at 1.4 Mev reported by Marion and Weber.[4] The angular distributions for this group, however, undergo noticeable fluctuations in shape both near 1.0 Mev and 1.4 Mev.

The first excited state group yield, integrated over angle, increases rapidly between 0.5 and 1.0 Mev, then remains nearly constant. In addition, each angular distribution measurement for this group is more nearly isotropic, and has a less energy-dependent shape, than the ground-state group. The yield is about 10 times the yield of the ground-state α particles.

Marion and Weber infer that the ground-state (d,α) reaction proceeds through states of the compound nucleus, and explain the variation of angular distribution with bombarding energy as arising from interference of levels of opposite parity. Such arguments could also be applied to the present results which show that, if such interference exists, its effects are less pronounced for the first excited state than for the ground-state particles.

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Excitation Curves and Angular Distributions for $N^{14}(d,n)O^{15}$†

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Excitation curves for the highest energy neutron group in the reaction $N^{14}(d,n)O^{15}$ have been measured at $\theta_{lab}=0°$, 30°, 90°, and 164° for deuteron bombarding energies between 0.66 and 5.62 Mev. A pulse shape discrimination detector was used to eliminate the pulses due to γ rays from the neutron spectra. There is considerable resonance structure in the excitation curves, with the anomalies appearing at different energies for the different angles. The angular distribution of this neutron group has also been measured at bombarding energies of 0.91, 1.17, 1.51, 1.88, 2.58, 3.13, 3.56, 4.36, 4.80, and 5.27 Mev. The shape of the angular distribution changes rapidly with energy at low bombarding energy, but above 3.5 Mev the shape becomes more stable. The maximum cross section at any angle was 5.5 millibarns per steradian.

INTRODUCTION

The present investigation of the $N^{14}(d,n)O^{15}$ reaction was undertaken for the following purposes: (1) to see if the exchange stripping theory of Owen and Madansky[1] can be applied to this reaction, (2) to see if information could be obtained about states in O^{16} above an excitation of 20 Mev, and (3) to investigate this reaction more thoroughly as a possible source of monoenergetic neutrons using a Van de Graaff accelerator. The recent development[2] of a neutron detection system which is insensitive to γ rays and has a high efficiency for neutron detection made possible the more complete investigation of this low cross-section reaction in a reasonable amount of time. The performance of this experiment is a demonstration of the capabilities of this detection system, because of the high γ-ray flux produced in this reaction.

There have been several earlier measurements on this reaction. Nonaka et al.[3] measured the angular distribution and absolute cross section at 1.96 Mev. Morita[4] has measured relative cross sections at $\theta=0°$, 90°, and 165° from 1.0- to 2.15-Mev bombarding energy. Weil and Jones[5] have measured the 0° differential cross section from 1.0- to 5.4-Mev bombarding energy. Their results showed three strong peaks in this energy region, but poor energy resolution and bad statistics prevented the observation of any fine structure. All these measurements are in good agreement where they can be compared.

A fairly good fit to Nonaka's angular distribution was made by Weil and Jones[5] using the exchange stripping theory of Owen and Madansky.[1] Weil and Jones also made a good fit to eight angular distributions of the $N^{15}(d,n)O^{16}$ reaction using this same theory. It was hoped, before the present measurements were started, that the angular distributions for $N^{14}(d,n)O^{15}$ would be amenable to the same type of analysis.

Photodisintegration experiments on O^{16} by several experimenters[6] have indicated that there are a number

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[1] G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).
[2] F. D. Brooks, Atomic Energy Research Establishment, Harwell Report NP/GEN 8 (unpublished).
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[5] J. L. Weil and K. W. Jones, Phys. Rev. **112**, 1975 (1958).
[6] A. S. Penfold and B. M. Spicer, Phys. Rev. **100**, 1377 (1955); L. Katz, R. N. H. Haslam, R. J. Horsley, A. G. W. Cameron, and R. Montalbetti, Phys. Rev. **95**, 464 (1954); L. Cohen, A. K. Mann,

