Experimental Determination of the Absolute Differential Cross Sections for the $O^{16}(d,p)O^{17}$, $O^{16}(d,p)O^{17*}$, and $O^{18}(d,p)O^{19*}$ Reactions*

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Nickel oxide foil targets were bombarded with deuterons in order to study the angular distributions of protons from the $O^{16}(d,p)O^{17}$ (ground state), $O^{16}(d,p)O^{17*}$ (0.875-Mev level), and $O^{18}(d,p)O^{19*}$ (1.468-Mev level) reactions. The absolute yield of the $O^{16}(d,p)O^{17}$ ground-state reaction was measured at $\theta_{c.m.}=53°$ in 35-kev steps of laboratory deuteron energy from 2.3 Mev to 3.9 Mev. A resonant-type yield was obtained, with cross sections per unit solid angle at $\theta_{c.m.}=53°$ of 17 mb at 2.65 Mev, 33 mb at 3.01 Mev, 19 mb at 3.25 Mev and 31 mb at 3.43 Mev. Angular distributions obtained over twenty-two center-of-mass angles from 5° to 161° at these four deuteron energies showed a forward maximum at 53° falling to a minimum of 13 mb in the neighborhood of 90° and rising gradually to 16 mb in the back angles. Fluctuations of intensity at the forward maximum provided the major contribution to maxima in the total yield at 3.0 Mev and 3.4 Mev. Differential cross sections for the $O^{16}(d,p)O^{17*}$ (0.875-Mev level) were measured at incident deuteron energies of 3.01 Mev and 3.43 Mev. The distributions obtained were of the typical stripping type with $l_n=0$. With NiO targets enriched to 23 percent in O^{18}, an angular distribution was obtained with 3.01-Mev deuterons for the $O^{18}(d,p)O^{19*}$ (1.468-Mev level) reaction. The distribution was of the character of a typical $l_n=0$ type stripping distribution with cross sections of 213 mb at 5°, falling to a minimum of 11 mb at 48° and rising to a secondary maximum of 27 mb at 84°. A spin and parity assignment of $\frac{1}{2}$, + to the 1.469-Mev level in O^{19} was made on the basis of the observed distribution.

INTRODUCTION

THE experimental work herein reported is a measurement of the absolute cross sections per unit solid angle as a function of deuteron energy and detector angle for the three reactions $O^{16}(d,p)O^{17}$, $O^{16}(d,p)O^{17*}$ (0.875-Mev level), and $O^{18}(d,p)O^{19*}$ (1.468-Mev level). The $O^{16}(d,p)O^{17}$ reaction is of particular interest because of the observed variations in the angular distribution of the emitted protons as a function of the incident deuteron energy. Evidence for interference between compound nucleus formation and a stripping mechanism is indicated. This report complements previous investigations by Heydenburg and Inglis[1] and present work at the University of Texas[2] with deuteron energies less than 3 Mev, and the experiments with the Liverpool cyclotron at 8 Mev.[3] Investigations of the $O^{16}(d,p)O^{17*}$ (0.875-Mev level) reaction have been reported by the above authors and by Berthelot *et al.*[4]

The present report is the only work known to the authors of an angular distribution for the $O^{18}(d,p)O^{19*}$ (1.468-Mev level) reaction. The Q-value for the reaction was determined by range measurements in nuclear emulsions to be 0.3 ± 0.2 Mev; presumably the reaction investigated corresponded to the second excited state of O^{19}, which has been found by magnetic analysis methods to have a Q-value of 262 ± 6 kev.[5–7] The stripping theory of S. T. Butler allowed a spin and parity assignment to be made for the level.

EQUIPMENT

The source of deuterons used in this work was the Minnesota electrostatic generator.[8] The design details of the reaction chamber which was used for this study have been given by Holmgren *et al.*[9] In the following description, letters designating parts of the apparatus will refer to Fig. 1 of reference 9.

