tectable in the rise and in the oscillations precursory to the rise by comparing the reactions $Pb^{208}(O^{16},O^{16})Pb^{208}$, and $Tb^{159}(F^{19},F^{19})Tb^{159}$. In the present work there is an indication of similar trends in the scan across projectiles (Fig. 6). However, experimental angular resolution and statistics do not allow quantitative evaluation of this effect. Further work in the rare-earth region would be of interest.

ACKNOWLEDGMENTS

We wish to thank the operating crew of the HILAC for their cooperation during exposures. We also would like to thank Dan O'Connell for his help in preparing the targets and Dr. George Farwell and Dr. Arthur Fairhall for the target materials. We are grateful for the assistance of our scanners, Charles Chiu, David Corey, Paul Hsu, and David Yu.

PHYSICAL REVIEW VOLUME 127, NUMBER 4 AUGUST 15, 1962

Measurement of the $O^{16}(n,p)N^{16}$ Cross Section from 11 to 19 MeV

J. A. DeJuren* and R. W. Stooksberry
Bettis Atomic Power Laboratory,† Westinghouse Electric Corporation, Pittsburgh, Pennsylvania

AND

M. Wallis
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received Nobember 27, 1961; revised manuscript received May 14, 1962)

The present experiment was undertaken to improve upon the accuracy and energy resolution of the $O^{16}(n,p)N^{16}$ cross section and to extend the neutron energy range covered. The oxygen was contained in a dioxane liquid scintillator which was irradiated by accelerator-produced neutrons. Shaped holders were used at appropriate angles from the target to obtain good energy resolution for neutrons produced by both $T(d,n)He^4$ and $D(t,n)He^4$ reactions. After the irradiation the scintillator was automatically transferred to a 4π β-counting system. The resulting cross section data exhibit a previously undetermined resonance near 11.8 MeV. Integration of the experimental cross sections over U^{235} fission spectrum formulations yield values of 16 to 19 μb per neutron.

I. INTRODUCTION

An earlier measurement of the $O^{16}(n,p)N^{16}$ cross section from 12.4 to 18 MeV was made by Martin[1] in 1953. The energy resolution below 15 MeV was ± 1 MeV and the absolute value near 14.7 MeV was a factor of 2 higher than later results obtained by DeJuren and Stooksberry,[2] Kantele,[3] and Seemann and Moore.[4] The present experiment was undertaken to improve the energy resolution and to extend the energy range covered. A cooperative experiment was undertaken by Bettis and Los Alamos personnel utilizing the Los Alamos 3.0-MeV Van de Graaff accelerators and the $T(d,n)He^4$ and $D(t,n)He^4$ reactions to cover the energy range from 11 to 19.4 MeV. As in the 14.7-MeV measurement[2] at Bettis Atomic Power Laboratory, the oxygen was contained in a dioxane-based liquid scintillator and was irradiated in various geometrically shaped holders at different angles with respect to the beam direction to obtain the different neutron energies. After an irradiation the liquid was automatically transferred to a Vycor cell between two EMI 7064 photomultipliers and the β rays were counted in a 4π system. The system used in the 14.7-MeV experiment was again used but without photomultiplier cooling. Beta particles above 20 keV were counted, with a detection beta efficiency of 99.5%.[2]

II. EXPERIMENTAL PROCEDURE

Two 3-MeV Van de Graaff accelerators were used to provide sources of monoergic neutrons by means of the $D(t,n)He^4$ and the $T(d,n)He^4$ reactions. The respective energy ranges available were 11 to 19.4 MeV and 12 to 19 MeV at accessible laboratory angles. Even though the first reaction provided the complete range of neutron energies covered in this experiment, of the two accelerators, only one could be used to accelerate tritons and the time that this machine could be used was limited. Therefore, some of the intermediate neutron energies were obtained using the $T(d,n)He^4$ reaction on the second machine. Backgrounds were present due to the t-T reaction[5] when the t-D source was being used and the $D(d,n)He^3$ reaction when the d-T source was being used. These two backgrounds

* Now at Atomics International, Canoga Park, California.
† Operated for the U. S. Atomic Energy Commission by Westinghouse Electric Corporation.
[1] H. C. Martin, Phys. Rev. **93**, 498 (1954).
[2] J. A. DeJuren and R. W. Stooksberry, Phys. Rev. **120**, 901 (1960).
[3] Juhani Kantele, Bull. Am. Phys. Soc. **6**, 252 (1961).
[4] K. W. Seemann and W. E. Moore, Bull. Am. Phys. Soc. **6**, 237 (1961).
[5] S. J. Bame, Jr., and W. T. Leland, Phys. Rev. **106**, 125 (1957).

have to be accounted for differently. Agreement in the measured cross sections at overlapping energies can be interpreted as some degree of confirmation of the way in which the backgrounds were handled.

