Study of Some Reactions of 14.8-Mev Deuterons with the Lithium Isotopes*

E. W. HAMBURGER AND J. R. CAMERON†
University of Pittsburgh, Pittsburgh, Pennsylvania
(Received August 25, 1959)

Metallic targets of enriched Li^6 and Li^7 were bombarded with 14.8-Mev deuterons. The outgoing particles were magnetically analyzed and detected in nuclear emulsions or scintillation counters. Angular distributions for the following reactions were measured: $Li^6(d,p)Li^{7*}$ 4.6 and 7.46 Mev. $Li^7(d,p)Li^{8*}$ 2.28 Mev, $Li^7(d,t)Li^{6*}$ 3.57 Mev, $Li^6(d,d')Li^{6*}$ 2.19 Mev, $Li^6(d,\alpha)$-He^4 ground state, $Li^6(d,t)Li^5$ and $Li^6(d,He^3)He^5$. A search was made for other levels produced in these reactions and in the $Li^7(d,d')Li^{7*}$ reaction. No new levels were observed; upper limits on the cross sections of unobserved levels are given. The results of the (d,p), (d,t), and (d,He^3) reactions were compared with stripping theory and with the predictions of the shell model. The agreement is, in general, satisfactory.

The $Li^6(d,t)$ and $Li^6(d,He^3)$ reactions produce a continuous spectrum of outgoing particles at each angle. The angular distribution of the tritons (or He^3 particles) is strongly peaked forward and can be fitted with Butler curves having $l=1$, $r_0=6$f. The spectra at small angles show a peak corresponding to the Li^5 (or He^5) ground state, but at large angles the peak disappears and the spectra are constant. The shape of the spectra can be explained by the Butler formula if the energy dependence of the reduced width is taken into account. The form of this dependence was deduced from the results of the nucleon-helium elastic scattering experiments.

I. INTRODUCTION

TARGETS of Li^6 and Li^7 were bombarded with 14.8-Mev deuterons and the following reactions were investigated: $Li^6(d,p)Li^{7*}$ to the higher excited states of Li^7, $Li^7(d,p)Li^{8*}$ to the higher excited states of Li^8, $Li^7(d,t)Li^{6*}$ to the higher excited states of Li^6, $Li^6(d,t)Li^5$, $Li^6(d,He^3)He^5$, $Li^6(d,d')Li^{6*}$, $Li^7(d,d')Li^{7*}$ to the higher excited states of Li^7, and $Li^6(d,\alpha)$. The present experiment is an extension of previous work at this laboratory,[1] where the lower excited states of the residual nuclei in some of the above reactions were studied.

The experiment is of interest from two points of view: nuclear spectroscopy and the study of the mechanism of the reactions. The primary spectroscopic interest lies in the determination of the configurations and stripping reduced widths of the levels of Li^8, Li^7, and Li^6 in (d,p) and (d,t) reactions. All levels studied belong to the p shell. The reduced width can be written as a product of a radial part θ_0^2 and an angular and spin part S.[2] The single-particle width, θ_0^2, is approximately constant in the p shell; the value found in the present experiment is 0.066. The measured values of the "spectroscopic factor" S are compared to the predictions of the intermediate coupling shell model using the techniques developed by French and collaborators.[2,3] The agreement is, in general, satisfactory.

The mechanism of the (d,t) and (d,He^3) reactions is compared with the simple direct interaction theory[4] by: (a) comparing the cross sections of the (d,t) and (d,He^3) reactions on Li^7 leading to analog states in Li^6 and He^6; and (b) studying the cross section of these reactions on Li^6 as a function not only of angle but also of the energy of the outgoing particle. It is found that the shape and angular distribution of the triton and He^3 spectra can be predicted by the theory if the variation of the "reduced width" with energy is taken into account. The form of this dependence is deduced from the results of the p-He^4 and n-He^4 elastic scattering experiments.

In the following sections, after describing the experimental procedure, we present and discuss the results for each of the reactions studied.

II. EXPERIMENTAL PROCEDURE[5]

The external deuteron beam from the University of Pittsburgh cyclotron is focussed and analyzed by two magnetic spectrometers.[6] The illuminated area of the target is 1.6×23 mm; the energy spread of the beam is $\sim$40 kev and its intensity is of the order of 0.5 μa. The deuteron energy varies from day to day; during the course of this experiment it remained in the range 14.8 $\pm$0.1 Mev. The reaction products are selected by a third magnetic spectrometer which can be rotated about the target, and are detected either with a scintillation counter or in nuclear emulsions.[7]

Most of the work was done with metallic targets prepared by evaporation of isotopically enriched lithium onto silver backings. The target and backing thicknesses were both $\sim$1 mg/cm^2. Various precautions were taken to minimize the contaminations of oxygen and carbon.[5] The purest target obtained had about 1 atom of C^{12} and 1.7 atoms of O^{16} per 400 Li atoms.

* Work done in the Sarah Mellon Scaife Radiation Laboratory and assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Now at the University of Wisconsin, Madison, Wisconsin.

[1] Levine, Bender, and McGruer, Phys. Rev. **97**, 1249 (1955). This reference will be denoted by LBM in the text.

[2] J. B. French and A. Fujii, Phys. Rev. **105**, 652 (1957).

[3] T. Auerbach and J. B. French, Atomic Energy Commission Report NYO-3711, University of Rochester, 1955 (unpublished); also Phys. Rev. **98**, 1276 (1955).

[4] S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley and Sons, New York, 1957), Chap. XII.

[5] Details of the experimental procedure are given in E. W. Hamburger Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

[6] The scattering apparatus is described by Bender, Reilley, Allen, Ely, Arthur, and Hausman, Rev. Sci. Instr. **23**, 542 (1952).

[7] The techniques used with nuclear emulsions are similar to those described by C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).

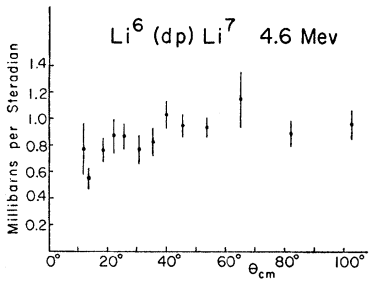

FIG. 1. Angular distribution for the $Li^6(d,p)Li^7$ reaction to the 4.6-Mev level in Li^7.

The relative cross sections of different reactions are estimated to be accurate to $\pm 10\%$. The error bars in Figs. 1 to 16 represent estimated upper limits on the errors of the relative cross sections unless otherwise specified. The absolute cross section scales in Figs. 1 to 16 were obtained by comparison with the $C^{12}(d,p)C^{13}$ ground state (g.s.) reaction and are estimated to be uncertain to $\pm 25\%$. The $C^{12}(d,p)C^{13}$ g.s. reaction was remeasured[8] and a value of $15.5 \pm 20\%$ mb per sterad was found for the cross section at the peak of the angular distribution.[5] All cross sections are given in the center-of-mass system. Several of the reactions measured by LBM[1] were remeasured; the cross sections agree within a few percent. The angular aperture of the detecting system was $\simeq 1°$ and the angular spread of the incident beam $\sim 1.5°$. The estimated uncertainty in the scattering angles is $\pm 0.5°$.

III. $Li^6(d,p)Li^7$

1. Experimental Results

Angular distributions for the Li^7 g.s. and first excited state were obtained by LBM.[1] The stripping reduced widths, in units of the Wigner limit $3\hbar^2/2\mu r_0$, are $\theta^2 = 0.053$ and 0.070, respectively. In the present experiment angular distributions for two other energy levels in Li^7 were obtained and a search was made for further states.

a. Li^7 4.6-Mev Level

The angular distribution for this level is shown in Fig. 1. The cross section is small and roughly isotropic; no stripping seems to occur. This result disagrees with measurements by Haffner,[9] who observed a forward peak in the cross section, at a similar bombarding energy (15 Mev). The excitation energy and total width of this level were not measured accurately in this experiment but are consistent with the values quoted by Browne.[10]

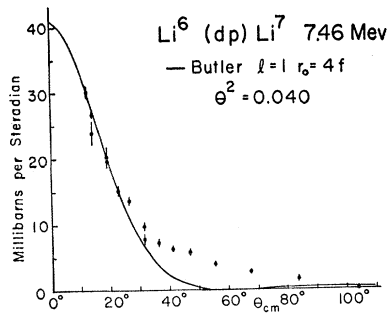

FIG. 2. Angular distribution for the $Li^6(d,p)Li^7$ reaction to the 7.46-Mev level in Li^7.

b. Li^7 7.46-Mev Level

The angular distribution for this level is shown in Fig. 2. At the forward angles an $l=1$ Butler curve can be made to fit the data. The best agreement is obtained for $r_0 = 4$f (1f = 1 fermi $= 10^{-13}$ cm), giving a reduced width $\theta^2 = 0.040$. A curve with $r_0 = 4.5$f does not fit the data as well but is still satisfactory; the corresponding reduced width is 0.052. The excitation energy and total width of this level were again not measured accurately in this experiment but are consistent with the values given by Browne.[10] At the low-energy side of the peak corresponding to this level there is a high continuous background, probably caused by the breakup of the deuteron

$$Li^6 + d \rightarrow Li^6 + n + p.$$

The background to be subtracted from the peak was found by linear interpolation of the background 200 kev above and 300 kev below the peak.

c. Other Levels

No other levels in Li^7 were observed. The level at 6.56-Mev excitation reported by LBM was found to arise from a contaminant. Proton spectra were recorded at laboratory angles $\theta_L = 11°$, 15°, and 25°, in the energy range corresponding to excitations E_x in Li^7 between 4 and 14 Mev; the excitation energy range from 4.5 to 7.5 Mev was also examined at $\theta_L = 45°$. A typical spectrum, at $\theta_L = 25°$, is shown in Fig. 3. Upper limits on the cross sections of unobserved levels were estimated from these spectra. Any level of width Γ with cross section larger than the value given below should have been identified:

$4.6 < E_x < 7.5$ Mev	$\Gamma \lesssim 200$ kev	$\sigma < 0.5$ mb/sterad
	$\Gamma \lesssim 500$ kev	$\sigma < 2$ mb/sterad,
$7.5 < E_x < 14.3$ Mev	$\Gamma \lesssim 200$ kev	$\sigma < 1$ mb/sterad
	$\Gamma \lesssim 500$ kev	$\sigma < 3$ mb/sterad.

From the upper limits on σ one can calculate upper limits on the reduced width θ^2 and these are quoted in Table I for the predicted levels having $E_x > 7.5$ Mev.

