encouragement. We are indebted to Dr. M. Morita and Dr. J. Weneser for their helpful discussion of the theory. Mr. F. A. Dugan contributed many constructive suggestions to the design of the pneumatic tube system. Finally it is a pleasure to acknowledge the assistance and cooperation of Dr. C. P. Baker and the cyclotron crew during the many cyclotron bombardments.

Note added in proof.—An accurate value for the neutron half-life, 11.7±0.3 minutes, has recently been reported by Sosnovskij *et al.* at the High Energy Conference, Geneva, July, 1958. The resulting *ft* value for the neutron decay is 1187±35 seconds which, when combined with the 0–0 transitions, gives a value for C_{GT}^2/C_F^2 of 1.42±0.06 and leads to an empirical Gamow-Teller matrix element for Ca^{39} of 0.30. We shall discuss this further in a future paper.

PHYSICAL REVIEW VOLUME 112, NUMBER 6 DECEMBER 15, 1958

$N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ Reactions*†

J. L. Weil and K. W. Jones‡
Columbia University, New York, New York

(Received August 29, 1958)

Absolute cross sections for the $N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ reactions have been measured at zero degrees to the incident deuteron beam from 0.6 to 5.3 Mev bombarding energy. Both excitation curves show strong resonance structure and have maximum cross sections of about 6 millibarns per steradian. Eight angular distributions were measured for the $N^{15}(d,n)O^{16}$ reaction at points on and off maxima in the excitation curve. A good fit to the angular distributions is obtained by use of the exchange stripping theory of Owen and Madansky.

I. INTRODUCTION

The present investigation of the $N^{14}(d,n)O^{15}$ ($Q=5.122$ Mev) and $N^{15}(d,n)O^{16}$ ($Q=9.885$ Mev)[1] reactions was undertaken primarily to ascertain their usefulness as neutron sources in the energy range from 8 to 14 Mev. Reactions which have hitherto been used as neutron sources with Van de Graaff accelerators do not provide neutrons in this energy region. The two reactions are not monoergic sources, but the first excited state is very well separated from the ground state in both O^{15} and O^{16} (5.27 and 6.06 Mev spacings, respectively). A neutron detector with only moderate energy resolution is needed to distinguish the ground state group in either reaction.

If the excitation functions for the $N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ reactions show evidence for compound nucleus formation, information can be obtained on excited states of O^{16} above 20.7 Mev and O^{17} above 14.0 Mev.[1] Angular distribution measurements may help in the determination of reaction mechanisms of deuteron induced reactions in this energy region.

Previous experimental work on the resolved ground state neutron groups from these reactions has not been extensive. Johnston and Bostrom[2] have reported measurements of the excitation curve and angular distributions of $N^{14}(d,n)O^{16}$ for energies below 2.4 Mev. Nonaka *et al.*[3] measured the angular distribution and absolute cross section at 1.96 Mev and Morita[4] has measured relative cross sections at $\theta=0°$, 90°, and 165° from 1.0 to 2.15 Mev bombarding energy. No previous measurements have been reported on the $N^{15}(d,n)O^{16}$ reaction.

II. EXPERIMENTAL METHOD

The deuteron beam from a Van de Graaff accelerator was magnetically analyzed (±0.1% in energy). The beam was then focused and collimated before it entered a gas target. This target was made of 10-mil-wall stainless steel tubing with a gold beam stop and a 0.01-mil nickel entrance window. The target thickness was 20 kev or less in both experiments, with the exception of the $N^{15}(d,n)O^{16}$ data below 1 Mev, where it was as large as 40 kev. The incident deuteron energy was corrected for the energy loss in traversing the nickel foil and one-half the target gas.[5]

Small plastic scintillators were used as proton recoil counters to detect the neutrons.[6] The small size was necessary in order to discriminate against gamma rays. A spheroid 4.90 mm by 2.45 mm, on edge to the beam and backed by an aluminum reflector, was used for the $N^{14}(d,n)O^{15}$ reaction. A right cylinder 5.49 mm long by

---

* This work partially supported by the U. S. Atomic Energy Commission.

† A preliminary report on this work was given at the Chicago Meetings of the American Physical Society, November 23 and 24, 1956 [Jones, Weil, Kruse, Baicker, and Lidofsky, Bull. Am. Phys. Soc. Ser. II, 1, 326 (1956)].

‡ Now at The Ohio State University, Columbus, Ohio.

[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).

[2] R. W. Johnston and N. A. Bostrom, Bull. Am. Phys. Soc. Ser. II, 2, 104 (1957).

[3] Nonaka, Morita, Kawai, Ishimatsu, Takeshita, Nakajima, and Takano, J. Phys. Soc. Japan 12, 841 (1957).

[4] S. Morita, J. Phys. Soc. Japan 13, 126 (1958).

