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A SUMMARY OF VARIOUS NEUTRON EXPERIMENTS

by

Jack Slattery

A THESIS
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Approved
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Neutron Thresholds

Introduction

It is an experimental fact that most nuclei have excited energy levels to which they can be raised from their ground state by the addition of a suitable amount of energy. This agrees with the principles of quantum mechanics, since quantum mechanically any energetically bound system of particles must exist in discrete energy states. In the case of atomic nuclei the lifetimes of states vary greatly, depending upon how many and what particular modes of decay are energetically available to a given level. Sometimes not even the ground state is stable for very long.

Ultimately, then, any good theory of nuclear forces and structure must make predictions about these levels. It is perhaps too much to expect that the energies should be predicted exactly, since this will probably require solution of the many body problem. There are other properties, however, such as the density of states in a given region of excitation, the average level spacing, or their ordering with respect to the quantum numbers characterizing them. One would hope that these things could be predicted.

In order to test existing or future theories, it is of interest to measure as many properties of energy levels as possible. Of the various properties of a level, by far the easiest to measure is its energy above the ground state,
and many methods exist for doing this. For example, one can bombard a nucleus X with particles x and observe the yield of one of the reaction products as a function of the bombarding energy. This will give information concerning the compound nucleus, X + X, in a region of excitation determined by the bombarding energy and the Q-value of the reaction. In another method the energies of γ-rays from (p, γ) reactions are measured. The energy of a γ-ray will be the difference between two energy states of the proton plus target nucleus system. Similarly, if the energies of neutron groups from (p,n) or (d,n) reactions are measured, one obtains energies of states in the residual nucleus.

The last two cases do not yield very precise information, because it is difficult to measure γ-ray and neutron energies with high precision. On the other hand charged particle energies can be measured very closely by magnetic or electrostatic analysis, and the determination of energy levels by the inelastic scattering of charged particles has been quite successful. In experiments of this type a particle of known energy is allowed to strike a target nucleus, to which it gives a part of its energy, raising it to a higher excited state. The energy of the scattered particle is then measured again, and using this and the original energy, the excited state energy is computed.

Of course, not all regions of excitation are available
to any one method, and a combination of all of them is usually necessary to study one nucleus.

The method to be discussed here is that of measuring the threshold energy for neutron production. Extensive discussions of this method are to be found in the literature\textsuperscript{1-5}. In particular we are concerned with neutrons resulting from deuteron bombardment.

Suppose we bombard a target nucleus $X$ with deuterons and observe the neutrons given off. The reaction is:

$$Z^A + Z +_1 H^2 \rightarrow n^1 + Z + \gamma^A + Z + l + Q_0$$  \hspace{1cm} (1)

$Q_0$ is the energy released, and is given by

$$Q_0 = \Delta Mc^2$$  \hspace{1cm} (2)

where $\Delta M$ is the mass difference ($X$ plus a deuteron) minus ($Y$ plus a neutron). Endothermic reactions are characterized by negative $Q$-values and exothermic reactions by positive $Q$-values.

If the reaction is exothermic, then the term threshold energy has no meaning. For negative $Q$-values the threshold energy is that bombarding energy at which the reaction just starts to go, i.e. when the kinetic energy of the bombarding particle in the center-of-mass system is equal to the $Q$-value. Since some of the bombarding energy is always lost to the motion of the center of mass of the system, the
threshold energy is always greater than the Q-value, and in fact is given by:

\[ E_t = \frac{x^A + Z + H^2}{x^A + Z} Q_o \]  

(3)

Thus, Q-values can be measured by finding the bombarding energy at which neutrons just start to come off. These neutrons will have zero energy in the center-of-mass system, but a small energy in the laboratory, due to the center-of-mass motion.

The energy of excited states in the residual nucleus can be measured by this method also. Let us define a Q-value for a reaction which leaves the residual nucleus excited to its n'th state numbering the ground state as zero.

\[ Q_n = Q_o - E_{ex} \]  

(4)

where \( E_{ex} \) is the excitation energy of the n'th level.

With this definition the previous discussion carries over exactly. The threshold energy is that bombarding energy where neutrons come off with zero energy. Of course, it will be more difficult to detect the excited state thresholds, since there will be a large number of higher energy neutrons already present, those leaving the residual nucleus in the lower excited states or else the ground state. How this is done is discussed in the next section.
The advantage of the neutron threshold method is that it supplies an accurate method of measuring levels accessible only by (p,n) or (d,n) reactions. The neutron energy need never be measured accurately, only the bombarding energy, and this can be done very precisely by magnetic analysis.

**Experimental Procedure**

The experimental apparatus consists of two counters, proportional counters filled with boron trifluoride. When a \( ^{10}B \) nucleus captures a neutron, it disintegrates as follows:

\[
^{9}B^{10} + {\text{n}}^{1} \rightarrow ^{2}He^{4} + ^{3}Li^{7} + 2.792 \text{ MeV}
\]

The recoiling \( ^{4}He \) and \( ^{7}Li \) nuclei produce a pulse in the counter. The crosssection for this reaction follows a \( 1/v \) law and is therefore much larger for thermal neutrons than for higher energy neutrons. It is for this reason that the counters are usually operated with paraffin around them. The hydrogen in the paraffin serves to moderate incoming neutrons, slowing them down sufficiently so that their probability of being captured in the counter is very high. A bare \( BF_{3} \) counter is extremely inefficient for counting any but thermal neutrons.

The arrangement of the two counters during the running
of an experiment is shown in Figure 1. The counter closest
to the target is surrounded by a two inch cylinder of
paraffin with an offset hole drilled in it. The hole is
located such that between the counter and the target there
is only about one-eighth inch of paraffin. This amount of
paraffin is insufficient to moderate any but very low
energy neutrons, and in practice the efficiency of the
counter is found to fall off sharply for energies greater
than about 300 Kev\(^3\). This counter is called the "slow
counter".

The second counter is similar to the unshielded long
counter developed by Hanson and McKibben\(^6\), although less
paraffin is used than in the original. This counter is
not very sensitive to low energy neutrons, which have a
high probability of being reflected from the front face
of the paraffin or else being captured in the cadmium cap
after moderation. On the other hand higher energy neutrons
will penetrate further into the paraffin and there be
moderated and counted. This counter will be referred to
as the "modified long".

With the two counters arranged as in Figure 1, con-
sider what happens as the bombarding energy is increased
bit by bit past an excited state threshold energy.

The modified long will be detecting the neutrons
which are leaving the residual nucleus in a lower state
and therefore have an appreciable energy. The slow counter
will have a low counting rate, since it has a low probability for detecting these neutrons. The ratio of counting rates, slow to long, will be small. When the threshold energy is reached, however, low energy neutrons are emitted and the slow counter counting rate increases, while that of the long remains the same. Thus the ratio rises.

At an energy just above threshold, only the front part of the target is contributing slow neutrons, but as the energy is raised, more and more of the target contributes. For this reason, the ratio continues to rise with increasing energy until the whole target is contributing. After this the ratio will slowly fall as the average energy of the neutrons increases. The threshold energy is the energy at which the ratio curve starts to rise.

The discussion above applies if the level in the residual nucleus is a narrow one, so that the neutrons have a sharply defined energy. However, if the level width is considerably more than target thickness, then the ratio curve will rise and fall with the level, its appearance being very similar to the familiar broad resonance shape. In this case, the level energy is computed from the peak value of the curve, instead of the point where it starts to rise.

The precise measurement of the threshold energies is accomplished through magnetic analysis of the beam of the
Rice Institute 5.5 Mev Van de Graaff. The accelerated beam is bent by the analyzing magnet through an angle of ninety degrees before striking the target. Entrance to the magnet is controlled by slits carefully positioned in the same place at all times. Thus one need only know the radius of curvature and the magnetic field to calculate the energy.

The magnetic field strength is measured with a Pound magnetometer. In this instrument a small probe containing lithium hydride is placed in the field. The frequency of precession of either the Li$^7$ nuclei or the protons is then proportional to the magnetic field strength. This frequency is measured by observing the output of a small oscillator which feeds a coil in the probe. A strong absorption is seen when the oscillator frequency is equal to the precession frequency.

The radius of curvature is determined by measuring the field strength at the Li$^7$(p,n)Be$^7$ ground state threshold. This threshold energy is 1882.5 ± 0.9 Kev$^7$. However, since the probe is not in exactly the same place as the beam tube, the field measured by the probe may not be the same as the average field seen by the particle for field strengths higher than the Li$^7$(p,n)Be$^7$ threshold. For this reason other calibration points must be taken and a correction applied to energies corresponding to higher field strengths. A complete discussion of the calibration procedure is given
in a thesis by R. A. Chapman.

The Reaction Li⁶(d,n)Be⁷

The Q-value of the reaction is 3.375 Mev, computed from the mass values of Ajzenberg and Leuritsen. The target was a thin lithium film evaporated onto a tantalum blank in the vacuum system of the Van de Graaff. The lithium used was obtained from the Separated Isotopes division of Oak Ridge, and contained 96% Li⁶ and 4% Li⁷.

