PHYSICAL REVIEW VOLUME 123, NUMBER 4 AUGUST 15, 1961

$C^{14}(d,n)N^{15}$ Reaction[*]

REN CHIBA[†]
University of Wisconsin, Madison, Wisconsin

(Received January 25, 1961)

Differential cross sections for ground-state neutrons from the $C^{14}(d,n)N^{15}$ reaction have been measured at $E_d=3.53$ Mev and 2.786 Mev by a neutron spectrometer. A stripping peak implying $l_p=1$ is observed. The excitation function of the ground-state neutrons has been measured from $E_d=1.2$ Mev to $E_d=3.53$ Mev. A number of resonances were found corresponding to virtual states of N^{16}. The angular distributions of neutrons associated with the 5.28-, 5.31-Mev doublet (unresolved) and 6.33-Mev levels of N^{15} were measured by photographic emulsion technique. A stripping peak characteristic of $l_p=0$ corresponds to the unresolved doublet, and $l_p=1$ to the 6.33-Mev state. The excitation function for all neutrons from $C^{14}(d,n)N^{15}$ was measured both by "slow" and "fast" neutron counters. Several possible slow-neutron thresholds were found corresponding to excited states of N^{15}. The sensitivity of the slow-neutron threshold technique was checked by the $O^{16}(d,n)F^{17}$. Accurate values of these thresholds are reported.

I. INTRODUCTION

THE energy levels of N^{15} have been extensively studied by many people,[1] using principally the $N^{14}(d,p)N^{15}$ reaction. The availability of C^{14} targets makes possible the investigation of N^{15} levels by the $C^{14}(d,n)N^{15}$ reaction. Since this reaction starts from the spin-zero C^{14} nucleus, the ambiguity of spin assignment to the levels of N^{15} is greatly reduced. The only previous study of the $C^{14}(d,n)N^{15}$ reaction was a neutron spectrum measurement in 1950 with low-energy incident deuterons.[2]

In the present work, the angular distribution of ground-state neutrons was taken with a neutron spectrometer. The angular distributions of neutrons from the 6.33-Mev level and 5.28-, 5.31-Mev doublet were measured with photographic emulsions. The angular distributions were analyzed by stripping theory.

The ratio of the $C^{14}(d,n)$ cross section to the 6.33-Mev N^{15} level and to the ground state is of considerable interest for intermediate-coupling calculations involving p-shell nuclei.[3,4] (The importance to theory of data concerning other N^{15} states has been reviewed by Halbert and French).[5]

The excitation function of the ground state neutrons shows resonances which correspond to virtual states of N^{16}.

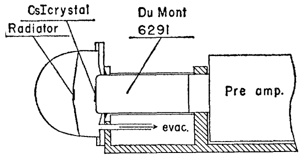

FIG. 1. Neutron spectrometer used for $C^{14}(d,n)N^{15}$ ground-state neutron cross sections. The radiator is 0.46-mm thick polyethylene.

A search for excited states of N^{15} was attempted by the "slow" neutron technique. The neutron threshold for the $O^{16}(d,n)F^{17}$ ground state and excited state were studied in order to find an optimum arrangement for "slow" and "fast" detectors and to explore the possibility of doublet structure of the first excited state of F^{17}.

II. EXPERIMENTAL ARRANGEMENTS

Deuterons accelerated by an electrostatic generator passed through an electrostatic analyzer which was calibrated in terms of the threshold for the $Li^7(p,n)Be^7$ reaction ($E_{\text{thresh}}=1.8811\pm0.005$ Mev.)[6]

Thin carbon targets were prepared by a discharge in C_2H_2 gas[7] which deposited carbon on the wolfram backing. For the C^{14} target, 38% enriched C^{14} was used. The thickness of the target was determined by weighing to be approximately 0.1 mg/cm^2.

