\pi} \int_0^a \int_0^h r^2 \sin^2 \beta \frac{1}{d-r \cos \beta} rd\rho dz d\theta}{\int_0^{2\pi} \int_0^a \int_0^h r^2 \sin^2 \beta \frac{1}{d-r \cos \beta} rd\rho dz} \]

where \(a\) and \(h\) were the radius and height of the active volume of the chamber, and \(d\) was the distance between the center of the ionization chamber and the neutron source. \(r\), \(\beta\), and \(z\) were the orthogonal cylindrical coordinates.

No satisfactory method of carrying out the integration was found.

The neutron energy angular spreads were about
10 to 15 Kev for $6.4^\circ$, the maximum angle subtended by the active volume with respect to the neutron source. The differential cross sections at $6.4^\circ$ was about 5% and 10% less than at zero degrees for the $T(p,n)He^3$ and $D(D,n)He^3$ reactions respectively. Since the neutron path length in the active volume of the ionization chamber varied much more rapidly with $\theta$ than $\sigma(\theta)$ and $E(\theta)$, the mean energy of the neutrons in the active volume was approximately $E(\bar{\theta})$.

$\bar{\theta}$ was approximated by halving the average of the vertical and horizontal angles subtended by the active volume (for $d=40\text{mm}$, $\bar{\theta}=2.8^\circ$; for $d=30\text{mm}$, $\bar{\theta}=3.7^\circ$).

At $E_n=3.8$ Mev the deuterium neutron source data were 76 Kev higher in energy than the tritium data. When all the energy corrections which were calculated for these two neutron sources were applied to some resonances found in $N_{14}$ earlier in the year with the same tritium and deuterium targets, the resonance energies for the deuterium data was lower by 15 Kev. This difference could be accounted for by minor changes in the magnet for those runs. Thus, the 76 Kev was explained, in part, by changing conditions in the foils. Carbon could have deposited on the nickel foil; however, the carbon would have been ~0.1 mg/cm$^2$ thick if it were the only cause. Multiple scattering of the deuterons coming through the nickel could have a mean angle of
deviation no greater than 2 degrees. This would slightly increase the angular energy spread over the chamber. The scattering of the neutrons by the iron wall could be larger, by a small amount, than assumed (the steel wall subtended an angle of 16.4° with respect to the neutron source at d=40 cm). However, this could account for a mean energy variation of less than 1 kev at $E_n = 3.7$ Mev. Since all these errors could not be estimated accurately, the energies for the deuteron data was arbitrarily lowered by 76 kev at $E_n = 3.8$ Mev (which corresponded to $E_n(20^\circ)$ and then linearly decreased to the values of $E_n(\bar{\theta})$ at $E_n 5.3$ Mev, since it was ascertained that the tritium neutron source data were correct. (At $E_n = 4.4$ Mev the correction was 45 kev).

E. Determination of the Absolute Cross Sections

The electronics were set so that the first and second groups of alpha particles could be detected when the resolution and background allowed. The resolution, as stated elsewhere, was usually about 12 to 16% for $E_n$ up to 4.4 Mev, and the first and second groups were resolved. Above 4.4 Mev the resolution was about 20 to 25%, and it was not possible to resolve the two groups. At 6.6 Mev another group was detected. From the Q values it was evident from the energy of the unknown that none of the reactions listed below were the contributors.
(Q values obtained from mass values (ref. 12) and from Ajzenberg²).

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Percentage Abundance</th>
<th>Reaction</th>
<th>Q (Mev)</th>
<th>E (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne²⁰</td>
<td>90.8</td>
<td>Ne²⁰(n,α)O¹⁷</td>
<td>- .603</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ne²⁰(n,p)F²⁰</td>
<td>- 6.19</td>
<td>6.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ne²⁰(n,d)F¹⁹</td>
<td>-10.56</td>
<td>11.09</td>
</tr>
<tr>
<td>Ne²¹</td>
<td>0.26</td>
<td>Ne²¹(n,α)O¹⁸</td>
<td>- 0.015</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ne²¹(n,p)F²¹</td>
<td>-10.72</td>
<td>11.24</td>
</tr>
<tr>
<td>Ne²²</td>
<td>8.9</td>
<td>Ne²²(n,d)O¹⁹</td>
<td>- 4.75</td>
<td>4.97</td>
</tr>
</tbody>
</table>