The ratio curve and yield of neutrons in the forward direction is shown in Figure 2. The ratio at the lower energies has a distinct downward slope, which is probably due to the fact that the average energy of neutrons from the three-body breakup (Q = 1.792 Mev) is increasing. The thresholds at A and C correspond to the well-known ground and first excited state thresholds of 0.16, and are probably due to a slight oxygen contamination. The effect at B corresponds to a very pronounced threshold in N¹⁴ at 1.967 Mev, and is consequently assigned to nitrogen contamination. At a deuteron energy of 3.3 Mev, the curve starts to rise and continues to do so for about one Mev, until it reaches a peak at D. This is attributed to a broad level in Be⁷, at 6.75 Mev excitation. Effect E is also due to a level in Be⁷ at 7.30 Mev excitation.

These last two excitation energies are accessible to
other methods of observation. For example, Reynolds\textsuperscript{10} has observed the $\alpha$-groups given off by the reaction $^7\text{Be}^{10}(p,\alpha)$ $^7\text{Be}$, at a bombarding energy of 18 Mev. He finds evidence for states in $^7\text{Be}$ at 0.49 ± 0.10 Mev, 4.72 ± 0.08 Mev, 6.27 ± 0.10 Mev, 7.21 ± 0.10 Mev and 14.6 ± 0.3 Mev. The state at 7.21 agrees within experimental error with the value of 7.30 observed in the present work. There is a definite discrepancy between his value of 6.27 Mev and ours of 6.75 Mev, but the present work shows that this state is extremely broad, which tends to make the exact energy hard to pick.

The reaction $^6\text{Li}^6(p,\alpha)^3\text{He}$ has been studied by many investigators\textsuperscript{11,12}, most recently by Marion, Weber and Mozer\textsuperscript{13}. The yield of $^3\text{He}$ particles exhibits a broad resonance at about one Mev and a pronounced resonance at 1.85 Mev. A resonance at one Mev would correspond to an excitation in $^7\text{Be}$ at about 6.6 Mev. Marion et al have fitted the 1.85 Mev resonance with a Breit-Wigner single level formula and their parameters give a $^7\text{Be}$ excitation energy of 7.80 Mev for that state, compared to the present value of 7.30 Mev. These same parameters yield a total width at resonance of 0.72 Mev, while we estimate the width to be 0.45 Mev.

There is evidence for a state in $^7\text{Be}$ at about 4.6 Mev excitation, mirror to the 4.61 Mev $^7\text{Li}$ level. Both an $\alpha$-particle group\textsuperscript{9} from $^7\text{Be}^{10}(p,\alpha)$ $^7\text{Be}$ and a neutron group\textsuperscript{14} from $^7\text{Li}^7(p,n)$ $^7\text{Be}$ going to this state have been observed.
More recently, what is undoubtably the same level has been observed in the scattering of He$^3$ from He$^4$. A preliminary analysis of the data give resonance parameters indicating an excitation in Be$^7$ of 4.59 Mev. This level should be observed in the Li$^6$(d,n)Be$^7$ reaction at a bombarding energy of 1.62 Mev, however it is not seen. The state we are trying to see in Be$^7$ has a total angular momentum of 7/2 and odd parity. Therefore it is possible that the angular momentum barrier for the outcoming neutrons is high enough so that they are not emitted in appreciable numbers until the slow counter efficiency has fallen off.

If the yield near threshold is mainly due to the formation of Be$^8$ in a low angular momentum state, say 2 or less, then the neutrons must carry off several units of angular momentum. Only if the Be$^8$ state has angular momentum 2 with even parity can a neutron come off with only one unit of angular momentum. Otherwise it must carry off two or more units. It is very likely that a threshold involving neutrons with orbital angular momentum of one or more units would not be seen.

Table 1 lists the thresholds, calculated Q-values, energies of excited states in Be$^7$, and the observed level widths.

The crosssection for neutron production was obtained by measuring the yield of neutrons from the Li$^7$(p,n)Be$^7$ reaction in the same target, at a proton energy of 2.35 Mev,
using the Li\textsuperscript{7}(p,n)Be\textsuperscript{7} crosssection of Taschek and Hemmendinger\textsuperscript{16}. This was compared to the Li\textsuperscript{6}(d,n)Be\textsuperscript{7} yield at a deuteron energy of 1.5 Mev. The crosssection is probably good to about 50%, since the two comparison neutron energies differ so widely. The yield of neutrons in the forward direction, normalized to the measured crosssection at a bombarding energy of 1.5 Mev, is the curve marked yield in Figure 2.

Since the Li\textsuperscript{6}(d,n)Be\textsuperscript{7} crosssection was measured at an energy below the O\textsuperscript{16}(d,n)F\textsuperscript{17} threshold, it was possible to estimate the oxygen contribution to the yield from the magnitude of the two oxygen thresholds. This was done, and then the estimated oxygen contribution subtracted from the total yield. The results are given in Figure 2 with the label "corrected yield". There is a small (about 4% at 2 Mev bombarding energy) contribution to the yield from the Li\textsuperscript{7} present, but the data have not been corrected for it.
Table 1

Thresholds from the reaction Li$^6$(d,n)Be$^7$

<table>
<thead>
<tr>
<th>Threshold Energy (Mev)</th>
<th>Q-value (Mev)</th>
<th>Excitation in Be (Mev)</th>
<th>Center-of-mass Width (Mev)</th>
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<tbody>
<tr>
<td>A</td>
<td>1.83</td>
<td>0$^{16}$ contamination</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.97</td>
<td>N$^{14}$ contamination</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2.40</td>
<td>0$^{16}$ contamination</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>4.50</td>
<td>-3.37</td>
<td>6.75</td>
</tr>
<tr>
<td>E</td>
<td>5.20</td>
<td>-3.90</td>
<td>7.30</td>
</tr>
</tbody>
</table>
The Reaction $^{19}\text{F}_{(d,n)}^{20}\text{Ne}$

The Q-value of the reaction is 10.645 Mev, computed from the mass values of Ajzenberg and Lauritsen. A target was obtained by evaporating $\text{BaF}_2$ onto a tantalum blank. The target used was about 50 Kev thick to two Mev deuterons. The ratio and yield of neutrons in the forward direction are shown in Figure 3.

Unfortunately, carbon deposits formed rather quickly on the targets used, and since the yield of neutrons from the reaction $^{12}\text{C}_{(d,n)}^{13}\text{N}$ is very large, an appreciable fraction of the neutron yield is due to carbon. We are in a region of excitation of about 11 Mev to 15 Mev in $^{20}\text{Ne}$ and it is known that the level density there is very high, making it extremely difficult to see any threshold effects. Above 4.746 Mev excitation, $^{20}\text{Ne}$ can decay by $\alpha$-particle emission, and above 12.870 Mev by proton emission. This will tend to make the levels broad, further obscuring any thresholds.

The reaction $^{12}\text{C}_{(d,n)}^{13}\text{N}$ has a Q-value of -0.281 Mev, or a threshold energy of 0.328 Mev. Low energy neutrons from this threshold account for the steeply falling ratio curve at lower energies in Figure 3, although the data do not go low enough to actually see the threshold. At A (1.75 Mev) there is a dip in the ratio, probably due to the known $^{12}\text{C}_{(d,n)}^{13}\text{N}$ neutron resonance at 1.73 Mev. The rise
in the ratio at B could be due to a broad level or several narrow ones in Ne\textsuperscript{20}. The excitation energy in Ne\textsuperscript{20} would be about 12.40 Mev. Another broad carbon resonance occurs at 2.35 Mev, which would account for the dip in the ratio at C. The apparent rise in the ratio at D is probably due to the ratio increasing again after dipping at C. The small deviations from a smooth curve at higher energies seem to be correlated with resonances in the C\textsuperscript{12} neutron yield.

The crosssection was measured by comparing the counting rates from a weighted BaF\textsubscript{2} target and a Ra-Be neutron source calibrated at the National Bureau of Standards. The comparison was done at a deuteron energy of 1.4 Mev. The crosssection measured at this energy was 29 mb/ster. Since the target used for this measurement was not bombarded prior to use, it contained no carbon, and the crosssection here is probably good to about 50%. At other energies it is probably not this good, due to the yield of the carbon, which was estimated to be about 25% of the total yield at a bombarding energy of 2.4 Mev.
Figure 1
Nonelastic Neutron Scattering

Introduction

Before the year 1936, very little was understood of the interaction of particles, charged or uncharged, with nuclei. Many experiments had been done with neutrons, especially neutron activation at different energies, but there were no adequate explanations of the variations of these cross sections.

Theoretical attempts to explain them all attempted to use the so-called one particle model. In this theory, a neutron sees a nucleus not as an assemblage of individual nucleons, but as a potential well, within which it is free to move. This model can predict only elastic scattering and radiative capture, and while it does give rise to resonance effects, the resonances are very widely spaced. Furthermore, the elastic scattering cross section should be considerably larger than the capture cross section.

These predictions were not borne out at all by experiments. In the first place, the total cross section at resonance was found to consist mainly of capture, and not of elastic scattering. Secondly, many very narrow and closely spaced resonances had been detected.

It was at this point that Niels Bohr made his now famous suggestion that perhaps the interaction could best be described in terms of an intermediate or compound nucleus.
In this model the incident particle interacts strongly with the other nucleons, quickly sharing its energy with them. For a particle to be emitted from this compound nucleus it must wait until, by chance, enough energy is concentrated on it. During this waiting time the compound nucleus is presumed to lose all knowledge of its mode of formation.