A neutron spectrometer (Fig. 1) was built to separate the ground state $C^{14}(d,n)N^{15}$ neutrons from excited state neutrons. A 1-cm diameter, 0.46-mm thick polyethylene radiator was supported in the hemisphere by a thin wire. The detector was a 1.9-cm diameter, 1.4-mm thick CsI crystal mounted on a Du Mont 6291 photomultiplier tube. In order to reduce the background counting rate,

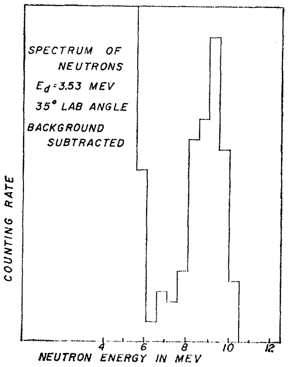

FIG. 2. Neutron spectrum from $C^{14}(d,n)N^{15}$ as given by the spectrometer of Fig. 1.

---

[*] Work supported by the U. S. Atomic Energy Commission and by the Graduate School from funds provided by the Wisconsin Alumni Research Foundation.

[†] Present address: Nippon Atomic Industry Group Co., Ltd., 1–12, 1, Yurakucho, Tokyo, Japan.

[1] See F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

[2] E. Hudspeth, C. F. Swann, and N. P. Heydenburg, Phys. Rev. **80**, 643 (1950).

[3] T. Auerbach and J. B. French, Phys. Rev. **98**, 1276 (1955).

[4] J. B. French, Phys. Rev. **103**, 1391 (1956).

[5] E. C. Halbert and J. B. French, Phys. Rev. **105**, 1563 (1957).

[6] K. W. Jones, R. A. Douglas, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **94**, 947 (1954).

[7] R. A. Douglas, B. R. Gasten, and A. Mukerji, Can. J. Phys. **34**, 1097 (1956).

the thickness of the CsI crystal is chosen just sufficient to stop the maximum energy recoil protons.

The pulse height in the CsI crystal was calibrated by protons from the $C^{12}(d,p)C^{13}$ reaction. A typical ground-state neutron group is shown in Fig. 2. The background was measured by operating the counter without a radiator. The background counting rate was 3% at 3.53-Mev deuteron energy, and has been subtracted from the data of Fig. 2.

For the angular distribution measurement, the spectrometer was mounted on a rotating arm. The radiator was 10.3 cm from the target. The angular resolution of the radiator was about ±3°.

For measurement of the ground-state excitation function, the spectrometer was placed close to the target. The angular resolution of the radiator was then about ±8°. The counting rate was normalized to the angular distribution data, and absolute cross sections were calculated. Background (beam on blank target backing) was 10% at $E_d = 3.53$ Mev, 5% at $E_d = 2.86$ Mev.

Unfortunately the spectrometer would not resolve the excited states of N^{15}. Hence for the angular distribution measurement of neutrons from N^{15} excited states, Ilford C-2, 200-μ nuclear photographic emulsions were used. The neutrons from the 6.33-Mev level of N^{15} were clearly resolved; however, the doublet 5.28-, 5.31-Mev levels were not resolved (see Fig. 3).

III. CROSS-SECTION RESULTS

For the ground-state neutrons, the neutron spectrometer (Fig. 1) was used to measure the excitation function at laboratory angles of 0° and 90°. The results are shown in Fig. 4. A number of broad resonances appear in the 0° data. Less pronounced fluctuations appear in the 90° data but it is possible to reproduce semi-quantitatively the 90° data as superpositions of resonances of the same energy and width as postulated to account for the 0° data. See Fig. 4. The results are summarized in Table I. Three of the resonances correspond well in energy and width to those reported by Douglas *et al.*[7] in the $C^{14}(d,p)C^{15}$ reaction. The resonance at $E_d = 3.10$ Mev is in parentheses because only the 90° data indicate its existence and the statistical uncertainty there is large.

TABLE I. Resonances in $C^{14}+d$.

Present work $C^{14}(d,n)N^{15}$			Earlier work[a] $C^{14}(d,p)C^{15}$	
E_d (Mev)	$\Gamma_{c.m.}$ (kev)	N^{16*} (Mev)	E_d (Mev)	$\Gamma_{c.m.}$ (kev)
1.30	220	11.56		
1.65	390	11.85		
2.04	305	12.20	2.0	270
			(2.15)[b]	(350)[b]
2.44	175	12.56	2.45	190
2.69	150	12.78	2.7	165
2.86	175	12.92		
(3.10)	(175)	(13.13)		

[a] See reference 7.

[b] J. A. Rickard, E. L. Hudspeth, and W. W. Clendenin, Phys. Rev. **96**, 1272 (1954).

