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Publication Date
1961-02-01

UCRL-9525

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ABSTRACT

The reactions $Li^{6}(\alpha,d)Be^{8}$ and $N^{14}(\alpha,d)O^{16}$ were studied with 48-Mev helium ions. Deuteron angular distributions were obtained for several energy levels in the final nuclei. They, as well as distributions for the reaction $C^{12}(\alpha,d)N^{14}$ previously studied, are compared with angular distributions calculated from the two-nucleon stripping theory of N. K. Glendenning. The integrated cross sections for formation of various levels of Be^{8} and O^{16} are discussed in terms of the spectroscopic states of these nuclei.

(α,d) REACTIONS ON ODD-ODD TARGETS*

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INTRODUCTION

The $Li^6(\alpha,d)Be^8$ and $N^{14}(\alpha,d)O^{16}$ reactions have been investigated as part of a continuing study of two-nucleon transfer reactions in the light elements. As noted earlier,[1] the (α,d) reaction with 48-Mev helium ions does not form all the T = 0 excited states of the product nucleus. Interest has centered upon understanding this selectivity and upon the possibility of spectroscopic identification of states from fitting the deuteron angular distributions from an (α,d) reaction with a two-nucleon transfer theory. The plane-wave, finite-size incident particle, two-nucleon stripping theory of N. K. Glendenning,[2] being a more complete development than that of el Nadi,[3] has been applied to the deuteron angular distributions from these odd-odd targets and to the data obtained previously[1] from the (α,d) reaction on the even-even target C^{12}. Comparisons with the results of the Butler theory[4] were made, since this theory has been fairly successful in interpreting one-nucleon transfer reactions and has been applied in some cases to two-nucleon transfer reactions.[5,6] Its use would be most appropriate if the residual state possessed a strong cluster parentage of the target plus a deuteron.

EXPERIMENTAL PROCEDURE

Bombardments with approximately 48-Mev helium ions were made in a 36-inch scattering chamber by using the deflected external beam of the Crocker Laboratory 60-inch cyclotron. Reaction products were identified with an

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

† National Science Foundation Predoctoral Fellow, 1958-1961.

$E - \frac{dE}{dx}$ counter telescope which operated a pulse multiplier; multiplied pulses corresponding to deuterons were used to trigger a Penco 100-channel pulse-height analyzer, which recorded the energy spectrum of deuterons. The experimental apparatus, counting equipment, and general data-analysis procedures were previously described.[1]

The previous $\frac{dE}{dx}$ component of the counter telescope— a CsI (Tl) crystal— was replaced by a 16.5-mil diffused-junction silicon detector. Under the experimental conditions used in the nuclear reaction measurements, the detector gave 0.9% energy resolution for the α particles from Po^{212} decay. About the same resolution was obtained with 20-Mev α particles from a (d,α) reaction, but in this case the resolution was probably determined by the approximately 0.8% energy spread in the cyclotron beam. The detector gave an output which was strictly proportional to helium ion energy in the range between 5 and 22.5 Mev, when used at 180 volts reverse bias. The introduction of the silicon detector resulted in a marked improvement in the multiplied spectra. Fig. 1 shows a typical spectrum for $Li^6 + He^4$ and Fig. 2 for $N^{14} + He^4$. As in the case of $C^{12} + He^4$, these reactions produced relatively few tritons.

Li^6 targets were unsupported foils rolled from 99.3% enriched Li^6 metal obtained from Oak Ridge National Laboratory. The target thickness was determined to be 9.8 mg/cm^2 by measuring the beam range with the target both in and out and then converting[7,8] this differential range in Al to the range in Li^6. N^{14} was bombarded in gaseous form in a 3-in.-diameter gasholder placed inside the evacuated scattering chamber. The gasholder had 0.001-inch Dural windows and could be rotated to permit measurements at any laboratory angle. This system was connected to an external manometer and to a pumping unit so that the gas pressure could be read and the gas changed if desired.

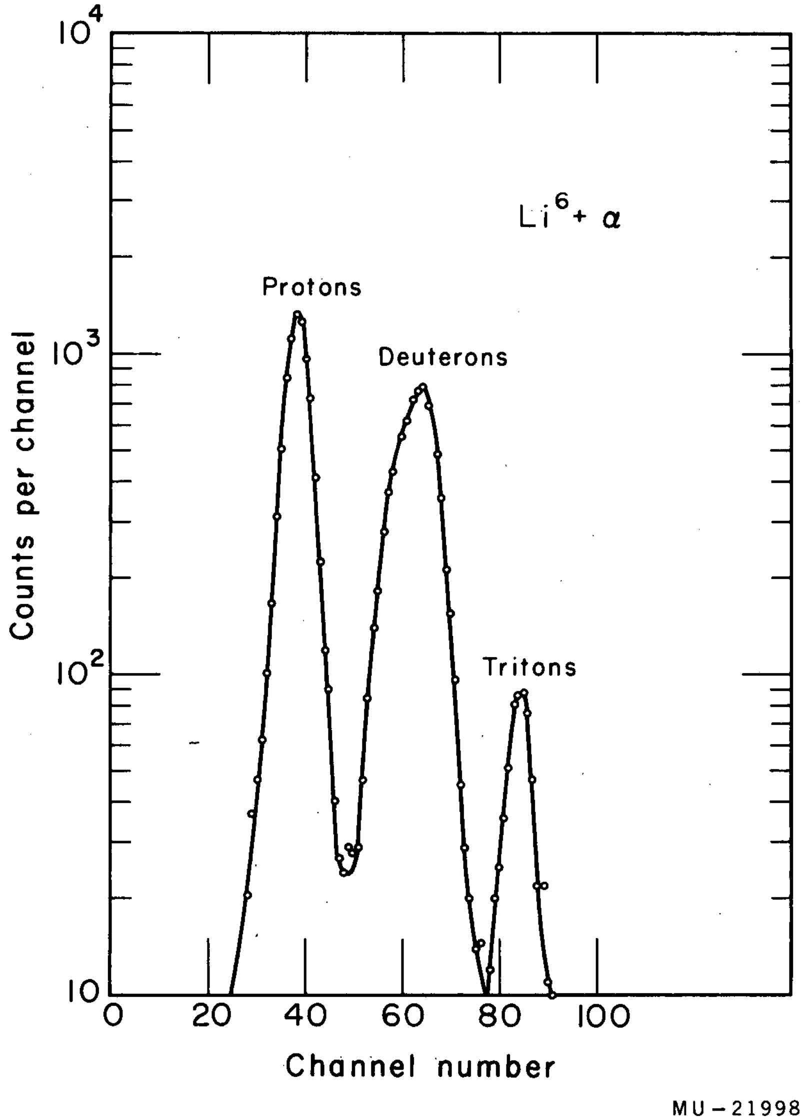

Fig. 1. Pulse multiplier spectrum from bombardment of Li^6 with 48-Mev helium ions.

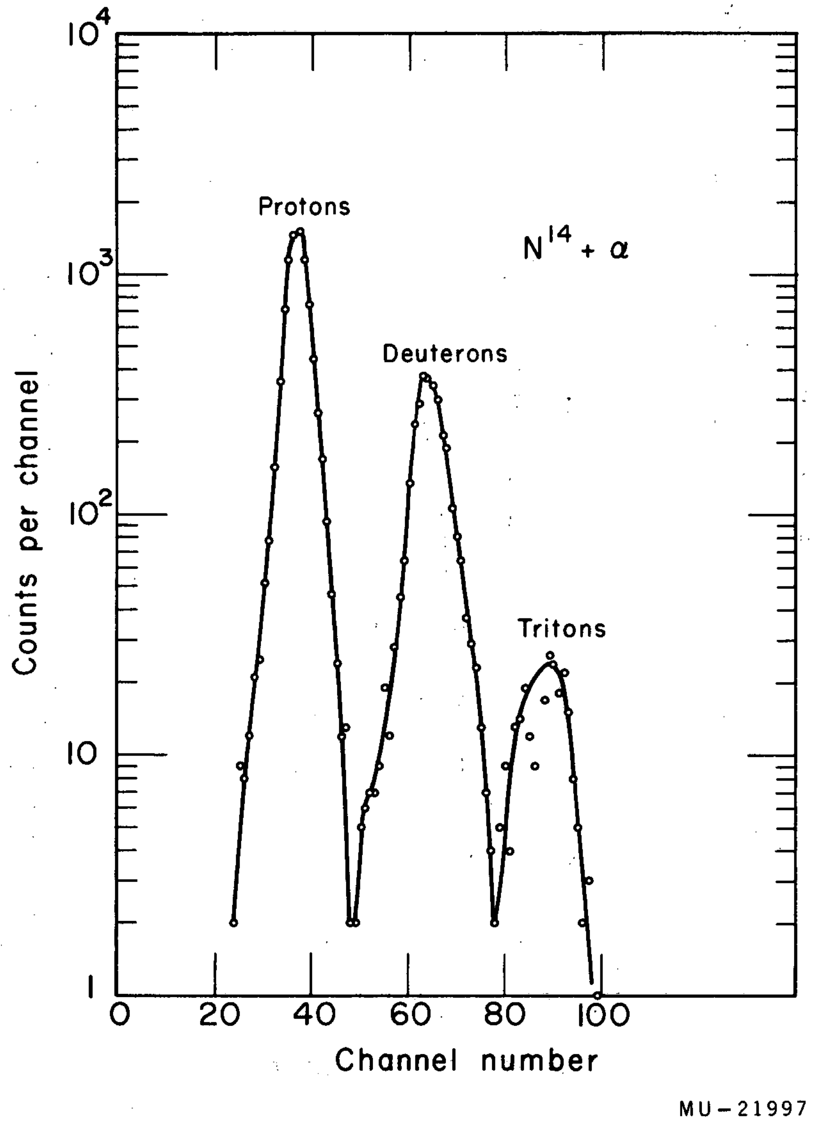

Fig. 2. Pulse multiplier spectrum from bombardment of N^{14} with 46.5-Mev helium ions.