The proton continuum in Fig. 3 probably is due to the reactions

$$Li^6 + d \rightarrow \alpha + t + p, \quad Li^6 + d \rightarrow Li^6 + n + p.$$

The maximum energies of the protons from these reac-

[8] In collaboration with S. Mayo. Measured previously by McGruer, Warburton, and Bender, Phys. Rev. **100**, 235 (1955).

[9] J. W. Haffner, Phys. Rev. **103**, 1398 (1956).

[10] C. P. Browne, Bull. Am. Phys. Soc. **2**, 350 (1957).

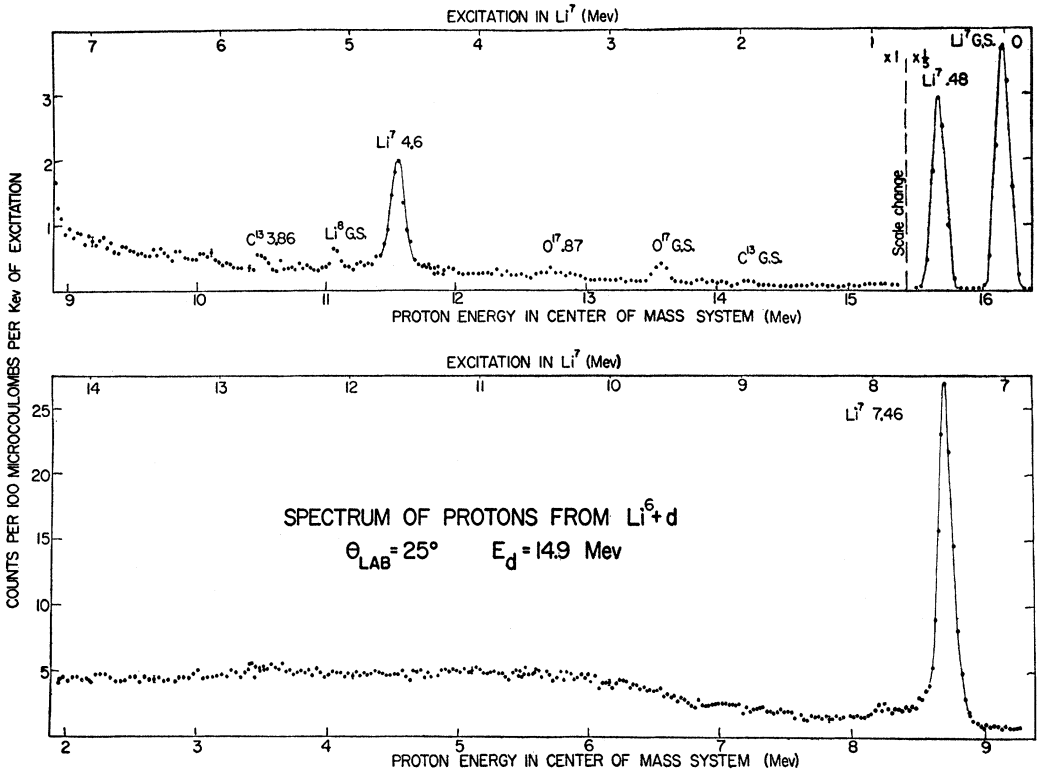

FIG. 3. Spectrum of protons from the $Li^6(d,p)$ reaction. The ordinate is proportional to the differential cross section per kev of excitation energy in Li^7.

tions correspond to $E_x=2.47$ and 7.25 Mev, respectively.

2. Discussion

The spectroscopic results from the $Li^6(d,p)Li^7$ reaction are summarized in Table I. Column 1 gives the energies of the various levels of Li^7 as calculated by Meshkov and Ufford.[11] Column 2 gives the predominant term in the wave function of each state. The notation is $[\alpha]^{2T+1,2S+1}L_J$ where α is the partition. Column 3 gives the spectroscopic factor S calculated for each level assuming pure LS coupling wave functions. S is the ratio of the reduced width to the single-particle reduced width and was calculated from the formulas given in references 2 and 3. Column 4 gives this factor calculated for intermediate coupling. The wave functions given by Auerbach and French[3] for $\zeta=2.4$ were assumed for the Li^6 g.s., Li^7 g.s., and 0.477-Mev level; pure LS coupling wave functions were assumed for the ^{24}P multiplet. Admixtures in this multiplet will not affect S strongly; the values given in the table are probably good within 10 or 20%. Column 5 gives the observed levels and their probable identification with Meshkov and Ufford's levels. Column 6 gives the experimentally measured reduced width θ^2 divided by the single-particle reduced width θ_0^2 taken equal to 0.066. Column 7 gives l and r_0 for the levels which show stripping. Finally column 8 gives the total width Γ used to estimate the upper limits on σ and θ^2. For the known levels, Γ is the measured value. For the unobserved levels Γ was estimated as follows: the reduced width for neutron emission was calculated from the value of S given in Column 3. A value $\theta_0^2=0.23$ was taken for the resonant single-particle reduced width; this value gives the correct width for the 7.46-Mev level. The total width was taken equal to the neutron channel width, which is given in terms of the reduced

[11] S. Meshkov and C. W. Ufford, Phys. Rev. **101**, 734 (1956).

TABLE I. Spectroscopic results from the $Li^6(d,p)Li^7$ reaction. The first four columns give the predictions of the shell model and the last four columns give the experimental results.

Calculated by Meshkov and Ufford		Calculated		Observed	Measured		Measur. or estim.
E_x (Mev)	Predominant term	S $\zeta=0$	S $\zeta=2.4$	levels	$\theta^2/\theta_0^2=0.066$	l, $r_0(f)$	Γ (kev)
0	$[3]^{22}P_{3/2}$	0.88	0.75	g.s.	0.80	1, 5	0
0.66	$[3]^{22}P_{1/2}$	0.88	1.02	0.477	1.06	1, 5	0
4.82	$[3]^{22}F_{7/2}$	0	0	4.6	···	···	90
6.38	$[3]^{22}F_{5/2}$	0	≃0				~1000[a]
6.97	$[21]^{24}P_{5/2}$	0.67	≃0.64	7.457	0.67	1, 4	90
8.37	$[21]^{24}P_{3/2}$	0.67	≃0.62		<0.2		≳500
8.82	$[21]^{24}P_{1/2}$	0.67	≃0.68		<0.7		≳700
8.97	$[21]^{24}D_{7/2}$	0	0				
10.03	$[21]^{22}P_{3/2}$	0.33			<0.5		≳600
10.48	$[21]^{22}P_{1/2}$	0.33			<0.5		≳700

[a] Estimated in reference 15.

width by[12]

$$\Gamma_n = 2KRv_l\gamma_n, \quad \gamma_n = (3\hbar^2/2\mu R^2)S\theta_0^2,$$

where K=neutron wave number in c.m. system, R=nuclear radius=5f, v_l=penetration factor, μ=reduced mass of neutron. These clearly are estimates of lower limits for Γ since all decay channels except Li^6+n (in particular $\alpha+t$) were neglected.

From the table we see that the measured values of θ^2/θ_0^2 agree very well with the calculated values of S for the 4 observed levels. For the unobserved levels the upper limits deduced from experiment are usually greater than the calculated values. A discrepancy exists for the $^{24}P_{3/2}$ level but if this level is broader than the estimated Γ, and if it overlaps appreciably with other levels, it could easily be buried in the background. In cases of overlapping levels the estimates of the upper limits on σ will no longer hold.

The results of the present experiment therefore confirm the assignment of the level at 7.46 Mev to the $^{24}P_{5/2}$ term and of the level at 4.6 Mev to the $^{22}F_{7/2}$ term. The assignment of the 4.6-Mev level to the ^{24}P multiplet[13] disagrees with these results.

S is zero for the $[3]\,^{22}F$ states (see Table I) because this multiplet has no fractional parentage with the predominant term in the Li^6 g.s. ($[2]\,^{13}S_1$). The $Li^6(d,p)Li^7$ reaction is therefore not suitable for the study of the ^{22}F levels. It is not surprising that the $^{22}F_{5/2}$ state at 6.6-Mev excitation[14] is not observed, particularly if it has $\Gamma\sim 1$ Mev.[15] These levels are probably best studied in the elastic scattering of He^4+He^3 (for Be^7) and He^4+t (for Li^7).[15]

There is an additional reason why S is zero for the 4.6-Mev level. This level is almost certainly $J=7/2^-$ [15] so that angular momentum and parity conservation forbid ordinary stripping with $l<3$. Since it is presumably a p-shell level, stripping to it should only occur with $l=1$ and could then only be spin-flip stripping.[16]

It is of interest to compare the reduced widths of a level when measured in a stripping reaction and in a resonance reaction. The resonant reduced width is usually much larger than the stripping reduced width. The Li^7 7.46-Mev level has been studied in the elastic scattering of neutrons from Li^6. The reduced width extracted from this reaction,[17] for an interaction radius of 3.94f, is $\gamma=1100$ kev in the laboratory system. In units of the Wigner limit this corresponds to $\theta^2=0.21$ in the center-of-mass system. The ratio of resonant reduced width to stripping reduced width, at a radius of 4 f, is therefore $0.21/0.040=5.1$ for this level.

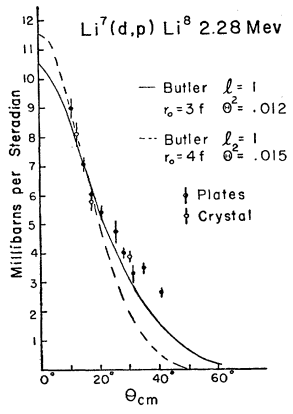

FIG. 4. Angular distribution for the $Li^7(d,p)Li^8$ reaction to the 2.28-Mev level in Li^8. The solid points were taken using nuclear emulsions to detect the scattered particles, the hollow circles were taken with a scintillation counter.