Energy Calibration and Resolution

Gas targets, having a nominal path length of one cm for the bombarding particles, were used as neutron sources. The accelerated deuterons passed through a 0.00005-in. nickel window before entering the tritium gas. A special high-current target having two such nickel windows was used when accelerating tritons. A cooling stream of helium passed between the windows, thus allowing greater beam currents. Since an accurate value of the ionization loss in the target windows and helium was needed to determine the tritium energy in the deuterium gas, the loss was measured directly. The threshold for the p-T reaction was measured using a thin, solid tritium target and a long counter in the forward direction one meter from the target. This measurement calibrates the energy of the accelerator at 1.019 MeV. Then the measurement was repeated using the double-window target with a tritium pressure of 10 cm of Hg. The shift in the accelerator energy at threshold gave the proton energy loss. This was converted into tritium energy loss at the different bombarding energies using the tabulation of Whaling.[6] During the experiment each machine was operated with a target gas pressure near 81 cm of Hg.

Measurement of Neutron Flux

The double window target was used for the $D(t,n)He^4$ portion of the experiment. A simplified proton recoil telescope of the Los Alamos design[7] was used as a neutron monitor during the sample irradiations. This telescope has a polyethylene radiator mounted on a nickel disk which may be rotated so that the radiator faces the CsI detection crystal for the foreground measurement. Background is determined by a separate irradiation, with the radiator facing away from the CsI crystal. The nickel disk is thick enough to stop all proton recoils from the radiator in this position. The background subtraction was then obtained by normalization to the current integral obtained in the foreground irradiation. The telescope was placed at 90° (lab angle) relative to the triton beam direction at approximately 20 cm from the target center. The neutron background that was present with helium in place of deuterium in the target chamber resulted in a rather large count rate in an auxiliary long counter, but was not present in the 14-MeV peak observed with the telescope. Standard sample irradiations with helium as the target resulted in a negligible activation when compared to irradiations with deuterium as the target for each triton energy used in the measurement. The background of low energy neutrons is believed due mainly to t-T reactions[5] from the contaminated beam tube.

The double-window target was not available for the $T(d,n)He^4$ portion of the experiment. A resultant lower neutron yield necessitated the use of a long counter as the monitor during the sample irradiations. An angle of 110° (lab angle) relative to the deuteron beam direction was chosen for the long counter position. The neutron energy is nearly independent of deuteron energy at this position for the range of deuteron energy used. In separate calibration irradiations, with the telescope positioned at 90° relative to the beam direction, the ratios of long-counter count rate to telescope count rate were obtained for each deuteron energy used in the measurement. These ratios could not be determined to an accuracy of better than 5% because of a variation in the $D(d,n)He^3$ background from the deuterium in the beam tube walls and the target. This was corroborated when it was shown the neutrons produced with the target filled with helium were of an energy too low for detection by the telescope but detectable by the long counter.

Irradiation, Transfer, and Counting Systems

The dioxane scintillation solution was contained in one of three types of geometrically shaped holders during the irradiations. An aluminum torus (14.84-cm av diam, 1.01-cm internal cross-section diam, and 0.071-cm wall thickness) was used for angles between 60 and 140° relative to the bombarding particle direction. A stainless steel spherical shell segment (24-cm av radius of curvature, 10-cm chord diameter, 0.9-cm internal thickness, and 0.038-cm wall thickness) centered at 0° was used for the forward angles. A third

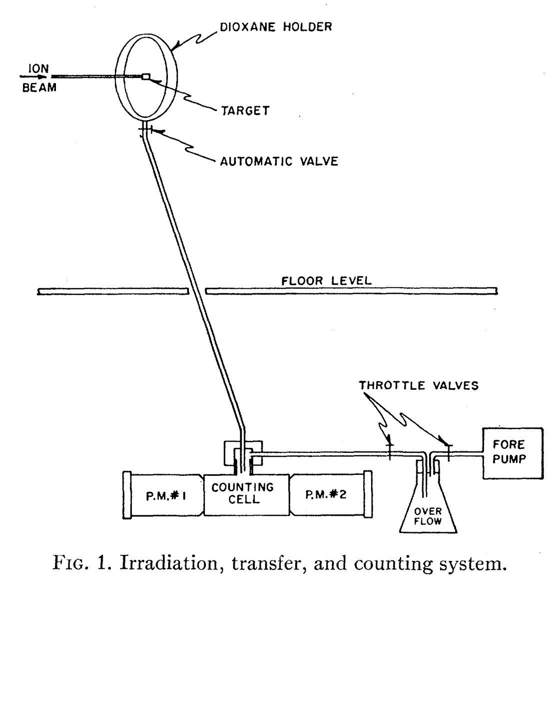

FIG. 1. Irradiation, transfer, and counting system.