The effective helium ion energy was 46.5 Mev when the gasholder contained 76 cm Hg pressure of nitrogen at 20°C. An additional slit was placed in front of the counter collimator to define the solid angle when bombarding a gas target.

RESULTS

Figs. 3 and 4 show typical deuteron energy spectra from the reactions $Li^6(\alpha,d)Be^8$, 27.5 deg, and $N^{14}(\alpha,d)O^{16}$, 60 deg, respectively. In neither case were any known T = 1 levels populated strongly enough to be distinguished from the background or from nearby T = 0 levels. Tables I and II show the levels observed; the energy resolution was not high enough to set low limits

TABLE I

Comparison of Be^8 levels observed in this experiment with levels previously reported.[a]

Levels identified (Mev)	Previously reported levels		
	Energy (Mev)	J^{π}	T
0[b]	0	0+	0
2.9[b]	2.90	2+	0
11.3 ± 0.4	11.4	4+	0

a. References 10 and 11.
b. These levels were identified by means of a deuteron energy scale constructed by the use of cyclotron-accelerated deuterons. After satisfactory identification, deuterons corresponding to these levels were used to extend the scale to higher energies.

on the cross sections to unobserved, known T=0 levels. The estimated error to be expected in these energy determinations is about ± 0.2 Mev. Ground-state Q values were taken from Ashby and Catron.[9]

The angular distributions of deuterons corresponding to formation of the ground state and the 2.90-Mev state of Be^8 are shown in Figs. 5 and 6, respectively. The errors shown represent counting statistics only; the angular accuracy is about ± 1 deg. Integrated cross sections will be found in Table III, and are discussed later.

TABLE II

Comparison of O^{16} levels observed in this experiment with those previously reported.[a]

Levels identified (Mev)	Previously reported levels		
	Energy (Mev)	J^{π}	T
0[b]	0	0+	0
6.1[b]	6.056	0+	0
	6.135	3-	0
7.0[b]	6.923	2+	0
	7.121	1-	0
8.9[b]	8.875	2-	0
	9.58	1-	0
	9.843	2+	0
	10.363	4+	0
	(10.804)		
11.0 ± 0.2	10.937	0-	0
	11.070	3+	(0)
	11.25	0+	0
	11.51	2+	0
	11.62	3-	0
	12.02		
	(12.29)		
12.3 ± 0.2	12.43	1-	0
	12.52	2-	
	12.78	0-	1
	12.96	2-	1
	13.09	1-	1
	13.25	3-	1
13.6±0.2	13.65	1+	0
14.3±0.2	13.97	2-	
14.7±0.2	14.93	4+	
	15.21	2-,3+	
	15.25	2+	
	15.41		
	15.79		
16.2±0.2	16.21	1+	
	16.3	0-	
	16.44		
	(16.82)		
	(16.93)		
	17.0		
17.0±0.2	17.12		
	17.29		

a. Reference 10.

b. See footnote b, Table I.

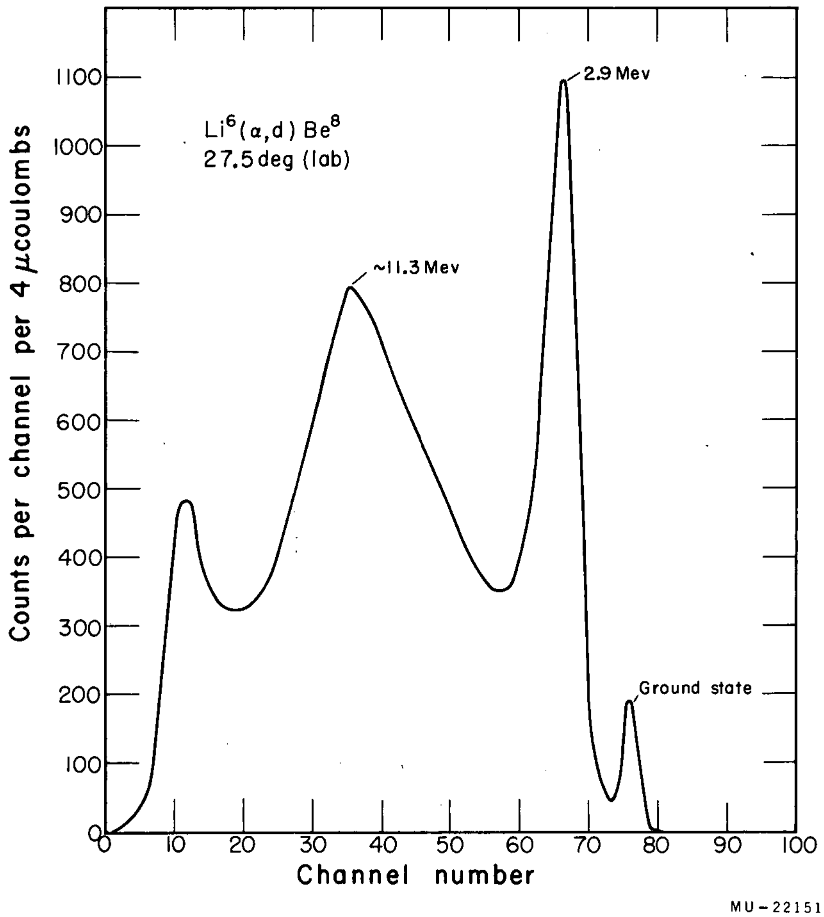

Fig. 3. Deuteron energy spectrum from the reaction $Li^6(\alpha,d)Be^8$.
Q values for the various peaks are shown.

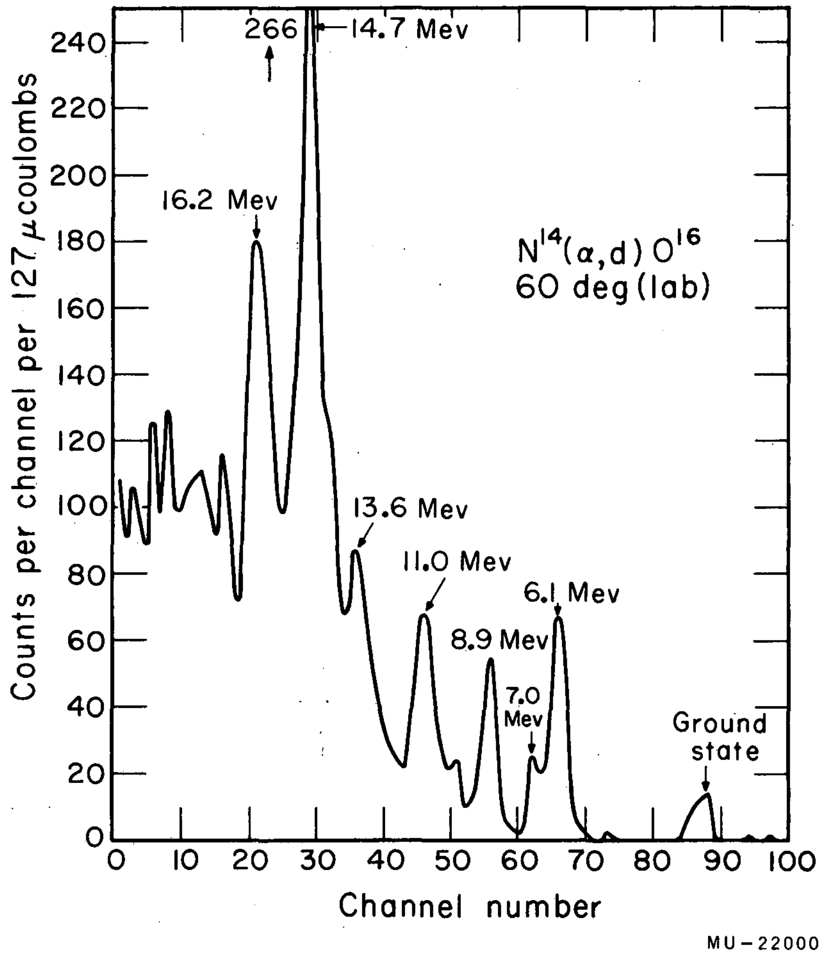

Fig. 4. Deuteron energy spectrum from the reaction $N^{14}(\alpha,d)O^{16}$. Q values for the various peaks are shown.