IV. $Li^7(d,p)Li^8$

1. Experimental Results

Angular distributions for the ground state and first excited state of Li^8 were obtained by LBM.[1] Their results have been discussed by French and Fujii.[2] In the present experiment the angular distribution corresponding to the second excited state of Li^8 (at 2.28-Mev excitation) was measured and a search for higher excited states was made.

a. Li^8 2.28-Mev Level

The differential cross section for this level is shown in Fig. 4. A Butler curve having $l=1$ and $r_0=3.0$ f can be made to fit the data. The value of r_0 is rather small; curves having larger values of r_0 fit only the smallest angles. The reduced width for $r_0=3.0$ f is $\theta^2=0.012$; for $r_0=4$ f it would be $\theta^2=0.015$.

b. Other Levels

No other levels in Li^8 were observed. Proton spectra were recorded at $\theta_L=10°$, 14°, and 25°, in the energy region corresponding to excitations in Li^8 between 2 and 8 Mev. Figure 5 shows a typical spectrum, at 14°. This spectrum was recorded using a natural lithium target. The peak labelled Li^8 2.28 contains a contribution from the Li^7 7.46-Mev level. The oxygen contamination in this target was rather high.

From the spectra one can estimate upper limits on the cross sections of unobserved levels. Narrow levels ($\Gamma\lesssim 100$ kev) with a cross section greater than ~ 0.6 mb/sterad should have been identified; this cross section corresponds to a peak of the size of the O^{17} 5.71-Mev level in Fig. 5. Broad levels of considerably larger cross section may, however, not be identified because of the large continuous background (see Fig. 5). This background arises primarily from the breakup of the deuteron:

$$Li^7+d \rightarrow Li^7+n+p.$$

[12] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, New York, 1952).
[13] F. R. Haig, Nuclear Phys. **7**, 429 (1958).
[14] C. A. Levinson and M. K. Banerjee, Ann. Phys. **2**, 471 (1957).
[15] J. B. Marion, Nuclear Phys. **4**, 282 (1957).
[16] J. E. Bowcock, Phys. Rev. **112**, 923 (1958); A. P. French, Phys. Rev. **107**, 1655 (1957).
[17] Willard, Bair, Kington, and Cohn, Phys. Rev. **101**, 765 (1956).

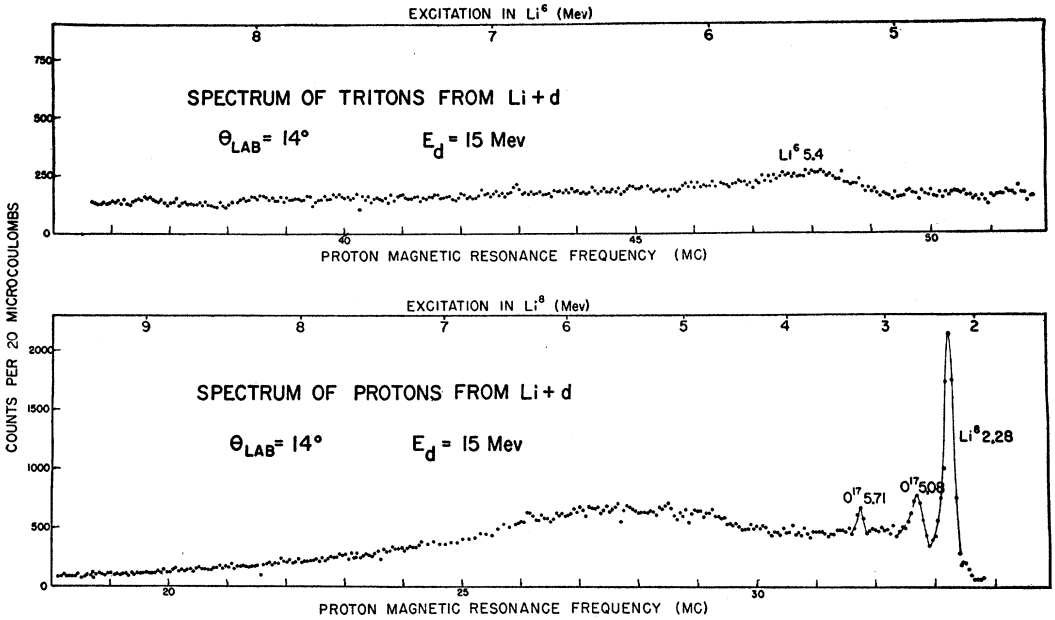

FIG. 5. Spectra of tritons and protons from a natural lithium target. Approximate factors for converting the ordinates to absolute cross sections are: (*a*) tritons 9, (*b*) protons 20 microbarns per sterad per Mev per count per 20 microcoulombs.

2. Discussion

a. Identified Levels

Table II summarizes the experimental results for the identified levels. Column 1 gives the excitation energy; column 2 gives the principal term in the wave function[2] of the state. Column 3 gives the value of S calculated by French and Fujii[2] for $\zeta=1$ in Li^8 and $\zeta=1.1$ in Li^7. Column 4 gives the measured value of θ^2/θ_0^2 where the single particle reduced width has been taken equal to 0.066. The values of θ^2 used to compute θ^2/θ_0^2 for the first two levels differ somewhat from the reduced widths extracted by French and Fujii[2] from the same data; part of this difference may be due to the different values of the Butler radius. Column 5 gives the values of l and r_0 used to fit the data.

The agreement between the calculated and measured values of S is satisfactory for the first two states but is not as good for the 2.28-Mev level. The calculated value of S for this state is insensitive to its detailed wave function because the $[31]\,^{33}D_3$ term can mix only with terms which have no fractional parentage to the principal term in the Li^7 g.s. ($[3]\,^{22}P_{3/2}$). The only way of changing the calculated value of S appreciably is to change the Li^7 g.s. wave function. Thus the wave function of Meshkov *et al.*[18] yields $S=0.32$ while the function given by Auerbach and French[3] for $\zeta=2.4$ yields $S=0.28$. It is probably impossible to change the Li^7 g.s. wave function sufficiently to reduce S to 0.18 without causing disagreement with other experiments.

[18] Meshkov, O'Reilley, and Eckert (unpublished). The authors are indebted to Dr. Meshkov for making the results available before publication.

Finally it should be remarked that the Li^8 2.28-Mev level is unbound by only 240-kev relative to neutron emission. The Butler formula is a sensitive function of its parameters in this energy region and the reduced width is correspondingly uncertain.

The Li^8 2.28-Mev level has been studied in the elastic scattering of neutrons by Li^7.[17] The reduced width, for an interaction radius of 4.08 f, is given as[17] 351 kev in the laboratory system. In units of the Wigner limit this corresponds to $\theta^2=0.072$ in the center-of-mass system. The ratio of resonant reduced width to stripping reduced width for this level, at a radius of $\simeq$4 f, is therefore

$$0.072/0.015=4.8.$$

b. Unobserved Levels

The lack of observed levels in Li^8 above 2.28-Mev excitation is at first sight surprising, and it would seem desirable to obtain precise predictions of the cross sections to be expected from the shell model. To this end a rough intermediate coupling calculation for the

TABLE II. Spectroscopic results for the identified levels in the $Li^7(d,p)Li^8$ reaction.

Excit. (Mev)	Predominant term	Calculated S	Measured θ^2/θ_0^2	l, $r_0(f)$
g.s.	$[31]\,^{33}P_2$	1.1	1.0	1, 3.8
0.97	$[31]\,^{33}P_1$	0.54	0.60	1, 3.5
2.28	$[31]\,^{33}D_3$	0.33	0.18	1, 3.0
			0.23	1, 4.0

TABLE III. Shell-model predictions for the $Li^7(d,p)Li^8$ reaction, from calculations by Macfarlane.[a]

Excit. (Mev)	J	Calculated S	Estimated σ/σ(g.s.)
0	2	1.	1
1.1	1	0.44	0.2
2.1	3	0.32	0.3
2.1	0	0.35	0.05
2.7	1	0.63	0.24
2.7	2	0.38	0.25
4.9	1	0.45	0.13
5	4	0	0
5.7	2	0.08	0.03
6.2	3	0.06	0.04

[a] See reference 19.

configuration p^4, $T=1$, has been made by Macfarlane.[19] A Rosenfeld exchange mixture was assumed, and the parameters used were $L/K=6$, $K=-1.25$ Mev, $\zeta\simeq 1.2$. The results are summarized in Table III. The numbers in the table are not to be taken too literally: the significant point is that many levels are expected in the region 2- to 6-Mev excitation and that some of the reduced widths are of the same order of magnitude as the widths for the first two excited states. The first column gives the calculated excitation energies of the states. Column 2 gives the total angular momentum J. Column 3 gives the value of S, computed using the Li^8 wave functions obtained from the calculation and the Li^7 g.s. wave function given by Auerbach and French[3] for $\zeta=1.2$. Column 4 gives the cross section σ for the different levels relative to the ground state, estimated from the calculated values of S using the Butler formula.

The values of S found for the first three levels agree with the calculations of French and Fujii[2] and, approximately, with experiment (see Table II). The fourth level has $J=0$ and is essentially pure $[31]\,{}^{33}P_0$ because it can only mix with the $[211]\,{}^{33}P_0$ term. The values of S and therefore of σ for this level can be changed by a factor of 2 or 3 by very slight changes in the Li^7 g.s. wave function. One can thus explain the absence of this level in the $Li^7(d,p)Li^8$ reaction.

The $J=1$ and 2 levels at $\sim$2.7 Mev have much larger expected cross sections. If they exist they must be very broad and overlapping. For example, if these levels had the expected cross sections, were $\sim$1 Mev wide and $\sim$0.5 Mev apart, they would produce a constant spectrum between 2.5- and 3.5-Mev excitation as observed in Fig. 9. If one estimates the width of these levels, as in Sec. III, for $\theta_0^2=0.4$, one finds $\Gamma\gtrsim 0.5$ Mev.

The level expected at 4.9 Mev would, similarly, have a width $\Gamma\sim 1.5$ Mev. It would therefore be very difficult to identify. The remaining three levels in Table III have very small expected cross sections, too small to be observed.

[19] M. H. Macfarlane (private communication). The authors are indebted to Dr. Macfarlane for many helpful comments on this reaction.

V. $Li^7(d,t)Li^6$ AND $Li^7(d,He^3)He^6$

1. Experimental Results

Angular distributions for the ground and first excited states of both Li^6 and He^6 were obtained by LBM.[1] The corresponding cross sections and reduced widths are quoted in Table IV (some of the Butler radii r_0 used to fit the data are different from the ones used by LBM[1]). The reduced widths are calculated from Eqs. (3) and (4) in Sec. VI where Θ^2 is replaced by θ^2. The constant B_0^2 is chosen so as to make the Li^7-Li^6 ground-state reduced width equal to the value found in the $Li^6(d,p)Li^7$ reaction: $B_0^2=1.2\times 10^{13}$ cm^{-1}.[20]

In the present experiment the angular distribution of the triton group corresponding to the second excited state of Li^6 (at 3.57 Mev) was measured and a search for states of higher excitation was made.

a. Li^6 3.57-Mev Level

The angular distribution for this level is shown in Fig. 6. Particularly large errors are indicated at small angles: the triton group corresponding to this level is difficult to observe at scattering angles below 25° (lab) because it is focussed by the analyzing magnet at the same magnetic field as the intense groups of deuterons elastically scattered from lithium and silver (the target backing).