However, the energy of the unknown group corresponded to that of alpha particles going to the 3.06 or 3.85 Mev levels in O¹⁷*. The resolution would not allow an accurate determination since these levels in O¹⁷* are only 79 Kev apart.² It is probable that alphas going to the 3.05 Mev level were observed. Since the cross section is defined as the fraction of incident particles, contained in one cm² of the beam, which react with a single target nucleus one can take:

\[
\sigma(n,α) = \frac{\text{(No. of alpha particles produced)}}{\text{(No. of Ne²⁰ target nuclei)}} \times \frac{1}{\text{(Area of neutron beam)}}
\]

The cross section for each group was calculated using this expression with the proper efficiencies taken into account.
There were several factors which distorted the alpha count as recorded on the 20 channel analyzer. The main correction was the wall effect. If a particle goes out of the active volume of the ionization chamber before losing all of its energy, it produces a smaller pulse than if its entire path length is confined to this volume. The probability, \( P \), of counting alpha particles whose complete path lengths were in the chamber was calculated assuming that the particles originated anywhere in the chamber.

It was further assumed that the alpha particles followed a straight path and that the emission of the alphas from the Ne\(^{21}\)\(^*\) compound nucleus was isotropic.

With the range of the alpha particle short compared to the dimensions of the chamber the probability that the particle went out of the chamber without producing a full sized pulse was \( 12 \)

\[
\rho = 1 - P = \frac{\gamma}{2} \left( \frac{1}{R} + \frac{1}{h} \right)
\]

where \( h = 6.42 \text{cm} \) was the full height of the active volume, \( R = 4.5 \text{ cm} \) was the radius of the chamber, and \( \gamma \) was the range of the particle.

The wall effect was measured experimentally by filling the chamber to 1.40 atmospheres of N\(^{14}\) and observing the protons from the N\(^{14}(n,p)C^{14}\) reaction. Successive amounts of argon were added to the chamber,
holding everything else constant, until the total pressure was brought to 10.96 atmospheres. Argon was chosen as the additive gas because the ranges of protons in argon and nitrogen are essentially the same. The $^{36}\text{Ar}^3(n,\alpha)^{33}$ and $^{36}\text{Ar}^3(n,\alpha)^{33\ast}$ alpha particles were separated from the protons by the 20 channel analyzer. The proton ranges in the two gases varied by no more than 10% from one another over the entire pressure range chosen. The experimental shape of $\rho$ versus $r_0$ was fitted to the theoretical curve at short ranges (Fig. V). The fraction, $\eta$, of alpha particles actually produced divided by the number of full-sized pulses recorded was then: 

$$\eta = \frac{l}{l_{\rho}} = \frac{l}{l_{\rho}}.$$ 

With the dimensions of the active volume of the ionization chamber known, page 5, the number of Ne$^{20}$ atoms in the chamber at room temperature and 4.05 atmospheres was: $N = 3.52 \times 10^{22}$ atoms.

The total number of neutrons incident on the active volume of the chamber was determined from the neutron flux as monitored by the Long Counter. There were $C = 4.137 \times 10^3$ neutrons per steradian per Long Counter count. The mean solid angle subtended by the ionization chamber with respect to the neutron source, the Long Counter efficiency as a function of neutron energy, and the correction for scattering of neutrons away from the Long Counter by the ionization chamber
were needed. The Long Counter efficiency as a function of the neutron energy was measured by a group under the direction of Dr. T. W. Bonner.\textsuperscript{29}

The number of neutrons scattered away from the Long Counter by the ionization chamber was measured (at $E_n = 3.3\ Mev$) by comparing the Long Counter count rate, $L$, with and without the ionization chamber in position. It was assumed that one half of the neutron counting rate difference was caused by the front steel wall of the ionization chamber. The ionization chamber and Long Counter subtended approximately the same angle with respect to the neutron source. Thus, experimentally the number of neutrons per steradian incident inside the chamber on the gas was $\epsilon \approx 106\% \left( \frac{dI}{dO} \approx -7\% \right)$ of the number per steradian reaching the Long Counter. It was further assumed that this number was approximately a constant.\textsuperscript{26,27}