This model was considerably more successful in predicting the qualitative, and also many quantitative aspects of the interaction cross sections. It has been the main basis of attempts to explain nuclear reactions since 1936.

However, as more data were accumulated, it was noticed that while the compound nucleus theory could explain the variation in cross-section over a small energy region, there were large scale energy variations which it could not explain. In particular, the total neutron cross sections exhibited broad resonances which were similar to those predicted by the one particle theory.

This led to the formulation of the optical model of the nucleus, in which the target nucleus is described in terms of a complex potential well\textsuperscript{17,18}. The imaginary part of this potential gives rise to an absorption, or compound nucleus formation, whereas the real part describes the "gross structure" properties of the nucleus.

In order to test this theory, and to determine the numerical values of the various parameters involved, the elastic scattering cross sections are of interest. These can
be obtained from the total crosssections and the measured nonelastic crosssections. The nonelastic crosssection is the difference between the total and the elastic crosssections.

Many experimenters have made measurements of nonelastic crosssections\textsuperscript{19-22}, including extensive work at the Rice Institute\textsuperscript{23}. It was decided that it would be instructive to obtain more of these data, both to be certain of the shapes of the curves at lower energies and to extend them to neutron energies of about 20 Mev. The data could then be compared to recent calculations of the optical model made by Beyster, Walt and Salmi\textsuperscript{24}.

**Experimental Procedure and Data**

The nonelastic scattering crosssection includes the crosssections for all processes in which the neutron gives energy to the target nucleus. This includes not only inelastic scattering, but also reactions such as radiative neutron capture, \((n,p)\) or \((n,2n)\). Therefore, if we surround a monoenergetic source of neutrons with a shell of material, then place a biased detector outside the shell, the counting rate in the detector with the shell on and then with the shell off will be a measure of the nonelastic scattering crosssection. Provided, that is, that the bias is high enough to discriminate against inelastically scattered
neutrons and low enough so that elastically scattered neutrons are counted with the same efficiency as unscattered neutrons. (Since the neutron loses a small amount of energy in elastic scattering, the efficiency is not the same and the data must be corrected for this.)

In practice, one usually places the shell of scattering material around the detector instead of the source. Bethe\textsuperscript{25} has shown that this exchange does not affect the results.

The experimental procedure followed is similar to that of Taylor, Lonsjo and Bonner\textsuperscript{23}, and is described in detail in H. L. Taylor's thesis\textsuperscript{26}. The detectors used were small plastic scintillator spheres, mounted on a Dumont 6291 phototube with a quartz light-pipe. Crosssections were measured at six different energies, 8.2, 9.8, 15.5, 17.0, 18.5 and 20 Mev. The detector sphere was 0.8 cm in diameter for the 8.2 and 9.8 Mev data and 1.0 cm in diameter for the other data.

Neutrons were obtained by suitable reactions using the Rice Institute 5.5 Mev Van de Graeff. The reaction $\text{Be}^9(\alpha,n)\text{C}^{12}$ ($Q = 5.708$ Mev) was used for the 8.2 and 9.8 Mev work. Although the neutrons from this reaction are not monoenergetic, the next highest group of neutrons has a $Q$-value of 1.28 Mev and so the lower energy neutrons are readily biased out. The higher energy data was taken using neutrons from the reaction $\text{H}^3(d,n)\text{He}^4$ ($Q = 17.577$ Mev).
The scattering shells were hollow spheres with an outside diameter of 3 inches and a 2 cm wall thickness. Each sphere had a 5/8 inch hole in it for insertion of the detector.

The data were taken by measuring the counting rate with the scattering shell on the detector and then with the shell off. The ratio of the counting rates (shell on/shell off) is the experimental transmission. In each case this was done enough times to ensure good statistics. The results are listed in Table 2 as $T_{(\text{expt})}$.

The transmissions were calculated from the counting rates corresponding to neutrons with 80% or more of the maximum neutron energy, but since the spectrum from the detector was usually displayed on a 20-channel pulse-height analyzer, it was possible to check the transmission for different biases. Changing the bias to 70% made no difference in the transmission within statistical errors.

The experimental transmissions thus measured need to be corrected for three effects. First is the correction for the decrease in detection efficiency for elastically scattered neutrons mentioned previously. Secondly, neutrons emitted at an angle $\theta$ to the beam have a lower energy than those emitted at $0^\circ$ to the beam, and there is consequently a lower efficiency for detecting them. The third correction is due to the fact that the angular distribution of neutrons from the source is not isotropic in the laboratory.
In general, more neutrons are emitted at $0^\circ$ than at an angle $\theta$, resulting in a nonuniform illumination of the scattering shells.

Once the experimental transmissions have been corrected, the cross-sections are derived from the general expression given by Bethe, Beyster and Carter\textsuperscript{27}:

$$(1-T) = (1-T_0) \frac{\sigma_n}{\sigma_n + \sigma_{et} P_m}$$

where $T$ is the (corrected) experimental transmission, $T_0$ is $\exp(-N\sigma_{tr})$, $N$ is the number of atoms per cm$^2$ in the scatterer, $P_m$ is the escape probability of the neutron, $\sigma_n$ is the nonelastic cross-section, $\sigma_{tr}$ is the transport cross-section:

$$\sigma_{tr} = \sigma_n + \sigma_e S$$

$$S = \frac{\int \sigma_{e}(\theta)(1-\cos\theta) d\theta}{\int \sigma_{e}(\theta) d\theta}$$

$\sigma_e$ is the elastic cross-section, and finally, $\sigma_{et}$ is the elastic transport cross-section:

$$\sigma_{et} = \sigma_e S$$

A method of successive approximations is necessary to calculate $\sigma_n$. One assumes $\sigma_n$ and obtains $\sigma_e$ by subtracting $\sigma_n$ from the known total cross-section. Usually only
one or two successive trials are necessary.

The corrected transmissions and the calculated nonelastic crosssections are given in Table 2. Also included are the total crosssections used.

In Figures 4 and 5 are shown the variation with neutron energy of the experimental nonelastic and elastic crosssections for tin and bismuth. The elastic crosssection is found by subtracting the nonelastic crosssection from the total crosssection. Also included are the theoretical curves calculated by Beyster, Walt and Salmi\textsuperscript{24}. They have calculated the crosssection using a diffuse edge nuclear potential, given by:

$$V_{(r)} = \frac{V_{0}(1+i\delta)}{1 + \exp \left[ \frac{(r-R)/a}{\delta} \right]}$$

$$R = r_0 A^{1/3} \times 10^{-13} \text{ cm}.$$  

The dashed curves in Figure 4 and 5 are obtained by using energy-independent parameters in the expression for the potential. At lower neutron energies there is a large amount of compound elastic scattering (elastic scattering through compound nucleus formation), and this makes comparison to experiment difficult. Beyster et al find some improvement when $V_0$ and $\delta$ are allowed to vary with energy, and the dot-dashed curves in Figures 4 and 5 are their
results when this is done.

It appears that calculations with the diffuse edge well are at least reasonable. They predict with a fair degree of accuracy the experimental values above the point where compound elastic scattering is appreciable. However, the theory cannot yet reproduce all the features of the crosssections even at these higher energies. Beyster et al are of the opinion that other forces, such as direct interactions, must be present also.
<table>
<thead>
<tr>
<th>Neutron Element</th>
<th>Energy: 8.2 Mev</th>
<th>9.8 Mev</th>
<th>15.5 Mev</th>
<th>17.0 Mev</th>
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<td>Cu T(expt):</td>
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<td>.780</td>
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Figure 4
Figure 5
The Scattering of High Energy Neutrons from Helium

Introduction

The nuclear reaction \( ^3\text{H}(\text{d,n})^4\text{He} \) \((Q = 17.577\ \text{Mev})\) has long served as a source of high energy neutrons. It has been especially useful for low deuteron bombarding energies, since the crosssection has a pronounced maximum at a deuteron energy of 109 Kev.

The reason for this maximum has been the subject of much speculation. The most common explanation is the existence of an isolated state in the compound nucleus, \( ^5\text{He} \), at some lower energy. This resonance shape, weighted by charged particle penetrabilities, then gives rise to the 109 Kev maximum. There has been an alternative theory, however, proposed by Flowers\(^28\), which does not need an isolated state in \( ^5\text{He} \). While both theories yield reasonable fits to the \( ^3\text{H}(\text{d,n})^4\text{He} \) neutron yield curve\(^28,29\), they predict very different results for scattering of neutrons from \( ^4\text{He} \). Flowers' theory predicts no anomaly for the scattering of 19 to 22 Mev neutrons. On the other hand, if there is a state in \( ^5\text{He} \) at around 16 to 17 Mev excitation, then the neutron scattering crosssection will be expected to show an effect. This was one of the reasons for initiating this experiment. Then, if a level was found, it was hoped that some idea of its location and width could be obtained.
Experimental Procedure

It was decided to use a large helium filled ionization chamber, built in 1953 by Robert Brugger and described in his thesis. A diagram of the counter is given in Figure 6.