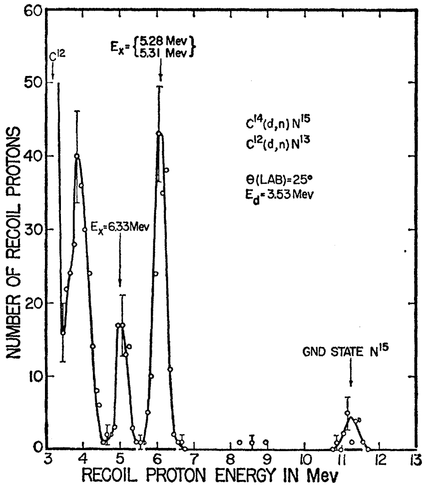

FIG. 3. Recoil protons in 200-μ thick Ilford C-2 photographic emulsions from the $C^{14}(d,n)N^{15}$ reaction [ground-state neutrons from $C^{12}(d,n)N^{13}$ are indicated by arrow at about 3.2 Mev].

Angular distributions of ground-state neutrons were obtained at deuteron energies of 3.53 and 2.786 Mev. The energy of 3.53 Mev was chosen as a convenient off-resonant value and 2.786 Mev is near a strong resonance. Figure 5 shows the observed angular distribution at $E_d = 3.53$ Mev. The data are in substantial agreement with the $l_p = 1$ Butler curve. This result is consistent with the known spin and parity of N^{15}. The angular distribution at $E_d = 2.786$ Mev (Fig. 6) shows almost no stripping peak. Apparently compound nuclear effects predominate near the resonance.

Angular distributions of neutrons from the 5.28-, 5.31-Mev doublet, and 6.33-Mev level of N^{15} were obtained only from the photographic emulsion data. See Figs. 7 and 8.

In contrast to protons from the $N^{14}(d,p)N^{15}$ reaction, the $C^{14}(d,n)N^{15}$ neutron yield from the N^{15} doublet 5.28-, 5.31-Mev level is more intense than the ground state yield and shows a strong $l_p = 0$ stripping peak. This strong forward peak requires that the spin of at

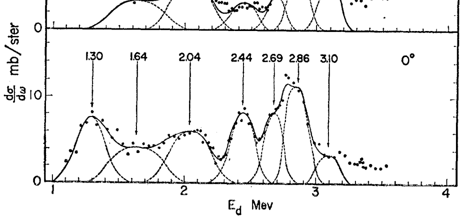

FIG. 4. Excitation function (laboratory coordinates) of ground-state neutrons from $C^{14}(d,n)N^{15}$. The dashed curves are postulated resonances (virtual states of N^{16}) to account for yield curve. Energies and widths are summarized in Table I.

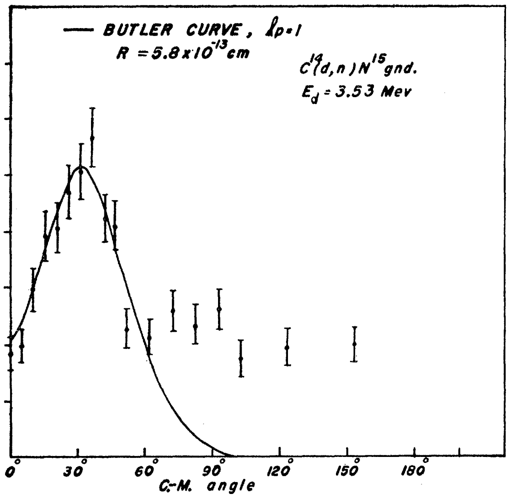

FIG. 5. $C^{14}(d,n)N^{15}$ ground-state differential cross sections for $E_d=3.53$ Mev.

least one of the doublet levels be $\frac{1}{2}$ with even parity. Halbert and French[5] predict that the 5.31-Mev level has spin $\frac{1}{2}$ and even parity and belongs predominantly to the $s^4p^{10}s^1$ configuration.

Figure 8 shows the angular distribution of neutrons from the 6.33-Mev level in N^{15}. The solid curve is Butler's curve for $l_p=1$ with the same nuclear radius as used in the calculation of the ground-state neutron angular distributions. An $l_p=1$ curve would imply $(\frac{1}{2}^-)$ or $(\frac{3}{2}^-)$ for the 6.33-Mev level. From shell-model consideration one expects the 6.33-Mev level to be the $\frac{3}{2}^-$ member of the ground-state spin doublet.