The cross section was then

$$\sigma(\eta, \alpha) = \frac{\eta \frac{\xi}{\bar{I}}}{L \epsilon \frac{\mu_{1/2}}{4.13 \times 10^3} \frac{N}{4 A}}$$

The solid angle subtended by the active volume of the Long Counter, $\varnothing$, was approximated by $\varnothing \approx \frac{A}{\bar{d}^2}$ where the areas, $A$, cancelled in $\sigma(\eta, \alpha)$. $\bar{d}^2$ was calculated by integrating over the active volume:
\[ \overline{d^2} = \frac{\int d^2 dV}{\int dV} = \left( \frac{R^2}{2} + \frac{h^3}{12} \right) + \delta^2 \]

where \( R \) and \( h \) were the radius and height of the chamber.

Thus, for a pressure of 4.05 atmospheres and \( d = 40 \) cm

\[ \sigma(\eta, \alpha) = 1.03 \times 10^{-7} \left( \frac{\eta \xi}{L} \right) \text{mB} \]

where \( \eta \) was the wall effect correction factor, \( \xi \) and \( L \) were the Long Counter efficiency and count rate, and \( \xi \) was the integrated alpha particle count under the peak of the pulse height distribution curve as recorded on the 20 channel analyzer. The constant in this expression was modified for changes in the pressure, the distance from the neutron source to the ionization chamber, and the gas composition.
IV. PRESENTATION AND DISCUSSION OF DATA

The cross sections for the $\text{Ne}^{20}(n,\alpha)\text{O}^{17}$ and $\text{Ne}^{20}(n,\alpha)\text{O}^{17*}$ reactions are plotted in Figure II. The values of the neutron energies and the cross sections were obtained as described in Section III. From $E_n = 2.8$ to $4.4$ Mev the $\text{Ne}^{20}(n,\alpha)\text{O}^{17}$ and $\text{Ne}^{20}(n,\alpha)\text{O}^{17*}$ cross sections, which were obtained using p,T neutrons, are plotted separately. Between $4.4$ and $7.3$ Mev only the sum of the two cross sections, which was obtained using d,d neutrons, is presented. The dashed lines show the shape of the large resonance discussed later in this section. The break in the dashed line is due to the two methods of presenting the $(n,\alpha)$ cross sections at $4.4$ Mev. The fixing of error limits is outlined in Appendix I and tabulated in Table II.

Area comparisons of the $(n,\alpha)$ versus $E_n$ curves from $2.8$ to $3.35$ Mev indicate that the $(n,\alpha)$ cross section is $20\%$ lower than reported by the Wisconsin group. At $E_n = 3.26$ Mev, Flack mentioned a cross section of $\sim 30$ mb while the Rice measurement was 90 mb. The estimated absolute cross section error limits were $\pm 15\%$ (Appendix I).

At $E_n = 6.3$ Mev the third ($Q = -3.663$ Mev) or fourth ($Q = -4.453$ Mev) group of alphas (probably third) was detected and had a cross section of about 5 mb. At $E_n = 7.2$ Mev,
the cross section had risen to about 25 mb. This group is not included anywhere in the tables or graphs.

Seventeen resonances were found on the excitation curves from 2.8 to 7.3 Mev. From the energy at the peaks, one is able to calculate the energy levels in Ne\textsuperscript{21*} from 9.4 to 13.6 Mev (Section I). The results are listed in Table I, and Figure I is an energy level diagram for Ne\textsuperscript{21*}.

From 2.8 to 4.4 Mev the total neutron energy spread was about 23 Kev, and it is probable that only very weak resonances were missed.

The ratios of the cross sections for decay to the ground state of O\textsuperscript{17} to the cross sections for decay to the first excited state (0.870 Mev) are listed in Table I. In general, this ratio is decreasing with increasing neutron energy as one would expect.