The data is seen to be fitted well with a Butler curve with $l=1$ and $r_0=6.5$ f. The reduced width, extracted as explained above, is $\theta^2=0.0090$. Butler curves with $r_0=6$ f and 7 f give a poorer fit; the reduced widths

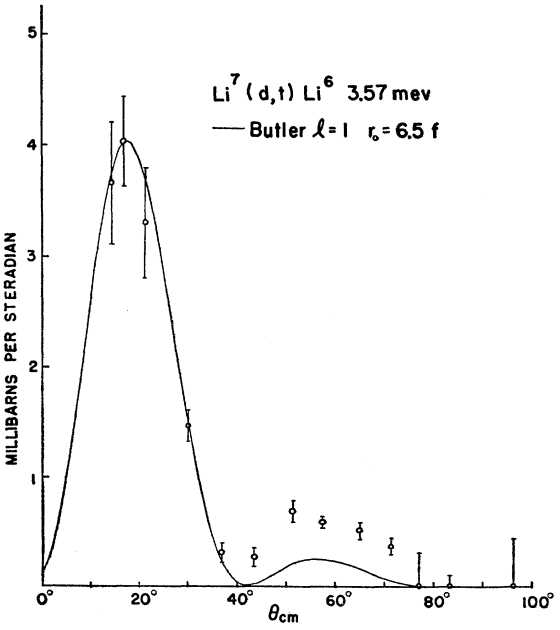

FIG. 6. Angular distribution for the $Li^7(d,t)Li^6$ reaction to the 3.57-Mev level of Li^6.

[20] A. I. Hamburger (private communication).

calculated with these radii would be 0.010 and 0.0088, respectively.

b. Other Levels

Triton spectra at $\theta_L=14°$ and 25° were recorded in the energy range corresponding to excitation in Li^6 between 4.4 and 8.5 Mev. A natural lithium target was used. Figure 5 shows the spectrum at 14°. There is a continuous triton background due to the three-body disintegration

$$Li^7+d\rightarrow\alpha+d+t,\quad Q=-2.465\text{ Mev}.$$

There is also a small contribution from

$$Li^6+d\rightarrow\alpha+p+t,\quad Q=2.55\text{ Mev}.$$

No narrow levels are observed. It is estimated that any narrow ($\Gamma\lesssim 100$ kev) level having a cross section larger than 0.3 mb/sterad would have been observed. The small narrow hump in the spectrum of Fig. 5 at 43 Mc is of instrumental origin.

A broad, asymmetrical hump is observed in the spectra at $E_x\sim 5.4$ Mev. Its width is $\Gamma\sim 600$ kev; its cross section is 2 mb/sterad at 14° and 0.4 mb/sterad at 25°. A reduced width was estimated from these cross sections by fitting them with a Butler curve having $l=1$, $r_0=5.6$ f; this is the reduced width quoted in Table IV. The cross section, width and reduced width for this group are uncertain to within a factor of 2 because it is difficult to distinguish the hump from the continuous background.

2. Discussion

The results of LBM for these reactions have been thoroughly discussed by French and Fujii.[2] We repeat part of their analysis and extend it to cover the recent results.

The Li^6 3.57-Mev level is the analog of the He^6 g.s., i.e., its wave function should be essentially the same as that of the He^6 g.s. except for the isotopic spin dependence, and the S factors, therefore, should be the same for the reactions leading to these two levels. The cross sections, however, will differ slightly because of the kinematical factors, and appreciably because of the isotopic spin coupling coefficients.[3] These coefficients are $\frac{1}{3}$ and $\frac{2}{3}$, respectively, for the Li^6 3.57-Mev level and the He^6 g.s. One would then expect the cross section for the Li^6 3.57-Mev level to be approximately one-half of that for the He^6 g.s. This is actually the case and the measured values of S for the two levels are equal within experimental error (see Table IV).

Table IV summarizes the spectroscopic results of the (d,t) and (d,He^3) experiments. Column 1 gives the previously observed levels of Li^6 up to 6-Mev excitation and of He^6 up to 2-Mev excitation.[21] Column 2 gives the predominant term in the wave function of the state.[22] Column 3 shows the calculated values of the spectroscopic factor S (see below). The last four columns give the experimental results: Column 4 gives the value of S deduced from the measured reduced width; the single-particle reduced width was taken equal to 0.066. Column 5 gives the values of l and r_0 which fit the data. Column 6 gives the absolute differential cross section in the center-of-mass system measured at the center-of-mass angle in column 7.

TABLE IV. Spectroscopic results of the $Li^7(d,t)Li^6$ and $Li^7(d,He^3)He^6$ reactions.

Level (Mev)		Predom. term	Calc. S	Measur. θ^2/θ_0^2	l, $r_0(f)$	σ mb/sterad	$\theta_{c.m.}$
$Li^7(d,t)Li^6$	g.s.	$^{13}S_1$	0.81	0.78	1, 5.6	29.4	11°
	2.19	$^{13}D_3$	0.56	0.55	1, 5.6	14.5	16°
	3.57	$^{31}S_0$	0.83	0.45	1, 6.5	4.0	17°
	4.52	$^{13}D_2$	0.24				
	5.4	$^{31}D_2$	0.69	0.42[a]	1, 5.6	2.0[a]	21°
	5.4	$^{13}D_1$	0.02				
$Li^7(d,He^3)He^6$	g.s.	$^{31}S_0$	0.83	0.40	1, 7.0	7.3	17°
	1.71	$^{31}D_2$	0.69	0.12	1, 7.5	1.8	16.5°

[a] Uncertain to within a factor 2.

The experimental reduced widths quoted in column 4 for the first two states of Li^6 and He^6 differ from those extracted from the same data by French and Fujii.[2] The difference may come partly from different values for r_0, but is mainly due to the different triton momentum wave functions $P_t(K)$ used in the two analyses. French and Fujii obtained both the form and normalization of $P_t(K)$ from computations based on Irving's wave function for the triton. In the present work the following form was assumed for $P_t(K)$ [see also Eq. (4)]:

$$P_t(K)\equiv\int\exp\{i\mathbf{K}\cdot[\mathbf{r}_3-\tfrac{1}{2}(\mathbf{r}_1+\mathbf{r}_2)]\}\times\phi_t(\mathbf{r}_1\mathbf{r}_2\mathbf{r}_3)\phi_d(\mathbf{r}_1\mathbf{r}_2)d\mathbf{r}_1d\mathbf{r}_2d\mathbf{r}_3\cong\frac{(4\pi)^{\frac{1}{2}}B_0}{K^2+\gamma^2},\tag{1}$$

where $\mathbf{K}=\frac{2}{3}\mathbf{K}_t-\mathbf{K}_d$, ϕ_t and ϕ_d are the triton and deuteron wave functions, respectively, B_0 is a constant (see above) and $\gamma^2=0.22\times10^{26}$ cm^{-1} is the wave number associated with the binding energy of the neutron in the triton.

The calculated values of S (column 3) for the first two levels of Li^6 and He^6 agree with those calculated by French and Fujii.[2] In the present calculation the wave functions given by Auerbach and French[3] for $\zeta=1.2$ were taken for the Li^7 and Li^6 ground states. All other states of Li^6 and He^6 were assumed to be pure LS coupling terms. This is a good assumption for the $^{13}D_{2,3}$ states, which are the only states with $TJ=02, 03,$

[21] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955); also Revs. Modern Phys. **24**, 321 (1952).

[22] See, e.g., J. P. Elliott and A. M. Lane, in *Handbuch der Physik* (Springer-Verlag Berlin, 1957), Vol. 39, p. 241.

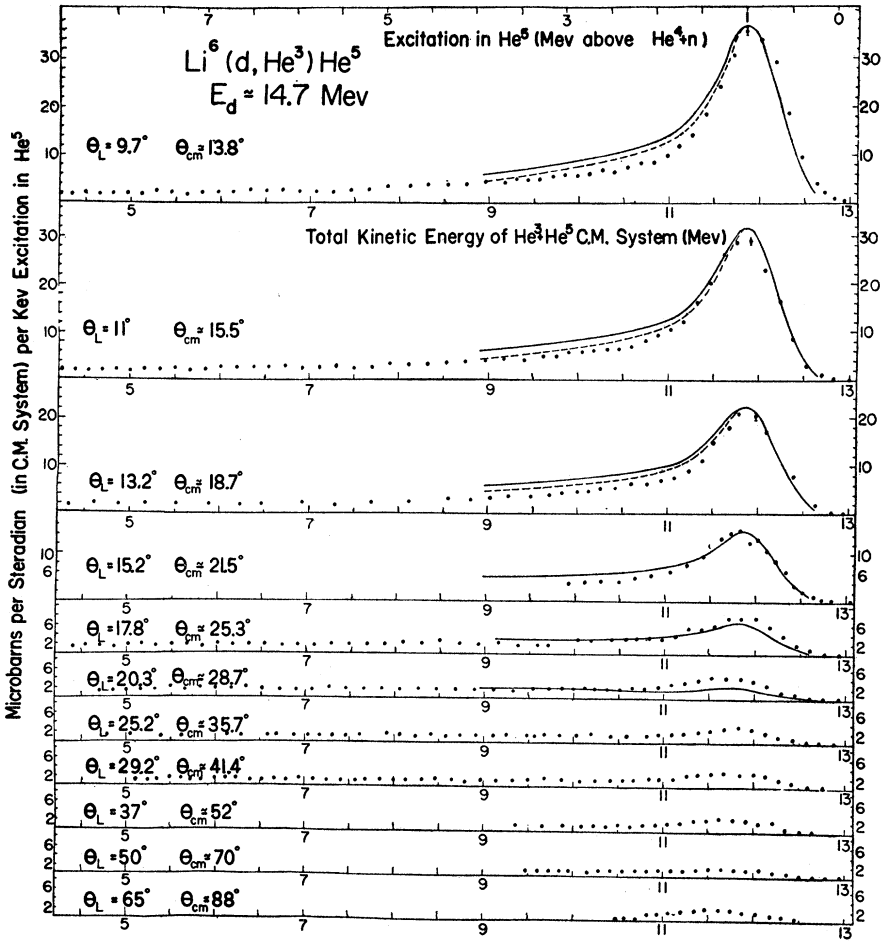

FIG. 7. He^3 spectra from the $Li^6(d,He^3)He^5$ reaction at various laboratory angles. The abscissa, E_{He^3} is the total kinetic energy of the He^3+He^5 system in the c.m. system. The top scale gives the corresponding value of E_n defined in Eq. (2). The solid and dashed curves are calculated from Eq. (11) for $a=2.9f$ and 2.0f, respectively.

respectively, in the p^2 configuration. The $^{31}S_0$ and $^{31}D_2$ states can mix only with terms of the ^{33}P multiplet. This multiplet has no fractional parentage with the predominant term of the Li^7 g.s. and should therefore not affect the value of S strongly. The $^{13}D_1$ term can mix with the $^{13}S_1$ and $^{11}P_1$ terms; its S value will depend strongly on the admixtures in the wave functions. The value given in Table IV for this level should not be taken too seriously; the actual S value is however expected to be small.