The general features of the chamber were that (1) the ion beam from the accelerator was collimated by a system of defining and antiscattering apertures, (A) and (B); (2) the angular range which was swept out by the detector system (parts G through K) extended from 0° to 160°; (3) current was collected by a Faraday cup with a secondary current suppressor guard ring (E) for angles of observation greater than 15°, while for smaller angles the beam was monitored by a proportional counter (L); (4) solid targets were required.

The chamber was adaptable to two types of detectors for the reaction products. The system described by Holmgren *et al.*,[9] used a region of strong magnetic field, (H), between the first and second analyzer defining slits, which served to spread the reaction products into momentum groups with about 15 percent resolution. The particles then entered a nuclear photographic emulsion, (K), serving as an energy sensitive detector, and the yield could then be determined by usual microscopic counting techniques. The combination of momentum and energy selection generally allowed rapid counting and positive identification of the particles entering the emulsion. At the extreme forward angles it sometimes happened that reaction protons

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[1] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).
[2] J. P. Grosscreutz (private communication).
[3] Burrows, Gibson, and Rotblat, Phys. Rev. **80**, 1095 (1950).
[4] Berthelot, Cohen, Cotton, Faraggi, Grjebine, Levêque, Naggiar, Roclawski-Conjeaud, and Szteinsznaider, Compt. rend. **238**, 1312 (1954).
[5] Thirion, Cohen, and Whaling, Phys. Rev. **96**, 850 (1954).
[6] C. Mileikowsky and K. Ahnlund, Phys. Rev. **96**, 996 (1954).
[7] Holmgren, Hanscome, and Willett, Bull. Am. Phys. Soc. **29**, No. 7, 26 (1954).
[8] Williams, Rumbaugh, and Tate, Rev. Sci. Instr. **13**, 202 (1942).
[9] Holmgren, Blair, Simmons, Stratton, and Stuart, Phys. Rev. **95**, 1544 (1954).

were completely obscured by an extremely large yield of Rutherford-scattered deuterons of approximately the same momentum, so that a further refinement was to wrap the nuclear plates with absorber foils of appropriate thickness and selectively absorb the deuterons. The solid angle defined by the system with emulsion detectors was 5.58×10^{-5} steradian.

For certain applications where the momentum and energy resolution provided by the magnetic field and the nuclear emulsions was not required, a proportional counter replaced the parts indicated by (*G*), (*H*), (*I*), (*J*), and (*K*). A different system of detector defining apertures preceded the proportional counter, replacing (*F*) and (*G*) with circular apertures. The diameter of the antiscattering slit at (*G*) was 0.180 inch; the defining aperture was measured to be 0.1505 ± 0.0005 inch and was 5.976 ± 0.005 inches from the center of the chamber. The resulting solid angle seen by the proportional counter was $(4.98\pm0.02)\times10^{-4}$ steradian. A selection of aluminum foils served to separate the proportional counter filling gas from the evacuated chamber, and to adjust the relative energy losses in the counter for the various reaction products. Pulses from the counter were amplified by a cathode-follower preamplifier preceding a linear amplifier (Los Alamos Model 100) and were then sorted by a ten-channel discriminator.[10]

The deuteron current was integrated by an electronic current integrator, which was semiautomatic in operation; after a predetermined charge was collected, the circuit interposed a shutter in the beam and grounded the counter signal.

The chamber was designed to use thin solid targets. For the work with oxygen, the problem was met by a process for manufacturing self-supporting nickel-monoxide targets containing approximately 10^{19} oxygen atoms per square centimeter. The procedure for preparing such targets has been described by Holmgren *et al.*[11]

All voltage calibrations of the incident deuteron energy and the energy losses by ionization in passing through the targets have been by reference to the threshold for the $Li^7(p,n)Be^7$ reaction.[12] Extrapolations of the ionization loss to deuterons and energies other than 1.882 Mev were made using theoretical formulas for energy loss by ionizing collisions.[13]

RESULTS

$O^{18}(d,p)O^{19*}$

The yields of reaction products from deuterons of 3.01-Mev incident on nickel-oxide targets prepared from natural oxygen (0.2 percent O^{18}) and from oxygen enriched[14] to 23 percent O^{18} were compared by using the magnetic analyzer and nuclear emulsion detectors. One group of protons appeared from irradiations of the enriched target which was not in evidence with exposures taken with the natural oxygen target.