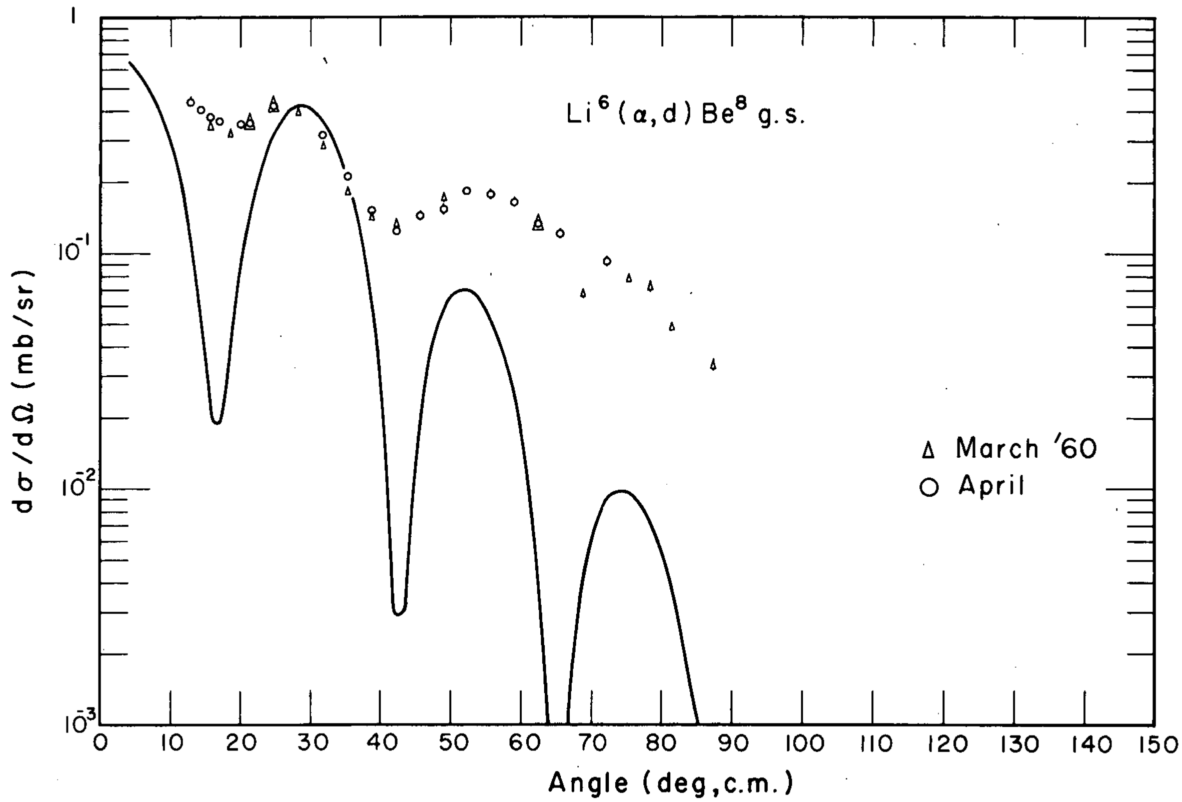

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Fig. 5. Angular distribution of deuterons from formation of the ground state of Be^8. The solid line was calculated from the Glendenning equation by using $j_n = j_p = 3/2$, $R_0 = 7.6$ fermis.

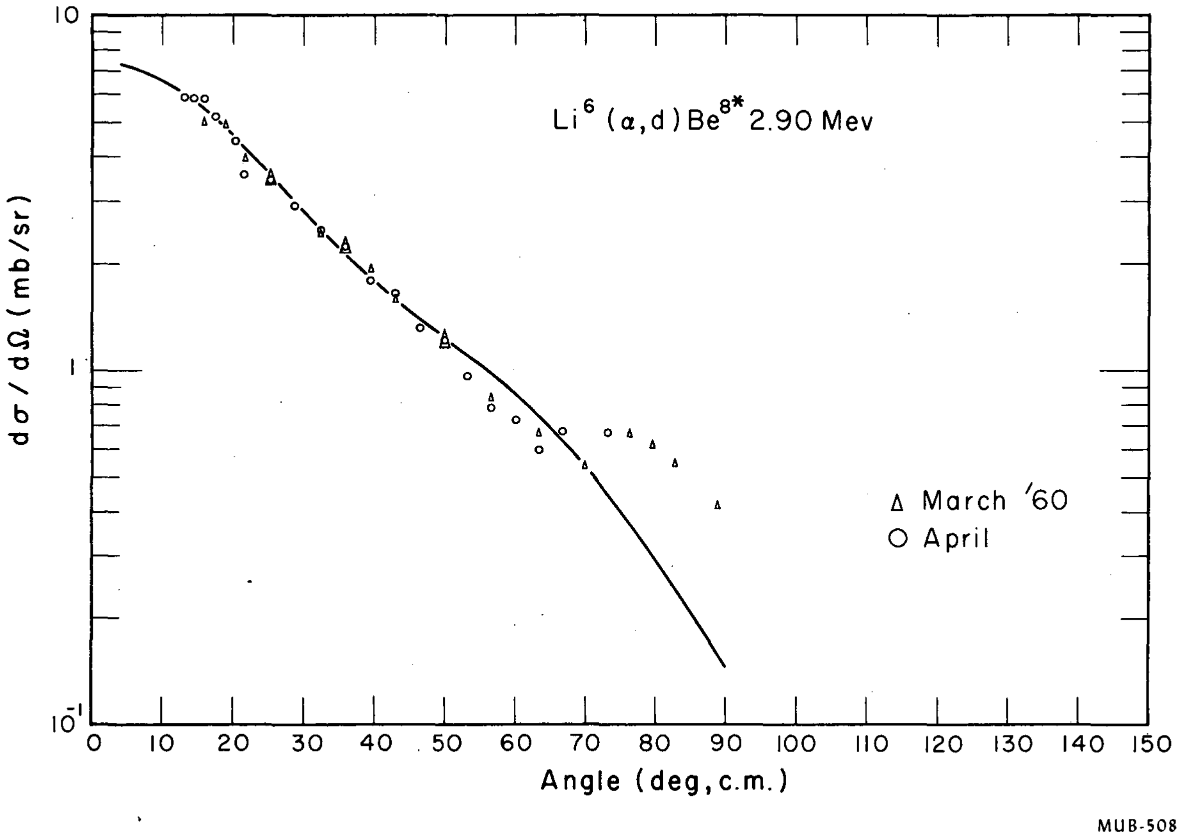

Fig. 6. Angular distribution of deuterons from formation of the 2.90-Mev level of Be^8. The solid line was calculated from the Glendenning equation by using $j_n = j_p = 3/2$, $R_0 = 2.1$ fermis.

TABLE III

Correlation in the low-lying states of Be^8

Energy[a] (Mev)	$J^{\pi};T$[a]	Decay[a]	θ_α^2[a]	$\frac{\langle\sigma_f\rangle}{2J_f+1}$[b] (mb)	Angular interval over which $\langle\sigma_f\rangle$ was calculated (deg, c.m.)
0	0+,0	α	0.15	1.0_2	12.8 - 104.5
2.90	2+,0	α	0.7	1.4_2	13.0 - 88.8
11.4	4+,0	α	0.95	$2.67^{+0.37}_{-0.22}$	12.5 - 85.6

[a] From Refs. 10, 11, 12.

[b] The absolute value of these cross sections is not known to better than ± 30% owing to uncertainties in the Li^6 target thickness.

The angular distributions of deuterons corresponding to formation of the O^{16} ground state ($\langle\sigma\rangle = 0.07_9$ mb, measured from 11 to 101.4 deg, c.m.), the 6.1-Mev level ($\langle\sigma\rangle = 0.2_5$ mb, measured from 11 to 102.7 deg, c.m.), and the 8.88-Mev level ($\langle\sigma\rangle = 0.09_2$ mb, measured from 11 to 103.4 deg, c.m.) are shown in Figs. 7, 8 and 9. The errors shown on Fig. 7 are due to counting statistics only; similar errors apply to the data of Figs. 8 and 9. Uncertainties in background subtraction and in separation of the 7.0-Mev states from the 6.1-Mev states are major contributors to the errors in the angular distribution data for the excited states.