S was also calculated assuming the Li^7 g.s. wave function computed by Meshkov *et al.*[18] and the same Li^6 functions. The results do not differ appreciably from those quoted in Table IV except for the $^{13}D_3$ and $^{13}D_1$ levels, whose S values become 0.41 and 0.10, respectively.

It is evident from Table IV that the measured values of S for the $T=1$ states are significantly smaller than the calculated values. The present work on the Li^6 3.57-Mev level shows that this is not due to a difference between the mechanisms of (d,t) and (d,He^3) reactions. The discrepancy is then due to one (or more) of the following effects:

(*a*) The calculated S factors are not correct. As shown above these factors are insensitive to the exact wave functions, at least as long as there is no configuration mixing. In view of the many successes of the intermediate coupling theory for $A=6$ it seems improbable that the S factors are seriously in error.[2]

(*b*) The radial part of the overlap integral, i.e., the single-particle reduced width, varies with the excitation energy in the final nucleus. An example of an analogous variation seems to exist in the $Li^6(d,t)Li^5$ reaction (see Sec. VI).

(*c*) The Butler formula does not apply to (d,t) reactions insofar as the relationship between the reduced width and the cross section is concerned. It should be remarked that the angular distributions for all these levels agree very well with the Butler formula.

A measurement of the (p,d) reduced width of the Li^6 3.57-Mev level can decide among these possibilities. If the reduced width has the value expected theoretically, (*c*) is correct; if it is about 60% of the expected value, (*a*) or (*b*) holds. The measurement has been

made,[23,24] but unfortunately the experimental uncertainties are too large to permit a decision; the reduced width is (70±20)% of the expected value.

If we assume that either possibility (*b*) or (*c*) is correct we can make the following remarks:

The Li^6 level at 4.52 Mev inferred from He^4+d scattering[25] is very broad ($\Gamma\sim900$ kev) and its S factor is expected to be only $\sim\frac{1}{3}$ of the S factor for the He^6 1.71-Mev level (see Table IV); this He^6 level has a cross section ~1.8 mb/sterad, so that the Li^6 4.52-Mev level would have a cross section ~0.6 mc/sterad. A level with such a small cross section and such a large width could easily be missed in the background (see, e.g., Fig. 5). The level at ~5.4 Mev has a relatively large reduced width and might therefore be identified with the $^3D_2$ term.[26] However, the large experimental uncertainties concerning this level should be borne in mind. The $^1D_1$ level and the ^3P levels (not shown in the table) have small calculated values of S and one should not expect to identify them.

VI. $Li^6(d,He^3)He^5$ AND $Li^6(d,t)Li^5$

These two mirror reactions are very similar and will be discussed together. The product nuclei He^5 and Li^5 are unbound and decay into an alpha particle plus a neutron or a proton. The reactions are, therefore, three-body breakups and continuous spectra of He^3 particles and tritons are observed at each angle.

The (d,He^3) reaction was observed by LBM[1] at one angle. The (d,t) reaction has been observed previously only at low bombarding energies.[27]

1. Experimental Results

He^3 and triton spectra were measured at some ten angles from 9.7° to 70° (lab), over energy ranges of ~5 Mev near their high-energy limits. Figures 7 and 8 show the spectra. No fine structure was found in the spectra, so that most of the data were taken in steps of ~200 kev. Typical statistical errors are shown.

The measured energy of the particles was corrected for the energy loss in the target before being converted to the center-of-mass system[5] (c.m. system). The abscissas in Figs. 7 and 8 are the total kinetic energies E_{He^3} and E_t of the He^3+He^5 and Li^5+t systems in the c.m. system. E_{He^3} and E_t are related to the Q's of the $Li^6(d,He^3)$ He^4+n and $Li^6(d,t)He^4+p$ reactions by the equations

$$E_{He^3}+E_n=Q+E_d, \quad E_t+E_p=Q'+E_d, \qquad (2)$$

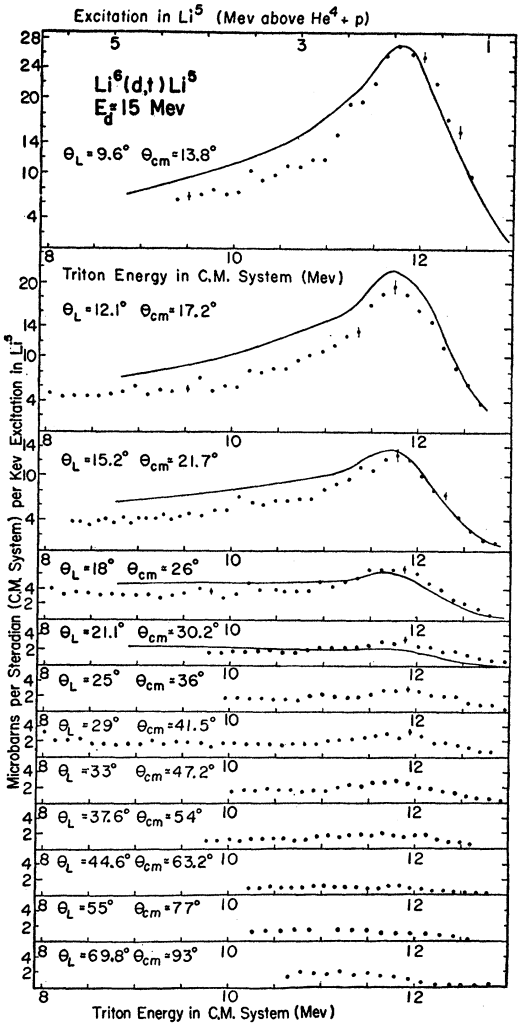

FIG. 8. Triton spectra from the $Li^6(d,t)Li^5$ reaction at various laboratory angles. The abscissa, E_t, is the total kinetic energy of the Li^5+t system in the c.m. system. The top scale gives the corresponding value of E_p defined in Eq. (2). The solid curves are calculated from Eq. (11).

where E_d is the c.m. kinetic energy in the incident channel and E_n and E_p are the relative kinetic energies of the alpha particle and the neutron and proton, respectively, in the He^5 and Li^5 c.m. system. E_n and E_p may be regarded as excitation energies in He^5 and Li^5 measured relative to the rest energies of He^4+n and He^4+p. The absolute energy scales in the figures are estimated to be uncertain to within ±200 kev, mainly from uncertainties in the calibration of the magnetic spectrometer.[5]

The center-of-mass scattering angle corresponding to a given laboratory angle varies along each spectrum: at $\theta_L=10°$, 30°, and 65°, $\theta_{c.m.}$ varies by ~0.3°, 0.6°, and 1.2° per Mev, respectively. This variation of $\theta_{c.m.}$ has been neglected in the analysis of the data; the value of $\theta_{c.m.}$ quoted is calculated for E_{He^3} and $E_t\simeq12$ Mev.

[23] D. R. Maxson and E. F. Bennet, Bull. Am. Phys. Soc. **2**, 180 (1957).
[24] D. R. Maxson (private communication). The authors are indebted to Dr. Maxson for having made the results available before publication.
[25] A. Galonsky *et al.*, Phys. Rev. **98**, 586, 590 (1955).
[26] In order to calculate the reduced width from the experimental data, the level was assumed to have $T=1$; if it had $T=0$ the reduced width would be 3 times smaller.
[27] R. T. Frost and S. S. Hanna, Phys. Rev. **110**, 939 (1958).

2. Discussion

The observed He^3 and triton spectra (Figs. 7 and 8) show a broad, asymmetric peak at E_{He^3} (or E_t) $\sim$12 Mev. This peak is very prominent at the smaller angles but decreases rapidly at larger angles, where the spectrum is quite flat. There is another way to look at the data which is instructive: one can examine the angular dependence of the cross section for a given E_{He^3} (or E_t); this corresponds to taking a vertical cut through Figs. 7 or 8. Such plots are shown in Figs. 9 and 10. The continuous curves in these figures are calculated from the Butler formula for (d,He^3) and (d,t) reactions for $l=1$ and $r_0=6$ f for the He^3 particles, $r_0=5.75$ f for the tritons. The shape of the curve is different for each value of E_{He^3} (or E_t), since each E_{He^3} (or E_t) corresponds to a different Q for the (d,He^3) or (d,t) reaction.

The curves fit the data at the smaller angles quite well. It seems, therefore, that at these angles the predominant reaction mechanism is Butler pickup. Having accounted for the angular dependence of the cross section at small angles, we now try to account for the energy dependence, i.e., for the shape of the spectra. This is equivalent to finding the energy dependence of the stripping reduced width Θ^2.

a. Calculation of the Reduced Width

In the following we shall, for definiteness, consider the $Li^6(d,He^3)He^5$ reaction. The calculation for the $Li^6(d,t)Li^5$ reaction is analogous.

The cross section can be written

$$\frac{d^2\sigma}{d\omega dE_{He^3}}=B\Theta^2, \tag{3}$$

where the kinematical factor from the Butler formula is:

$$B=\frac{3}{2}\frac{\mu_{He^3}\mu_d}{\mu_n^2}\frac{K_{He^3}}{K_d}\frac{B_0^2}{(K^2+\gamma^2)^2}\frac{r_0W_l^2}{[h_l^{(1)}(i\kappa r_0)]^2}. \tag{4}$$

Here the μ's are reduced masses, $\hbar\mathbf{K}_{He^3}$ and $\hbar\mathbf{K}_d$ are the final and initial momenta in the c.m. system, B_0, K, and γ are defined in Sec. V and the last factor is the usual Wronskian expression.