The energy release associated with the proton group was computed from the measured range of the protons in the Ilford C-2 emulsions, the detector angle, and the incident deuteron energy. The method could be checked by comparison of the Q's determined in the same plates for the $O^{16}(d,p)O^{17}$ ($Q=1.92$ Mev) and the $O^{16}(d,p)O^{17*}$ ($Q=1.04$ Mev) reactions. The best estimate for the Q-value of the (d,p) reaction on O^{18} was determined to be 0.3 ± 0.2 Mev. Since this work was completed, three reports on the magnetic analysis of the reaction products from deuterons incident on O^{18} have been made.[5-7] All three are consistent with a Q of 0.262 ± 0.006 Mev corresponding to a level in O^{19} at 1.468 Mev.

An angular distribution was determined for the protons leaving O^{19} in the 1.468-Mev level, at an incident deuteron laboratory energy of 3.01 Mev. The data were taken with nuclear photographic plates as the detectors. For detector laboratory angles from 15° to 160° the incident deuteron current was integrated directly from the collector cup by the integrating circuit. For the 5° and 10° data it was necessary to remove the collector cup and monitor the incident deuteron beam by means of the monitor proportional counter at a fixed angle of 55°. The monitor calibration was determined by direct comparison of the yield of elastically scattered deuterons and the integrated deuteron current with the target at the exact position at

TABLE I. Center-of-mass differential cross sections σ for the $O^{18}(d,p)O^{19*}$ reaction for 3.01-Mev incident deuterons (laboratory system) as a function of the center-of-mass angle θ. The cross sections are in millibarns (10^{-27} cm^2).

$\theta_{c.m.}$ (degrees)	$\sigma_{c.m.}$ (mb)
5.4	213 ±16
10.7	198 ±12
16.1	166 ± 6
21.4	137 ± 6
32.1	53 ± 3
37.4	22.7± 1.1
42.7	15.7± 1.0
48.0	12.5± 0.7
53.2	14.2± 0.9
58.5	15.2± 0.9
68.5	18.2± 1.0
73.9	24.1± 1.1
84.1	27.0± 0.9
94.2	23.1± 0.9
104.1	19.8± 0.8
113.9	17.8± 0.8
123.6	16.1± 0.7
133.2	14.2± 0.7
147.4	10.1± 0.8
161.4	12.1± 0.9

[10] W. C. Elmore and M. Sands, *Electronics* (McGraw-Hill Book Company, Inc., New York, 1949).
[11] Holmgren, Blair, Famularo, Stratton, and Stuart, Rev. Sci. Instr. **25**, 1026 (1954).
[12] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).
[13] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937).
[14] We are indebted to Professor A. O. Nier for making available to us the enriched oxygen.

which it was to be used for the small angle measurements.

The data, corrected to the center-of-mass system of coordinates, are presented in Table I, and the resulting angular distribution is plotted in Fig. 1. The errors quoted in the table apply to the relative angular distribution. For angles between 15° and 160° the errors are composed of the counting statistics in the plates; the 5° and 10° points include, in addition to the plate statistics, the statistical errors incurred in the calibration of the monitor counter and the number of monitor counts for a given plate exposure. The geometry of the plate detector system and the resolving time of the proportional counter required that the number of monitor counts be of the same order as the number of reaction protons detected by the emulsions.