At 3.26 Mev the Wisconsin group\textsuperscript{3} reported only one resonance with a peak cross section of 160 mb. The excitation curve shows that there are resonances at 3.19 and 3.29 Mev, instead of one at 3.26 Mev, with absolute cross sections of 163 ± 15\% mb and 209 ± 15\% mb. However, at 3.26 Mev, the Wisconsin group, using a proportional counter, had a neutron energy spread of 60 Kev. The Rice neutron energy spread was approximately 22 Kev. The resonance at 2.89 Mev (σ(n,α) = 100 ± 15 mb) was located by the Wisconsin group at 2.87 Mev (σ(n,α) = 130 mb).
From $E_n^* = 10.61$ Mev to $12.36$ Mev, Flack reported levels in the Ne$^{21*}$ nucleus with the binding energy of the neutron above the ground state of Ne$^{21}$, $E_B = 7.52$ Mev. However, the latest value of $E_B$ is $6.756$ Mev.$^2$

From neutron energies of $4.4$ to $7.3$ Mev the peaks are wider than those below $4.4$ Mev. It is possible that a number of narrow resonances were missed in this energy range. Only the sum of the cross sections for the first and second groups is presented. Figure I and Tables I and II show the pertinent data.

The increase in the experimental widths of resonances (Figure I) from $4.4$ to $7.3$ Mev is due, in part, to the roughly 4 to 2 times greater neutron energy spreads using the d,d neutron source.

From $E_n = 2.9$ to $6.3$ Mev a broad resonance ($\Gamma_n \approx 2.2$ Mev) exists with a maximum cross section of $115$ mb at $E_n = 4.5$ Mev. Considering only the neutron channel ($\lambda = 0$), the ratio of the reduced width of the resonance, $\gamma_n^2$, to the Wigner limit $\gamma^2/W.L.$ is (See Appendix II):

$$\Theta = \frac{\gamma_n^2}{\gamma^2/W.L.} = 0.19$$

Thus it is conceivable that there is a single particle level in Ne$^{21*}$ consisting of the Ne$^{20}$ nucleus plus a neutron.
## TABLE I

RESONANCES IN THE REACTION Ne^{20}(n, \alpha)O^{17}

<table>
<thead>
<tr>
<th>Resonant Energy (MeV)</th>
<th>E* (MeV)</th>
<th>(\Gamma^*) (Kev)</th>
<th>(\Gamma^\alpha) (Kev)</th>
<th>(\Gamma^\beta) (Kev)</th>
<th>Absol. Peak (\sigma_\alpha) (mb)</th>
<th>(\sigma_\alpha) at R, exp.</th>
<th>(\sigma_\alpha) at A.S.R, exp.</th>
<th>(\sigma_\alpha) at A.S.R, calc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.89</td>
<td>9.50</td>
<td>44</td>
<td>21</td>
<td>39</td>
<td>100</td>
<td>91</td>
<td>103</td>
<td></td>
</tr>
<tr>
<td>3.19</td>
<td>9.79</td>
<td>44</td>
<td>22</td>
<td>39</td>
<td>163</td>
<td>135</td>
<td>152</td>
<td></td>
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<tr>
<td>3.29</td>
<td>9.88</td>
<td>51</td>
<td>22</td>
<td>46</td>
<td>209</td>
<td>170</td>
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<tr>
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**RESONANCES IN THE REACTION Ne^{20}(n, \alpha)O^{17} and O^{17}**

<table>
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<tr>
<th>Energy (MeV)</th>
<th>E (MeV)</th>
<th>(\Gamma^*) (Kev)</th>
<th>(\Gamma^\alpha) (Kev)</th>
<th>(\Gamma^\beta) (Kev)</th>
<th>Absol. Peak (\sigma_\alpha) (mb)</th>
<th>(\sigma_\alpha) at R, exp.</th>
<th>(\sigma_\alpha) at A.S.R, exp.</th>
<th>(\sigma_\alpha) at A.S.R, calc.</th>
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* - Observed only in Ne^{20}(n, \alpha)O^{17}*

** - Third group of alphas not included
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<th>Resonance Energy (MeV)</th>
<th>$\sigma_{\text{Peak}}$ (mb)</th>
<th>$\pm (\sigma(\eta,\pi))_{\text{Stat.}}$ (mb)</th>
<th>$\pm (\sigma(\eta,\pi))_{\text{Absol.}}$ (mb)</th>
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</table>
Figure I

Energy Level Diagrams

\[ J = \frac{1}{2}^+ \]

\[ J = \frac{3}{2}^+ \]

\[ ^1\text{H} \quad (\text{Ref. 2}) \]

\[ ^{21}\text{Ne} \quad (\text{RICE DATA}) \]
GRID IONIZATION CHAMBER

FIGURE III
FIGURE IV
PULSE SPECTRUM
$E_n = 4.150$ MEV.