[6] W. Whaling, Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 193.
[7] S. J. Bame, Jr., E. Haddad, J. E. Perry, Jr., and R. K. Smith, Rev. Sci. Instr. 28, 997 (1957).

holder with flat stainless steel faces (12.79-cm o.d., 8.25-cm i.d., 1.00-cm thickness, and 0.015-cm wall thickness) positioned 22.76 cm to the rear of the target center was used for irradiation at an average angle of 166° 25′. The first two holders described were supported by a very light aluminum framework while the latter holder was supported by the beam tube. Figure 1 shows the physical arrangement for irradiation, transfer, and counting of the sample contained in the torus holder. The 4π β-counting system was located in the basement approximately 20 ft below the target to reduce background irradiation from the Van de Graaff generator. The machine voltage was also turned off at the end of each irradiation to further reduce background.

The duration of the sample irradiation was 30 sec, during which the time variation in the flux monitor count was obtained by use of a 200-channel time analyzer (1-sec channels). The monitor count integral and the current integral were also obtained for the 30-sec irradiation. At the end of irradiation the beam was deflected from the target and the valve at the bottom of the holder opened automatically. This allowed the sample solution to drain into the previously evacuated line and counting cell. The surplus solution was pulled into the overflow container and the volume in the counting cell was kept constant by continued pumping through the throttled line. During the transfer, which takes place in about 5 sec, the monitor output was replaced by the 4π β-counting system output.[2] The remaining channels of the time analyzer were used to follow the N^{16} decay and the subsequent background.

III. REDUCTION OF DATA

During the irradiation the long-counter activity was counted by the 200-channel time analyzer set for one-second intervals for 30 sec. Then the 4π β-coincidence decay was followed for three minutes. The average background rate was determined from a 21-sec interval after the N^{16} activity had died away. Usually about 5 sec elapsed before the liquid transfer was completed. The N^{16} activity at the end of the irradiation was usually obtained from a 21-sec interval after the decay had become clearly exponential. As in the 14.7-MeV experiment[2] the saturated activity was computed from the long-counter data. The neutron flux at 90° was determined from the telescope foreground-background difference for the 30-sec irradiation. At the liquid holder positions the flux was obtained from the relative d-T angular distributions of Bame *et al.*[8] The c.m. distribution was transformed to the laboratory system for the measurements with tritions as the bombarding particles using a Los Alamos relativistic code referred to as "Rog."

A correction must be made for the attenuation of the neutron flux in the liquid and the wall of the sample holder facing the target. In the 14.7-MeV experiment[2] an attenuation constant of 0.0637 cm^{-1} was used for the liquid, based on poor geometry measurements at 14 MeV. A similar correction has been made for the present data. As the effective flux reduction in the worst case is only 4%, the error introduced by the correction should be less than 1%. In addition, the neutrons impinging on the 165° cell had to pass through the walls of the beam tube and a flange. A correction of 9.3% was made for this attenuation and an error of 5% assigned because of the complicated geometry. An error of 5% was assigned to the flux measurements based on the relative angular distribution of the d-T and t-D reactions. Finally the error due to the counting statistics was incorporated. The data are presented in Table I, and in graphical form in Fig. 2. Adjacent points from the same machine exhibit less staggering than the absolute errors since the relative errors are usually 2% or less. Only the extreme neutron energy limits which exceed 0.1 MeV are shown in Table I. The energy variation shown represents the total energy variation across the scintillator holder during irradiation taking into account the holder geometry and the neutron energy angular dependence. The effective energy resolution would be less than 0.1 MeV for nearly all energies.

TABLE I. $O^{16}(n,p)N^{16}$ cross section values.

Neutron energy (MeV)	Cross section (mb)	Production reaction [$A\equiv T(d,n)He^4$, $B\equiv D(t,n)He^4$]
11.08	9.47±0.80	*B*
11.36	22.30±1.76	*B*
11.76	80.47±5.40	*B*
11.80	85.60±5.05	*B*
11.85	81.28±5.29	*B*
11.98	52.14±2.86	*B*
12.11	31.92±1.73	*B*
12.69	21.79±1.68	*A*
13.00	31.49±2.30	*A*
13.44	45.89±3.35	*A*
13.85±0.12[a]	47.68±3.43	*A*
14.22±0.19	41.82±2.38	*B*
14.30±0.15	42.00±3.02	*A*
14.76±0.16	33.29±2.40	*A*
14.91±0.22	34.10±1.81	*B*
15.22±0.16	40.85±2.94	*A*
15.44±0.18	29.12±1.54	*B*
15.61±0.17	30.31±2.27	*A*
16.00±0.21	29.84±1.58	*B*
16.13±0.17	30.44±2.22	*A*
17.08±0.16	33.61±1.95	*B*
17.21±0.17	32.32±2.35	*A*
17.61±0.11	28.14±2.05	*A*
17.74±0.11	28.85±1.64	*B*
18.28±0.12	26.38±1.47	*B*
18.79±0.11	24.84±1.86	*B*
19.04	25.90±1.50	*B*

[a] The neutron energy variations shown represent extreme limits and those for the remaining cases are less than 0.1 MeV.