$O^{16}(d,p)O^{17}$

At a center-of-mass angle of 53°, the yield of protons from the $O^{16}(d,p)O^{17}$ reaction was measured over a range of deuteron energies from 2.19 Mev to 3.84 Mev in approximately 35-kev steps. The yield was found to exhibit the general character of a resonance type process with maxima occurring at $E_d=2.93$, 3.39, and 3.67 Mev. A curve showing the experimental results is shown in Fig. 2. Since the earlier work of Heydenburg and Inglis[1] showed extreme variations in the angular distribution of the protons as a function of the deuteron energy, a systematic attempt was made to measure the angular distributions of the protons at deuteron energies

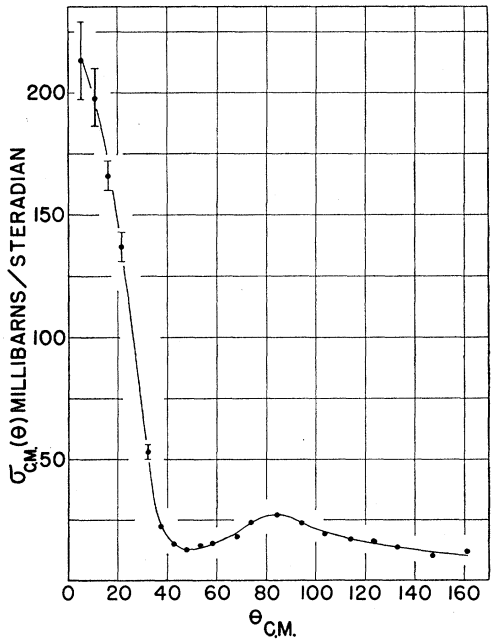

FIG. 1. Center-of-mass differential cross sections for the $O^{18}(d,p)O^{19*}$ reaction *vs* center-of-mass angles, for incident deuterons of 3.01 Mev.

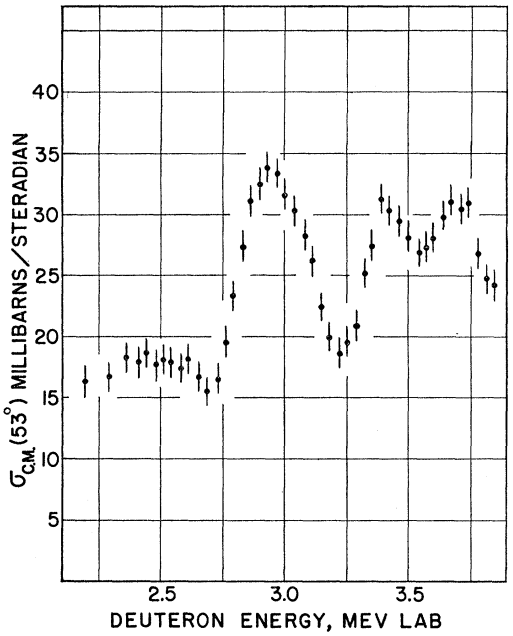

FIG. 2. Center-of-mass differential cross sections for the $O^{16}(d,p)O^{17}$ reaction *vs* laboratory deuteron energy, observed at an angle of 53° in the center-of-mass system.

corresponding to maxima and minima in the excitation function.

For this purpose the nuclear emulsions were not used, except at $E_d=3.01$ Mev; instead the rotatable proportional counter was installed because of the greater ease of obtaining data. The $O^{16}(d,p)O^{17}$ protons had the greatest range of any of the reaction products [except $O^{17}(d,p)O^{18}$, but O^{17} was only 0.04 percent of the oxygen in the target] and so they could be easily isolated by absorbers placed before the counter window.

Angular distributions from 16° to 161° in the center-of-mass were obtained at deuteron energies of 2.65, 3.01, 3.25, and 3.43 Mev. These data are plotted in Fig. 3 and are tabulated in Table II. As in the $O^{18}(d,p)O^{19*}$ data, the errors shown or tabulated represent the estimated relative errors. The proportional counter data was subject to background corrections, particularly at the small and large angles. At the back angles the counter was very near the first deuteron-beam defining slit, a strong source of neutrons and gamma rays; at the forward angles, protons of almost any energy from secondary (d,p) processes in the absorber foils (aluminum) contributed background counts.