[5] J. L. Fowler and J. E. Brolley, Jr., Revs. Modern Phys. 28, 103 (1956); Reynolds, Dunbar, Wenzel, and Whaling, Phys. Rev. 92, 742 (1953); Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663 (unpublished).

[6] Taylor, Lönsjö, and Bonner, Phys. Rev. 100, 174 (1955).

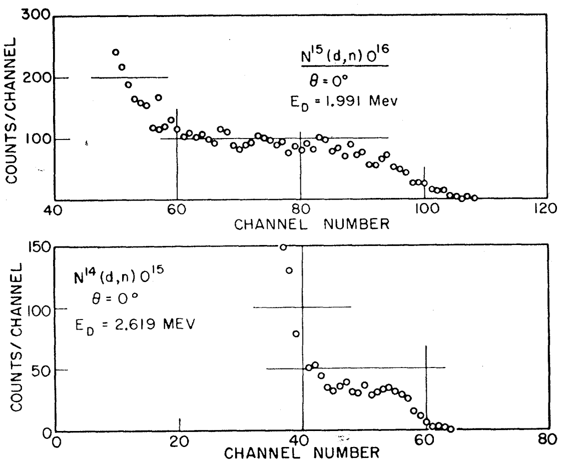

FIG. 1. Typical pulse-height spectra for the $N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ reactions.

6.36 mm in diameter was used as a detector in the $N^{15}(d,n)O^{16}$ experiment except for the angular distributions at 1.806, 2.103, and 2.999 Mev where two such cylinders mounted in a copper block were used. The detectors were mounted on Dumont 6292 phototubes whose output pulses were amplified and fed to a hundred-channel analyzer. Complete pulse-height spectra were taken at each bombarding energy. Typical spectra from the first two counters are shown in Fig. 1. The rapid rise at low pulse height for N^{14} is probably due to background neutrons from the $Ni^{61}(d,n)Cu^{62}$ reaction[7] in the entrance foil or from the $D(d,n)He^3$ reaction from deuterium absorbed on the nickel entrance foil or on the gold beam stop. The rapid rise at low pulse height for N^{15} is probably due to gamma rays from the de-excitation of O^{16*} because this rise remains in the same position when the deuteron energy is varied.

Backgrounds were measured with the target filled with helium. This gave the contribution of gamma rays and neutrons produced in the target materials and from nitrogen or deuterium driven into the beam stop. The corrections to the cross section for this background amounted to a maximum of 15%. An additional check of the background for the $N^{15}(d,n)O^{16}$ reaction was made by exposing the detector for the N^{15} experiment to radiations from the $N^{14}+d$ reactions. The $N^{14}(d,n)O^{15}$ neutrons leaving the product nucleus in its ground state have approximately the same energy, although not necessarily the same intensity, as the neutrons from $N^{15}(d,n)O^{16*}$ leaving the product nucleus in its first excited state. The gamma rays from the reactions are also of nearly equal energy. The results of this exposure indicated that the biases used in the $N^{15}(d,n)O^{16}$ experiment discriminated effectively against the excited state neutrons and gamma rays.

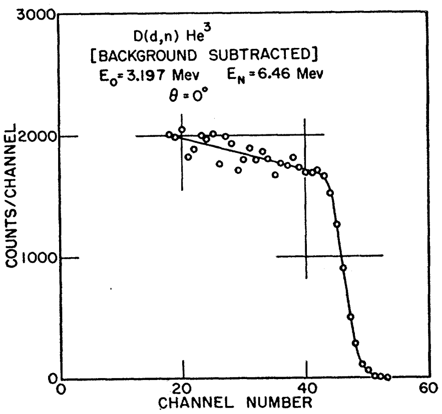

FIG. 2. Typical pulse-height spectrum observed in one of the $D(d,n)He^3$ runs with which the system was calibrated.

Absolute cross sections were calculated from the measured pulse-height distributions, with suitable consideration of the dependence of pulse height on proton recoil energy.[8] Corrections were made for the loss of recoil protons from the sides and ends of the counter.

The complete technique was checked by measuring the cross section for the $D(d,n)He^3$ reaction with the counter used in the $N^{14}(d,n)O^{15}$ experiment. Figure 2 shows a typical spectrum from the $D(d,n)He^3$ reaction. Measurements were made at four different deuteron energies: 2.12, 3.20, 4.20, and 5.22 Mev. The cross sections calculated from these measurements agree within 6% with the values quoted in the review article of Fowler and Brolley,[5] except for the one at 5.22 Mev which is 14% larger. This agreement is very satisfactory considering the numerous corrections necessary for the calculation of the absolute cross section.

III. RESULTS

The differential cross section at $\theta = 0°$ for the $N^{15}(d,n)O^{16}$ reaction is shown in Fig. 3. The solid line is drawn so as to show only the structure which repeated from run to run. Eight angular distributions were taken at points corresponding to peaks and valleys in the 0° yield curve, as indicated by the arrows in Fig. 4. The angular resolution ranged from ±2° at $\theta = 0°$, to ±11° at $\theta = 90°$.