There are included in the chamber facilities for inserting a Thorium B $\alpha$-particle source, and the $\alpha$-particle spectrum was used to test the counter. Some difficulty was encountered initially, since electron capture due to impurities in the gas was distorting the pulse shape. This was finally overcome by filling the chamber extremely slowly through two or three liquid air traps in series. The final filling was of spectroscopically pure helium, after flushing with the helium purified through the liquid air traps.

The chamber was operated with a positive collecting voltage of 3000 volts on the center wire. The pulses were fed into an Atomic Instrument Co. Model 219 preamplifier attached to the counter, and from there into an Atomic Instrument Co. Model 204-B linear amplifier. The amplifier used had a five microsecond rise time, since ionization chamber pulses are in general slow rising.

The neutron source was a tritium target which was bombarded by deuterons from the Rice Institute 5.5 Mev Van de Graaff. The target was about 42 Kev thick to 500 Kev deuterons. At each bombarding energy the same amount of
charge was allowed to strike the target, while the number of counts was recorded. Two different methods of recording counting rates were used; the methods will be described below.

The center of the chamber was carefully positioned horizontally and vertically before each run, and was a distance of 15" from the target, where it subtended a solid angle of 0.07 steradians. This solid angle corresponds to a spread in neutron energy over the chamber of 50 Kev at a deuteron energy of 5.0 Mev.

The pulses from the counter, after amplification, were treated in two different ways. For the preliminary runs, a complete pulse-height versus voltage curve was run at a low bombarding energy with one channel of a five-channel pulse-height analyzer. Then four of the available channels were used as discriminators, and set on baselines such that they recorded all the pulses approximately 40%, 30%, 20% and 10% below the maximum pulse size. The fifth channel was used to monitor the number of very large pulses, to ensure that there were no unnoticed changes in the amplification of the system.

As the bombarding energy was increased, the percentage change in the neutron energy was calculated, and the discriminator baselines changed accordingly. The baselines were moved every few points so that they were never more than 1% off. In this manner the main features of the
excitation curve were found.

For the final run, it was desired to have closely spaced data points, in order to be sure that no small effects had been overlooked. To this end, the Rice Institute's 20-channel analyzer, Atomic Instrument Co. Model 520, was used. The 20-channel analyzer had not been used previously because of the nature of the ionization chamber pulses.

Proper operation of the analyzer requires a short (about one microsecond long), flat pulse, and therefore pulses are shaped by a delay line before being fed into the pulse-sorter circuits. Ionization chamber pulses, with a rise time of five microseconds, cannot be clipped this short with a delay line. In order to overcome this difficulty, an instrument was designed and built by Dr. F. W. Prosser of the Nuclear Laboratory.

Briefly, the operation of this circuit is as follows. When a pulse arrives at the input (after amplification by the linear amplifier), all the charge above a small bias is stored on a condenser. When the pulse voltage drops below the bias voltage, the condenser is suddenly discharged, making a very fast-rising pulse. This fast pulse is attenuated and fed to the 20-channel amplifier to be shaped and then counted.

With this modification of the 20-channel analyzer, it was possible to run a complete spectrum in a relatively
short time. Therefore the excitation curve was rerun and a complete spectrum recorded at each point. A graph was made of each of these spectra, and an end-point selected for each one. The end point was taken to be that point where the curve had dropped to half the value of the small peak near the end (see Figures 9 through 13 for typical spectra). The area under the graph was then computed for three different percentage distances back from the end-point. The three percentages were 30%, 20% and 10%. These data are shown in Figure 7, plotted with open circles, as a function of neutron energy. The lowest curve is the 10% one and the highest the 30% one. Starting at about 21.7 Mev neutron energy, the solid points are from an earlier run, when the region from 21.7 Mev to 22.3 Mev was gone over in very small steps.

These earlier data were taken by the first method discussed, although the bias voltages were not changed for this small energy interval. The three curves have been separately normalized to fit onto the three lower energy curves. The complete data for this energy interval is shown in Figure 8. It is worth noting that not all the points in Figure 8 have been plotted in Figure 7.

The bias voltages used in obtaining the data in Figure 8 may be related to the angle of scattering of the neutron. The highest curve then corresponds to the integral of the differential cross section, $d\sigma/d\Omega$, from 90° to
180°; the lowest is the integral from 137° to 180°.

Some of the angular distributions which were taken are illustrated in Figures 9 through 13. The labeled arrows in Figures 7 and 8 mark the places where the angular distributions are given.

**Discussion**

Because the nucleus He\textsuperscript{5} is light, with widely separated energy levels, it is ideal for study in an attempt to learn more about the properties of nuclear forces. The same may be said of the nucleus Li\textsuperscript{5}, which is mirror to He\textsuperscript{5}. For this reason, there has been much work done on both the scattering of neutrons from He\textsuperscript{4} and the scattering of protons from He\textsuperscript{4}.

In the neutron energy range of 0.4 Mev to 2.7 Mev, the angular distributions of neutrons scattered from He\textsuperscript{4} has been studied by Adair\textsuperscript{31}. Dodder and Gammel\textsuperscript{32} have analyzed the existing data on proton-He\textsuperscript{4} scattering up to 9.5 Mev proton energy and have used their results to predict phase shifts for neutron-He\textsuperscript{4} scattering. The data have been extended to higher energies by Smith\textsuperscript{33}, who used a cloud chamber to look at the angular distribution of 14.1 Mev neutrons scattered from He\textsuperscript{4}. Seagrave\textsuperscript{34} has used a large proportional counter filled with helium and krypton to look at the angular distributions of 2.61, 4.53, 5.54, 6.50 and 14.3 Mev neutrons.
The theoretical analysis of the data is usually made in terms of the phase shifts of different waves in a partial wave expansion of the incoming neutron beam. The phase shift of a wave is the number of degrees it is shifted by the nuclear potential relative to where it would be if the potential were not there. This is illustrated below; the dotted curve is the wave with no potential, the solid curve the wave with a nuclear potential, and $\Phi$ the phase shift.

Specification of the phase shifts at all energies will specify all properties of the interaction; the total cross-section, the differential crosssections, and the angular distributions.

For neutrons scattered elastically by $^4$He, the differential crosssection is given by:

$$
K^2 \sigma(0) = \left| \sum_l P_l(\omega, \Theta) \left\{ (l+1) \sin \delta^+_l e^{i\delta^+_l} + l \sin \delta^-_l e^{i\delta^-_l} \right\} \right|^2
$$

$$
+ \sin^2 \Theta \left| \sum_l \frac{dP_l(\omega, \Theta)}{d(\omega, \Theta)} \left\{ \sin \delta^+_l e^{i\delta^+_l} - \sin \delta^-_l e^{i\delta^-_l} \right\} \right|^2
$$

(1)
k is the neutron wave number, \( P_{\ell}(\cos \theta) \) are the Legendre polynomials and the \( \delta_\ell \) are the phase shifts. In the case of neutrons on helium, we need consider only 1-values of 2 or less and so the phase shifts will be the \( S_0, P_{\frac{1}{2}}, P_{\frac{3}{2}}, D_{\frac{3}{2}}, \) and \( D_{\frac{5}{2}} \) ones, abbreviated \( \delta_0, \delta_{\frac{1}{2}}, \delta_{\frac{3}{2}}, \delta_{\frac{5}{2}}, \) and \( \delta_{\frac{3}{2}} \).

In the present work, using a helium filled ionization chamber, we obtain directly the angular distributions of the scattered neutrons, \( \sigma(\theta) \), from the pulse height distributions. This may be shown readily. \( \sigma(\theta) \) is the cross-section for scattering into an angular interval between \( \theta \) and \( \theta + d\theta \), where \( \theta \) is the angle in the center-of-mass system. The number of particles scattered into this interval is then proportional to \( \sigma(\theta) \) times the fractional solid angle:

\[
\frac{dN}{d\Omega} \propto \frac{2\pi \sin \theta d\theta}{4\pi} \sigma(\theta) = -\frac{1}{2} \sigma(\theta) \cos \theta
\]

However, a particle recoiling at an angle \( \theta \) has an energy given by:

\[
E_2 = \frac{2m_1m_2}{(m_1+m_2)^2} E_1 (1 - \cos \theta)
\]

where \( E_1 \) is the energy of the incident particle and \( m_1 \) and \( m_2 \) are the masses of the incident and target particles,
respectively. From equation (3) we see that

$$d(\omega_0 \theta) = -C dE_2$$

where C is a constant. Therefore the number of particles per unit energy interval, $dN/dE_2$ (the pulse-height distribution), is directly proportional to the differential crosssection $\sigma(\theta)$.

$$\frac{dN}{dE_2} = A \sigma(\theta) \quad (4)$$

where A is a constant.

The pulse-height distributions given in Figures 9 through 13 give directly the shape of the center-of-mass angular distributions as a function of cosine $\theta$. The highest voltage pulses correspond to neutrons scattered at $180^\circ$ and the lowest ones to scattering at small angles.

In Figure 14 is presented some of the data computed by Seagrave$^{34}$, a summary of phase shifts and total crosssections from 0 to 20 Mev neutron energies. Figure 15 is a graph of the angular distributions to be expected from these phase shifts (extrapolating them to 22 Mev), calculated from equation (1). We have plotted $k^2 \sigma(\theta)$ in Figure 15, removing the energy dependence. This makes no difference, since we wish to compare shapes and not absolute values.

