Neutron Thresholds in the Deuteron Bombardment of Neon†

JERRY B. MARION,* *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

AND

J. C. SLATTERY AND R. A. CHAPMAN, *The Rice Institute, Houston, Texas*

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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 $Ne^{20}+p$ and will influence the cross section for the $Ne^{20}(p,\gamma)Na^{21}$ reaction at low energies. Two additional thresholds were observed which are attributed to the $Ne^{22}(d,n)Na^{23}$ 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.[1–6] 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 $Ne^{20}(p,\gamma)Na^{21}$ 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^{21}, there should be three levels in Na^{21} below 3.57 Mev.[8] The results of Swann and Mandeville[9] 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 $Ne^{20}(p,\gamma)Na^{21}$ 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.[1–6] 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

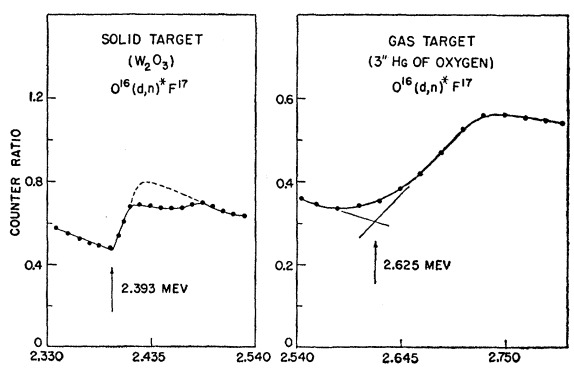

FIG. 1. Counter ratio curve for the $O^{16}(d,n)F^{17*}$ threshold corresponding to the first excited state of F^{17} measured with a solid W_2O_3 target and with a gas target. The 0.10-mil nickel foil was used with the gas target.

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[9] C. P. Swann and C. E. Mandeville, Phys. Rev. **87**, 215(A) (1952).
[10] R. Middleton (private communication to Professor W. A. Fowler).
[11] J. B. Marion and W. A. Fowler (to be published).
[12] Manufactured by the Linde Air Products Company, Buffalo, New York.

diameter and 1.5 in. in length. The entrance aperture, $\frac{1}{4}$ 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 $O^{16}(d,n)F^{17*}$ threshold corresponding to the first excited state of F^{17} were made with the gas target and with a solid W_2O_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 $O^{16}(d,n)F^{17*}$ 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

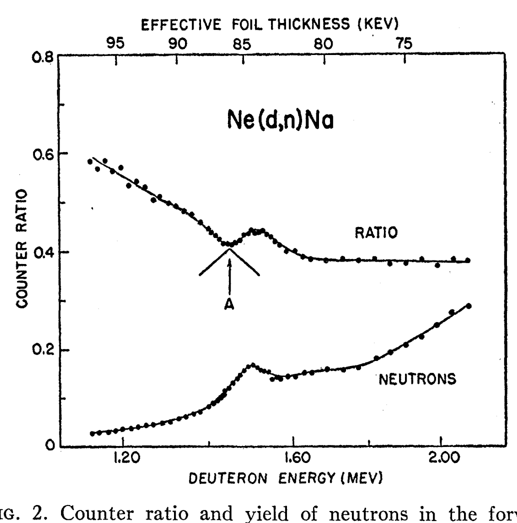

FIG. 2. Counter ratio and yield of neutrons in the forward direction from the deuteron bombardment of neon from $E_d=1.1$ to 2.1 Mev. The gas target with the 0.025-mil nickel foil was used. The pressure of natural neon was 5 in. Hg. The upper scale gives the "effective thickness" of the foil as a function of the bombarding energy.