The differential cross section at $\theta = 0°$ for the $N^{14}(d,n)O^{15}$ reaction is shown in Fig. 5. There is very good agreement between the present results and the data of Nonaka *et al.*[3] and Morita.[4] Their data are also plotted in Fig. 5.

The $N^{14}(d,n)O^{15}$ and $N^{15}(d,n)O^{16}$ reactions can be used as neutron sources, but the low cross sections for neutron production will be a serious drawback to such use.

The typical errors shown in Figs. 3, 4, and 5 are those due to counting statistics only, and range between 2%

---

[7] Jones, Kruse, Weil, Baicker, and Lidofsky, Rev. Sci. Instr. **28**, 56 (1957).

[8] MacGregor, Ball, and Booth, Phys. Rev. **108**, 726 (1957).

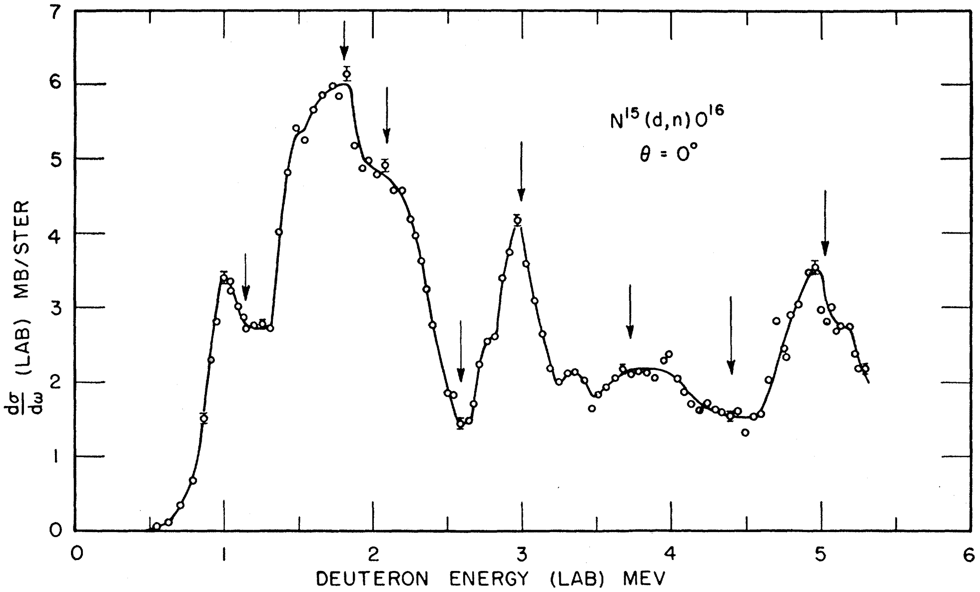

FIG. 3. The excitation curve for the $N^{15}(d,n)O^{16}$ reaction. The arrows indicate the energies at which angular distributions were measured. The error bars indicate typical statistical errors only.

and 10%. They are largest for the $N^{14}(d,n)O^{15}$ reaction where the low counter efficiency and the nearness of the background groups made it difficult to obtain good statistics. The other major sources of error in the cross sections are (1) errors in reading the target pressure, (2) errors in the conversion from a pulse height to energy scale, (3) approximations in calculating the detector solid angles, and (4) approximations in the calculation of side and end effect corrections. The over-all accuracy of the absolute cross sections is estimated at ±20%.

IV. DISCUSSION

A. $N^{15}(d,n)O^{16}$ Reaction

The yield curve rises sharply from 500 kev with a shape that can be fitted by the calculated penetrability of a deuteron through the Coulomb barrier of the target nucleus. Above 1 Mev bombarding energy, there is pronounced resonance-like structure. For the most part, the structure appears to be due to overlapping resonances, which is to be expected at such a high excitation