These angular distributions are to be compared with Figures 9 through 13, which give the experimentally determined angular distributions. The experimental curves are
smeared out because of the finite resolution of the counter, however the general features are clear enough.

The theoretical curves change very little in going from 16 to 22 Mev, in fact the only change is at the smaller angles. This behaviour agrees fairly well with the experiment, up to about 22 Mev the angular distributions have not changed markedly. At this point however, a small increase in the neutron energy causes a very definite change in the shape of the angular distributions (Figures 12 and 13). It is obvious that one of the phase shifts is changing quite rapidly with energy.

This is exactly what is expected in the vicinity of a resonance in the compound nucleus, where the phase shift for the level should go through 90°. Further evidence for a compound nucleus level is supplied by the excitation curves, Figures 7 and 8. In the region from 16 Mev to just below 22 Mev, where the angular distributions are changing very slowly, the excitation curves are monotonically decreasing functions of energy. But at a neutron energy of around 22.1 Mev, all four curves in Figure 8 exhibit anomalies; the two curves for the largest angles peak, while the lowest angle curves dip slightly.

Assuming a level in the compound nucleus He⁵, we can calculate the excitation energy. It is difficult to pick an exact resonant energy from the excitation curve, but it can be estimated as:
-40-

\[ E_{\text{RES}} = 22.15^{+0.05}_{-0.10} \text{ Mev} \]

The bombarding energy for the resonance is over 5 Mev, and for bombarding energies this high a correction must be applied to the measured energy. This correction is not known very well and introduces the possibility of another error. This estimated error in bombarding energy is ±30 Kev. This corresponds to an estimated error in neutron energy of ±35 Kev.

The neutron energy computed from the bombarding energy was corrected for the finite solid angle of the counter, and a possible error is introduced here. This error is estimated to be ±5 Kev. There would be an additional error introduced if the counter were not centered at 0° to the bombarding beam. This error is estimated as ±0.8 Kev, which corresponds to displacing the counter ½" at a distance of 19" from the target.

Finally, the estimated total error in the neutron energy is ±40, -48 Kev.

Therefore:

\[ E_{\text{RES}}^{(\text{LAB})} = 22.15^{+0.09}_{-0.15} \text{ Mev} \]

\[ E_{\text{RES}}^{(\text{C.M.})} = 17.67^{+0.07}_{-0.12} \text{ Mev} \]

The separation energy for He⁴ and a neutron is -0.95 Mev,
so the excitation energy in \( \text{He}^5 \) is:

\[
E_{\text{excit.}} = 17.67 - 0.95 = 16.72^{+0.07}_{-0.12} \text{ MeV}
\]

There is little doubt that we are observing the same level which is responsible for the peak in the \( \text{H}^3(d,n)\text{He}^4 \) neutron yield. It occurs at about the same energy and we observe no other levels. (The peak in the \( \text{H}^3(d,n)\text{He}^4 \) yield comes at an energy which corresponds to an excitation energy in \( \text{He}^5 \) of 16.69 Mev. However, because of the coulomb barrier effect, the level responsible for this peak must be at a lower energy, unless it is extremely narrow (a few Kev), in which case it can be at the same energy as the peak.)

It is somewhat surprising that the level is as narrow as we observe it to be. The width of the peak of the \( 90^\circ-180^\circ \) curve of Figure 3 is 200 Kev, this would correspond to a center-of-mass width of 160 Kev. Since \( \text{He}^4 \) is a very tightly bound nucleus, one might expect the levels of \( \text{He}^5 \) to be single-particle levels, a neutron orbiting about a \( \text{He}^4 \) core. This is definitely not the case, however. The width is far too narrow for a single-particle level.

There is obviously a need for more work in this energy range on both \( \text{He}^5 \) and \( \text{Li}^5 \). Probably the most promising line would be the \( \text{Li}^5 \) work. The mirror level in \( \text{Li}^5 \) can be expected to be as sharp as this one in \( \text{He}^5 \) and probably easily located. Very accurate data may be obtained from
charged particle scattering, and hence, accurate phase-shifts derived. Unfortunately, the proton energy needed is in the 20 to 25 Mev range, which is not accessible to Van de Graaff accelerators.
Figure 8
Figure 9
Figure 10
Figure 11

F
$E_N = 21.01 \text{ MEV}$

E
$E_N = 19.97 \text{ MEV}$
Figure 12
Figure 14
Acknowledgements

The author would particularly like to acknowledge the aid and advice of Dr. T. W. Bonner, under whose guidance the work was done. Mr. Richard Chapman helped materially with the taking of much of the data.

The author is also indebted to Dr. F. W. Prosser for aid and advice.

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Neutron Thresholds in the Deuteron Bombardment of Neon

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The counter ratio technique has been used to detect neutron thresholds in the deuteron bombardment of neon. Energy levels in Na$^{21}$, observed in the Ne$^{20}$(d,n)Na$^{21}$ reaction, were found at 1.46±0.04 and 2.426±0.037 Mev. The latter state is bound by only 26±8 kev from dissociation into Ne$^{20}+\gamma$ and will influence the cross section for the Ne$^{20}(p,γ)$Na$^{21}$ reaction at low energies. Two additional thresholds were observed which are attributed to the Ne$^{20}$(d,n)Na$^{21}$ reaction. The neutron yield indicates that for bombarding energies above 2.5 Mev a large fraction of the neutrons from the Ne$^{20}$(d,n)Na$^{21}$ reaction leave Na$^{21}$ in the excited state at 2.43 Mev.

INTRODUCTION

The counter ratio technique has been very successful in the measurement of the energies of excited states in the light nuclei produced in $(p,n)$ and $(d,n)$ reactions.$^{1-4}$ This procedure makes use of two paraffin-moderated BF$_3$ counters, one preferentially sensitive to neutrons with energies up to about 300 kev and the other sensitive only to those neutrons whose energy is greater than about 300 kev.$^3$ An abrupt change in the number of low-energy neutrons relative to the number of fast neutrons as the bombarding energy is increased indicates a neutron threshold and, consequently, an energy level of the residual nucleus in the reaction being investigated. This technique has been applied in the deuteron bombardment of neon in an effort to investigate the level structure of Na$^{21}$, formed in the Ne$^{20}$(d,n)Na$^{21}$ reaction ($Q=0.225$ Mev).

Previously, a study of the Ne$^{20}(p,γ)$Na$^{21}$ reaction had established$^7$ an excited state in Na$^{21}$ at 3.57 Mev. On the basis of the positions of the low-lying states in the mirror nucleus, Ne$^{20}$, there should be three levels in Na$^{21}$ below 3.57 Mev.$^9$ The results of Swann and Mandeville$^7$ and of Middleton$^{10}$ indicate the possibility of states at 0.40 and 2.40 Mev. No other information has previously been available concerning states below an excitation energy of 3.57 Mev.

An energy level near the binding energy of a proton in Na$^{21}$ (2.452 Mev) would be expected to influence the cross section for the radiative capture of low-energy protons by Ne$^{20}$. An enhancement of the Ne$^{20}(p,γ)$Na$^{21}$ yield appears necessary in the theories of the synthesis of the elements in helium-burning stars. The effects of the present investigation of Na$^{21}$ energy levels on the calculated reaction rates of the Ne-Na cycle in stars will be presented in a later paper.$^{11}$

EXPERIMENTAL PROCEDURE

The details of the counter ratio technique have been described previously.$^{1-5}$ In these experiments, solid targets were used exclusively in the measurement of threshold energies. Since neon is chemically inert, it is difficult to prepare a solid target containing a sufficient amount of neon to make neutron measurements possible. For this reason, a gas cell containing natural neon (90.9 percent Ne$^{20}$, 0.26 percent Ne$^{21}$, and 8.8 percent Ne$^{22}$) was employed. The neon gas was spectroscopically pure.$^{12}$ The gas cell was a platinum tube, $\frac{1}{4}$ in. in

![Fig. 1. Counter ratio curve for the O$^{17}$(d,n)F$^{18}$ threshold corresponding to the first excited state of F$^{18}$ measured with a solid WO$_3$ target and with a gas target. The 0.10-mil nickel foil was used with the gas target.](image)

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$^2$ National Science Foundation Postdoctoral Fellow.


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diameter and 1.5 in. in length. The entrance aperture, \( \frac{1}{2} \) in. in diameter, was covered with a nickel foil, either 0.025 mil or 0.10 mil in thickness. Gas pressures of 5 in. Hg were used. This amount of neon is about 135 kev thick to 2-Mev deuterons. During prolonged periods of bombardment with beam currents of 0.5 microampere, no leakage was detected. The usual arrangement of the neutron counters was employed.\(^1\)\(^-\)\(^6\)

Since the shape of the counter ratio curve to be expected at a neutron threshold when using the gas target was not known, measurements of the O\(^{18}\)(d,n)F\(^{17}\)\(^*\) threshold corresponding to the first excited state of F\(^{17}\) were made with the gas target and with a solid W\(_2\)O\(_3\) target. The results are shown in Fig. 1. The bombarding energy at this threshold has been previously determined\(^2\) to be 2.393±0.004 Mev. The reason for the dip at the peak of the ratio curve taken with the solid target has been discussed previously.\(^2\) When the gas target with the 0.10-mil nickel foil was used, the threshold energy, as determined by the intercept of the linear portions of the counter ratio curve, was found to be 2.625 Mev. Figure 1 shows that the threshold obtained with the solid target rises much more sharply than does that obtained with the gas target. By extrapolating the linear portions of the gas target curve, however, a well-defined energy may be obtained. This procedure, carried out on the O\(^{18}\)(d,n)F\(^{17}\)\(^*\) threshold, serves to determine an “effective thickness” of the nickel foil at 2.62 Mev, by which is meant the energy shift from the solid target threshold to the intercept of the extrapolated linear portions of the gas target curve. By using the “effective thickness” of the foil measured in this manner, straggling effects are automatically taken into account; furthermore, if other threshold energies are determined by the linear extrapolation technique, they may be measured to an energy of 10 kev or better. The “effective thickness” of the foil at 2.62 Mev was 232 kev, and the thickness at other energies was obtained by normalizing this value to the stopping cross-section curve for nickel as given by Fuchs and Whaling.\(^1\)\(^3\) The difference between the “effective thickness” and the thickness calculated from Fuchs and Whaling’s curve for a nominal 0.10-mil nickel foil is only 10%.