DISCUSSION

I. Energy-Level Analysis.

A comparison of the levels of O^{16} observed in the $N^{14}(\alpha,d)O^{16}$ reaction with those previously reported (Table II) again illustrates that the (α,d) reaction at these energies does not appreciably populate certain product nuclear states,[1]

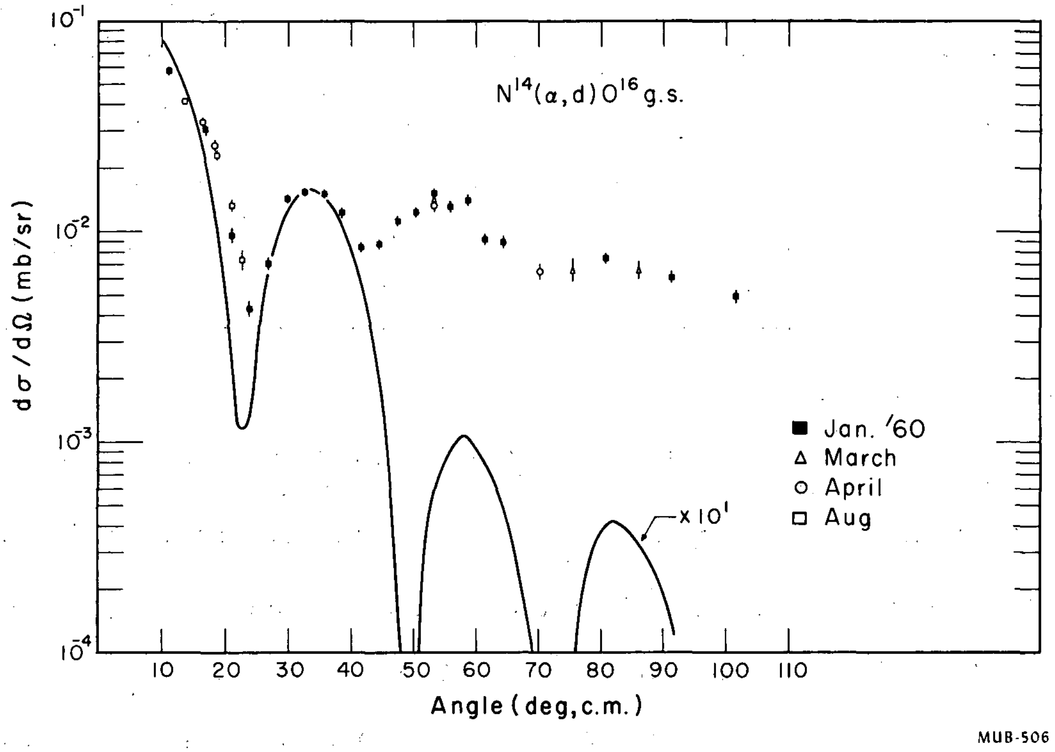

Fig. 7. Angular distribution of deuterons from formation of the ground state of O^{16}. The solid line was calculated from the Glendenning equation by using $j_n = j_p = 1/2$, $R_0 = 5.35$ fermis.

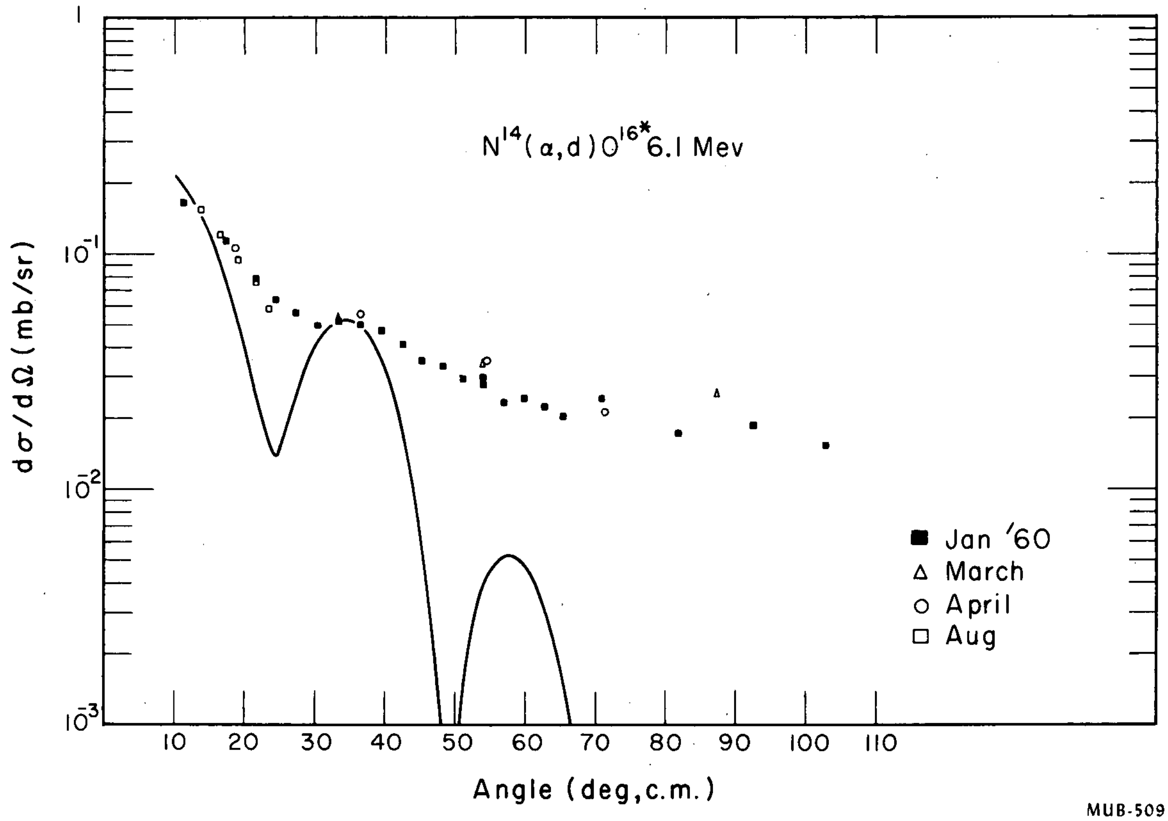

Fig. 8. Angular distribution of deuterons from formation of the 6.1-Mev level(s) of O^{16}. The solid line was calculated from the Glendenning equation by using $j_n = 1/2$, $j_p = 5/2$, $R_0 = 6.20$ fermis.

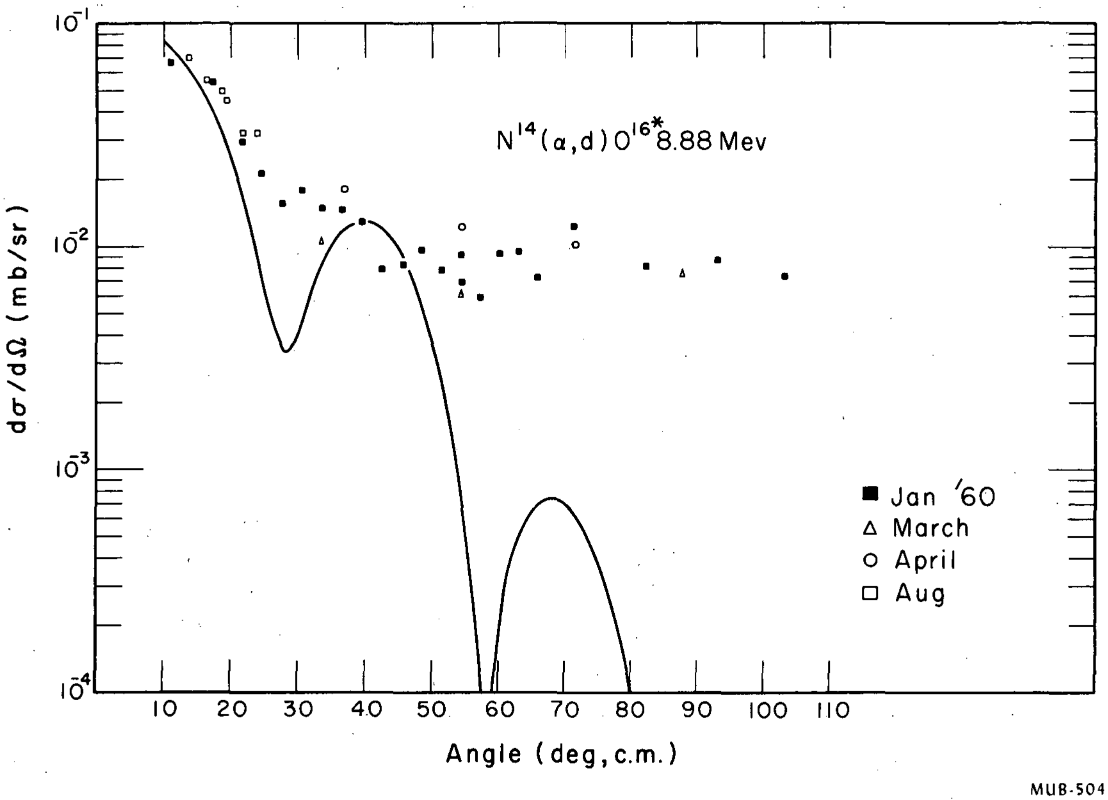

Fig. 9. Angular distribution of deuterons from formation of the 8.88-Mev level of O^{16}. The solid line was calculated from the Glendenning equation by using $j_n = 1/2$, $j_p = 5/2$, $R_0 = 5.48$ fermis.

even when no isotopic spin conservation rules are violated. An analysis of this selectivity in the formation of excited states of O^{16} is complicated: first, the N^{14} ground-state configuration is not pure $(p_{1/2})^2$, but possesses a strong admixture of the $(p_{3/2}{}^{-1}p_{1/2}{}^{-1})$ configuration;[13] second, most of the excited states of O^{16} are of a complex nature, arising from interactions among many simple shell-model states.