$E_\alpha = 2.67$ MEV.

$E_\alpha = 1.97$ MEV.

8.9% RESOLUTION

ALPHA COUNT DIVIDED BY 16

PULSE HEIGHT (CHANNEL NO.)
FIGURE V
WALL EFFECT

-+ NORMALIZED EXPERIMENTAL DATA

RADIUS OF CHAMBER = 4.5 CM.
HEIGHT OF CHAMBER = 6.42 CM.

\[ \rho = r_0 \left( \frac{1}{2h} + \frac{1}{2R} \right)^2 \]

\[ = 0.188 r_0 \]
BY SIMILAR TRIANGLES

\[ \frac{\Delta R}{R_1 - \Delta R} = \frac{y_f}{\chi + q_f} \]

\[ \frac{\Delta R}{y_f} = \frac{q_f + \Delta R}{\chi + q_f} \]

\[ (\Delta R) = \frac{y_f R}{R + \chi}, \quad ((\Delta R)^2 \to 0) \]

\[ R_1 - \frac{\Delta R}{2} = R \]

\[ \frac{\Delta E}{E} = \frac{2\Delta R}{R} \approx \frac{2y_f}{R + \chi} \]

BEAM ENERGY SPREAD FOR ANALYZING MAGNET
APPENDIX I

ESTIMATED ERROR LIMITS

A. Neutron Energy Estimated Errors

The errors in the neutron energy which were considered were the beam energy spread, the limits of the target thickness, and the solid angle effect.

The energy of particles being bent through the magnet at a radius $R$ was (non-relativistically):\(^{19}\)

$$E_B = \left( \frac{e^2 h^2 f^2}{\varepsilon \gamma^2 \mu_p} \right) R^2$$

Thus one had, at a particular magnetometer frequency, $f$:

$$\frac{(\Delta E)_B}{E_B} = \frac{2(\Delta R)}{R}$$

Since

$$K = \frac{13811 \pm 5}{\text{Li thres.}} \quad \frac{\text{Mev}}{(\text{megacycles})^2} = \frac{e^2 h^2}{\varepsilon \gamma^2 \mu_p} R^2$$

and the 1956 average of the radius was $R = 39.741$ cm for $K = 4.1716 \times 10^{-3}$ Mev/(mc)$^2$, one obtained 39.856 cm for the present experiments.\(^{19}\)

Referring to Figure VI one assumed that $(\Delta R)$ was small compared to $R$, and by simple geometry obtained:

$$\frac{(\Delta R)}{R} \approx \frac{\gamma}{R + \chi}$$

Thus the beam energy spread was:

$$(\Delta E)_B \approx \left( \frac{2\gamma}{R + \chi} \right) E_B$$
where $E_B$ was the mean beam energy, $y$ the height of the target, and $x$ the distance from the center of the analyzing magnet to the target.

With $y = 0.75$ cm, $x = 6$ meters, and $R = 39.856$ cm one had:

$$(\Delta E)^2 \approx 2.3 \times 10^{-3} E_B$$

For the tritium neutron source the target energy spread was taken as the energy loss of the full thickness. For the deuterium gas neutron source the straggling in the nickel foil, the full length loss in the $D_2$ gas, and the estimated errors introduced by the arbitrary energy corrections were taken as the target energy spread.

The geometrical energy spreads were assumed to be the total angular energy variation over the active volume of the ionization chamber.

Since these energy spreads were almost independent of one another, the total energy spread, $(\Delta E)^2$, was the square root of the sum of the squares of the beam and target, (after being converted to a neutron energy spread), and geometrical spreads. Table I is a tabulation of the results of these calculations.
B. Cross Section Error Estimations

The deviation in the cross section from one neutron energy value to another within the energy resolution and, also, the error limits on an absolute scale were estimated separately.