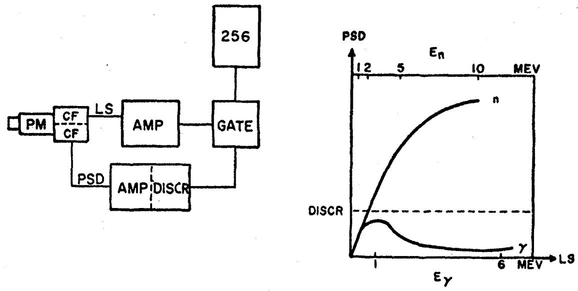

FIG. 1. Block diagram of electronics and schematic plot of PSD versus LS pulses. There is actually a vertical spread of about $\pm 30\%$ in these pulses, which is not shown in the figure.

of resolved excited states in O^{16} in the region of excitation between 20 and 25 Mev. In particular, Penfold and Spicer have found ten levels in this region whose widths are less than 40 kev. $N^{14}+d$ lies at an excitation energy of 20.73 Mev in the compound nucleus O^{16}. In none of the previous experiments on the $N^{14}(d,n)O^{15}$ reaction mentioned above were the measurements good enough to determine whether or not such fine level structure could be seen. The high neutron detection efficiency in the present experiment made it possible to obtain data with much higher energy resolution and better statistics than was heretofore practical. It could therefore be expected that narrow levels in the compound nucleus might show up in this experiment.

The only other experiment which gives information on excited states in O^{16} in this region of excitation is that of Cohen, Fisher, and Warburton[7] who have measured the differential cross section at 90° of the reaction $N^{15}(p,\gamma_0)O^{16}$. Their results show resonances in the γ-ray yield having widths of the order of several hundred kev to one Mev. There is fairly good agreement between the excitation energies observed in the capture experiment and those obtained from the positions of the peaks in the 0° yield curve observed by Weil and Jones.[5]

This reaction has a high Q of 5.073 Mev and a spacing between ground and first excited states in the final nucleus of 5.20 Mev.[8] For these reasons this reaction can be used as a source of high-energy neutrons for doing neutron experiments, and a detector with only moderate energy resolution is needed. Measurement of the angular distributions determines the most favorable angular position for the transmission or scattering sample with respect to the N^{14} target.

EXPERIMENTAL PROCEDURE

The nitrogen gas was contained in a platinum thimble 1.50 cm long. The beam entered the target through a 0.7 mg/cm² nickel window. The beam was accelerated in the Rice Institute 5.5-Mev Van de Graaff accelerator and, after being magnetically analyzed (energy spread $\leq 0.1\%$), was collimated by two 3-mm tantalum apertures spaced 2 m apart. A 300 volt electrostatic secondary electron suppressor was used to insure proper beam integration. The gas pressure was continuously monitored by a mercury manometer on the gas filling system and was varied so as to maintain the correct target thickness. The excitation curves were measured with target thicknesses between 20 and 120 kev, depending on the spacing of the data points. The current integration was done with a circuit of the type designed by Bouricius and Shoemaker.[9]

A stilbene crystal 2.54 cm diam by 1.27 cm long was used as a proton recoil counter to detect the neutrons. Pulse shape discrimination[2] was used to eliminate all gamma- and beta-ray pulses from the spectra. Figure 1 shows the block diagram of the electronics. The PSD pulse, upon which the discrimination depends, was generated within the photomultiplier by decreasing the potential between the last dynode and the anode to about 1 volt, following the suggestion of the Chalk River group.[10] This method works very well with such high-energy neutrons as were observed in the present experiment. Figure 1 also shows the typical shape of the neutron and γ-ray branches of the PSD pulses plotted against the energy of the respective radiations. The linear signal (LS), which was fed to the RCL 256 channel pulse-height analyzer after gating, was taken from the seventh dynode of the RCA 6903 photomultiplier. The energy resolution of this system is about 10% for 5-Mev neutrons.