If the strongly populated states in the product nucleus arising from an (α,d) reaction are at most two-particle excitation states-- i.e., assuming that cross sections for transitions to states whose description requires core (target nucleus) excitation are less by at least an order of magnitude than cross sections for states not involving core excitation-- then at least two levels of O^{16} should not be seen in this reaction. One level is the 9.58-Mev 1- level, which is thought to be a three-particle excitation state.[14] The other is a 0+, T = 0 level arising from a $C^{12} + (2s)^4$ configuration calculated[15] to lie at 11.57 Mev -- the nearest established 0+,T = 0 level of O^{16} is the state at 11.25 Mev. Table II indicates that gaps were observed in the energy spectrum; both these levels fall within these gaps, although the accuracy of the experimental energy-level determinations is not sufficient to exclude some contribution from the 11.25-Mev level to the observed peak at 11.0 Mev.

As noted earlier, the addition of the captured nucleons to different shells does not appear to be strongly inhibited; therefore, the odd-parity levels of O^{16} at 6.14, 7.12, 8.88, and 10.94 Mev, which have been fairly well accounted for as admixtures of $(p^{-1}d)$ and $(p^{-1}s)$ configurations with the predominating part of the final wave functions arising from $(p_{1/2}{}^{-1}d)$ and $(p_{1/2}{}^{-1}s)$ components,[14] should be observed. Deuteron groups corresponding to all these level energies were detected, but only the transition to the 8.88-Mev level could be separately resolved. The wave function of the 8.88-Mev state is[14]

$\sim 75\% \left[(p_{1/2})^{-1} d_{5/2}\right]_{2-} + \sim 7\% \left[(p_{1/2})^{-1} d_{3/2}\right]_{2-}$ — the captured particles enter adjacent shells — and the "reduced" reaction cross section, $\langle\sigma_{8.88}\rangle \times \frac{2J_i+1}{2J_f+1} \equiv \langle\sigma_{8.88}\rangle_w$ is 0.05_5 mb. The O^{16} ground state is formed with a reduced reaction cross section, $\langle\sigma_{gs}\rangle_w$, of 0.2_4 mb and arises from the entry of both captured nucleons into the p shell. For this case, then, stripping into different shells is only one-fourth as probable as stripping into the same shell. The $N^{15}(\alpha,d)O^{17}$ ground-state transition, which involves the capture of a proton into the $p_{1/2}$ subshell and a neutron into the $d_{5/2}$ subshell, should also possess a lower cross section than the $N^{14}(\alpha,d)O^{16}$ ground-state transition by approximately this factor of four. The $N^{15}(\alpha,d)O^{17}$ g.s. reduced cross section, $\langle\sigma_{gs}\rangle_w$, of 0.04_5 mb agrees with this prediction, being less by a factor of five than the cross section determined for stripping both particles into p shell-model states. (All the cross sections referred to in this paragraph arise from data taken in the angular interval between 11 and 101 to 103 deg in the center-of-mass system.) These results are in qualitative agreement with the (p,t) data of Ball and Goodman,[16] who estimated that the pick-up of two $1g_{9/2}$ neutrons is $\gtrsim \frac{8}{3}$ as probable as the pickup of one $2d_{5/2}$ and one $1g_{9/2}$ neutron.

Table I indicates the energy levels observed in the $Li^6(\alpha,d)Be^8$ reaction. The first three levels of Be^8 have been described as $\alpha+\alpha$ clusters; some indication of the validity of this description can be obtained by correlating with each state its reduced α-particle width in terms of the Wigner limit (θ_α^2) as obtained from the scattering of helium ions on helium.[12] Large reduced widths should belong to states which are well-represented by $\alpha+\alpha$ clusters. The levels and the reduced widths are reproduced in Table III. Also shown in Table III are the statistically weighted cross sections to these Be^8 levels from the $Li^6(\alpha,d)Be^8$ reaction. These cross sections follow the increasing reduced widths— a result which would be difficult to interpret if the reaction mechanism involved were stripping onto a Li^6 "core", since all three levels on a simple shell-model picture arise from capturing the two nucleons into $p_{3/2}$ states and might be expected to possess comparable (α,d) reaction cross sections. The Li^6 ground state, however, may possess considerable $d + \alpha$ cluster parentage,[12,17] and a reaction mechanism involving

(a) stripping a deuteron which coupled to an α particle with the deuteron cluster present in the Li^6 configuration, or

(b) knocking out this deuteron,

might be expected to result in transition cross sections with the observed behavior.

2. Angular Distribution Analysis

Since Li^6 and N^{14} can be visualized as an even-even core plus a deuteron, both stripping and knockout processes appear as attractive possibilities for the reaction mechanism. In general, though, the determination of the reaction mechanism (and the angular-momentum transfer) is difficult when the reaction involves a large linear momentum transfer. The difficulty inherent in investigating a reaction mechanism through an angular-distribution analysis can be seen by analyzing the results of Starodubtsev and Makaryunas[5] on the $Li^6(\alpha,d)Be^8$ g.s. transition with 10.15 to 13.2-Mev helium ions. These authors compared their results with Butler theory and simple knockout kinematics, and a typical angular distribution and fit ($L = 0$, $R_0 = 8.5$ f) are reproduced in Fig. 10. The momentum transfer involved in these results, however, is such that acceptable angular distribution fits can be obtained for either a stripping or a knockout mechanism. Fig. 11 shows stripping fits calculated on Butler theory, as described below, for $L = 0$, $R_0 = 5.5$ f and $L = 2$, $R_0 = 9.1$ f. ($L = 0,2$ are allowed from angular momentum and parity conservation for this transition.) These results indicate that the mechanism of this reaction cannot be established from these

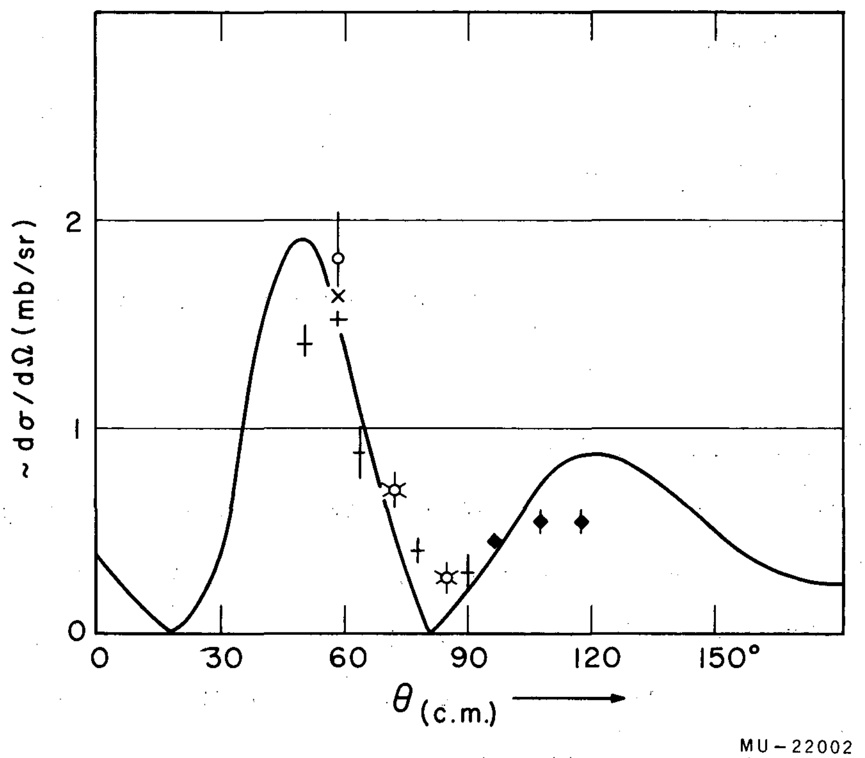

Fig. 10. Reproduction of the deuteron angular distribution from the Li^6 $(\alpha,d)Be^8$ g.s. transition with 11.5-Mev helium ions. The solid line was calculated by using Butler theory for a knockout reaction; L=0, R_0= 8.5 fermis. (After Starodubtsev and Makaryunas, Ref. 5.)