The reduced width is, apart from constant factors, given by

$$\Theta^2\propto\left[\int Y_l^m(\Omega_p)d\Omega_p\int\phi_5(\xi_5;E_n)\phi_6(\xi_5,r_p)d\xi_5\right]^2_{r_p=r_0}. \tag{5}$$

Here $Y_l^m(\Omega_p)$ is the spherical harmonic of order l, m; Ω_p, r_p are the angular and radial coordinates for the transferred proton. ξ_5 represents the internal coordinates of He^5 and $\phi_5(\xi_5;E_n)$ is the wave function of He^5 at the excitation energy E_n defined in Eq. (2). The normalization of ϕ_5 is determined by

$$\int\phi_5^*(\xi_5;E_n)\phi_5(\xi_5;E_n')d\xi_5=\delta(E_n-E_n'). \tag{6}$$

$\phi_6(\xi_5,r_p)$ is the wave function of the Li^6 ground state.

$\Theta^2(E_n)$ is a reduced width per unit energy range because the final state is one of a continuous set of states. It measures the amplitude of the He^5 state at energy E_n in the Li^6 ground state; it is not related to an actual width of a level. The reduced width θ^2 which is usually quoted for similar reactions when the final state is unbound (e.g., in the $Li^7(d,t)Li^{6*}$ 2.19-Mev reaction) refers to an integration of Θ^2 over a resonance

$$\theta_{\rm res}^2=\int_{\rm res}\Theta^2dE, \tag{7}$$

and is a pure number.

We wish to find the dependence of Θ^2 on E_n. We consider both He^5 and Li^6 as consisting of an alpha-particle core and the outside nucleons; and we assume that in Li^6 these nucleons are in p states. Then the overlap integral (5) reduces to an integral over the neutron radial coordinate and only p states in He^5

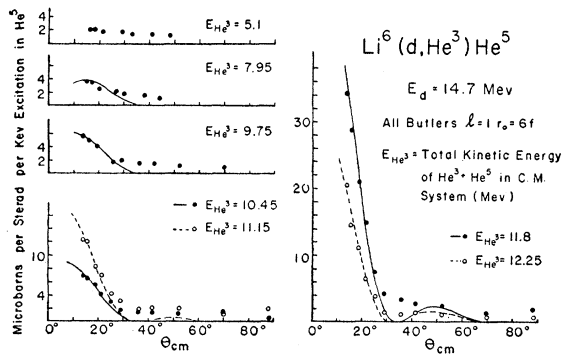

FIG. 9. Angular distributions for the $Li^6(d,He^3)He^5$ reaction for various values of E_{He^3}.

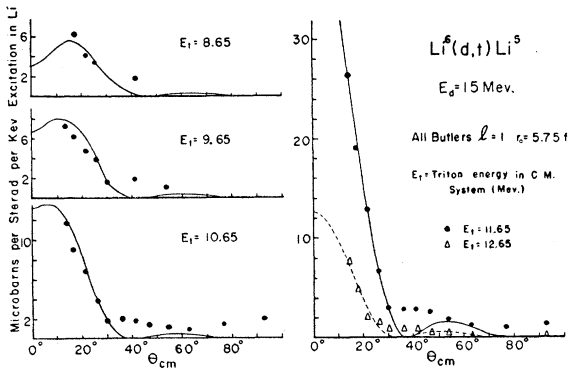

FIG. 10. Angular distributions for the $Li^6(d,t)Li^5$ reaction for various values of E_t.

contribute:

$$\Theta^2 \propto \left[\int_0^\infty f_5(r_n; E_n) f_6(r_p; r_n) r_n^2 dr_n\right]^2_{r_p=r_0}, \quad (8)$$

where $f_5(r_n; E_n)$ is the radial part of the He^5 wave function for $l=1$ at energy E_n and $f_6(r_p,r_n)$ is the radial wave function for the valence nucleons in Li^6.

The only energy dependent factor in Eq. (8) is the He^5 wave function. This is the wave function of a neutron in the presence of an alpha particle and has been extensively studied by means of the elastic scattering of neutrons by He^4.[28,29] In the neutron energy range from 0 to 4 Mev (corresponding to E_{He^3} from 13 to 9 Mev) this function can be well approximated by the wave function of a particle scattered by a potential well.[30] The well can have a depth $\sim$25 Mev and a radius $\sim$3 f. The shape of the wave function at small r in such a well does not change very much when E varies from 0 to 4 Mev; the amplitude, however, does change significantly, since the p wave goes through a resonance at $E_n \simeq 1$ Mev. We can, therefore, write $f_5(r_n; E_n)$ approximately as the product of an energy dependent function and a radial, energy independent, function

$$f_5(r_n; E_n) \cong f_1(E_n) g_1(r_n), \quad (9)$$

and the energy dependence of Θ^2 will be given by $[f_1(E_n)]^2$. The approximation (9) overestimates the value of the integral (8) at high E_n, but the error is probably less than 10% in the energy range covered.

The energy variation of the radial wave function at a constant radius, $f_1(E_n)$, can be found from the n-He^4 scattering data. The exact form of the wave function outside the potential well is known in terms of the phase shift.[31] The value at the nuclear surface $r_n=a$ is found to be (only energy dependent factors are included):

$$[f_1(E_n)]^2=[f_5(r_n=a; E_n)]^2=(A_1^2/K_n)\sin^2(\delta+\phi), \quad (10)$$

where $A_1^2=F_1^2(a)+G_1^2(a)$, $\phi=\arctan F_1(a)/G_1(a)$. $F_1(r)$ and $G_1(r)$ are the regular and irregular solutions of the free particle radial equation for $l=1$, as defined by Blatt and Weisskopf.[31]

$$K_n=2\mu E_n/\hbar^2, \quad \mu=M_n M_\alpha/(M_n+M_\alpha).$$

M_n, M_α=mass of neutron and alpha particle, respectively. δ=n-He^4 scattering phase shift at energy E_n.

So far we have neglected the spin of the neutron. Actually He^5 has two p states, $P_{\frac{3}{2}}$ and $P_{\frac{1}{2}}$, and two corresponding phase shifts δ^+ and δ^-. Since these states are orthogonal we may add the cross sections leading to them. This is equivalent to adding the reduced widths since the factor B in Eq. (3) has no spin dependence. The reduced widths are products of a radial part Θ_0^2 and an angular momentum part S. In the preceding paragraphs we have calculated the energy dependence of Θ_0^2; the functional form of this dependence is the same for the $P_{\frac{3}{2}}$ and $P_{\frac{1}{2}}$ states, although the S factors are different. If we assume a pure $^3S_1$ wave function for the Li^6 ground state, we obtain $S=\frac{4}{3}$ for the $P_{\frac{3}{2}}$ state and $S=\frac{2}{3}$ for the $P_{\frac{1}{2}}$ state. The energy dependence of the reduced width is therefore given by

$$\Theta^2 \propto (A_1^2/K_n)[\sin^2(\delta^+ +\phi)+\tfrac{1}{2}\sin^2(\delta^- +\phi)]. \quad (11)$$

It is interesting to note that the phase shifts δ^+ and δ^- can be well represented by single level Breit-Wigner formulas.[28,32] Therefore, one can express Θ^2 in terms of the Breit-Wigner parameters of the $P_{\frac{3}{2}}$ and $P_{\frac{1}{2}}$ states. The relationship is

$$\delta^+ +\phi=\arctan[\tfrac{1}{2}\Gamma^+/(E-E_0^+)],$$

and similarly for δ^-. Γ^+ is the neutron width (not reduced) of the $P_{\frac{3}{2}}$ state and E_0^+ is the "actual resonance energy." [31] The result is

$$\Theta^2 \propto \frac{A_1^2}{K_n}\left[\frac{(\frac{1}{2}\Gamma^+)^2}{(E-E_0^+)^2+(\frac{1}{2}\Gamma^+)}+\frac{1}{2}\frac{(\frac{1}{2}\Gamma^-)^2}{(E-E_0^-)^2+(\frac{1}{2}\Gamma^-)^2}\right]. \quad (12)$$

In practice, however, Θ^2 was computed directly from the experimentally determined phase shifts using Eq. (11).

b. Comparison with Experiment

Θ^2 was calculated from Eq. (11) for He^4+n and for He^4+p scattering. The phase shifts given by Seagrave[29] and Clementel and Villi[33] for $He^4(n,n)$, and by Critchfield and Dodder[34] for $He^4(p,p)$, were used. A_1^2 is easy to calculate for neutrons; for the p-He^4 scattering it was found from the graphs of Sharp *et al.*[35] For both reactions the interaction radius was taken as

$$a=2.9 \text{ f}. \quad (13)$$

This is the value used in the analyses of nucleon-alpha scattering.[29,32]

The solid curves in Figs. 7 and 8 are the spectra calculated from Eqs. (3), (4), (11), and (13). The curve at the smallest angle was normalized to agree with the experimental points; the normalization of the curves at all angles is then determined by Eqs. (3) and (4). The absolute energy scales in Figs. 7 and 8 are uncertain within $\pm$200 kev. The calculated curves were shifted horizontally to fit the peak; the shift was less than 100 kev and was the same at all angles.

The curves reproduce the shape and size of the observed spectra approximately. In particular, the most striking feature of the data is reproduced: the

[28] R. K. Adair, Phys. Rev. **86**, 155 (1952).
[29] J. D. Seagrave, Phys. Rev. **92**, 1222 (1953).
[30] This is shown for the analogous He^4-p scattering by Sack, Biedenharn, and Breit, Phys. Rev. **93**, 321 (1954).
[31] See reference 12, Chap. VIII.
[32] D. C. Dodder and J. L. Gammel, Phys. Rev. **88**, 520 (1952).
[33] E. Clementel and C. Villi, Nuovo cimento **2**, 1121 (1955).
[34] C. L. Critchfield and D. C. Dodder, Phys. Rev. **76**, 602 (1949).
[35] Sharp, Gove, and Paul, Atomic Energy of Canada Limited Report AECL No. 268 (unpublished).