**RESULTS AND DISCUSSION**

The counter ratio and the yield of neutrons in the forward direction\(^4\) from the deuteron bombardment of neon were measured over the energy range from 1.1 to 3.0 Mev, using the deuteron beam from the Rice Institute Van de Graaff accelerator. From \( E_d = 1.1 \) to 2.1 Mev, the 0.025-mil nickel foil was used; these results are presented in Fig. 2. From \( E_d = 2.2 \) to 3.0 Mev, the 0.10-mil foil was used; these results are presented in Fig. 3. Four thresholds, marked A through D, were observed. The threshold energies, Q values, and excitation energies are given in Table I.

\(^{13}\) R. Fuchs and W. Whaling (unpublished).

\(^{14}\) By “forward direction” is meant the forward cone of half-angle 15°.
TABLE I. Neutron thresholds in the deuteron bombardment of neon.

<table>
<thead>
<tr>
<th>Threshold reaction</th>
<th>Effective foil thickness (keV)</th>
<th>E₀ (MeV)</th>
<th>Q value (MeV)</th>
<th>Excitation energy² (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A² Ne³⁰(d,ν)Na²¹</td>
<td>1.45±0.02</td>
<td>86</td>
<td>-1.24±0.02</td>
<td>1.46±0.04</td>
</tr>
<tr>
<td>B² Ne³⁰(d,ν)Na²¹</td>
<td>2.29±0.010</td>
<td>230</td>
<td>-1.56±0.0010</td>
<td>8.41±0.011</td>
</tr>
<tr>
<td>C² Ne³⁰(d,ν)Na²¹</td>
<td>2.64±0.007</td>
<td>231</td>
<td>-2.20±0.007</td>
<td>4.26±0.017</td>
</tr>
<tr>
<td>D² Ne³⁰(d,ν)Na²¹</td>
<td>1.88±0.015</td>
<td>222</td>
<td>-2.44±0.015</td>
<td>9.02±0.0124</td>
</tr>
</tbody>
</table>

* Calculated by using the mass values and uncertainties list by A. H. Wagner, Physics 21, 367 (1955).
* See reference 15.
* Assumed due to Ne²⁺; see text.

Threshold A is assigned² to the Ne³⁰(d,ν)Na²¹ reaction since it indicates a state in Na²¹ at 1.46 MeV which is close to that of a known level⁸ (1.73 MeV) in the mirror nucleus, Ne²¹. Similarly, threshold C yields a Na²¹ level at 2.426 MeV, mirror to a known Ne²¹ level (2.80 MeV); furthermore, the magnitude of this effect makes it almost certain that it is due to the most abundant (91%) isotope, Ne²⁰. The thresholds B and D do not correspond to mirror levels if they are due to the Ne³⁰(d,ν)Na²¹ reaction, and since these effects are small compared to threshold C, they are probably due to the Ne²²(d,ν)Na²³ reaction and have been listed accordingly in Table I. A further investigation with enriched neon isotopes will be necessary to establish this point with certainty.

In order to determine if all of these thresholds were due to neon, the gas was removed from the cell and the experiment repeated. Two weak thresholds, due to oxygen in the nickel foil, were observed. The magnitudes of these effects were too small to be observed when the neon bombardments were made. These measurements also served to obtain the background counting rates and these have been subtracted from the yield curves of Figs. 2 and 3. The background in the modified long counter amounted to about 30% over most of the energy range studied. The absolute cross sections are based on the long counter efficiencies previously measured,²⁴ and are probably accurate to about 40%.

The neutron yield shown in Figs. 2 and 3 increases smoothly except for a few broad resonances up to the threshold for emission to the 2.43-Mev state. For energies above the threshold, the yield increases much more rapidly and strongly suggests that a large fraction of the neutrons emitted in the Ne³⁰(d,ν)Na²¹ reaction leave Na²¹ in the 2.43-Mev state. This effect has been observed in other (d,ν) reactions when an intense threshold occurs near 2.2–2.5 MeV; the most pronounced case is found in the Ne³⁰(d,ν)O²⁰ reaction.² If thresholds B and D have been correctly assigned to the Ne²²(d,ν)Na²³ reaction, these thresholds must also be rather intense since they appear to be as much as 10% of the Ne³⁰(d,ν)Na²¹ threshold C and the abundance is only 9%.

The energy levels which are known below 5 Mev in the mirror nuclei Ne²¹ and Na²¹ are shown in Fig. 4. The Na²¹ level at 2.43 MeV should affect the Ne³⁰(ν,γ)Na²¹ cross section at low energies much more strongly than will any other Na²¹ level, since it is bound by only 26±8 kev.¹⁶

ACKNOWLEDGMENTS

The authors would like to express their appreciation for several helpful discussions with Professor William A. Fowler and Professor T. W. Bonner. One of us, (JBM) would like to thank the Rice Institute for extending to him the use of the facilities of the Nuclear Research Laboratory in order to conduct this experiment.

¹⁴ This threshold appears to be a real effect and not associated with the nearby resonance although it is known that resonances can affect the ratio curve when there are low-energy neutrons present. In the case of threshold A, however, there should be only two other neutron groups present, the ground state group and that to the first excited state (which as yet has not been detected with certainty). On the basis of the mirror levels in the Ne²⁰, these groups should have an energy difference of only 350 kev and consequently there should be no neutrons present at the resonance with energies low enough to affect the ratio curve.

¹⁶ The 37-kev uncertainty in the energy of this level in Na²¹ is due largely to the uncertainty (35 kev) in the mass of Na²¹; however, this latter value does not enter when the energy difference Na²¹–(Ne²⁰+γ) is computed.
(\(\rho, n\)) Reactions in Mn\(^{55}\), Co\(^{59}\), Zn\(^{57}\), and Zn\(^{68}\)+

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(Received October 8, 1956)

The counter ratio technique has been applied to the study of (\(\rho, n\)) thresholds in Mn\(^{54}\), Co\(^{59}\), Zn\(^{57}\), and Zn\(^{68}\). The ground state thresholds were found at proton energies of 1.185±0.005 Mev for Co\(^{59}\), 3.762±0.005 Mev for Zn\(^{57}\), and 1.805±0.005 Mev for Zn\(^{68}\). Thresholds were found corresponding to excited states in Fe\(^{56}\) at 0.924, 1.327, 2.16, 2.554, 2.92, and 3.76 Mev; in Ni\(^{58}\) at 0.325, 1.195, 1.776, 2.531, 3.043, 3.543, and 3.340 Mev; in Ga\(^{49}\) at 0.188, 0.342, 0.574, and 0.884 Mev; and in Ga\(^{67}\) at 0.337, 0.85, and 1.54 Mev. Absolute cross sections were measured for neutrons at 0° to the incident beam.

INTRODUCTION

The study of (\(\rho, n\)) reactions in elements of atomic number greater than 20 is more complicated than in the lighter elements because of the usual presence of several isotopes for each element and the smaller cross sections for the reactions in the 2- to 4-Mev range of bombarding energy. Cobalt and manganese are ideal for (\(\rho, n\)) investigations since they occur normally as single isotope elements.

Enriched samples of Zn\(^{67}\) and Zn\(^{68}\) are available from electromagnetic separation at Oak Ridge allowing separate study of these isotopes. The ground state thresholds for these elements lie in the lower portion of the proton energy range of the 6-Mev Rice Institute Van de Graaff accelerator. This allows, by means of the counter ratio technique, the study of the various excited states of the residual nucleus as well as the ground state thresholds.

The method of detection of neutron thresholds by the counter ratio method has been described in a number of articles.\(^1\) This method utilizes two paraffin-moderated BF\(_3\) proportional counters; the one, called the modified long counter, has a fairly uniform sensitivity for neutrons with energies above 200 kev and the other counter, called the slow counter, has its strongest sensitivity for neutrons of less than 400 kev. The yields shown in the present paper are determined by the modified long counter in its position behind the slow counter and are not corrected for variation of its sensitivity with neutron energy. The geometrical arrangement of the counters and the counter efficiencies are similar to those given by Brugger, et al.\(^2\)

When one uses this arrangement, the ratio of the counts in the slow counter to that in the modified long counter will indicate the presence of thresholds in the production of neutrons. When there is considerable yield of high-energy neutrons below the energy of a particular neutron threshold, the counter ratio rises to a maximum value above each threshold in an energy increment roughly equal to target thickness provided that the slow-neutron yield shows no strong resonances in this energy increment. In the absence of resonances, the rise of the ratio is due to the increasing number of slow neutrons relative to the high-energy neutron yield and continues until the whole target is contributing to the slow-neutron yield. When the proton energy is increased further, the ratio will in general decrease because of the increase in the energy of the threshold neutrons.