Absolute cross sections for the photographic emulsion data (Figs. 7 and 8) are found indirectly by comparing the excited state yields to the ground state yields in the photoemulsions. The intensity ratios were corrected for the geometrical escape factor[8] and the energy dependence of the n-p cross section. The ground-state cross sections come from the neutron spectrometer data and have an uncertainty of about 30%. The later uncertainty corresponds to C^{14} target thickness and composi-

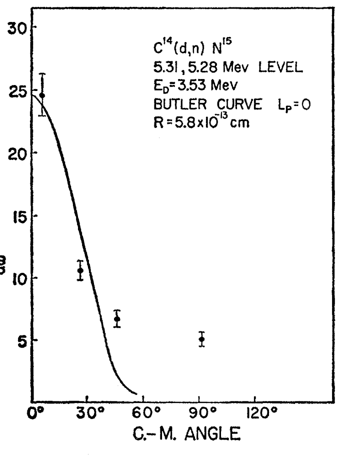

FIG. 7. Photoemulsion data: angular distribution of neutrons associated with the unresolved 5.31-, 5.28-Mev doublet state of N^{15}. Cross sections are from normalization to spectrometer ground-state measurements (e.g., see Figs. 2, 3, and 5).

tion uncertainty of ~20%, spectrometer solid angle and efficiency uncertainty, ~20%, and a statistical uncertainty of ~10%. The excited state absolute cross sections have an additional large (~25%) statistical uncertainty because of the small number of ground state recoil proton tracks available for the intercomparison with the spectrometer data.

French[4] has pointed out the ratio of the $C^{14}(d,n)N^{15}$ ground state yield to the 6.33-Mev state yield specifies almost uniquely the C^{14} wave function. For pure j-j coupling one expects no cross section to the 6.33-Mev level. The present experiment shows the ***higher*** cross section to be to the 6.33-Mev level: $\sigma^*/\sigma=1.5\pm0.4$. For comparison with Fig. 1 of French's paper,[4] this ratio should be corrected for kinematic stripping factors (e.g., as in the Appendix of Auerbach and French[3]). This correction gives $\sigma^*/\sigma\cong0.6$ and French's Fig. 1 would imply (in his notation) for $x\geq 0$, either $y\cong0.3$ or $y\cong\pm1$. The former solution (i.e., $y\approx0.3$) is in better agreement with other data on the $A=14$ and $A=15$ nuclei and would imply that the ground state of C^{14} is predominantly ${}^1S_0$. This value for y (the amplitude of the ${}^3P_0$ wave function) is about a factor of two less than Sherr *et al.*[9] deduce indirectly from the decay rates of the $A=14$ polyad. The largest uncertainty in the ${}^3P_0$ amplitude from the present work probably lies in the

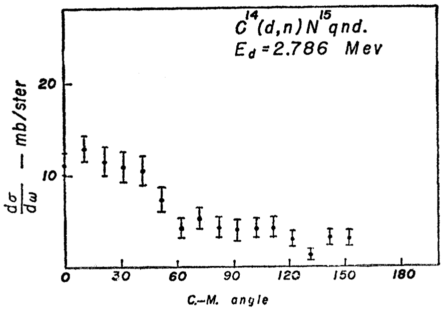

FIG. 6. $C^{14}(d,n)N^{15}$ ground-state differential cross sections for deuteron energy near a resonance.

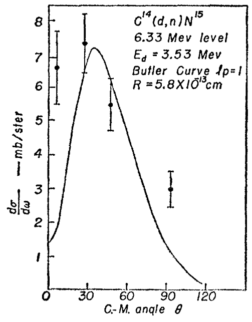

FIG. 8. Same as Fig. 7 except for the resolved 6.33-Mev state of N^{15}.

---

[8] H. T. Richards, Phys. Rev. 59, 796 (1941).

[9] R. Sherr, J. B. Gerhart, H. Horie, and W. F. Hornyak, Phys. Rev. 100, 945 (1955).