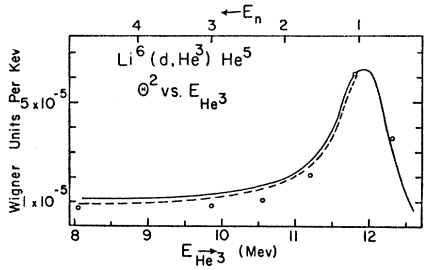

FIG. 11. The reduced width Θ^2 *vs* E_{He^3}. The solid and dashed curves are calculated from Eq. (11) for $a=2.9$f and 2.0f, respectively; the open circles are experimental.

calculated curves show a prominent peak at small angles which decreases rapidly at larger angles and finally leaves a nearly constant spectrum. This effect can now be explained: the shape of the spectra is determined not only by Θ^2 but also by the kinematical factor B, which is different at each angle. At the larger angles B yields a very low probability for the formation of fast He^3 particles (or tritons), and thus "wipes out" the high-energy peak in Θ^2 (see Fig. 11). This is clear from Fig. 12, where B is plotted *versus* E_{He^3} at various angles.

The reduced widths were extracted from the angular distributions of Fig. 9 using the same value of B_0^2 as for the $Li^7(d,t)Li^6$ reaction. Figure 11 shows these experimental reduced widths (open circles) compared with Eq. (11), computed for $a=2.9$ f and for $a=2.0$ f (see below). The curves were normalized at the peak. As in the spectra of Fig. 7, the experimental values at low energies are smaller than the calculated values by a factor ~ 1.5. It is interesting that almost perfect agreement may be obtained by multiplying Eq. (11) by an additional factor $1/K_n$; there is, however, no theoretical justification for such a factor.

The calculation involves two parameters r_0 and a, which may be varied to improve the agreement with experiment. The Butler radius r_0 was chosen to obtain the best agreement with the angular distributions. The values used are probably the best within ± 0.5 f.

The nucleon-alpha particle interaction radius a was taken from Adair[22] and Dodder and Gammel,[32] who chose the value 2.9 f in order to fit the scattering cross section with the Breit Wigner formula and to account for the Li^5-He^5 energy difference in terms of the Coulomb potential. Neither of these criteria for the choice of a is pertinent to the $Li^6(d,He^3)He^5$ and $Li^6(d,t)Li^5$ reactions, so that a may be varied to obtain the best fit. The dashed curves in Figs. 7 and 11 give the results for $a=2.0$ f for the $Li^6(d,He^3)He^5$ reaction. The agreement at low energies is better than for $a=2.9$ f. An even smaller value of a might improve the agreement more, but does not seem reasonable in the light of the size of the alpha particle and nucleon, as determined by electron scattering.[36]

[36] R. Hofstadter, Revs. Modern Phys. 28, 214 (1956).

c. B_0^2 and the Single-Particle Reduced Width

The $Li^6(d,He^3)He^5$ cross section can be compared with the $Li^6(n,d)He^5$ cross section to yield a value of the constant B_0^2 for He^3. Frye[37] has measured the (n,d) cross section integrated over the deuteron energy range corresponding to E_n between 0 and 2.8 Mev. The neutron energy was approximately 14 Mev. The deuteron angular distribution obtained by Frye shows a strong forward maximum; a Butler curve having $l=1$ and $r_0=4.5$ f fits the data, albeit rather poorly. The reduced width is $\theta^2=0.080$. If the (d,He^3) cross section is integrated over the same range of E_n, which corresponds to E_{He^3} between 12.8 and 10 Mev, the resulting angular distribution can be fitted well with a Butler curve having $l=1$ and $r_0=6$ f. (The Butler curves for both reactions are calculated at $E_n \simeq 1$ Mev.) The value of $B_0^2\theta^2$ is 0.084×10^{13} cm^{-1}. The value of B_0^2 is then

$$B_0^2=(0.084/0.080)\times 10^{13}=1.05\times 10^{13}\ \text{cm}^{-1}.$$

This value agrees very well with the value 1.2×10^{13} cm^{-1} found for the triton from the $Li^7(d,t)Li^6$ and $Li^6(d,p)Li^7$ reactions. The uncertainty in the value of B_0^2 due only to the experimental uncertainties in the (n,d) and (d,He^3) cross sections is $\sim 30\%$.

The single-particle reduced width θ_0^2 may be extracted from the (n,d) experiment in the usual manner by dividing the reduced width by the spectroscopic factor S. Here the appropriate S is that for the $P_{\frac{3}{2}}$ state because in the energy range considered the contribution of the $P_{\frac{1}{2}}$ state to the integral (5), as calculated from Eq. (11), is negligible. Some correction to the reduced width θ^2 quoted above must be made, however, to take into account that part of the $P_{\frac{3}{2}}$ cross section which lies in the region $E_n>2.8$ Mev. It is estimated from Eq. (11) that θ^2 should be increased from 0.08 to 0.10 in order to include the whole $P_{\frac{3}{2}}$ cross section. The spectroscopic factor S is $\frac{4}{3}$ (see above) and the isobaric spin coupling coefficient is $\frac{1}{2}$, so that the single-particle reduced width is

$$\theta_0^2=0.10/\tfrac{1}{2}\cdot\tfrac{4}{3}=0.15.$$

This value of θ_0^2 is much larger than the value 0.066 found for the other reactions on lithium (see Secs. III, IV, and V) or than the value found for other stripping reactions in the p shell.

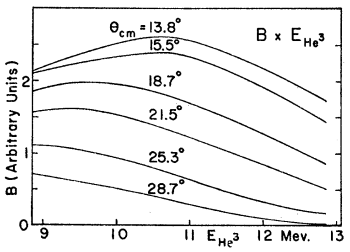

FIG. 12. The kinematical factor B *vs* E_{He^3} at various angles.

[37] G. M. Frye, Jr., Phys. Rev. 93, 1086 (1954).

d. Conclusions

The agreement with experiment is sufficiently good to show the essential correctness of the theory developed in paragraph *a*. A very simple model represents a complicated reaction and gives quite accurate results. The discrepancies which do exist between the calculated curves and the experimental points in Figs. 7, 8, and 11 may be due to any of many assumptions made in the calculation. In particular, the calculation of the overlap integral (5) is probably more reliable than the basic Eq. (3).

At angles less than 30° (c.m. system) pickup is the predominant reaction mechanism. Here the Butler formula determines not only the angular distribution, but also the shape of the spectra—a feature which has not been observed before.

At angles beyond the first minimum of the stripping curves ($\theta_{c.m.}>30°$) the reaction mechanism no longer can be described by the Butler formula. This is clear from the angular distributions shown in Figs. 9 and 10. The cross section in this region is approximately independent of both angle and energy.

VII. $Li^6(d,d')Li^{6*}$

The angular distribution for the first excited state of Li^6 was measured and a search for further excited states was made.

Figure 13 shows the angular distribution for the 2.19-Mev level. In the range $30°<\theta_{c,m,}<90°$ the shape of the angular distribution agrees with the one found by Haffner[8] for the same reaction at a similar bombarding energy (15 Mev). At angles below and above this range Haffner's points are much higher than the ones shown in Fig. 13. The angular distribution does not show sharp maxima and minima and cannot be accounted for by the simple direct interaction theories.[14]

The deuteron spectrum was recorded at two angles, $\theta_L=15°$ and 25°, in the energy range corresponding to excitation in Li^6 between 2 and 6 Mev. No levels beyond the first excited state were observed. The spectra show a continuous background of deuterons due partly to slit edge scattering and partly to the reaction

$$Li^6+d\rightarrow\alpha+2d.$$

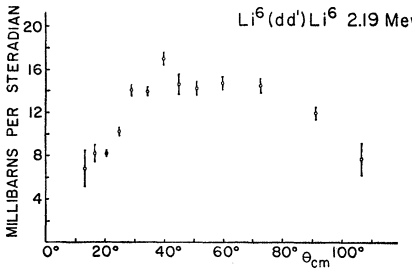

FIG. 13. Angular distribution for the $Li^6(d,d')Li^6$ reaction to the 2.19-Mev level of Li^6.

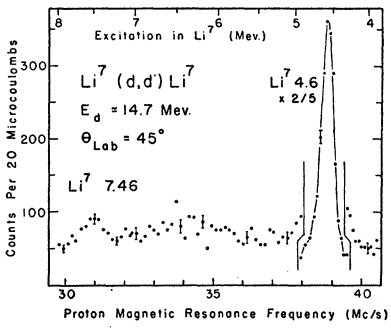

FIG. 14. Deuteron spectrum from the $Li^7(d,d')$ reaction at $\theta_{lab}=45°$.

This background makes the identification of broad levels difficult. Thus the level at 4.5-Mev excitation inferred from the He^4+d scattering,[25] which has $\Gamma\sim1$ Mev, would only have been identified if its cross section were larger than 8 mb/sterad. The narrow level at 3.57-Mev excitation would have been identified if it had $\sigma>1.3$ mb/sterad. This level has isobaric spin $T=1$ and should therefore not appear in the $Li^6(d,d')$ reaction if isobaric spin is conserved.

The results of this survey are consistent with the results found by Browne and Bockelman[38] for the same reaction at $E_d\sim7$ Mev.

VIII. $Li^7(d,d')Li^{7*}$

Angular distributions of the inelastic deuteron groups corresponding to the two lowest excited states of Li^7, at 0.477- and 4.61-Mev excitation, were obtained by LBM.[1]

In the present experiment deuteron spectra were recorded at two angles, $\theta_L=25°$ and 45°, in the energy region corresponding to excitation in Li^7 between 4 and 8 Mev. Figure 14 shows the spectrum at 45°; typical statistical errors are shown. The levels at 4.61 and 7.46 Mev were identified. The results for the former agree with the angular distribution of LBM.[1] The level at 7.46 Mev is only weakly excited; its cross section is:

$$\theta_L=25°,\quad \theta_{c,m,}=36.7°,\quad \sigma=0.5\pm0.1 \text{ mb/sterad},$$
$$\theta_L=45°,\quad \theta_{c,m,}=64.8°,\quad \sigma=0.4\pm0.1 \text{ mb/sterad}.$$

The uncertainties quoted are estimated upper limits on the errors.

No other narrow levels were observed. It is estimated that any narrow ($\Gamma\lesssim100$ kev) level with cross section larger than 0.3 mb/steradian would have been identified. There is some evidence for broad structure at ~6.4-Mev excitation[39]; if it corresponds to a level it would have $\Gamma\sim700$ kev, $\sigma\lesssim1$ mb/steradian. However, this hump in the spectrum may also be due to the continuous

[38] C. P. Browne and C. K. Bockelman, Phys. Rev. **105**, 1301 (1957).

[39] Similar structure appears in the $Li^7(p,p')$ reaction; see reference 14.