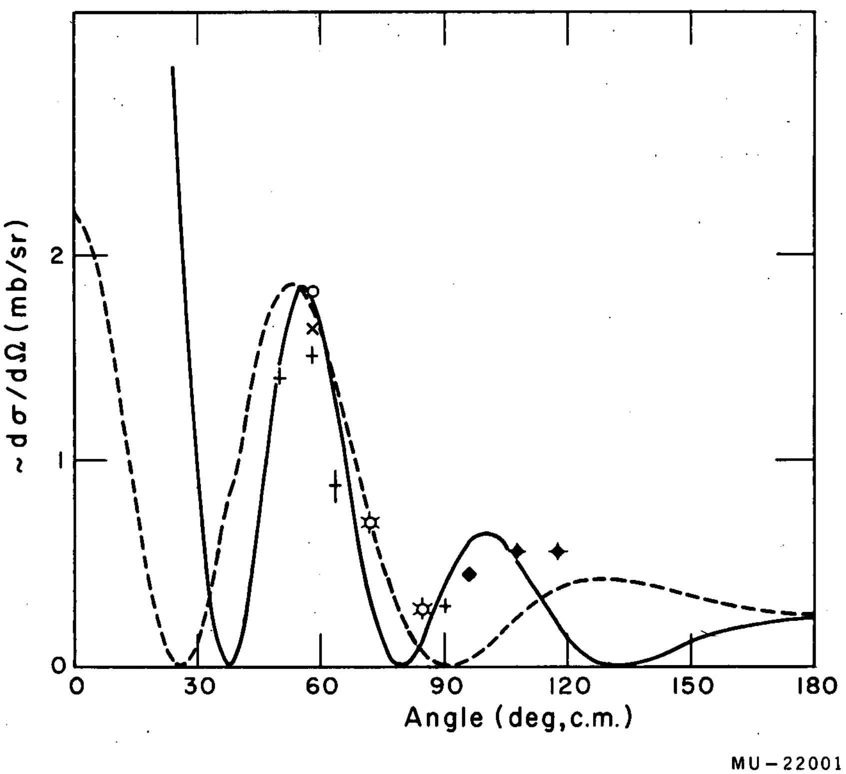

Fig. 11. Reproduction of the deuteron angular distribution from the $Li^6(\alpha,d)Be^8$ g.s. transition with 11.5-Mev helium ions (Ref. 5). The solid line was calculated by using Butler theory for a stripping reaction, L = 2, R_0= 9.1 fermis; the dotted line, for L= 0, R_0= 5.5 fermis.

angular distribution data. Since this situation usually holds for (α,d) reactions at our energies, primary attention in the analysis of the angular-distribution data has not been directed toward attempts to establish the reaction mechanism, but toward determining the closeness of fits obtained from the two-particle stripping theory of Glendenning[2] and the possibility of obtaining spectroscopic information from these fits about the product levels observed.

The analysis of the deuteron angular distributions to the ground state and 2.90-Mev state of Be^8 and to the ground-state, 6.1-Mev, and 8.88-Mev states of O^{16} has utilized the theory of Glendenning.[2] This model assumes explicit coupling schemes in the j-j coupling limit. However, many features of the level structure of the 1p-shell nuclei have been described by coupling intermediate between L-S and j-j: Li^6 is near the L-S limit, with the relative strengths of the spin-orbit forces increasing as the shell fills, resulting in considerable zero-order j-j coupling near the shell closure.[18,19,20] Therefore, the theory should be more successful in describing the $N^{14}(\alpha,d)O^{16}$ reaction than the $Li^6(\alpha,d)Be^8$ reaction (although the fit to the $Li^6(\alpha,d)Be^8$ (2.90-Mev) data is surprisingly good). The calculations with the complete, finite α-particle theory were performed on the University of California IBM 704 computer. (A copy of the Fortran listing will be sent on request. The program requires a machine with a 32K memory.) The differential cross section for these odd-odd target nuclei was given by

$$\frac{d\sigma}{d\Omega} \approx e^{-K^2/8\gamma^2} \sum_L \frac{C_L}{2L+1} \left| B(\ell_n \ell_p L;Q) \right|^2 \qquad (1)$$

for $B(\ell_n \ell_p L;Q)$ defined in Eq. (24), reference 2,

$R\lambda_n\lambda_p n$ defined in Eq. (29), reference 2,

so that

$$B(\ell_n \ell_p L;Q) = \sum_{n=0}^{\infty} (-1)^n (2n+1) \; I_{n+1/2}(4\gamma^2 R_0^2) \sum_{\lambda_n = |\ell_n - n|}^{\ell_n + n, 2} \; \sum_{\lambda_p = \max(|\ell_p - n|, |L-\lambda_n|)}^{\min(\ell_p + n, L+\lambda_n), 2}$$

$$j_{\lambda_n}(QR_0/2)\, j_{\lambda_p}(QR_0/2) \sqrt{(2\lambda_n+1)(2\lambda_p+1)}\; i^{\lambda_n+\lambda_p} \quad W(\ell_n \ell_p \lambda_n \lambda_p ; Ln) \qquad (2)$$

$$C^{\lambda_n \lambda_p L}_{0\ 0\ 0} \quad C^{l_n\ n\ \lambda_n}_{0\ \ 0\ 0} \quad C^{l_p\ n\ \lambda_p}_{0\ \ 0\ 0} \quad .$$

and

$$C_L = \sum_{I=|L-1|}^{L+1} (2I+1) \left[W(J_i J_f j_n j_p; I j_p) \times \alpha_{L1I}(j_n j_p) \right]^2 \; . \text{ (odd-odd target)}$$

A value of 0.279×10^{13} cm^{-1} was chosen for gamma to represent the RMS radius of the α-particle charge density.[21] Comparison of the calculated angular distributions with the experimental results shows that in all cases, except the 2.90-Mev level of Be^8, the theoretical differential cross sections decrease too rapidly with angle. Decreasing the size of the helium ion permits more high-momentum transfers and therefore increases the large-angle cross section through the damping factor $e^{-K^2/8\gamma^2}$ of Eq. (1). However, even reducing the helium ion radius to zero in some cases does not sufficiently decrease the large-angle damping, and this reduction generally produces much poorer agreement at small angles. There may be a compound-nucleus contribution which is important at large angles, but it does not seem possible to account for all the divergence between theory and experiment in this way.

In all the following calculations, only the simple shell-model configuration of the target nucleus was employed.

Additional restrictions were placed on the coupling scheme for calculations of stripping to odd-odd targets. It was required that at least one of the captured particles must enter the same shell-model state as one of the original pair about the core and couple with it to zero total angular momentum; in some cases, this reduced the plausible shell-model descriptions, and hence angular momentum transfers, to be tried. For the $N^{14}(\alpha,d)O^{16}$(g.s.) and $Li^{6}(\alpha,d)Be^{8}$(g.s.) reactions, the restrictions define only a single set of reasonable individual-particle total angular momentum states in the final nucleus, so that only the interaction radius can be varied to fit the data. For $Li^{6}(\alpha,d)Be^{8*}$(2.90 Mev), the $[(p_{3/2})^{3}(p_{1/2})^{1}]_{2+}$ configuration was compared with the expected[19] $[p_{3/2}{}^{4}]_{2+}$ configuration; similarly, two configurations were tried for the $N^{14}(\alpha,d)O^{16*}$(8.88-Mev) results. Lastly, the $N^{14}(\alpha,d)O^{16*}$ (6.1-Mev) angular distributions were calculated on the assumption that the 6.14-Mev 3- level is involved, rather than the 6.06-Mev 0+ level, since a plausible configuration for these calculations is more readily acquired for the former level.

The reactions, shell-model states of the captured particles, radii which gave fits and figure numbers corresponding to the plotted results of the better fits are given in Table IV. In addition, the ratio of

$$\frac{C_{L'max}}{C_{L'min}} = \frac{C_{Lmax}/(2Lmax + 1)}{C_{Lmin}/(2Lmin + 1)}$$

i.e., the relative weighting of the total orbital angular momentum transfers involved in the reaction, is given.

TABLE IV

Results of the application of Glendenning's theory to the $Li^6(\alpha,d)Be^8$ and $N^{14}(\alpha,d)O^{16}$ reactions.

Reaction	Captured j_n	Captured j_p	Final nuclear configuration	Radius for best fit (f)	Figure number of graph	$C'_L \text{max} / C'_L \text{min}$
$Li^6(\alpha,d)Be^8$(g.s)	3/2	3/2	$[(p_{3/2})^4]_{0+}$	7.6	5	$\frac{C_2'}{C_0'} = 0.0400$
$Li(\alpha,d)Be^{8*}$(2.90 Mev)	3/2	3/2	$[(p_{3/2})^4]_{2+}$	2.1	6	$\frac{C_2'}{C_0'} = 0.513$
" "	3/2	1/2	$[(p_{3/2})^3(p_{1/2})^1]_{2+}$	No fit as acceptable	-	$\frac{C_2'}{C_0'} = 3.10$
$N^{14}(\alpha,d)O^{16}$(g.s.)	1/2	1/2	$[(p_{1/2})^4]_{0+}$	5.35	7	$\frac{C_2'}{C_0'} = 4.00$
$N^{14}(\alpha,d)O^{16*}$(6.14 Mev)	1/2	5/2	$[(p_{1/2})^{-1}(d_{5/2})^1]_{3-}$	6.20	8	$\frac{C_3'}{C_1'} = 0.345$
$N^{14}(\alpha,d)O^{16*}$(8.88 Mev)	1/2	5/2	$[(p_{1/2})^{-1}(d_{5/2})^1]_{2-}$	5.48	9	$\frac{C_3'}{C_1'} = 1.42$
" "	1/2	3/2	$[(p_{1/2})^{-1}(d_{3/2})^1]_{2-}$	5.46	Equally acceptable but not graphed	$\frac{C_3'}{C_1'} = 1.71$

The fit to the $Li^6(\alpha,d)Be^8$(g.s.) results is fairly unsuccessful. Zeidman and Yntema[6] attempted to distinguish the mechanism involved in the $Li^6(\alpha,d)Be^8$ g.s. transition with 43-Mev helium ions, using simple Butler theory, and trying both stripping and knockout parameters for this reaction. Under their conditions the data were better represented by stripping parameters and $R_0 = 8$ f, L= 0, although the fit is not very satisfactory and involves an interaction radius too large to be meaningful.