Figure 2 shows a typical spectrum observed from the reaction $D(d,n)He^3$. Part of the rising slope of the recoil

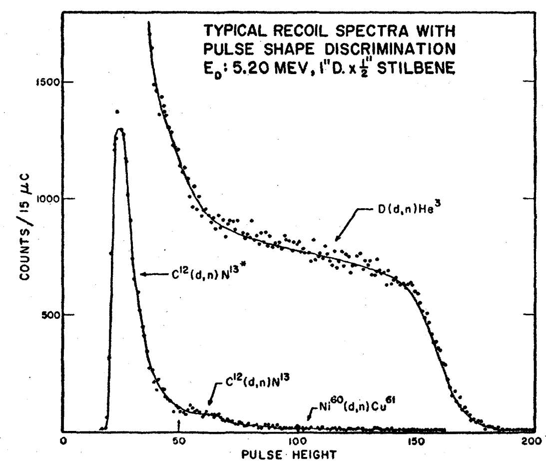

FIG. 2. Recoil proton spectra from the $D(d,n)He^3$ reaction, and from background reactions which can be seen when the gas target is evacuated.

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spectrum is due to the nonlinearity of the energy response of the stilbene crystal, which was determined using neutrons between 1 and 11 Mev emitted in the reactions $T(p,n)He^3$, $D(d,n)He^3$, and $N^{14}(d,n)O^{15}$. Another part of the rising slope is caused by the detection of the neutrons coming from (d,n) reactions in the materials of the target container itself. The spectrum of this "background" observed with an evacuated target is also shown in Fig. 2. Though the intensity is weak, the neutrons from the different reactions still appear as resolved groups. Figure 3 shows the spectrum from the reaction $N^{14}(d,n)O^{15}$ with and without gating by the PSD pulses. The intensity of the γ rays is approximately 50 times greater than that of the neutrons which one wishes to observe. From the relative intensities of the two kinds of radiation and the shape of the gated neutron spectrum, it is apparent that more than 99.8% of the γ-ray pulses have been eliminated from this spectrum by pulse shape discrimination.

Complete pulse-height spectra were measured at each bombarding energy in the $N^{14}(d,n)O^{15}$ experiment. The background was measured for $\theta=0°$, 30°, 90°, and 164° with the target evacuated at intervals of 300 to 400 kev, as well as at all angles for each angular distribution. Two complete sets of data were taken, in addition to several preliminary and check runs, and the agreement is good between different runs.

The following method was used to determine the neutron yield from the pulse-height spectra. First, pulse-height spectra taken at 0° at intervals of 300 to 400 kev were plotted and from them a calibration curve of pulse height versus neutron energy was established. The mid-

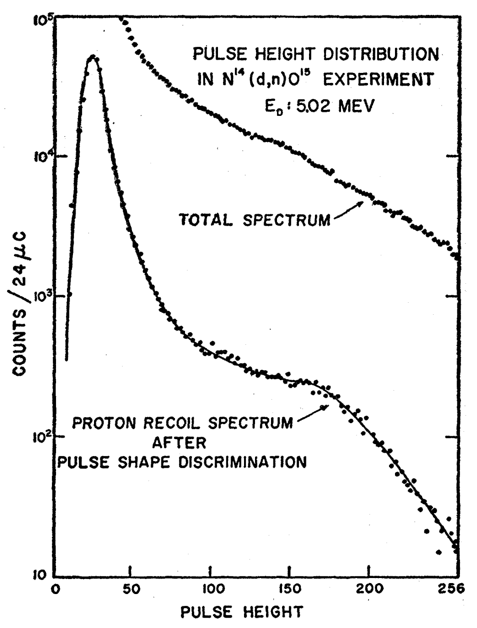

FIG. 3. Pulse-height spectra from the reaction $N^{14}(d,n)O^{15}$. The pulses in the ungated spectrum are mostly due to γ rays coming from excited states in the final nucleus. In the gated spectrum, the γ-ray pulses were eliminated by pulse shape discrimination.