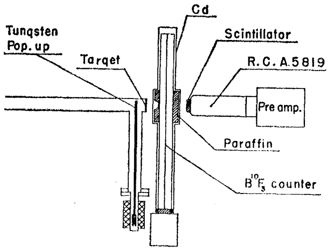

FIG. 9. Experimental arrangement for "slow" neutron threshold measurements. Blank tungsten disks could be inserted by solenoid activated pop-up for background measurement. The "fast" neutron scintillator was ZnS powder in a high viscosity silicone fluid. The "slow" neutron detector is the conventional $B^{10}F_3$ counter plus a small cylinder of paraffin.

adequacy of the stripping calculations for the relatively low-deuteron energy (3.53 Mev) and the large energy difference (6.3 Mev) between the two single-hole states of N^{15}.

IV. SLOW-NEUTRON THRESHOLDS

A search for N^{15} excited states in the 9–11 Mev region was made by using the counter ratio technique to locate thresholds for new groups of neutrons from $C^{14}(d,n)N^{15}$. The technique is difficult for this reaction in that the Q for the ground-state reaction is large and hence many different neutron groups are already present whose relative yield may vary radically between resonances. In addition the target is $\sim 60\%$ C^{12}. The "slow"-neutron detector was the usual enriched BF_3 counter with a small paraffin cylinder (4.5 cm o.d. by 4 cm long) surrounding it. See Fig. 9. The counter was covered by 0.8-mm cadmium sheet to reduce the thermal neutron background.

A mixture of high-viscosity silicone fluid[10] and Ag-activated ZnS powder ($\frac{1}{3}$ by volume) mounted on an RCA 5819 photomultiplier tube was used as the detector for the fast neutrons. Discriminator bias was set so that the counter responded primarily to neutrons above 1-Mev energy. A thick hydrogenous scintillator like this should have approximately constant sensitivity over a wide range of neutron energies above the bias cutoff energy.[11] This type of energy insensitive fast detector was preferred to the conventional "long counter" because the large CH_2 mass of such a counter scattered back many epithermal neutrons to the "slow" detector, thereby reducing the relative effect of slow neutrons from the target.

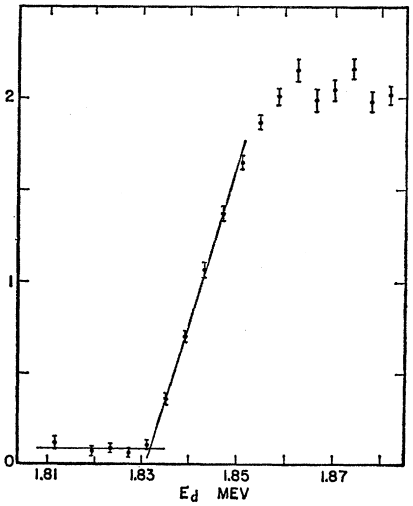

FIG. 10. $O^{16}(d,n)F^{17}$ ground-state slow-neutron threshold data taken with setup of Fig. 9. (There were negligible counts in the "fast" detector.) Ordinate is neutron counts (arbitrary scale).

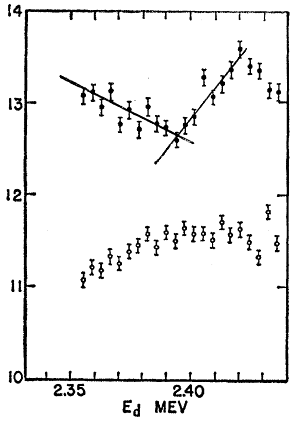

FIG. 11. $O^{16}(d,n)F^{17}$ excited-state slow-neutron threshold. Note suppressed zero on ordinate scale. Solid circles are "slow" neutron data; open circles, "fast" neutron data. See Table II.

A large and fluctuating neutron background was corrected for by taking many short runs alternately with background runs. For the background run a clean wolfram disk was popped in front of the target by a solenoid. An ordinary C^{12} target was used to correct the neutron yield from the 62% of C^{12} in the C^{14} target in the slow neutron threshold measurement.