The deviation of the cross section due to the statistical fluctuations of the alpha count, $\xi$, was taken as:

$$\langle \Delta \sigma(n,\alpha) \rangle_{\text{stat.}} = \pm \frac{1}{\sqrt{\xi}} \sigma(n,\alpha) = \pm \frac{\sqrt{(n,\alpha)}}{\sqrt{\xi}}$$

Table II lists the results of the calculations.

The error limits on the absolute scale were determined by estimating the experimental errors of all the terms in $\sigma(n,\alpha)$. These individual estimates were:

$$\langle \Delta \sigma \rangle = \pm 5 \times 10^{-2} \quad \text{Measurement of the number of neutrons incident inside the chamber.}$$

$$\langle \Delta \xi \rangle = \pm 5 \times 10^{-2} \quad \text{Long Counter efficiency.}$$

$$\langle \Delta C \rangle = \pm 10^{-1} \quad \text{Number of neutrons per steradian per Long count, L.}$$

$$\langle \Delta d^2 \rangle = \pm 5 \times 10^{-2} \quad \text{Distance}^2 \text{ from neutron source to ionization chamber.}$$

$$\langle \Delta N \rangle = \pm 5 \times 10^{-2} \quad \text{Number of } \text{Ne}^{20} \text{ nuclei in active volume.}$$
\[
\frac{\Delta \eta}{\eta} = \pm 5 \times 10^{-2}, \quad \text{Wall effect.}
\]

Combining these error estimations with the statistical errors one has:

\[
\left( \frac{\Delta \sigma(n, \alpha)}{\sigma(n, \alpha)} \right)_{\text{Absol.}} \approx \pm \left[ \frac{1}{\varepsilon} + \frac{1}{L} + 2.25 \times 10^{-2} \right]^{1/2}
\]

Since the Long Counter count, \(L\), was usually greater than \(3 \times 10^4\) counts, it was neglected. The controlling factor was the constant \((2.25 \times 10^{-2})\); so (to within .5 percent except in the second group of alphas)

\[
\left( \frac{\Delta \sigma(n, \alpha)}{\sigma(n, \alpha)} \right)_{\text{Absol.}} \approx \pm 15\%
\]

Table II has the results.
APPENDIX II

SINGLE PARTICLE LEVEL FOR
THE Ne\(^{20}(n,\alpha)O^{17}\) and \(O^{17*}\) REACTIONS

If the ratio, \(\Theta\), of the reduced width \(\frac{\gamma^{2}_{l}}{A_{\ell,n}}\) to the Wigner Limit \(\frac{3 \hbar^{2}}{2MR}\) is appreciable, a single particle model of the compound nucleus may exist.

Since the total cross section, \(\sigma_{T}\), is about 30 times larger than the \((n,\alpha)\) cross section, the total width of the resonance \(\Gamma = \frac{\sigma(n,\alpha)}{\sigma_{T}} \Gamma_{\alpha} + \frac{\sigma(n,\alpha)}{\sigma_{T}} \Gamma_{\pi}\) approximately equals the neutron width, \(\Gamma_{\pi}\). Thus the ratio \(\Theta\) can be taken as:

\[
\Theta = \frac{\gamma^{2}_{l}}{\gamma^{2}_{W,L}} = \frac{3 \Gamma A_{\ell,n}}{4MRk_{n}}
\]

where the parameters are \(\Gamma\), the total experimental width expressed in the center of mass system; \(A_{\ell,n}\), the neutron penetration factor for a particular orbital momentum \(\ell\); \(M\), the reduced mass of the neutron and the Ne\(^{20}\) nucleus; \(R\), the interaction radius; and \(k_{n}\), the wave number for the neutron energy at the resonance peak.
Using $R = 5.39 \times 10^{-13}$ cm, $r = 2.0$ Mev, $M = 0.9602$ amu, $k_n = 4.55 \times 10^{-12}$ cm$^{-1}$, and assuming $S$-wave neutrons one has

$$\Theta = 0.19$$

where

$$\gamma_n^2 = 0.227 \times 10^{-12} \text{ Mev cm}$$

$$\gamma_{\text{W.L.}}^2 = 1.21 \times 10^{-12} \text{ Mev cm}$$
ACKNOWLEDGEMENTS

I wish to express sincere appreciation to Dr. T. W. Bonner for his guidance throughout the project, and to Mr. Fletcher Gabbard for assistance in all phases of the work.
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