dle of the steep slope at the high-energy end of the spectrum, the "mid-end point," was taken as a measure of the pulse height. The low-energy portion of the curve was constructed by normalization to the energy response curve of the stilbene crystal. The plotted spectra were also used to determine an appropriate place to make a low-energy cutoff. The recoil proton energy, E_c, corresponding to the cutoff channel could then be determined from the calibration curve. The criteria for selecting the cutoff energy were (1) that the cutoff should be high enough that the number of background counts in the energy interval between the low-energy cutoff and the high-energy end point should be no greater than 30% of the total number of counts in the same interval, and (2) that the cutoff should be low enough that $E_c<0.75E_n$, where E_n is the neutron energy for the particular angle of observation and bombarding energy at which the yield was being measured. In almost all cases there was no conflict in satisfying both these criteria, and in general the cutoff was placed low enough that $0.4E_n<E_c<0.7E_n$ and still the background was no more than 10–20% of the total number of counts. The background, which comes from $Ni(d,n)Cu$, is strongly peaked forward so that for $\theta>30°$ the background was less than 10% of the total number of counts. With the aid of interpolation graphs of the background yield as a function of energy and cutoff channel, it was possible to make the background subtraction at all energies with a minimum amount of labor and an error of less than 10% in the background, which leads to an error of less than 3% in the total yield. The neutron yield from the reaction under observation was taken to be the fraction $E_n/(E_n-E_c)$ multiplied by the difference between the total number of counts above the cutoff and the number of background counts above the cutoff. This calculated yield was insensitive to changes of the cutoff within the limits prescribed by the above two criteria. Calculations of the loss of counts due to wall effects showed that this effect was so small that it could be safely neglected.

To check the performance of the detector, as well as the method of calculating the cross section, the yield of the reaction $D(d,n)He^3$ was measured at several energies between 1.0 and 5.5 Mev. The absolute cross section calculated from these measurements is shown in Fig. 4 together with a curve taken from the review article of Fowler and Brolley,[11] which summarizes the results of other experiments. None of our points disagrees with the curve by more than 5.5%. The error bars are asymmetric to account for the possible systematic errors in the measurement of (1) the target gas pressure due to heating of the gas by the beam and by contact with the beam stop, and (2) the solid angle. Both of these errors were such that they could only have decreased the measured yield. The good agreement leads us to believe that there is no large systematic error in the measurement of the $N^{14}(d,n)O^{15}$ cross section.

[11] J. L. Fowler and J. E. Brolley, Jr., Revs. Modern Phys. 28, 103 (1956).

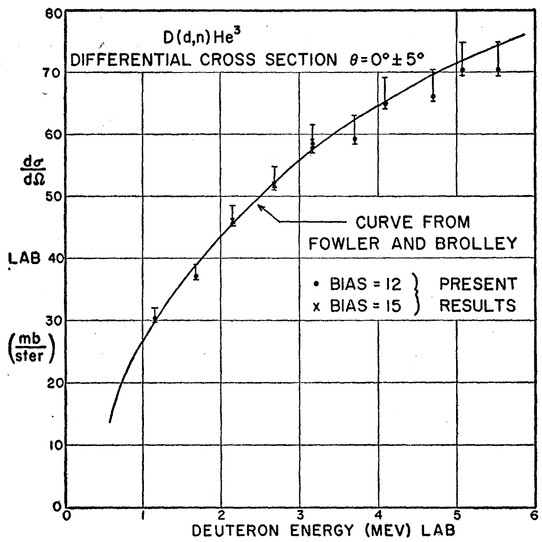

FIG. 4. Differential cross section at 0° for the $D(d,n)He^3$ reaction. The curve is taken from Fowler and Brolley (reference 11), and the data points are absolute measurements made in the present experiment.