To check the performance of the "slow" and "fast" neutron detectors the $O^{16}(d,n)F^{17}$ thresholds to the ground and first excited state were studied. Thin oxygen targets were prepared by heating wolfram disks in oxygen at $\sim$1-cm pressure. Results are shown in Figs. 10 and 11. Linear extrapolations to thresholds has been used to facilitate comparison with previous measure-

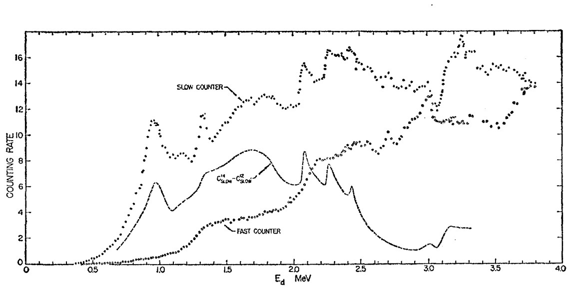

FIG. 12. Survey "slow" (solid circles) and "fast" (open circles) neutron yield at 0° from a thin carbon target (38% C^{14}) bombarded by deuterons. Experimental arrangement as in Fig. 9. Dashed C^{14}"$_{slow}$"$-C^{12}$"$_{slow}$" curve is computed from additional survey data (not shown) for an ordinary thin C^{12} target.

---

[10] Dow Corning 200.

[11] H. H. Barschall and H. A. Bethe, Rev. Sci. Instr. 18, 148 (1947).

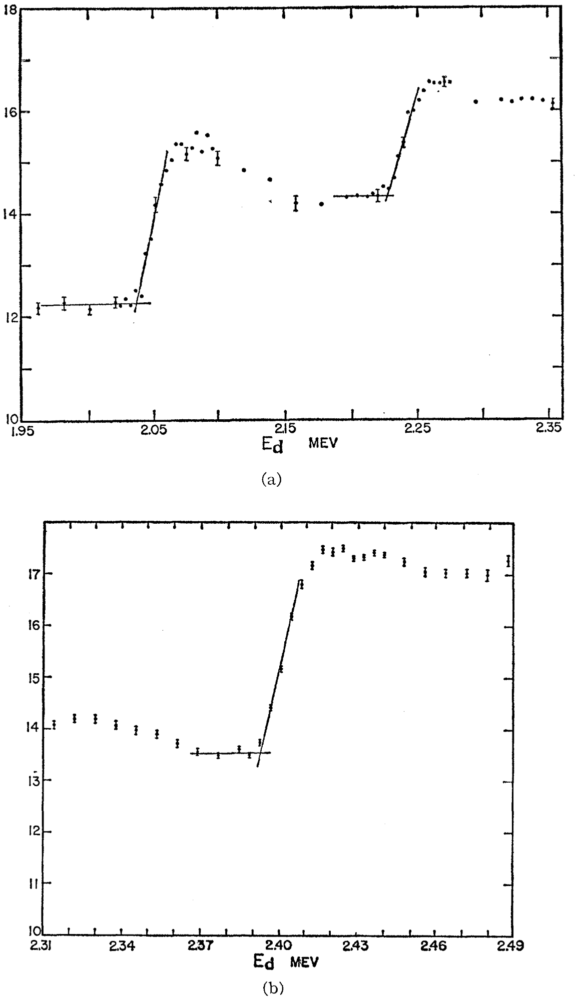

FIG. 13. Detailed study of several slow-neutron thresholds made with thinner targets. Note suppressed zero of ordinate. Results are summarized in Table III.

TABLE II $O^{16}(d,n)F^{17}$ Slow-neutron thresholds (linear extrapolations except for *b*).

	Present work Threshold	Earlier work[13] Threshold
Ground	1.832±0.003	1.830 ±0.004 1.835 ±0.005[a] 1.8292±0.0006[b]
Excited	2.393±0.003	2.393 ±0.004

[a] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951).
[b] R. O. Bondelid, J. W. Butler, and C. A. Kennedy, Phys. Rev. **120**, 889 (1960).

ments and because a linear extrapolation was used for the Li(p,n) standard. A two-thirds power extrapolation is preferred on theoretical grounds. Bondelid *et al.*[12] find the two-thirds power extrapolation lowers the threshold of this reaction by about three kev.

The data of Fig. 11 are of interest in that the anomalous dip in ratio of slow to fast yield reported by Marion *et al.*[13] at $E_d = 2.42$ Mev is absent.