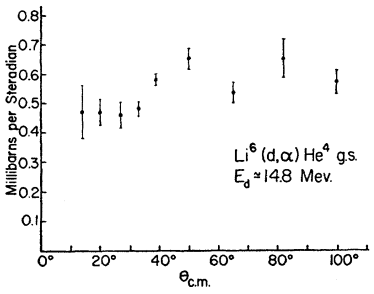

FIG. 15. Angular distribution for the $Li^6(d,\alpha)He^4$ reaction to the g.s. of He^4.

background. The background is due partly to slit edge scattering and partly to the reaction

$$Li^7+d \rightarrow \alpha+t+d.$$

IX. $Li^6(d,\alpha)He^4$

This reaction has been studied previously at low bombarding energies[21] and recently at 21.6 Mev.[40] In the present experiment the angular distribution of the alpha-particle group corresponding to the ground state of He^4 was measured and alpha-particle spectra were recorded at two angles, 15° and 25° in the laboratory.

1. $Li^6(d,\alpha)He^4$ g.s.

Figure 15 shows the angular distribution for the He^4 g.s. At angles $\theta_{c.m.}<33°$ the alpha-particle group was partially obscured by the intense deuteron group due to elastic scattering. The cross section is small and approximately isotropic. Sawicki[41] has calculated the differential cross section for this reaction assuming the "$\alpha+d$" model for Li^6 and a pickup mechanism. Zeidman and Monahan[40] have rederived the cross section using Sawicki's approach and find approximate agreement with the 21.6-Mev data, both in the absolute magnitude and angular dependence of the cross section. They have also made calculations for 14.8-Mev deuterons; the calculated cross section is very anisotropic. Sawicki's reaction mechanism does not, therefore, seem to be the most important one for 14.8-Mev deuterons.

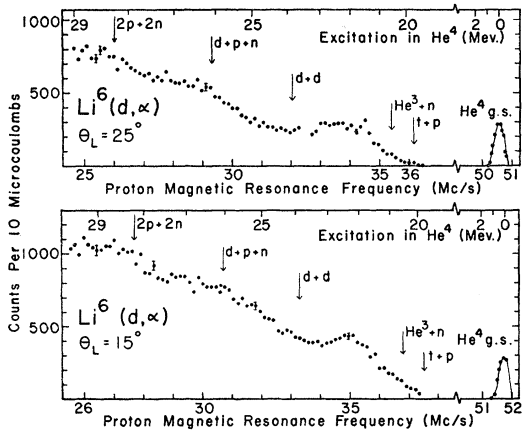

FIG. 16. Alpha-particle spectra from Li^6+d.

2. Alpha-Particle Spectra

The alpha-particle spectra at $\theta_L=15°$ and 25° are shown in Fig. 16. Typical statistical errors are shown. The ordinate in Fig. 16 is proportional to $(E/\beta)(d^2\sigma/d\omega dE)$ where E is the alpha-particle energy in the laboratory system and β is the solid angle conversion factor to the center-of-mass system. The cross section in the center-of-mass system, at $\theta_L=15°$ ($\theta_{c.m.}=24°$), at 35 Mc/sec, is $d^2\sigma/d\omega dE=10.6$ microbarns per steradian per kev (of lab energy).

The energy range corresponding to excitation in He^4, E_x, from 0 to 29 Mev was covered. No alpha particles corresponding to excitation between 0 and 19.5 Mev were observed, i.e., no bound excited states of He^4 were found, in agreement with previous work. The arrows in Fig. 16 indicate the high-energy limits of the spectra due to the various reactions which produce alpha particles:

$$\begin{aligned} Li^6+d \rightarrow \alpha+\alpha \quad & Q=+22.357 \\ \alpha+p+t \quad & Q=+2.555 \\ \alpha+He^3+n \quad & Q=+1.791 \\ \alpha+d+d \quad & Q=-1.477 \\ \alpha+d+n+p \quad & Q=-3.702 \\ \alpha+2n+2p \quad & Q=-5.927. \end{aligned}$$

The position of the arrows and the excitation energy scale in Fig. 16 are estimated to be uncertain within ±300 kev.

The spectra of Fig. 16 show changes of slope to the left of the $p+t$, $d+d$, $d+p+n$ and (perhaps) He^3+n arrows, suggesting that the corresponding reactions occur with appreciable probability. Other fragments from some of these reactions have been identified elsewhere in this report [see the sections on the reactions $Li^6(d,p)Li^7$, $Li^6(d,t)Li^5$, $Li^6(d,He^3)He^5$, $Li^6(d,d')Li^6$].

There is a broad peak in the 15° spectrum at $E_x=22$ Mev; this hump also appears, less clearly, at 25°. The difference between "peak" and "valley" (at ~34 Mc/sec) is not much larger than the statistical uncertainty and the possibility of an experimental error cannot be ruled out: it is possible, although improbable, that in reality the spectrum is constant between 35 and 33 Mc/sec. Corresponding peaks have been observed in other reactions [$H^3(p,n)He^3$,[42,43] $H^3(d,n)$,[44] $He^4(p,p')He^4$ [45]] and have been interpreted as an indication of a broad excited state in He^4 at ~22-Mev excitation.[42]

[40] J. L. Yntema (private communication). The authors are indebted to Dr. Yntema for making the Argonne results available before publication and for sending the calculations of Dr. Zeidman and Dr. Monahan.

[41] J. Sawicki, Acta Phys. Polonica **15**, 71 (1956).

[42] N. A. Vlasov *et al.*, J. Exptl. Theoret. Phys. U.S.S.R. **28**, 639 (1955) [translation: Soviet Phys. JETP **1**, 500 (1955)].

[43] H. B. Willard *et al.*, Phys. Rev. **90**, 865 (1953).

[44] G. F. Bogdanov *et al.*, Physica **22**, 1150 (1956).

[45] H. Tyrén *et al.*, Nuclear Phys. **4**, 277 (1957).

X. ACKNOWLEDGMENTS

The authors thank Dr. N. Austern, Dr. E. Baranger, Dr. J. B. French, and Dr. S. Meshkov for invaluable help in the theoretical interpretation of the data; A. I. Hamburger, S. Mayo, E. L. Keller, and C. A. Low, Jr., for help in the collection of the data; and Dr. A. J. Allen and Dr. J. N. McGruer for encouragement and advice. One of us (E.W.H.) wishes to acknowledge a travel grant from the Conselho Nacional de Pasquisas (Rio de Janeiro, Brazil).

PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

Effect of Compression on the Decay Rate of Tc^{99m} Metal*

R. A. PORTER, *Theoretical Division, The Lawrence Radiation Laboratory, University of California, Livermore, California*

AND

W. G. MCMILLAN, *Department of Chemistry, University of California, Los Angeles and the RAND Corporation, Santa Monica, California*

(Received August 28, 1959)

Motivated by Bainbridge's measurement, we have attempted a theoretical calculation of the change in lifetime of the internal conversion of Tc^{99m} in compressed Tc metal. We have employed the Thomas-Fermi statistical potential, corrected for the self-potential of the electron in question, to obtain the initial and final state electronic wave functions for two volumes: the normal uncompressed state, and ten percent compression. Because the energy available is so low ($\sim$2 kev), the only contributions to the internal conversion coefficient come from the M and higher shells, and mainly from the $3p$ and $3d$ levels. The principal contribution to the *change* in the internal conversion coefficient comes, however, from the valence electrons, particularly the $4p$, $4d$ and $5s$ levels. In order to relate compression to pressure, we have estimated the compressibility of technetium metal to be 0.27 megabar^{-1}. From this compressibility and the assumption that the internal conversion coefficient is linear in pressure, we calculate for the experimental pressure of 0.1 megabar a fractional decrease in lifetime of $(2 \text{ to } 4)\times10^{-4}$, the quoted variation residing in the uncertainty of the structure of the $4p$ band. This result agrees with Bainbridge's measurement, $(2.3\pm0.5)\times10^{-4}$, within the accuracy of our calculation.

I. INTRODUCTION

THE decay rate of the 2-kev electric octupole isomeric transition of Tc^{99m} is known to be measurably dependent upon the external environment. Differences in the lifetime have been observed for different chemical compounds,[1] for the metal under high static pressure,[2] and for the superconducting state.[3] Of these environmental effects, that due to compression of the metal is most amenable to a theoretical treatment. In the present work we attempt a calculation of this effect on the basis of a simple metallic model. Although technetium is far from being a simple metal it appears possible to incorporate the most essential features without excessive complication. The use of a consistent treatment of initial and final wave functions for different atomic volumes makes the fractional change in lifetime, to be compared with experiment, considerably more reliable than any single element of the calculation.

II. THEORY OF THE DECAY RATE OF Tc^{99m}

Because of the very low transition energy and the large change in angular momentum involved, the decay of Tc^{99m} occurs almost entirely by internal conversion. The decay rate is therefore proportional to the internal conversion coefficient α, which is given by the relation[4]

$$\alpha=(2\pi^3W)\mathfrak{S}|(f|\mathfrak{H}|i)|^2, \tag{1}$$

where W is the transition energy, $\mathfrak{H}$ the interaction Hamiltonian, i and f are the initial and final electronic wave functions, and $\mathfrak{S}$ indicates summation over all directions of emission and all substates of the initial (bound) and final (continuum) states. The present calculation will be nonrelativistic, since only valence and near-valence electrons are involved. We shall treat the metallic problem as spherically symmetric, and thus ignore effects of the lattice structure except for the periodicity of the Bloch waves. The interaction Hamiltonian is therefore

$$\mathfrak{H}=ie\mathbf{B}_L{}^M\cdot\nabla+(ie/2)\nabla\cdot\mathbf{B}_L{}^M+e\Phi_L{}^M, \tag{2}$$

* Based on a thesis submitted by R. A. Porter in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Department of Chemistry, University of California, Los Angeles.

[1] Bainbridge, Goldhaber, and Wilson, Phys. Rev. **84**, 1260 (1951); **90**, 430 (1953).

[2] K. T. Bainbridge (private communication). We are much indebted to Professor Bainbridge for permission to quote this result prior to publication. Previous mention of his work has also been made by Chem. Eng. News **30**, 654 (1952) and by R. Daudel, J. phys. radium **13**, 562 (1952).

[3] D. H. Byers and R. Stump, Phys. Rev. **112**, 77 (1958).

[4] In this section we employ the notation and units of M. E. Rose, *Multipole Fields* (John Wiley and Sons, New York, 1955).