If there is no appreciable yield of high-energy neutrons below a threshold, then the ratio will rise to its value immediately above the threshold.

Resonances may occur which have strong effects on the counter ratio for proton energies of less than a few hundred kev above an excited state threshold. A rough estimate of this effect can be obtained from the variation of counter efficiencies with neutron energy.\(^2\) Consider the case of a residual nucleus whose first excited state (5/2+) is one Mev above the ground state (3/2−) and a resonance in the compound nucleus that is 1−. At this resonance, neutrons with \(l = 0\) are emitted when the nucleus is left in the ground state but \(l = 2\) neutrons are required to leave the nucleus in the first excited state.
Near threshold the number of these neutrons with $l=2$
will be very small and so the number of fast neutrons
might be doubled at the resonance with no increase in
the number of threshold neutrons. If such a resonance
comes at 100 kev above the first excited state threshold,
the counter ratio will decrease by approximately 30%.
On the other hand, if this resonance occurs 500 kev
above the threshold, the effect on the ratio will be less
than 4%.

Experiments carried out with targets that are thick
compared to the spacing between resonances increase
the number of neutrons which are not due to the
resonance in question and thus decreases its relative
effect.

Nevertheless, pronounced decreases in the counter
ratio can occur at a resonance and the subsequent rise
in the counter ratio above the resonance may be mis-
taken for a threshold.

Because of these anomalies in the counter ratio which
are not due to thresholds, an effort has been made
throughout this work to be conservative in assigning
the thresholds. Questionable effects in the ratio will not
be listed as thresholds but will be discussed in the text
as anomalies.

The energy calibration of the beam-analyzing magnet
is accomplished by means of a proton and lithium
resonance magnetometer and the conventional elec-
tronics. The Li$^7 ($p,$n$)Be$^7$ threshold served as the
primary standard for the calibration. A correction to
the calibration was applied at higher energies because
of saturation effects. The correction was derived by
checking the calibration at higher energies against
every well-known thresholds.

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threshold: 1882.5±0.9 kev.

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(1948).

---

Cross sections were obtained in the case of Co$^{59}$, Zn$^{67}$,
and Zn$^{65}$ by comparison to the Li$^7 ($p,$n$)Be$^7$ cross
section at equal neutron energies to avoid having to
know the exact counter efficiency variation with neutron
energy.

The lithium targets used were in the form of weighted
LiF evaporated on 2-mil pure aluminum blanks. To
reduce the chance of error, at least two different LiF
targets were used for each comparison. The comparisons
were made at proton energies of 2.18, 1.95, and 3.92 Mev
for Co$^{59}$, Zn$^{67}$, and Zn$^{65}$, respectively, and at these
energies the cross sections were found to be 0.074, 0.025,
and 1.65 mb/sterad, respectively, at 0° to the
beam of protons. These cross sections are believed to
be accurate to about 30%. The cross sections noted on
the figures are less accurate because the yields have not
been corrected for the variation of counter efficiency
with neutron energy. This correction would be impossible
to apply without knowledge of the percentage of
neutrons going to the various excited levels. Thus, a
cross section read off one of the figures is accurate to
only about 50%.

Because of the low yield involved, the cross section
for Mn$^{54}$($p$,n)Fe$^{58}$ had to be checked at a bombarding
energy of 1.97 Mev where two neutron groups were
present. The approximate energy of the two groups were
900 kev and 500 kev. Monoenergetic 630-kev neutrons
from Li$^7 ($p,$n$)Be$^7$ were used for cross-section compar-
ison, and since the efficiency of the modified long
counter does not change materially in this energy range,
no additional errors were introduced by the two groups
of neutrons. Thus, for Mn$^{54}$ the cross section of 0.15
(\(\rho, n\)) Reactions

mb/sterad at 1.97 Mev is approximately of the same accuracy as the other cross sections.

All cross sections given are averaged values from 0° to 10° in the laboratory system and represent the averaged values of the true cross sections over target thickness immediately below the comparison proton energies.

\[
\text{Mn}^{54}(\rho, n)\text{Fe}^{54}
\]

Initial difficulties were encountered in making thick manganese targets by evaporation. It was later found that aluminum blanks, sanded with No. 320 emery paper, would accept the manganese without flaking. This was either due to the removal of the thin oxide layer or to the roughness of the surface.

Figure 1 shows the ratio and yield obtained with a target of 2.1 mg/cm² which corresponds to a thickness of approximately 175 kev for 2.0-Mev protons. Even with a target of this thickness, several resonances in the yield can be noted. Owing to the small yield at low energies, the data were not extended below 1.5 Mev. Thus, the ground state threshold and possibly an excited state threshold were missed. Table I presents a list of thresholds observed, the calculated \(Q\) values, and the excited levels in \(\text{Ni}^{54}\). Since the ground state threshold was not observed in the present investigation, all excitation energies are given relative to the ground state \(Q\) value of 1.015±0.003 Mev as measured by Johnson.²

Some anomalous effects can be seen in the yield curve of Fig. 1. Threshold \(A\) rises for 150 kev which agrees with the known target thickness at this energy. Threshold \(B\), however, rises for 60 kev and is then followed by a dip in the ratio at 2.496 Mev. Experiments with a target approximately \(\frac{1}{2}\) as thick, showed a dip which is much more pronounced. However, since the dip is associated with several resonances in the yield and since the ratio above \(B\) has not risen for target thickness before the anomalous effect, the anomaly at 2.496 Mev is attributed to resonance effects. Stelson and Preston,⁶ using nuclear emulsion plates to measure proton recoil energies, reported level \(B\) to be 60 kev wider than level \(A\) and suggested the possibility of a doublet for \(B\). The present results do not prove the existence of such a doublet but cannot rule out this possibility.

Threshold \(C\) rises for 200 kev which is somewhat larger than the 140-kev target thickness at this energy. This rise might be caused by a delayed rise in the slow-neutron yield due to high-angular-momentum slow neutrons.

Thresholds \(E\) and \(F\) have indications of resonance dips immediately below threshold at 3.97 Mev and 4.8 Mev, respectively. This possibility introduced a larger error in choosing the energy at which the thresh-

| Table I. Neutron thresholds in the reaction Mn\textsuperscript{54}(\(\rho, n\))Fe\textsuperscript{54}. |
|-----------------|-----------------|-----------------|
| Threshold energy (Mev) | \(Q\) (Mev) | \(E_{\text{max}}\) (Mev) |
| \(A\) 1.975±0.010 | -1.939 | 0.924²⁴ |
| \(B\) 2.385±0.015 | -2.342 | 1.327 |
| \(C\) 3.24 ±0.03 | -3.18 | 2.17 |
| \(D\) 3.635±0.015 | -3.569 | 2.554 |
| \(E\) 4.01 ±0.04 | -3.94 | 2.92 |
| \(F\) 4.87 ±0.04 | -4.78 | 3.76 |

⁴ See reference ⁷.  
⁵ This is only the lowest level measured. It is possibly the second excited level.  

old occurs. Thresholds \(A\), \(B\), and \(C\) all agree within quoted errors to the excited levels observed by Stelson and Preston.⁶ There is a small anomaly in the ratio at 4.44 Mev which stays flat for target thickness. This could possibly be attributed to a threshold, but since it is close to a resonance and is not prominent, the effect is not listed as a threshold.

No level in the present work corresponds to the 1.84-Mev excited \(\text{Fe}^{54}\) level reported by Caird and Mitchell,⁸ who examined the positron decay of \(\text{Co}^{54}\). Other levels which they report at 0.935, 1.41, and 2.17 Mev roughly correspond to ones observed here.

\[
\text{Co}^{55}(\rho, n)\text{Ni}^{55}
\]

The \(\text{Co}^{55}\) target was normal cobalt electroplated from a cobalt chloride solution buffered with boric acid onto a tungsten blank which had been cleaned in boiling potassium hydroxide. The cobalt was evenly electroplated so that, after finishing the threshold investigation, the foil was peeled from the tungsten backing and weighed on a quartz spring balance and found to be 1.6 mg/cm², which corresponds to a thickness of approximately 120 kev for 2.0-Mev protons.

The ratio and yield for \(\text{Co}^{55}(\rho, n)\text{Ni}^{55}\) are shown in Fig. 2. Many resonances appear in the yield. Table II presents the thresholds observed. The ground state threshold of 1.895±0.005 Mev is in agreement with the value given by McCue and Preston⁹ of 1.889±0.003 Mev.