The survey data from both the slow and fast counter are shown in Fig. 12. Since the target is only 38% C^{14} an additional (but not as extensive) survey run with an ordinary carbon target was made. The C^{14} "slow" yield after subtraction of the C^{12} "slow" yield is shown by the dashed curve. Three sharp anomalies, $E_d = 2.04$, 2.25, and 2.40 Mev, which are of the character expected for a slow-neutron threshold remain. Other anomalies in the "slow" yield from C^{14} appear $\approx E_d \sim 0.9$, 1.25, 2.9, and 3.2 Mev. Some of these anomalies may be associated with slow neutron thresholds but the present data are unconvincing particularly as regards the shape. The three sharp anomalies whose shape corresponds to slow neutron thresholds were examined in more detail with thinner targets to accurately fix the threshold energies. The results are shown in Fig. 13(a) and Fig. 13(b) and summarized in Table III. It will be noted that very few

TABLE III. Slow-neutron thresholds, $C^{14}(d,n)N^{15}$.

Possible thresholds[a] $E_d \pm 0.01$ Mev	Observed thresholds Figs. 12, 13 E_d (Mev)	Q $C^{14}(d,n)N^{15*}$ (Mev)	E_x of N^{15} levels in Mev	
			From thresholds[b]	Previous data[c]
0.67				8.575±0.008
1.23	(1.25)?		(9.1)?	9.062±0.010
1.34				9.165±0.010
	2.036±0.003	−1.780±0.003	9.768±0.008	
2.11				9.834±0.010
	2.227±0.003	−1.947±0.003	9.935±0.008	
2.38	2.393±0.004	−2.092±0.004	10.080±0.008	10.069±0.010
2.82				10.458±0.010
2.92	(2.9)?		(10.5)?	10.544±0.010
3.22	(3.2)?		(10.7)?	10.705±0.010

[a] As calculated from the known N^{15} levels listed in the last column.
[b] The Q for the ground-state $C^{14}(d,n)N^{15}$ reaction is most accurately found from the reaction cycle: $C^{14}(p,n)N^{14}$, ($Q = -0.6264 \pm 0.0005$ Mev, R. Sanders, Phys. Rev. **104**, 1434 (1956) and $N^{14}(d,p)N^{15}$, [$Q = 8.614 \pm 0.007$, D. Van Patter and W. Whaling, Revs. Modern Phys. **26**, 416 (1954)].
[c] See reference 14.

---

[12] R. O. Bondelid, J. W. Butler, and C. A. Kennedy, Phys. Rev. **120**, 889 (1960).
[13] J. B. Marion, P. Brugger, and T. W. Bonner, Phys. Rev. **100**, 46 (1955).

of the previously known N^{15} levels show up as distinct slow-neutron thresholds. This result is not too surprising for one would expect sharp thresholds only for those N^{15} states for which the compound nucleus level had a large reduced width for s wave neutron emission. More puzzling is the fact that the two strongest and sharpest observed thresholds, $E_d=2.036$ and 2.227 Mev, do not correspond to any previously observed N^{15} level. However, the only previous data on N^{15} levels in this region come from M. I. T. magnetic spectrometer data[14] on $N^{14}(d,p)N^{15}$. Unfortunately their nitrogen target (nylon) contained enough carbon that the prominent proton groups from $C^{12}(d,p)$ reactions to the 3.855- and 3.684-Mev states of C^{13} completely swamp the plate region where these N^{15} groups would be expected to occur. (See, e.g., their Figs. 1 and 4.)

Since the threshold at $E_d=2.393$ Mev occurs at the same energy as the $O^{16}(d,n)$ threshold to the first excited state of F^{17} (see Fig. 11), oxygen contamination of the target must be considered. Absence of the much stronger $O^{16}(d,n)F^{17}$ ground-state threshold ($E_d=1.832$ Mev) excludes this possibility.

ACKNOWLEDGMENTS

The author wishes to express thanks to Professor Hugh T. Richards who suggested and guided this work. The author would also like to thank Dr. William R. Phillips and Dr. E. A. Silverstein for their assistance in taking data.

---

[14] A. Sperduto, W. W. Buechner, C. K. Bockelman, and C. P. Browne, Phys. Rev. **96**, 1316 (1954).