RESULTS

The differential cross section at $\theta=0°$, 30°, 90°, and 164° for the highest energy neutron group in the reaction $N^{14}(d,n)O^{15}$ is shown in Fig. 5. At 0° the yield was measured in steps of 20 to 40 kev in an attempt to see fine structure that might not have been resolved in previous experiments on this reaction. Many weak, narrow anomalies were discovered. The graph line is drawn so as to show only that structure which repeated on more than one run. At the other three angles the data were taken in steps of about 100 kev in an attempt to determine the gross features of the cross section at all angles and energies.

The statistical errors ($<2\%$) are no greater than the size of the data points and hence have not been indicated. Other possible random errors are: (1) error in reading the target pressure, $<0.5\%$, (2) error in beam integration, $<0.5\%$, (3) error in yield due to background interpolation, $<3\%$, and (4) error in the yield from the determination of the cutoff energy, $<1\%$. The main systematic errors are (1) error due to target gas heating, $<5\%$, and (2) error in the measurement of the solid angle, $<2.5\%$. We estimate that our cross sections have total relative errors of less than $\pm4\%$ and a possible systematic error which tends to decrease them from the true value by no more than 5%. There is a possible systematic error in the scale of the bombarding energy ranging from negligible at the lowest energy to 1% at the highest bombarding energy.

There is some disagreement with an earlier experiment[5] in the value of the cross section for the 0° yield below 3-Mev bombarding energy, the present results being up to 40% lower. However, the crudity of the earlier measurement, in which one of us (JW) participated, could easily account for this discrepancy. In particular, in the earlier experiment the subtraction of the neutron background was rather poor compared to the present method, and the only means of discrimination against γ rays was to use a very small piece of scintillator. There is good agreement between the two experiments at higher bombarding energies where the earlier data should be more reliable. There is also disagreement with the absolute values of the cross section measured by Nonaka et al.[3] This measurement was at 1.96 Mev and was made with a detector similar to that of Weil and Jones, so that it is possible that some of the same errors are present in both experiments. Also, Nonaka's cross section was obtained by a comparison to a measurement of the $D(d,n)He^3$ made at the same time. The shapes of the yield curves of Morita[4] agree well with the present results, but the absolute cross sections do not agree because Morita has normalized to Nonaka's measurement. It is felt that the lack of agreement at the lower energies is not significant, and that the present results are correct.

The angular distribution of the ground-state neutrons was measured at ten energies distributed throughout the whole energy range, and the results are shown in Fig.6. The graph lines are only a "best eye" fit to the data points. The error bars show typical statistical errors only. There was very good agreement between angular distributions measured at the same bombarding energy on different runs. Our angular distribution at 1.88 Mev agrees fairly well in shape, but not in absolute magnitude, with an angular distribution measured at 1.96 Mev by Nonaka et al.,[3] as would be expected from the yield curve measurements.

It should be noted that there may be an error above 3.5 Mev in the present measurement of the cross section at 0°, both in the angular distributions and in the yield curve. This error is a result of the fact that the detector subtended an angle of $\pm5°$. Above 3.5 Mev the yield drops very rapidly from a maximum at about 20° to a

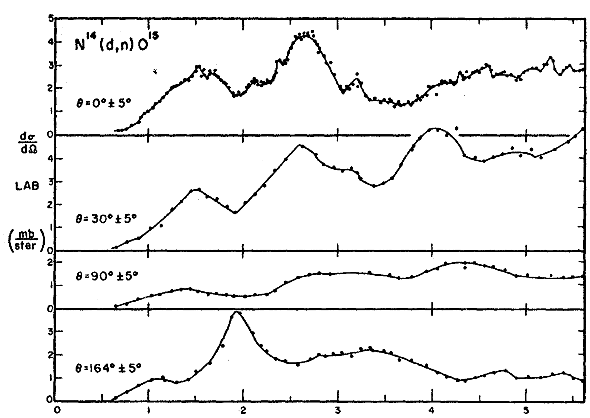

FIG. 5. Differential cross sections at 0°, 30°, 90°, and 164° for the $N^{14}(d,n)O^{15}$ reaction. The statistical errors are no larger than the size of the data points.