It is immediately apparent that the most prominent variations in the magnitude and appearance of the distributions with deuteron energy appear at the 53° maximum. It is at the proper place to correspond to a stripping theory prediction for the forward maximum of a process with parameters $l_n=2$ and $R_0=6.5\times10^{-13}$ centimeter (if one uses the Born approximation formula

TABLE II. Center-of-mass differential cross sections σ for the $O^{16}(d,p)O^{17}$ reaction as a function of the center-of-mass angle θ for incident deuterons of 2.65, 3.01, 3.25, and 3.43 Mev in the laboratory system. The cross sections are in millibarns (10^{-27} cm^2).

$\theta_{c.m.}$ (degrees)	$\sigma_{c.m.}$ (millibarns) $E_D=2.65$	$E_D=3.01$	$E_D=3.25$	$E_D=3.43$
5.3		8.2±2.1		
10.7		9.2±1.5		
16.0	9.2±0.9	13.7±1.0	5.4±0.9	9.9±0.7
21.3	11.1±0.5	15.8±0.8	8.2±0.7	12.0±0.7
26.6	12.4±0.5	20.7±0.6	11.4±0.5	16.9±0.7
31.9	14.0±0.5	24.8±0.7	15.7±0.4	21.7±1.0
37.2	15.1±0.5	27.4±0.5	17.2±0.4	26.2±1.0
42.4	16.4±0.5	31.6±0.5	19.2±0.4	29.1±1.0
47.7	17.4±0.5	32.8±0.5	19.3±0.4	31.5±1.2
52.9	17.1±0.7	32.6±0.5	19.2±0.4	31.2±1.0
58.1	16.9±0.4	31.9±0.5	18.6±0.4	30.1±1.0
63.3	16.1±0.4	30.8±0.5	17.0±0.5	27.2±1.0
68.4	14.6±0.4	28.7±0.5	14.8±0.5	24.5±1.0
73.6	13.6±0.4	25.0±0.5	13.5±0.6	22.6±0.7
83.7	12.8±0.5	20.9±0.6	11.3±0.5	18.1±0.5
93.8	11.3±0.5	18.2±0.6	10.7±0.5	15.2±0.5
103.7	12.2±0.5	16.6±0.5	11.9±0.6	12.8±0.8
113.6	13.5±0.8	15.3±0.5	12.5±0.8	14.2±0.5
123.3	14.8±0.8	15.6±0.5	14.4±0.8	15.4±0.6
132.9	16.9±0.9	16.2±0.6	13.6±0.8	17.4±0.6
147.2	17.2±0.9	15.1±0.6	13.1±0.7	18.5±0.6
161.3	17.2±1.4	14.2±0.6	12.7±0.8	19.7±1.3

of Bhatia *et al.*[15]). The present state of the refinements in all stripping theories does not, however, include the possibility of resonance processes.

$O^{16}(d,p)O^{17*}$

Angular distributions of the emitted protons at laboratory deuteron energies of 2.65, 3.01, 3.25, and 3.43 Mev were obtained for the $O^{16}(d,p)O^{17*}$ (0.875-Mev level) reaction. The process has been studied previously[1–4] with particular emphasis on changes of the angular distribution with deuteron energy. The data obtained in the present experiment showed that the angular distribution could be described by a stripping mechanism with $l_n=0$. The first minimum occurred at about 40° and the secondary maximum around 70°. The positions of these minima and maxima were observed to shift slightly with deuteron energy, but no general trend could be discerned.

Figure 4 shows angular distributions obtained at 2.65, 3.01, 3.25, and 3.43 Mev. In addition, Fig. 5 shows the observed yield at $\theta_{c.m.}=53°$ as a function of deuteron energy. It should be noticed that 53° corresponds to a portion of the angular distributions where slight shifting of the position of the secondary maximum would give rise to fluctuations in the excitation function and obscure any real resonance effects.