PHYSICAL REVIEW VOLUME 123, NUMBER 4 AUGUST 15, 1961

Neutrons and Gamma Rays from the Bombardment of O^{16} by He^3

K. L. Dunning and J. W. Butler
Nucleonics Division, U. S. Naval Research Laboratory, Washington, D. C.

(Received April 11, 1961)

The threshold energy for the $O^{16}(He^3,n)Ne^{18}$ reaction has been measured. The value obtained, 3.811 ± 0.015 Mev, determines the mass of Ne^{18} to be 18.011446 ± 0.000014 amu (O^{16} standard, 1960 mass tables). The slow-fast ratio method for the observation of neutron thresholds was employed at bombarding energies from the ground-state threshold to 5.6 Mev, corresponding to a region of excitation in the residual nucleus from zero to 1.5 Mev. No excited states in Ne^{18} were identified. The bombardment of O^{16} by He^3 also produced the reactions $O^{16}(He^3,p)F^{18}$ and $O^{16}(He^3,\alpha)O^{15}$. Energy spectra were obtained by means of a scintillation spectrometer for gamma rays resulting from certain transitions in F^{18} and O^{15}. For 4.5-Mev He^3 particles impinging on a 1-Mev thick target of TiO_2, gamma rays of the following energies were observed and attributed to F^{18}: 0.652 ± 0.007, 0.939 ± 0.005, 1.041 ± 0.005, 1.17 ± 0.01, 1.61 ± 0.02, 1.68 ± 0.02, 2.09 ± 0.01, 2.51 ± 0.01, 2.65 ± 0.05, 3.06 ± 0.05, 3.35 ± 0.10?, and 3.84 ± 0.10 Mev. The following gamma rays were also observed and attributed to O^{15}: 5.25 ± 0.05, 6.22 ± 0.10, and 6.87 ± 0.10 Mev.

INTRODUCTION

THE first experimental evidence for Ne^{18} was reported by Gow and Alvarez[1] who produced it in the reaction $F^{19}(p,2n)Ne^{18}$, and found it to be a positron emitter with an end point of 3.2 ± 0.2 Mev, a half-life of 1.6 ± 0.2 sec, and a log*ft* value of 2.9 ± 0.2. In the present experiment, the reaction $O^{16}(He^3,n)Ne^{18}$ has been used to determine the mass of Ne^{18} by means of a ground-state threshold measurement and also to search for excited states of Ne^{18}. Bombarding energies up to 5.6 Mev have been used. Also, energy spectra have been obtained for gamma rays arising from the reactions $O^{16}(He^3,p)F^{18}$ and $O^{16}(He^3,\alpha)O^{15}$ at a bombarding energy of 4.5 Mev. These gamma rays have been correlated to transitions in F^{18} and O^{15}. A preliminary report has been made on part of this work.[2]

EXPERIMENTAL PROCEDURE

Four thin targets and one fairly thick target of O^{16} were bombarded with the magnetically analyzed singly-charged He^3 beam from the NRL 5-Mv Van de Graaff accelerator. The energy spread in the beam was about $\frac{1}{3}\%$. The neutron yields from the four thin targets were examined with the counter-ratio method, as a function of the bombarding energy. The apparatus and procedures used for these measurements have been described previously.[3,4] The gamma rays resulting from the bombardment of the fairly thick target with a 4.50-Mev beam were detected in a 3-in.×3-in. NaI(Tl) crystal mounted on a type-6363 multiplier phototube after they had passed through a composite shield designed to reduce the intensity of x rays and annihilation radiation relative to that of higher-energy radiation. The materials through which the gamma rays passed after leaving the target and before entering the NaI crystal were as follows, and are given in the order of flight: stainless steel, 0.025 in. (target chamber wall); paraffin, 0.25 in.; lead, 0.31 in.; tantalum, 0.016 in.; cadmium, 0.012 in.; zinc, 0.010 in.; aluminum, 0.031 in.

---

[1] J. D. Gow and L. W. Alvarez, Phys. Rev. **94**, 365 (1954).

[2] K. L. Dunning and J. W. Butler, Bull. Am. Phys. Soc. **4**, 444 (1959).

[3] K. L. Dunning, R. O. Bondelid, and J. W. Butler, Phys. Rev. **110**, 1076 (1958).

[4] J. W. Butler, K. L. Dunning, and R. O. Bondelid, Phys. Rev. **106**, 1224 (1957).