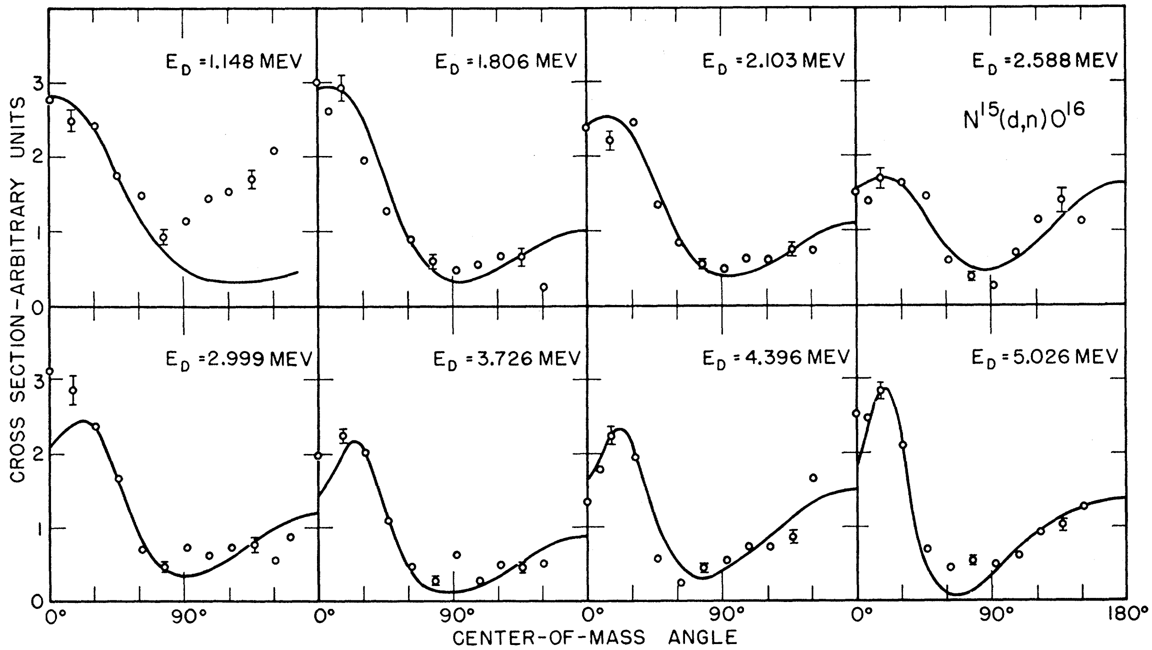

FIG. 4. Angular distributions for the $N^{15}(d,n)O^{16}$ reaction. The error bars indicate statistical errors only. The lines are theoretical fits calculated from exchange stripping theory.

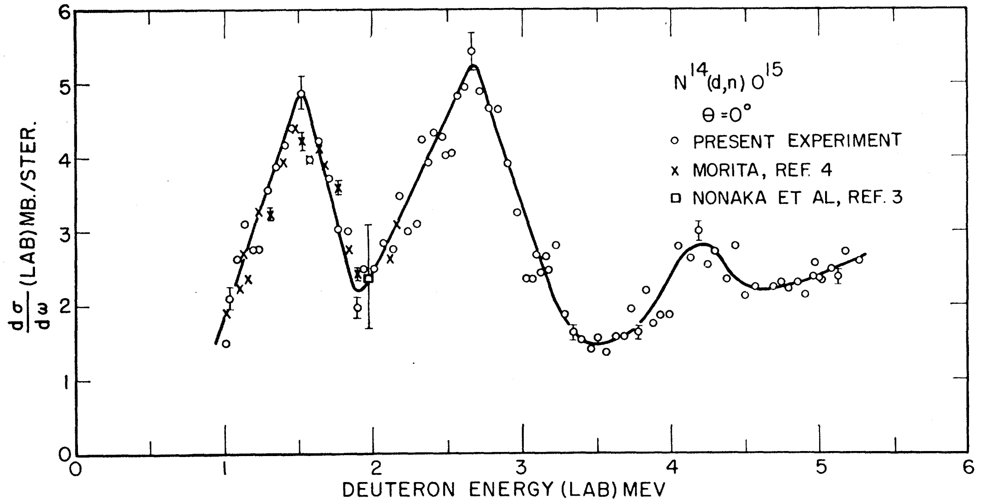

FIG. 5. The excitation curve for the $N^{14}(d,n)O^{15}$ reaction. The error bars indicate typical statistical errors only.

(≥ 15 Mev in O^{17}). Detailed runs on the yield curve in which data were taken in 10-kev steps did not reveal anything but the gross structure that is shown in Fig. 3. In general, the structure of the yield curve is very complex, and for this reason no effort has been made to interpret it in terms of excited states in O^{17}.

More definite information is obtained from the angular distributions. Six of the eight angular distributions show a striking similarity in shape, namely a large forward peak and a smaller backward rise. This similarity of structure over a wide region of bombarding energy and the strong forward peaking immediately suggest that the dominant mechanism of the reaction is stripping. The backward rise can also be accounted for as resulting from the stripping of an outer neutron from the N^{15} by use of the exchange stripping theory of Owen and Madansky.[9] The solid lines in Fig. 4 are the theoretical angular distributions calculated from this theory.