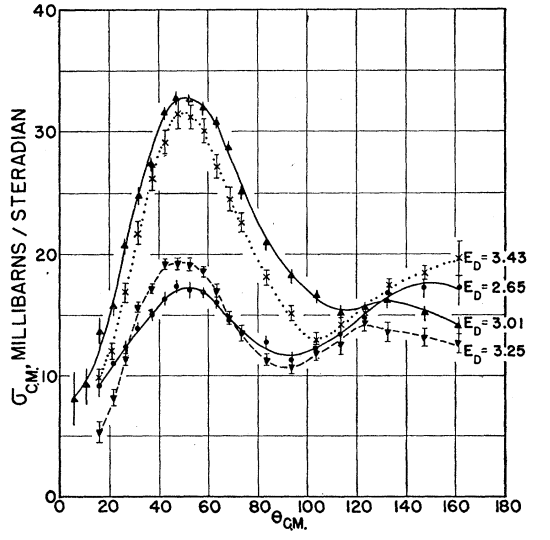

FIG. 3. Center-of-mass differential cross sections for the $O^{16}(d,p)O^{17}$ reaction *vs* center-of-mass angles, for various deuteron energies in the laboratory system.

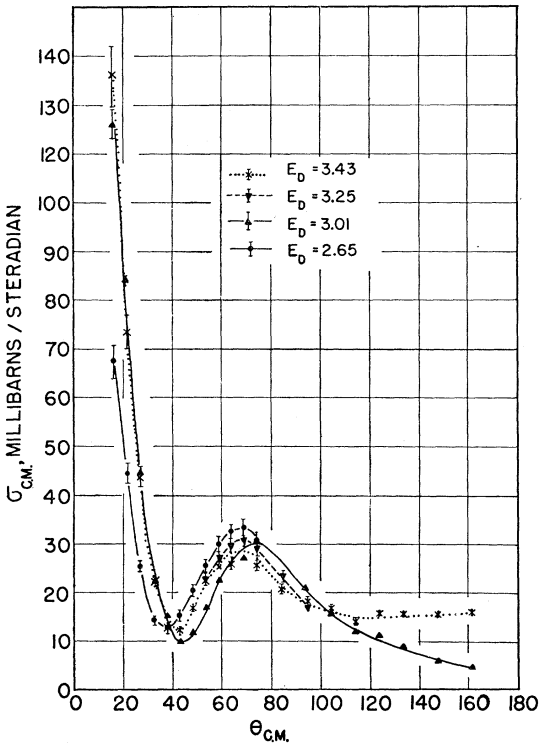

FIG. 4. Center-of-mass differential cross sections for the $O^{16}(d,p)O^{17*}$ reaction (0.875 Mev level) *vs* center-of-mass angles, for various deuteron energies in the laboratory system.

ERRORS

Throughout the discussion of each of the three reactions, the estimated relative errors due to counting statistics have been reported. In addition to relative errors it is necessary to estimate the absolute errors.

It is believed that the absolute geometry determinations are known to one-half percent for either detector system. A check on the geometry factor for the two systems was made by comparing the data obtained with the two for the $O^{16}(d,p)O^{17}$ reaction at 3.01 Mev.

[15] Bhatia, Huang, Huby, and Newns, Phil. Mag. **43**, 485 (1952).

No systematic variation was seen. However, the same instruments were used to measure the slit widths and other pertinent data for both detectors.

The electronic current integrator was calibrated by a current-time scheme. The absolute calibration was estimated at one percent. The relative comparison between integrator scales was believed better than one-half percent. It may be remarked that during two years of service, the maximum drift observed in the calibration of any scale was less than one-half percent.