[8] S. J. Bame, Jr., and J. E. Perry, Jr., Phys. Rev. **107**, 1616 (1957).

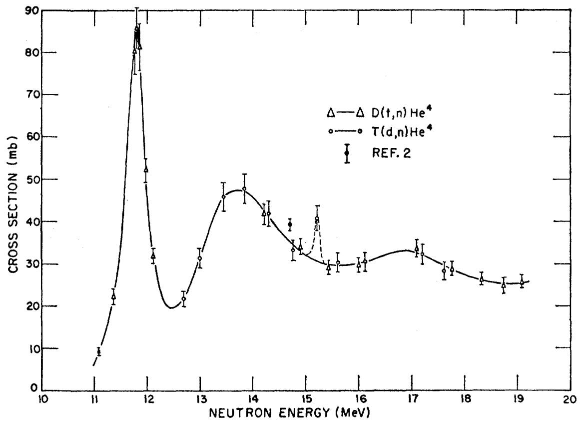

FIG. 2. $O^{16}(p,n)N^{16}$ cross section vs energy.

IV. RESULTS AND DISCUSSION

Previously it was believed that the oxygen cross section decreased monotonically from 12.4 MeV to the threshold at 10.2 MeV. The large resonance at 11.8 MeV came as a surprise. Martin[1] could not observe this resonance since his measurement extended to a minimum energy of 12.5 MeV. If it were not for the Coulomb barrier attenuation, the resonance would be even higher and would peak at a slightly lower energy. A slight rise in the excitation curve of the $N^{15}(d,p)N^{16}$ reaction has been noticed at 1.9-MeV deuteron energy,[9] corresponding to a level at 15.8 MeV in the compound nucleus O^{17*}. This level corresponds to a neutron energy of 11.65 MeV for the $O^{16}(n,p)N^{16}$ reaction leading to the same compound nucleus. A small peak in the total cross section of oxygen at 11.5 MeV has also been observed.[10] There is also evidence for a resonance at a neutron energy of 15.2 MeV from our data. The previously measured value at 14.7 MeV is about 10% higher (Fig. 2) than the corresponding value on the line drawn through our present excitation data. Because of time limitations on equipment and personnel, a greater chance for systematic errors was present in the latter measurement.

The integral of the $O^{16}(n,p)N^{16}$ cross section over the U^{235} fission spectrum is of interest for CO_2-cooled and H_2O-moderated reactors. Both the "Watt"[11] and "Cranberg"[12] spectra are often used. They are of the form

$$N(E)dE = KC^{-E/T}\sinh[(EE_f)^{\frac{1}{2}}]dE,$$

where the parameters are given in Table II.

TABLE II. Parameters for the Watt and Cranberg spectra.

Spectrum	K (MeV^{-1})	T (MeV)	E_f (MeV)
Watt	0.484	1.0	2.00
Cranberg	0.453	0.965	2.29

Integration of our data yields a value of 19 μb for the Watt spectrum and 16 μb for the Cranberg spectrum. A more detailed study of the integral cross section over the fission spectrum will appear later.[13]

ACKNOWLEDGMENTS

The authors are indebted to Dr. Ben C. Diven for his valuable discussions and suggestions. It was through his courtesy that this work was performed using the Los Alamos Physics Department Van de Graaff accelerators.

The computational assistance of Miss Gay Sickman is gratefully acknowledged. The authors wish to thank Steve J. Hogya and John W. Jordan for their assistance in the construction of the apparatus. We also wish to express our gratitude to other members of the staffs of both laboratories, who were helpful in the completion of the measurements.

[9] N. A. Bostrom, E. L. Hudspith, and I. L. Morgan, Phys. Rev. **105**, 1545 (1957).

[10] D. B. Fossan, R. L. Walter, W. E. Wilson, and H. H. Barschall, Phys. Rev. **123**, 209 (1961).

[11] B. E. Watt, Phys. Rev. **87**, 1037 (1952).

[12] Cranberg, Frye, Neuson, and Rosen, Phys. Rev. **103**, 662 (1956).

[13] K. Shure, Bettis Atomic Power Laboratory.