The theoretical fit to the data was obtained as follows. The formula for the differential cross section at a given energy, using the notation of Owen and Madansky,[9] is

$$d\sigma/d\omega=\text{Const}\left|G_{\text{D}}(K_1)j_1(k_1R_1)+\frac{\Lambda_2}{\Lambda_1}G_{\text{H}}(K_2)j_0(k_2R_2)\right|^2,$$

where

$$G_{\text{D}}(K_1)=1/(K_1^2+\alpha_{\text{D}}^2),$$

$$G_{\text{H}}(K_2)=\left[\frac{1}{\alpha_{\text{N}}^2-K_2^2}+\frac{1}{\beta_{\text{N}}^2+K_2^2}\right][K_2r_{\text{N}}j_1(\alpha_{\text{N}}r_{\text{N}})j_0(K_2r_{\text{N}})-\alpha_{\text{N}}r_{\text{N}}j_0(\alpha_{\text{N}}r_{\text{N}})j_1(K_2r_{\text{N}})],$$

and Λ_2/Λ_1 = ratio of the deuteron and the nuclear stripping amplitudes. Λ_2/Λ_1 is essentially a ratio of reduced widths for the two different modes of formation of the final nucleus. The known spins and parities[1] of the ground states of N^{15} and O^{16} have been used to determine the values of the angular momentum of the captured particle, $l_p=1$ and $l_c=0$. A good fit to the data was obtained using $l_c=0$ only, so the possibility $l_c=2$ was neglected. Since $j_2(k_2R_2)$ approaches zero at the back angles and the d-wave penetrability is much less than the s wave, inclusion of the $l_c=2$ term would cause very little change in the shape of the theoretical angular distributions.

The radius and depth of the potential well used to determine the neutron wave function for the calculation of $G_{\text{H}}(K_2)$ were 4.3 fermis (1 fermi $\equiv 10^{-13}$ cm) and 42 Mev respectively. The parameters that are adjusted to get a best fit to the experimental data are the interaction radii R_1 and R_2 and the ratio of the two stripping amplitudes Λ_2/Λ_1. Owen and Madansky have pointed out that none of these parameters would be expected to remain constant as a function of energy since they represent phenomenological expressions for the behavior of rather complicated wave functions. Indeed, it is found that these parameters must be allowed to range over at least a factor of two in order to get a good fit to the data. The values used to get the fits shown in Fig. 4 are given in Table I and the behavior of Λ_2/Λ_1 is plotted in Fig. 6. The behavior of this parameter is the same as

TABLE I. Values of adjustable parameters used in calculating theoretical fits to the experimental angular distributions.

E_d (Mev)	R_1 (fermis)	R_2 (fermis)	Λ_2/Λ_1
1.148	5.5	5.5	0.93
1.806	6.0	5.5	1.61
2.103	5.5	5.5	1.94
2.588	5.5	5.5	3.38
2.999	5.5	4.5	2.11
3.726	5.5	4.5	2.11
4.396	6.0	3.5	2.54
5.026	7.0	3.5	2.11

---

[9] G. E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).

in the case of $B^{11}(d,n)C^{12}$;[9] the ratio increases until the bombarding energy reaches the height of the Coulomb barrier and then remains fairly constant. The increase of the ratio at low energy can be interpreted as due to the increasing penetrability of the deuteron through the Coulomb barrier of the N^{14} core. Unlike the case of $B^{11}(d,n)C^{12}$, it is found necessary to vary the interaction radii as a function of the bombarding energy. No simple explanation can be offered for the fact that R_1 increases with energy while R_2 decreases.

It is not possible to obtain a good fit to the angular distribution at 1.148 Mev for any values of the parameters. A good fit to the forward peak can be made with parameters similar to those used at other energies, but it is not possible to fit the rise at large angles. The amplitude for compound nucleus formation may therefore be larger than the stripping amplitude at this energy. In order to fit the 2.588-Mev angular distribution, it is necessary to use a ratio of stripping amplitudes Λ_2/Λ_1 which is somewhat larger than those used for the other angular distributions. This could indicate either that the deuteron stripping amplitude at this energy has decreased or that the nuclear stripping amplitude has increased. Since the 0° cross section has a minimum at this energy, it is probable that the former is the case.

The 0° yield curve and the angular distributions are two apparently conflicting pieces of evidence on the nature of the mechanism by which this reaction takes place. To judge from the angular distributions alone, it would appear that this is a surface reaction. It is unlikely that the angular distributions would remain so similar in shape over such a wide energy range if the reaction proceeded by compound nucleus formation. But if this is a surface reaction, then there is difficulty in explaining the resonance-like structure in the yield curve. Stripping theory predicts a monotonic and slowly changing cross section as a function of energy at a given angle.

Some other reactions which have stripping-type angular distributions and resonance-type yield curves are $C^{12}(d,p)C^{13}$,[10,11] $O^{16}(d,p)O^{17}$,[12] and $N^{14}(d,n)O^{15}$.[3,4] In the $C^{12}(d,p)C^{13}$ experiments the angular distributions off the peaks of the 2.74-Mev and 3.01-Mev resonances are observed to be more nearly symmetric about 90° than the distributions at the peak of the resonances. This is the same phenomenon as is observed in the present experiment at the 1.148-Mev and the 2.588-Mev angular distributions.