Two independent estimates of the number of oxygen atoms per square centimeter in the target area were possible. The first was based on the fact that x-ray crystallographic analysis[16] of the oxidized nickel foils showed that the target area was greater than ninety-five percent nickel monoxide. Before oxidation, the nickel foils were weighed on a precision microbalance and their areas measured. Assuming complete oxidation of the target area to NiO meant that the number of oxygen

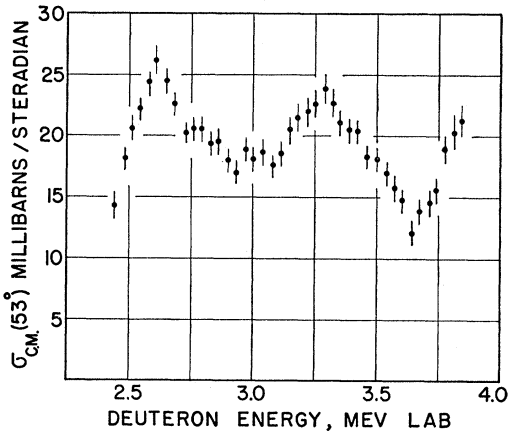

FIG. 5. Center-of-mass differential cross sections for the $O^{16}(d,p)O^{17*}$ reaction (0.875-Mev level) *vs* laboratory deuteron energy, observed at an angle of 53° in the center-of-mass system.

atoms per square centimeter in the target could be computed directly.

The second determination of the foil thicknesses was less direct, but possessed the distinct advantage that the target thickness was measured under conditions very similar to those in which it was used for the experiment. The Faraday cage for beam collection was removed and a thick LiCl target put in its place. The ionization loss of protons passing through the nickel foil before and after oxidation was measured by the shift of the $Li^7(p,n)Be^7$ threshold, determining the oxygen thickness at the exact position that the beam would normally strike the target. The addition of the oxygen to the nickel increased the thickness by thirty percent, so that with estimated errors of about four

[16] Appreciation is expressed to Professor W. N. Lipscomb of the Department of Physical Chemistry of the University of Minnesota for the use of the x-ray diffraction apparatus and for analysis of the data which were obtained.

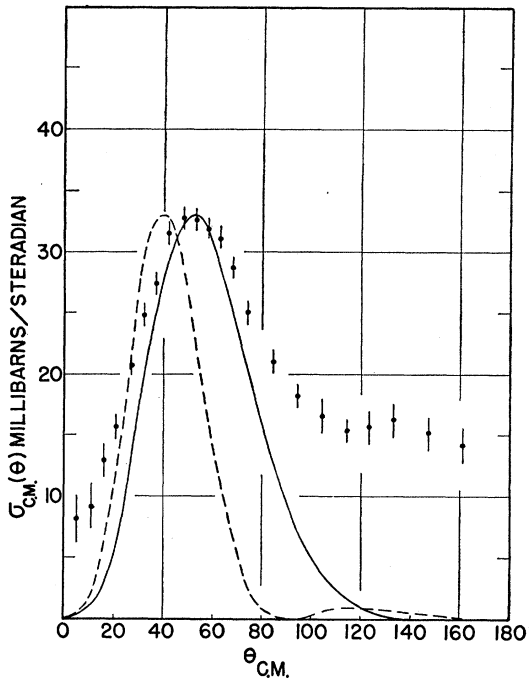

FIG. 6. Center-of-mass differential cross sections for the $O^{16}(d,p)O^{17}$ reaction *vs* center-of-mass angle, for incident deuterons of 3.01 Mev. Points represent experimental determinations. Curves are theoretical angular distributions on the basis of Bhatia's formula using $l=2$ for two values of R. ————: $R=6.5\times10^{-13}$ cm. – – – – –: $R=9.0\times10^{-13}$ cm.

percent in the individual ionization loss measurements, the difference between nickel and nickel monoxide could not be determined with extreme precision. The best over-all absolute estimate of the number of O^{16} atoms per square centimeter in the targets used for the $O^{16}(d,p)O^{17}$ and the $O^{16}(d,p)O^{17*}$ reactions was ten percent; for the $O^{18}(d,p)p^{19*}$ work, twelve percent is estimated for the determination of the number of O^{18} atoms per square centimeter.