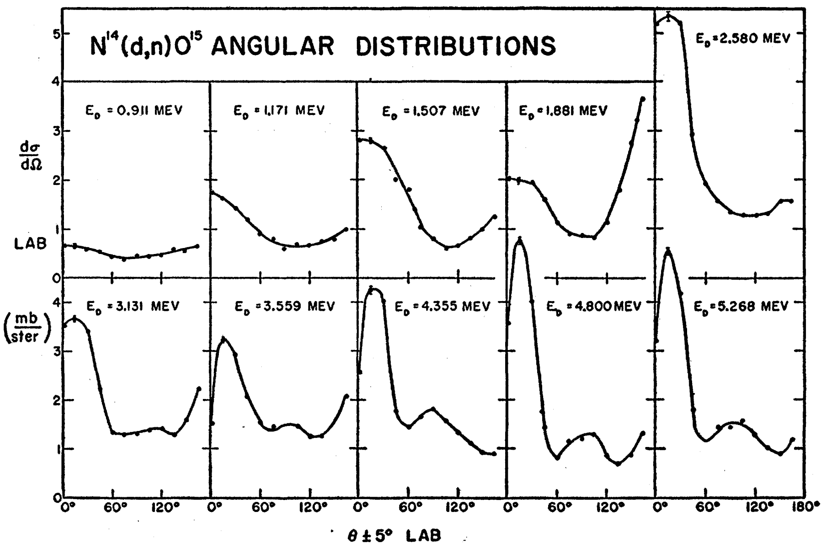

FIG. 6. Angular distributions from the $N^{14}(d,n)O^{15}$ reaction. The typical errors shown are the statistical errors only.

minimum at 0°. The relatively poor angular resolution of the detector could easily lead to a measured cross section at 0° that is much larger than the true one in a case like this. Similarly, the peak at 20° may really be considerably higher and sharper than we have measured. Since the detector in the experiment of Weil and Jones[5] subtended an even larger angle,[12] the above comment applies as well to their results.

The angular distributions were integrated to give the total cross section which is shown in Fig. 7. The errors shown are compounded from the random errors mentioned above and an estimated maximum error of 5% that may be caused by the poor angular resolution of the detector and the process of the numerical integration. The total cross section rises smoothly with increasing energy, after which it is relatively constant. None of the strong energy dependence of the differential cross sections at the various angles is seen in the total cross section.

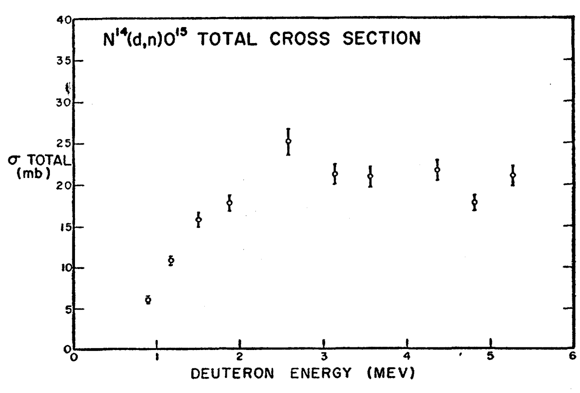

FIG. 7. The total cross section for the $N^{14}(d,n)O^{15}$ reaction obtained by integrating the angular distributions shown in Fig. 6. All the random errors were compounded to give the errors shown here.

[12] J. L. Weil and K. W. Jones (private communication).