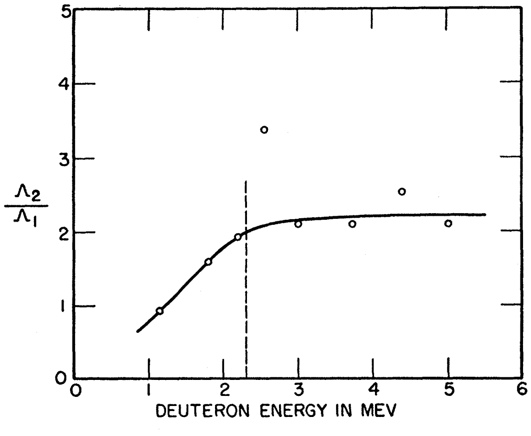

FIG. 6. The ratio of the nuclear stripping amplitude to the deuteron stripping amplitude as a function of bombarding energy. The dashed line represents the height of the Coulomb barrier.

There are several possible viewpoints for the interpretation of this type of data. Perhaps the most straightforward is that a small amount of compound nucleus formation could interfere with the stripping amplitude and cause the resonant behavior of the yield curve, while barely affecting the shape of the angular distributions.[13] Such a viewpoint has been taken by Bonner *et al.*[10] in their analysis of the reaction $C^{12}(d,p)C^{13}$. However, no thorough theoretical analysis of the effect of such interference on the yield curve and angular distributions has yet been made.

A second possibility is a refinement of the calculation of the pure stripping cross section. Many approximations are made in the usual derivation of the stripping formula. One of them is that the incoming deuteron and the outgoing neutron or proton can be represented by plane waves. A more exact solution would be obtained if one took into account the distortion of these waves by the Coulomb and nuclear forces. The effect of the use of distorted waves on the angular distribution has been considered by several people,[14] but no theoretical work has been done on the yield curve. It is possible that the use of distorted waves will result in a theoretical yield curve with considerable gross structure. However, it is not probable that such an approach will predict any fine structure with widths of a few hundred kev.

A third approach that has been suggested by Thomas[15] is to consider those mechanisms that are intermediate between direct interaction and compound nucleus formation. An example of such a mechanism in a stripping reaction would be one in which the emitted neutron was elastically scattered one or more times from the outer nucleons in the final nucleus. Such a scattering could have a resonant behavior as a function of energy. More scatterings would make the width smaller and smaller, until the mechanism would be indistinguishable from what is usually called compound nucleus formation. Such an intermediate mechanism might explain the

---

[10] Bonner, Eisinger, Kraus, and Marion, Phys. Rev. **101**, 209 (1956).

[11] McEllistrem, Jones, Chiba, Douglas, Herring, and Silverstein, Phys. Rev. **104**, 1008 (1956).

[12] E. Baumgartner and H. W. Fulbright, Phys. Rev. **107**, 219 (1957); Stratton, Blair, Famularo, and Stuart, Phys. Rev. **98**, 629 (1955).

[13] J. R. Holt, "Proceedings of the Amsterdam Conference" [Physica **22**, 1069 (1956)].

[14] J. Horowitz and A. L. M. Messiah, J. phys. radium **14**, 695 (1953); W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955); I. P. Grant, Proc. Phys. Soc. (London) **A68**, 244 (1955).

[15] R. G. Thomas, Brookhaven National Laboratory Report BNL-331 (unpublished).

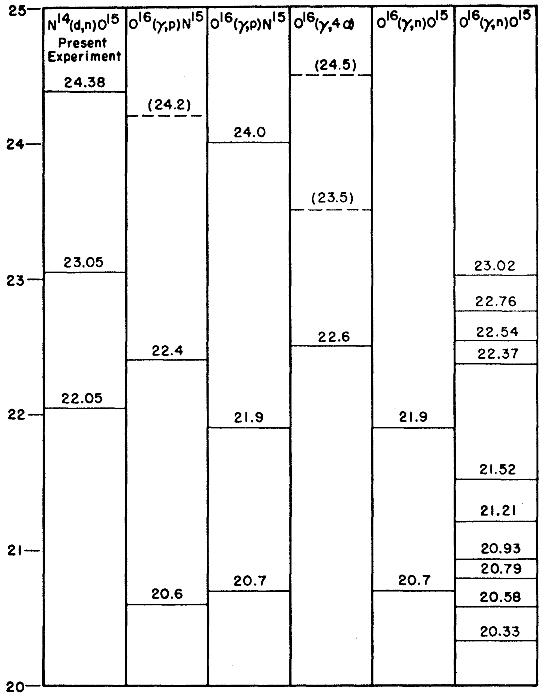

FIG. 7. Energy level diagram for O^{16} in the region of 20-Mev excitation showing the results of several experiments. The results are quoted from the following papers: Col. 2 from reference 18, Col. 3 from reference 19, Col. 4 from reference 20, Col. 5 from reference 17, Col. 6 from reference 16.

large widths of the peaks that are observed in the present experiment.