(The best calculation for our data, using Butler stripping theory— L= 0, R_0 = 6.9 f— is worse, and there is no equivalent knockout fit for L= 0, R ≤ 8 f.) Conversely, our extremely successful fit to the $Li^6(\alpha,d)Be^{8*}$(2.90-Mev) results (no Butler stripping or knockout fit) occurs at a very small interaction radius— one implying interaction within the nuclear volume. This small radius, the absence of an acceptable ground-state fit, and the uncertainty in applying a stripping theory based on j-j coupling for transitions to low-lying Be^8 levels weakens the conclusion that the $Li^6(\alpha,d)Be^{8*}$(2.90-Mev) reaction follows a stripping mechanism.

The successful fit to the $N^{14}(\alpha,d)O^{16}$(g.s.) results produced r_0= 1.5_5f, but the angular distributions of the excited states required somewhat higher r_0 values. For comparison, Fig. 12 shows the best stripping and knockout fits for the $N^{14}(\alpha,d)O^{16}$(g.s.) reaction based on the Butler equation:

$$\frac{d\sigma}{d\Omega} \propto \left| \frac{1}{q^2+\kappa^2} \quad W\,[j_L(qR_0), h_L(\kappa R_0)] \right|^2 .$$

The definitions of the symbols for stripping reactions are given elsewhere.[1] For knockout reactions

$$\kappa = \left\{ \left[4.783\ m_1\xi_1 + 6.887\ \left(\frac{m_1 Z\ z_1}{R_0}\right)\right]^{1/2} + \left[4.783\ m_2\xi_2 + 6.887\ \left(\frac{m_2 Z\ z_2}{R_0}\right)\right]^{1/2} \right\} \times 10^{12}\ ,\ \text{in cm}^{-1},$$

where m_1, ξ_1, and z_1 (or m_2, ξ_2, z_2) are the ejected (or incident) particles' reduced mass in amu in the initial nucleus (or final nucleus), binding energy in initial nucleus (or final nucleus) in Mev, and charge, respectively; and Z is the charge of the core. Also

$$\vec{q} = \frac{m_T - m_f}{m_T}\ \vec{k}_2 - \frac{m_F - m_i}{m_F}\ \vec{k}_1 ,$$

where m_i and m_f are the masses of the incident and ejected particles,

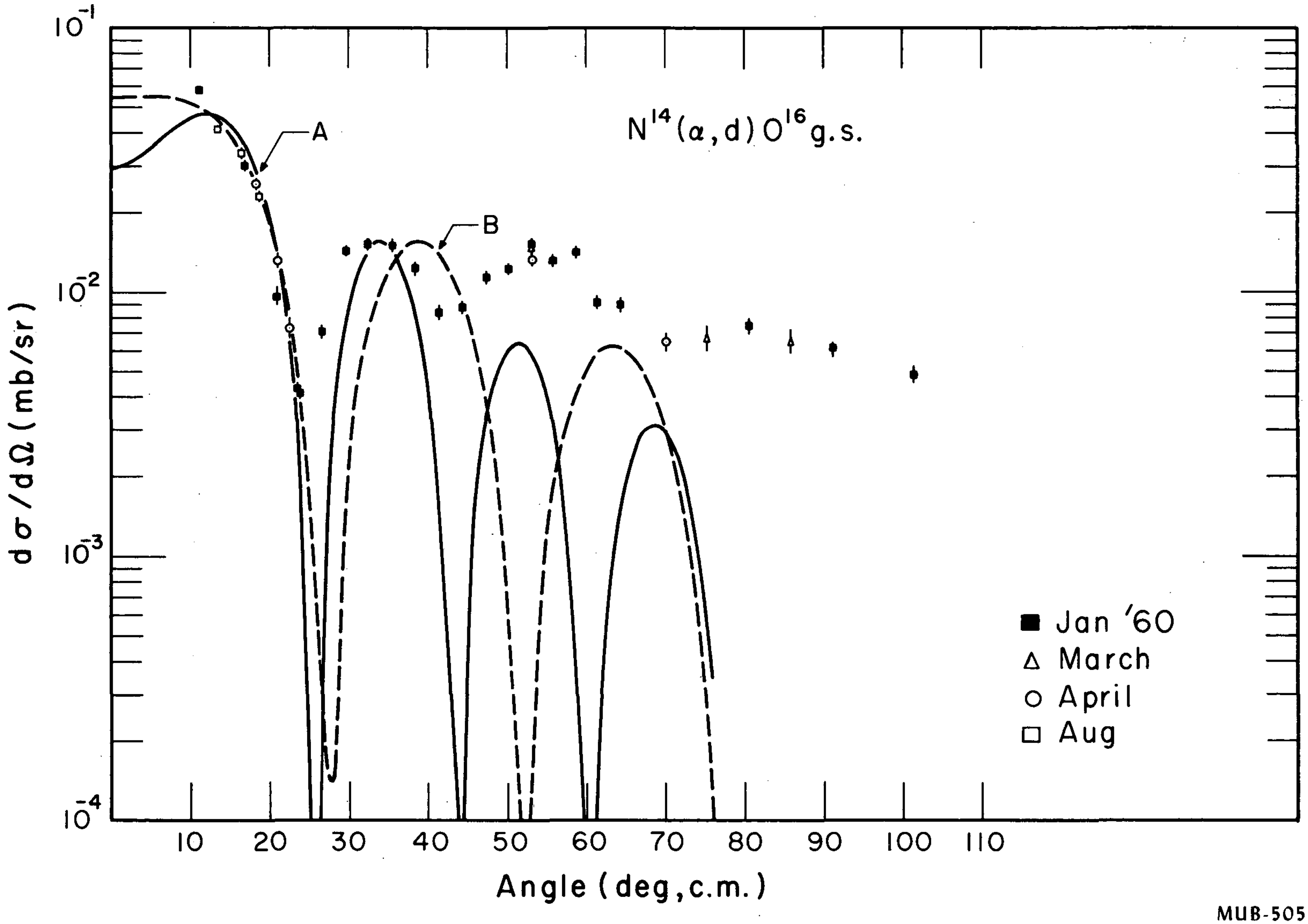

Fig. 12. Angular distribution of deuterons from formation of the ground state of O^{16}. Curve A was calculated from the Butler equation by using stripping parameters and L=2, R_0= 7.1 fermis; curve B by using knockout parameters and L= 0, R_0= 5.6 fermis.

and m_T and m_F are the masses of the target and final nuclei, and $\vec{k}_1$, $\vec{k}_2$ are the wave numbers of the ejected and incident particles. The "best" stripping fit requires L = 2, R_0= 7.1 f; the "best" knockout fit requires L = 0, R_0= 5.6 f. These fits either fail to match the success of Glendenning's or require unrealistically large interaction radii, or both. In general, though not in all cases, the interaction radius producing the best fit based on Glendenning's theory is considerably smaller than the best fit on Butler theory.

The $\frac{C_L'\,max}{C_L'\,min}$ column of Table IV again illustrates that the nature of the captured-particle shell-model states determines the preferred total orbital angular momentum transfer, and that the dominant L is not necessarily the lowest of the allowed values. For example, in the $Li^6(\alpha,d)Be^8$(g.s.) transition B(112;Q)/B(110;Q) is typically 1→4 and in the $N^{14}(\alpha,d)O^{16}$(g.s.) transition B(112;Q)/B(110;Q) is typically 1/2→3; thus the $Li^6(\alpha,d)Be^8$(g.s.) transition is dominated by L= 0 transfer whereas the $N^{14}(\alpha,d)O^{16}$(g.s.) transition with C_2'/C_0' = 4.0 strongly prefers L = 2 to L = 0 transfer.

Finally, Glendenning's theory was applied to the $C^{12}(\alpha,d)N^{14}$(g.s. and 3.95-Mev) angular distributions reported earlier. (Reference 1 used the theories of Butler[4] and el Nadi.[3]) For an even-even target the definition of C_L to be substituted into Eq. (1) is

$$C_L = \left\{\alpha_{L1J}\ (j_n j_p)\right\}^2 , \qquad \text{(even-even target)}$$

and there are no inherent restrictions on the final states of the captured particles. Good fits to the experimental angular distributions were found for all the sets of j_n, j_p, R_0 presented in Table V. The shell model requires $j_n = j_p$ = 1/2 for the $C^{12}(\alpha,d)N^{14}$(g.s.) reaction, and the best fit for this configuration is shown in Fig. 13. The 3.95-Mev 1+ level of N^{14} presumably has the dominant configuration[22] $\left[(p_{3/2}{}^{-1})(p_{1/2})^{-1}\right]_{1+}$, so that the angular

TABLE V

Results of the application of Glendenning's theory to the $C^{12}(\alpha,d)N^{14}$ reaction.