DISCUSSION

The angular distributions of the $N^{14}(d,n)O^{15}$ reactions show large changes in shape as the bombarding energy is increased from 0.9 to 3 Mev. Above this energy, the shape becomes fairly stable, the main change being that the maxima move slowly to smaller angles. It is not clear that exchange stripping theory will give a good fit to the experimental data over the whole energy range. In the cases of $B^{11}(d,n)C^{12}$ [1] and $N^{15}(d,n)O^{16}$ [5] it was possible to fit the data using interaction radii which were constant or else changed smoothly with increasing energy, and a ratio of nuclear to deuteron stripping amplitude Λ_2/Λ_1 which increased linearly with energy until the Coulomb barrier was reached and then remained constant. In order to fit the rapidly changing shape of the $N^{14}(d,n)O^{15}$ angular distributions below 3.5 Mev it will probably be necessary to allow large fluctuations in Λ_2/Λ_1 and perhaps also in the interaction radii R_1 and R_2. This would not be consistent with the previous experience with fits of this type. Above 3.5 Mev, the values of the parameters necessary to obtain a good fit to the data would probably change slowly, if at all.

In the $N^{15}(p,\gamma_0)O^{16}$ experiment of Cohen et al.,[7] resonances are observed in the 90° yield curve at excitation energies of 21.8, 22.9, 24.3, and 25.0 Mev, as read from their published curve. The agreement with previous measurements on $N^{14}(d,n)O^{15}$ has already been mentioned in the introduction. Even better agreement with the capture γ-ray excitation energies is obtained from a comparison with the peak positions in the 30° yield curve observed in the present experiment. These peaks occur at 21.9, 23.0, 24.3, and 24.9 Mev. There are no other broad peaks in the $N^{14}(d,n)O^{15}$ yield curve, so the correspondence is one to one with the peaks in the $N^{15}(p,\gamma_0)O^{16}$ yield curve. Interference between stripping and compound nucleus formation amplitudes will probably cause some shift in the position of the peaks in

going from one angle to another. In spite of this shifting, the peaks show up at all angles except at 164°, where valleys occur at the same energy. Again, this is probably due to some interference effect. Selection of the 30° yield curve for obtaining the excitation energies is perhaps arbitrary, except that one might expect the compound nucleus effects to show up most strongly near the peak of the stripping angular distribution. In any event, the correspondence of the number of peaks and their excitation energies indicates that some compound nucleus formation is taking place in the $N^{14}(d,n)O^{15}$ reaction.

The lack of any marked structure in the total cross section can be interpreted by saying that the main reaction mechanism is a direct interaction and that there is only a small amplitude for compound nucleus formation. The penetrability of the Coulomb barrier could account for the rise in the total cross section at low energy, and interference of a small compound nucleus formation amplitude with a large direct interaction amplitude could give the fine structure in the differential cross sections. Another possibility is that there are very many levels formed in the compound nucleus. Interference effects between them might then account for structure in the differential cross section, while the smooth total cross section could be explained by saying that the interference effects average out when integrated over angle. These two explanations are, in some sense, really the same.

It is not possible to say whether or not the narrow anomalies in the 0° yield curve are associated with the same excited states in O^{16} which are responsible for the breaks in the $O^{16}(\gamma,n)O^{15}$ [6] yield curve. The poor precision of the energy calibration in the photodisintegration experiment and the shifting of peak position with angle in the present work make it impossible to show a correspondence between excitation energies observed in the two reactions.

It would be interesting to measure the total cross section of the $N^{14}(d,n)O^{15}$ reaction in 20-kev energy steps across a region in which some of the small anomalies occur. The appearance of resonances in the total cross section would be good evidence for compound nucleus formation, and then perhaps it would be possible to see a correspondence with the levels seen in the $O^{16}(\gamma,n)O^{15}$ reaction.

In conclusion, this reaction does not appear to take place via any one pure reaction mechanism. Effects which can be attributed to both compound nucleus formation and to direct interaction are found in the measurement of the cross section as a function of angle and bombarding energy. Such a reaction makes it quite evident that it is really improper to speak about pure reaction mechanisms which are based on particular approximations.

The only new piece of information obtained concerning the use of this reaction as a neutron source is that above 3-Mev bombarding energy the best place to put the object to be bombarded with neutrons is at 15–20° to the direction of the incident deuteron beam. Below 3 Mev the best place is at 0°. Because of its low yield, this reaction will not be too useful as a neutron source.

ACKNOWLEDGMENTS

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