B. N^{14}(*d*,*n*)O^{15} Reaction

Broad anomalies are observed at 1.52, 2.67, and 4.19 Mev bombarding energy. If one assumes that a compound nucleus is formed, the peaks correspond to states at 22.05, 23.05, and 24.38 Mev excitation in O^{16*}. The peak at 1.52-Mev bombarding energy has also been observed by Morita.[4] However, his data also show that when the angle of observation is 165°, the position of the peak is shifted to 1.95 Mev, perhaps as the result of some interference effect. It is not known whether the other peaks are also shifted at different angles of observation. Because of this possibility, the excitation energies quoted above may be in error by as much as 500 kev. For the purposes of discussion, it will be assumed the above energies are correct. Figure 7 summarizes the information obtained from the reactions O$^{16}(\gamma,n)$O^{15},[16,17] O$^{16}(\gamma,p)$N^{15},[18,19] and $\mathrm{O}^{16}+\gamma\rightarrow 4\alpha$[20] on the region of excitation between 20 and 25 Mev. These are the only experiments which give information on this region of excitation.

In all the photonuclear experiments except O$^{16}(\gamma,n)$O^{15}, the levels are detected on nuclear emulsions as broad groups with poor resolution. The determination of the level energies in the (γ,p) and $(\gamma,4\alpha)$ experiments depends on knowing the range-energy relation for the emulsion. In the O$^{16}(\gamma,n)$O^{15},[16] many narrow levels are observed by detecting breaks in the yield curve for the O^{15} activity. The data points in the present experiment are not spaced closely enough to detect the narrow levels (<40 kev) seen in O$^{16}(\gamma,n)$O^{15} by Penfold and Spicer.[15] The determination of the level energies here depends on a calibration at lower energies using several photodisintegration thresholds. This energy scale is then extrapolated from the calibration points to the energy region above 20 Mev. The authors[16,17] state that even if there is no error in the calibration, the extrapolation can be in error by as much as 300 kev at 23 Mev.

There seems to be general agreement that there are levels at about 22 and 24 Mev, within the errors of the various energy calibrations. The 22–23 Mev doublet is not seen in any but the present experiment, except perhaps in O$^{16}(\gamma,4\alpha)$. The experiment by Cohen *et al.*[18] should have been able to resolve two levels more than 0.5 Mev apart.[21]

It is possible to explain this difference in the number of levels observed on the basis of isotopic spin selection rules, assuming that the N$^{14}(d,n)$O^{15} reaction proceeds by compound nucleus formation. Because of these selection rules, it may be that different levels are reached by the present experiment and by the photonuclear reactions. N^{14} and the deuteron are both $T=0$ nuclei, so that $\mathrm{N}^{14}+d$ can only form $T=0$ states in O^{16}. The gamma ray absorption in the 20 Mev region of excitation is mainly electric dipole, which has the isotopic spin selection rule $\Delta T=\pm1$.[22] If isotopic spin is a good quantum number, only $T=1$ states in O^{16} should be excited by the gamma absorption. Then it would not be surprising that there is a difference in the structure of the N$^{14}(d,n)$O^{15} and the photonuclear cross sections.

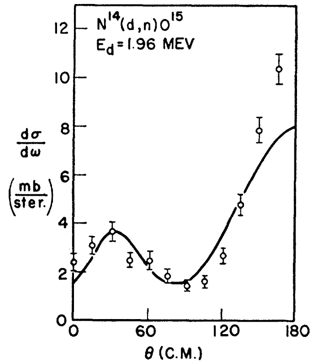

FIG. 8. Angular distribution of neutrons from the N$^{14}(d,n)$O^{16} reaction, for $E_d=1.96$ Mev. The data points are those of Nonaka *et al.* (reference 3). The solid line is a fit to the data using the exchange stripping theory of Owen and Madansky. $R_1=R_2=6.5$ fermis.

---

[16] B. M. Penfold and A. S. Spicer, Phys. Rev. **100**, 1377 (1955).

[17] Katz, Haslam, Horsley, Cameron, and Montalbetti, Phys. Rev. **95**, 464 (1954).

[18] Cohen, Mann, Patton, Reibel, Stephens, and Winhold, Phys. Rev. **104**, 108 (1956).

[19] D. L. Livesey, Can. J. Phys. 34, 1022 (1956).

[20] F. K. Goward and J. J. Wilkins, Proc. Phys. Soc. (London) **A65**, 671 (1952).

[21] W. E. Stephens (private communication).

[22] M. Gell-Mann and V. L. Telegdi, Phys. Rev. **91**, 169 (1953).

Wilkinson[23] states that isotopic spin is not a very good quantum number in this region, the impurity ranging from 10 to 50% in intensity. Better data on all these reactions might permit a more accurate determination of the impurity.