Anomalies in the ratio, which might be interpreted as thresholds, occur immediately following thresholds \(C\), \(D\), \(E\), and \(F\). However, since these effects follow so soon after thresholds and therefore are probably connected with resonances, they cannot be regarded as thresholds on the basis of present data. The ratio effect at \(G\) is chosen as a threshold since it occurs 300 kev above threshold \(F\) and is a relatively large effect considering that it occurs where the ratio would be dropping normally. The ratio effect at \(H\) is chosen as a threshold since if we considered it a resonance effect the ratio would rise for three times target thickness above

threshold $G$. There is a definite possibility that either effect $G$ or $H$ is not due to a threshold. There must be at least one threshold, however, to explain the fact that the ratio remains high for such a long energy interval above threshold $F$. The levels in Ni$^{59}$ at 0.325, 1.195, and 1.776 Mev agree with the results of Pratt$^{10}$ who studied the Ni$^{58}(d,p)$Ni$^{59}$ reaction.

Thresholds $C$, $D$, $F$, and $G$ give levels in Ni$^{59}$ which agree within the experimental errors to levels obtained from the Ni($n,\gamma$) data of Kinsey and Bartholomew,$^{11}$ if one assumes that $\gamma$ rays of energy 7.817, 7.22, 5.99, and 5.70 Mev are due to neutron capture in Ni$^{58}$.

The present results are in agreement with threshold work from 1.8 to 5.0 Mev performed by Butler, Dunning, and Bondelid,$^{12}$ although interpretation is different. The anomalies in the ratio curves above thresholds $C$, $D$, and $E$ of the present work are not listed as thresholds while Butler et al.,$^{12}$ have designated these effects as thresholds.

| TABLE II. Neutron thresholds in the reaction Co$^{59}(p,\alpha)$Ni$^{58}$. |
|---|---|---|
| Threshold energy ($\text{MeV}$) | $Q$ ($\text{MeV}$) | Ni$^{58}$ ($\text{MeV}$) |
| $A$ | 1.895±0.005 | -1.863 | 0 |
| $B$ | 2.225±0.015 | -2.188 | 0.325 |
| $C$ | 3.110±0.010 | -3.058 | 1.195 |
| $D$ | 3.701±0.010 | -3.639 | 1.776 |
| $E$ | 4.489±0.015 | -4.414 | 2.551 |
| $F$ | 4.990±0.010 | -4.906 | 3.043 |
| $G$ | 5.292±0.015 | -5.203 | 3.540 |
| $H$ | 5.499±0.015 | -5.406 | 3.543 |

$^{10}$ W. W. Pratt, Phys. Rev. 95, 1517 (1954).
$^{12}$ Butler, Dunning, and Bondelid (private communication).

**Zn($p,n$)Ga**

Enriched samples of Zn$^{64}$ and Zn$^{67}$ were obtained in the form of zinc oxide by loan from the Isotopes Division of the Oak Ridge National Laboratory. One sample had a composition (weight percent) of 93.9% Zn$^{64}$ and 0.4% Zn$^{65}$, while the other sample had a composition of 8.1% Zn$^{64}$ and 36% Zn$^{67}$. The remainder of the isotopes present to an appreciable extent were Zn$^{64}$ and Zn$^{66}$ whose ($p,n$) ground state thresholds of 8.1±0.5 Mev$^{13}$ and 6.05±0.05 Mev$^{14}$, respectively, are beyond the range of the present investigations.

Because of the small amounts of zinc oxide available, several methods of target making were investigated by using normal zinc. The low boiling point of zinc made reduction and evaporation of the metal quite inefficient. Electroplating was found to be more efficient and to produce satisfactory targets.

Some targets were made on aluminum blanks and weighed on a quartz balance. Those made on tungsten backings were more uniform and were used. The weights used for the Zn$^{64}$ and Zn$^{65}$ targets were obtained by assuming the same weight as for weighed targets made on aluminum blanks under identical conditions.

| TABLE III. Neutron thresholds in the reaction Zn$^{64}(p,n)$Ga$^{64}$. |
|---|---|---|
| Threshold energy ($\text{MeV}$) | $Q$ ($\text{MeV}$) | Ga$^{64}$ ($\text{MeV}$) |
| $A$ | 3.762±0.005 | -3.707 | 0 |
| $B$ | 3.953±0.006 | -3.895 | 0.188 |
| $C$ | 4.103±0.008 | -4.049 | 0.342 |
| $D$ | 4.345±0.012 | -4.281 | 0.574 |
| $E$ | 4.623±0.010 | -4.555 | 0.848 |

$^{13}$ B. L. Cohen, Phys. Rev. 91, 74 (1953).
Zn\(^{66}(p,n)\)Ga\(^{68}\)

The ratio and yield for a 1.6-mg/cm\(^2\) Zn\(^{66}\) enriched target is shown in Fig. 3. This weight corresponds to a thickness of approximately 90 kev for 3.7-Mev protons. The data extend from 3.6 Mev, which is below the Zn\(^{68}(p,n)\)Ga\(^{68}\) ground state threshold, to 5.6 Mev where the effects due to new thresholds are already becoming quite small. The region from 3.6 Mev to 5.05 Mev was also examined with a normal zinc target (results not shown). There was a one-to-one correspondence between the thresholds observed with the normal zinc target in this region and the Zn\(^{68}\) thresholds. The two strong resonances which appear in the Zn\(^{68}\) yield at 4.15 Mev and 4.92 Mev also appear in the normal zinc data.

Fig. 3. Zn\(^{68}(p,n)\)Ga\(^{68}\). The thresholds are marked by labeled arrows.

Zn\(^{67}(p,n)\)Ga\(^{67}\)

Fig. 4. Zn\(^{67}(p,n)\)Ga\(^{67}\). The thresholds are marked by labeled arrows.
TABLE IV. Neutron thresholds in the reaction $\text{Zn}^{67}(\rho,n)\text{Ga}^{67}$.

<table>
<thead>
<tr>
<th>Threshold energy (MeV)</th>
<th>$Q$ (MeV)</th>
<th>$\text{Ga}^{67\text{w}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1.805±0.005</td>
<td>-1.778</td>
<td>0</td>
</tr>
<tr>
<td>B 2.157±0.010</td>
<td>-2.135</td>
<td>0.357</td>
</tr>
<tr>
<td>C 2.67 ±0.02</td>
<td>-2.63</td>
<td>1.85</td>
</tr>
<tr>
<td>D 3.37 ±0.02</td>
<td>-3.32</td>
<td>1.54</td>
</tr>
<tr>
<td>E Zn$^{68}$</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

The thresholds observed in Zn$^{68}(\rho,n)\text{Ga}^{68}$ are presented in Table III.

The ground state threshold rises quite rapidly due to the smallness of the background in comparison to the neutron yield slightly above threshold. This ground state threshold of 3.762±0.005 Mev, which represents an average of three runs, is slightly higher than 3.749±0.006 Mev as measured by Brugger et al.$^2$ The first excited state at 188±8 kev is to be compared to 170±9 kev as measured by Brugger et al. In the present data, with separated isotopes, the first excited threshold is more pronounced and should be more accurate than the older measurements.

The resonance at 4.15-Mev bombarding energy seems to affect threshold C in Fig. 4. Data with a slightly thicker target of 1.8 mg/cm$^2$ did not show the dip above threshold C. A ratio anomaly at 4.884 Mev can be associated with the strong resonance at 4.92 Mev. Another ratio anomaly at 5.02 Mev can be associated with a resonance at 5.1 Mev. A small anomaly occurs at 5.36 Mev. Although this last anomaly shows a rise in the ratio for target thickness and does not appear to be connected with a strong resonance, it is such a small effect that it is not listed as a threshold.

$\text{Zn}^{67}(\rho,n)\text{Ga}^{67}$

The Zn$^{67}$ target was made under identical conditions to the Zn$^{68}$ target used and is also 1.6 mg/cm$^2$. For 2.0-Mev protons this target has a thickness of approximately 120 kev. The ratio and yield for this target are shown in Fig. 4. The data extend from 1.75 Mev, which is below the Zn$^{67}(\rho,n)\text{Ga}^{67}$ ground state threshold, to 4.5 Mev which is some distance above the Zn$^{68}(\rho,n)\text{Ga}^{68}$ ground state threshold. The ratio has been corrected for background below 2.35 Mev. Several resonances appear in the yield. The thresholds are given in Table IV.

Owing to the presence of 8.1% Zn$^{68}$ in this sample, the data above $E$ (3.762 Mev) are complicated by the Zn$^{68}$ yield. Knowing the percentages of Zn$^{67}$ and Zn$^{68}$ in the target and the Zn$^{68}(\rho,n)\text{Ga}^{68}$ cross section, a correction could be applied to the yield above the Zn$^{68}$ threshold. Figure 4 does not include this correction which would lower the ratio above 3.762 Mev by roughly 10%. It appears from the experimental curve that there are one or more thresholds in Zn$^{67}$ above $E$ in the energy range of from 3.9 to 4.1 Mev.

No previous information is available on the excited levels in Ga$^{67}$. Trail and Johnson,$^{14}$ however, have measured the ground state threshold to occur at 1.812±0.005 Mev. There is a ratio anomaly at 3.06 Mev which is attributed to the resonance at 3.08 Mev.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to Professor T. W. Bonner for his advice, assistance, and encouragement. Also, the authors wish to extend their appreciation to Dr. J. B. Marion for his assistance during the initial work on Mn$^{54}(\rho,n)\text{Fe}^{54}$. Discussion with other members of the staff of the Nuclear Research Laboratory have been most helpful.