In view of the large errors estimated for the absolute target thickness determinations in comparison with the errors associated with charge and geometry measurements, the overall absolute error for the $O^{16}(d,p)O^{17}$ and $O^{16}(d,p)O^{17*}$ data is ten percent, and is twelve percent for the $O^{18}(d,p)O^{19*}$ distribution.

The absolute voltage calibration is considered accurate to ±20 kev, based on 1.882 Mev for the $Li^7(p,n)Be^7$ threshold. The energy quoted for any angular distribution may be compared directly with the same energy on the excitation curves.

CONCLUSIONS

It has been shown[5–7] that the reaction of deuterons with O^{18} investigated here corresponds to the second excited state in O^{19}, having an energy level of 1.468 Mev. The angular distribution obtained for the reaction may be compared with a stripping mechanism and the parameter $l_n=0$ is indicated. Together with the fact

that O^{18} is known to have zero spin, the stripping theory will therefore require that the 1.468-Mev level in O^{19} have even parity and spin $\frac{1}{2}$.

Figure 6 shows angular distributions calculated from the theoretical formula of Bhatia *et al.*[15] with the angular momentum carried into the target nucleus by the absorbed neutron taken to be two, for two values of the interaction radius. The spin of the ground state of O^{17} has been measured to be 5/2, so that the assumption of $l_n=2$ is justified. The maximum in the distribution observed at about 50° is predicted by the theoretical calculations, which assume as a basic approximation that the proton does not interact with the target nucleus. The neutron is captured in a definite energy state of the final system, and there has been no way yet proposed by which resonance processes can occur with a stripping mechanism. The data show that the part of the angular distribution generally associated with the stripping process behaves in an unpredictable manner, and a more complicated picture of the (d,p) process than has been yet formulated is indicated.

ACKNOWLEDGMENT

It is a pleasure to acknowledge the encouragement, advice, and interpretations of Professor John H. Williams and Professor Warren B. Cheston. In addition, the assistance provided by the several other members of the Minnesota electrostatic generator group whose names do not appear as authors was of invaluable service: Dr. G. Freier, Dr. H. Holmgren, Dr. D. Van Patter, B. Simmons, and D. Zipoy.

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Liquid Scintillator Measurements of Angular Elastic Scattering of Neutrons from Carbon, Aluminum, and Sulfur*†

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Angular elastic scattering cross sections have been measured for carbon, aluminum, and sulfur using 2.7-Mev neutrons from the D(d,n) reaction. A liquid organic scintillator, terphenyl in xylene, was used as the neutron detector. The differential pulse-height spectra for the neutrons scattered from sulfur and for Co^{60} gamma rays are given.

INTRODUCTION

THE angular distribution of scattered neutrons of a few Mev energy, having wavelengths comparable to nuclear radii, has been the subject of many investigations because the interaction of the neutrons with the scattering nuclei affords one of the simplest methods of attack on the problem of nuclear structure.

Sufficiently intense mono-energetic neutron sources and adequate neutron detector efficiencies have only now begun to yield data accurate enough to select between some of the postulated nucleon-nucleon interactions. The development of a high-efficiency liquid scintillation detector for neutrons prompted the present attempts to measure differential angular scattering cross sections using this detector.

The theory of the experiment is simple and the geometry of a ring scatterer has been used in previous scattering experiments.[1–4] Most of the discussion will concern the analysis of the detector readings since the detector responds with comparable efficiencies to both gamma rays and neutrons. The discussion of the experiments in this article include measurements from which it is felt that the differential angular elastic scattering can be identified without equivocation. A subsequent article will report the measurements being made on iron, copper, cadmium, wolfram, and lead where inelastically scattered neutrons and de-excitation gamma rays make the identification more difficult.

CROSS SECTION CALCULATION

The differential angular scattering cross section, $\sigma(\theta)$, for a thin scatterer is defined as

$$\sigma(\theta)=I_s(\theta)/I_0'N, \quad (1)$$

where θ is the angle between the original velocity of the neutron and its velocity after being scattered, $I_s(\theta)$ is

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