An alternative explanation of the difference is that the $N^{14}(d,n)O^{15}$ reaction proceeds largely by means of a surface reaction, while the photonuclear reactions proceed mainly by compound nucleus formation. The angular distribution measured by Nonaka *et al.*[3] can be fitted reasonably well using the exchange stripping theory of Owen and Madansky[9] mentioned previously, as is shown in Fig. 8. If $N^{14}(d,n)O^{15}$ is predominantly a surface reaction, then it may be coincidental that some of the peaks in the yield curve correspond to energy levels found in the photonuclear reactions. The discussion on the $N^{15}(d,n)O^{16}$ reaction concerning stripping angular distributions and resonant yield curves can also be applied to this reaction.

ACKNOWLEDGMENTS

We wish to thank Dr. L. J. Lidofsky, Mr. T. H. Kruse, and Mr. J. A. Baicker for their assistance throughout the course of the experiment. The N^{15} was provided by Professor T. I. Taylor and Dr. W. Spindel, Department of Chemistry, Columbia University. We also wish to thank Professor G. E. Owen, Professor L. Madansky, and Dr. B. Margolis for discussion of the theory of these reactions.

---

[23] D. H. Wilkinson, Phil. Mag. **1**, 379 (1956).

PHYSICAL REVIEW VOLUME 112, NUMBER 6 DECEMBER 15, 1958

Elastic Scattering of C^{12} from Gold*

E. Goldberg and H. L. Reynolds
Radiation Laboratory, University of California, Livermore, California

(Received August 18, 1958)

The angular distribution of C^{12} ions elastically scattered by gold has been measured at the following laboratory energies: 118±2, 101±2, 79.4±3, and 73.6±3 Mev. Heavy ions from the Berkeley heavy-ion linear accelerator (HILAC) were recorded in two Ilford E-1 plates from a scattering angle of 19° to 159°. In all cases the differential cross sections exhibited a Coulomb-like behavior at small angles, a rise above Coulomb of about twenty percent as the scattering angle increased, and then a rapid drop below Coulomb in much the same manner as alpha particles scattered from heavy elements in the 20–40 Mev range. The Blair "sharp cutoff" model reproduces closely the character of the data; however, small oscillations predicted from the model are not experimentally observed. Interaction distances of $(11.8\pm0.3,\ 12.1\pm0.3,\ 11.85\pm0.4,$ and $11.85\pm0.45)\times10^{-13}$ cm, respectively, for the foregoing energies are inferred from application of the Blair model.

INTRODUCTION

From the time of Rutherford's classic experiment,[1] the elastic scattering of nuclear particles has been used in the study of the nucleus and nuclear forces. Recently the elastic scattering of α particles of intermediate energy (10–50 Mev) by nuclei has received considerable attention.[2–7] Analysis of this data by means of the Blair[8,9] "sharp cutoff" model and by the optical model[10,11] has been quite successful. The α-particle elastic scattering is particularly useful in the study of the nuclear potential at the edge of the nucleus since the mean free path of α particles in nuclear matter is small. The mean free path and the ability to penetrate barriers will be reduced as the size and charge of the elastically scattered particle increases, leading to the conclusion that the elastic scattering of particles heavier than α particles should provide useful information concerning the outer surface of the nucleus.

The first experiment involving the elastic scattering of energetic particles heavier than α particles was done by Reynolds and Zucker[12] and concerned the scattering of N^{14} by N^{14}. In spite of the added complexity introduced by the identical nature of the particles the "sharp cutoff" model showed good agreement with the results.

The heavy-ion linear accelerator (HILAC) at the University of California Radiation Laboratory produces an average beam current of 0.5 μa of heavy ions from carbon through neon with energies of 10.2 Mev per nucleon. The beam energy may be reduced below

---

* This work done under the auspices of the U. S. Atomic Energy Commission.

[1] E. Rutherford, Phil. Mag. **21**, 669 (1911).

[2] G. W. Farwell and H. E. Wegner, Phys. Rev. **95**, 1212 (1954).

[3] Wall, Rees, and Ford, Phys. Rev. **97**, 726 (1955).

[4] Wegner, Eisberg, and Igo, Phys. Rev. **99**, 825 (1955).

[5] R. E. Ellis and L. Schechter, Phys. Rev. **101**, 636 (1956).

[6] Kerlee, Blair, and Farwell, Phys. Rev. **107**, 1343 (1957).

[7] J. R. Rees and M. B. Sampson, Phys. Rev. **108**, 1289 (1957).

[8] J. S. Blair, Phys. Rev. **95**, 1218 (1954).

[9] J. S. Blair, Phys. Rev. **108**, 827 (1957).

[10] W. B. Cheston and A. E. Glassgold, Phys. Rev. **106**, 1215 (1957).

[11] G. Igo and R. M. Thaler, Phys. Rev. **106**, 126 (1957).

[12] H. L. Reynolds and A. Zucker, Phys. Rev. **102**, 1378 (1956).