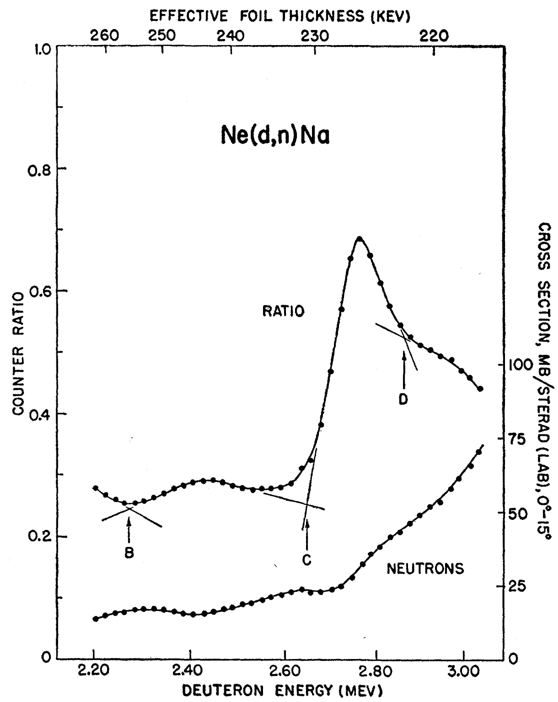

FIG. 3. Counter ratio and yield of neutrons in the forward direction from the deuteron bombardment of neon from $E_d=2.2$ to 3.0 Mev. The gas target with the 0.10-mil nickel foil was used. The pressure of natural neon was 5 in. Hg. The upper scale gives the "effective thickness" of the foil as a function of the bombarding energy.

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.[13] 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[14] 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.

Threshold reaction	E_d (Mev)	Effective foil thickness (kev)	Q value (Mev)	Excitation energy[a] (Mev)
A[b] $Ne^{20}(d,n)Na^{21}$	1.45 ±0.02	86	−1.24 ±0.02	1.46 ±0.04
B[c] $Ne^{22}(d,n)Na^{23}$	2.292±0.010	256	−1.866±0.010	8.435±0.021
C $Ne^{20}(d,n)Na^{21}$	2.654±0.007	231	−2.201±0.007	2.426±0.037
D[c] $Ne^{22}(d,n)Na^{23}$	2.887±0.015	222	−2.443±0.015	9.012±0.024

[a] Calculated by using the mass values and uncertainties list by A. H. Wapstra, Physica **21**, 367 (1955).
[b] See reference 15.
[c] Assumed due to Ne^{22}; see text.

Threshold A is assigned[15] to the $Ne^{20}(d,n)Na^{21}$ reaction since it indicates a state in Na^{21} at 1.46 Mev which is close to that of a known level[8] (1.73 Mev) in the mirror nucleus, Ne^{21}. Similarly, threshold C yields a Na^{21} level at 2.426 Mev, mirror to a known Ne^{21} level (2.80 Mev); furthermore, the magnitude of this effect makes it almost certain that it is due to the most abundant (91%) isotope, Ne^{20}. The thresholds B and D do not correspond to mirror levels if they are due to the $Ne^{20}(d,n)Na^{21}$ reaction, and since these effects are small compared to threshold C, they are probably due to the $Ne^{22}(d,n)Na^{23}$ 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,[2–6] 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 $Ne^{20}(d,n)Na^{21}$ reaction leave Na^{21} in the 2.43-Mev state. This effect has been observed in other (d,n) reactions when an intense threshold occurs near 2.2–2.5 Mev; the most pronounced case is found in the $N^{14}(d,n)O^{15}$ reaction.[2] If thresholds B and D have been correctly assigned to the $Ne^{22}(d,n)Na^{23}$ reaction, these thresholds must also be rather intense since they appear to be as much as 10% of the $Ne^{20}(d,n)Na^{21}$ threshold C and the abundance is only 9%.

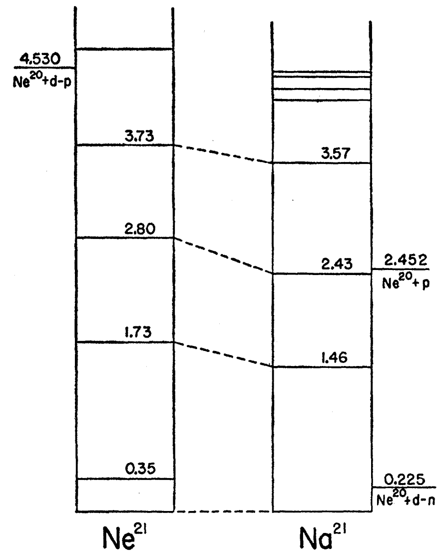

FIG. 4. Energy levels below 5 Mev in the mirror nuclei Ne^{21} and Na^{21}.

The energy levels which are known below 5 Mev in the mirror nuclei Ne^{21} and Na^{21} are shown in Fig. 4. The Na^{21} level at 2.43 Mev should affect the $Ne^{20}(p,\gamma)Na^{21}$ cross section at low energies much more strongly than will any other Na^{21} level, since it is bound by only 26±8 kev.[16]

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[15] This threshold appears to be a real effect and not associated with the nearby resonance although it is known[3] 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 Ne^{21}, 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 Na^{21} is due largely to the uncertainty (35 kev) in the mass of Na^{21}; however, this latter value does not enter when the energy difference $Na^{21*}-(Ne^{20}+p)$ is computed.