Reaction	Captured j_n	j_p	Final nuclear configuration	Radius (f)	Butler stripping fit for $L=2,R_0$: (f)
$C^{12}(\alpha,d)N^{14}$(g.s.)	1/2	1/2	$[(p_{1/2})^2]_{1+}$	4.70 (r_o= 1.35 f)	6.3
"	1/2	1/2	$[(s_{1/2})^2]_{1+}$	5.08	
"	5/2	5/2	$[(d_{5/2})^2]_{1+}$	4.92	
$C^{12}(\alpha,d)N^{14*}$(3.95 Mev)	1/2	1/2	$[(p_{1/2})^2]_{1+}$	4.33	5.5
"	1/2	1/2	$[(s_{1/2})^2]_{1+}$	4.67	
"	5/2	5/2	$[(d_{5/2})^2]_{1+}$	4.50	

distribution to this level cannot be treated with this theory. However, since the (α,d) cross section to this level is less than that to the ground state by a factor of five, and on the assumption that a reaction leading to a hole in the $p_{3/2}$ levels is strongly inhibited, it is possible to assume that the transitions producing this decreased cross section arise from a $[(p_{1/2})^2]_{1+}$ configuration admixture contributing to the wave function of the 3.95-Mev level. This assumption was made, and the best $j_n = j_p = 1/2$ fit for the $C^{12}(\alpha,d)N^{14*}$(3.95-Mev) results is shown in Fig. 14. Other final-state descriptions were again calculated.

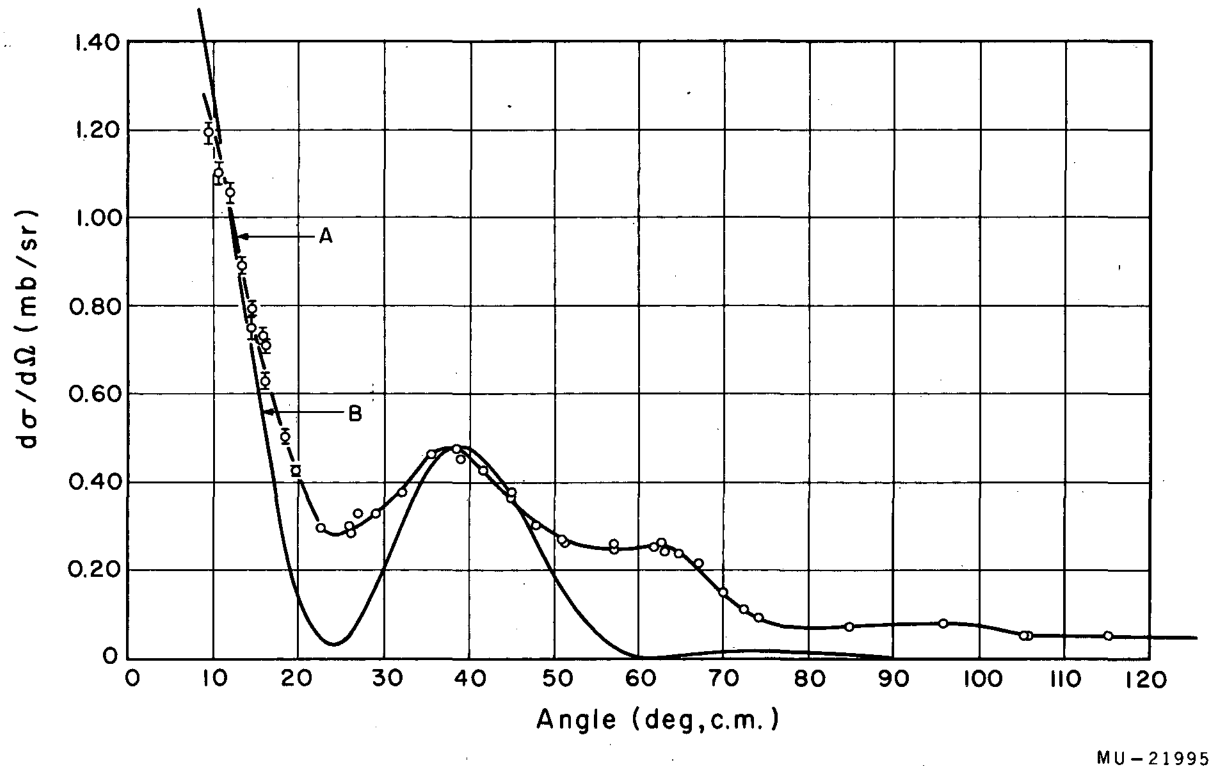

Fig. 13. Angular distribution of deuterons from formation of the ground state of N^{14}. Curve A presents the experimental results; curve B, calculated results from the Glendenning equation using $j_n = j_p = 1/2$, $R_0 = 4.70$ fermis.

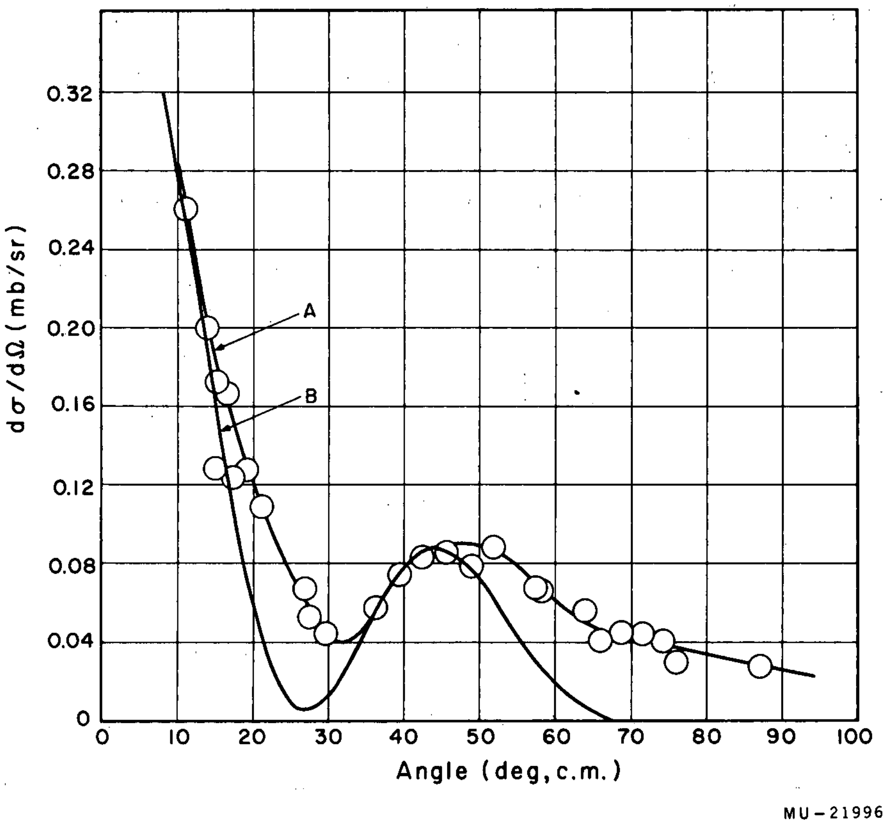

Fig. 14. Angular distribution of deuterons from formation of the 3.95-Mev level of N^{14}. Curve A presents the experimental results; curve B, calculated results from the Glendenning equation using $j_n = j_p = 1/2$, $R_0 = 4.33$ fermis.

It should be noted that the successful fits for the reactions to the product ground states, $N^{14}(\alpha,d)O^{16}$(g.s.) and $C^{12}(\alpha,d)N^{14}$(g.s.), required interaction radii which implied quite acceptable r_o parameters.

The general result of the application of Glendenning's theory to these data is that the high momentum transfer under the experimental conditions used in this work produces multiple fits when several final nuclear configurations are reasonable, and so permits no spectroscopic identification of the final states. A significant exception to this is the excellent fit to the $Li^6(\alpha,d)Be^{8*}$(2.90-Mev) results for a final state $\left[(p_{3/2})^4\right]_{2+}$ description and no fit for the possible $\left[(p_{3/2})^3(p_{1/2})\right]_{2+}$ configuration.

ACKNOWLEDGMENTS

We wish to thank the crew at Crocker Laboratory for their efficient operation of the cyclotron and for their willing assistance with all phases of the experiments. It is a pleasure to thank Jack H. Elliott for developing the solid-state detectors, Fred Goulding for the reduced-noise amplification equipment, and Fred E. Vogelsberg for technical assistance with the general counting equipment. We wish finally to thank Dr. Norman K. Glendenning for very valuable discussions.

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