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$^{12}C(^{6}Li, d)^{16}O$ AT $E(Li) = 90$ MeV

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Abstract: The $^{12}C(^{6}Li, d)^{16}O$ reaction has been studied at $E(^{6}Li) = 90.2$ MeV with a magnetic spectrometer. Spectra up to $E_x \approx 30$ MeV in ^{16}O have been obtained and decay line widths, $\Gamma_{c.m.}$, have been extracted for broad levels. Known α-cluster states ($J^{\pi} = 2^{+}$, $E_x = 6.9$ MeV; $J^{\pi} = 4^{+}$, $E_x = 10.35$ MeV) are preferentially populated and exhibit sharply forward peaked angular distributions in contrast with (^{6}Li, d) data obtained at lower bombarding energies. These features are well reproduced by reaction calculations assuming direct alpha-particle transfer provided one utilizes realistic optical model, target, and projectile wave functions. Alpha spectroscopic factors and reduced alpha widths have been extracted for levels $E_x < 12$ MeV including $J^{\pi} = 1^{-}$ levels of astrophysical interest. The results are compared with other recent measurements and theoretical calculations. There is generally at least qualitative agreement (within × 2) between the various experiments and theories. The analysis indicates a non-negligible alpha width for the $J^{\pi} = 1^{-}$ level at $E_x = 7.1$ MeV in ^{16}O (which determines the $^{12}C \rightarrow {}^{16}O$ stellar helium burning rate) with $0.3 < \theta_{\alpha}^2$ (7.1 MeV)/θ_{α}^2 (9.6 MeV) < 0.6 and $0.1 < \theta_{\alpha}^2$ (7.1 MeV)/θ_{α}^2 (6.9 MeV) < 0.4.

E | NUCLEAR REACTION $^{12}C(^{6}Li, d)$, $E = 90.2$ MeV; measured $\sigma(E_d, \theta_d)$. ^{16}O deduced α-cluster states, α-reduced widths, S_{α}, resonances, Γ. Optical model, direct α-transfer mechanism, realistic target, projectile wave functions. Magnetic spectrometer.

1. Introduction

The determination of α-widths and α-spectroscopic factors for $^{16}O \rightarrow {}^{12}C + \alpha$ is of much interest in nuclear astrophysics [1–6]) as well as nuclear structure theory [7–10]). The conversion of carbon to oxygen takes place in stars via the helium burning reaction $^{12}C(\alpha, \gamma)^{16}O$. Extrapolation of this reaction rate to very low α-particle energies depends on the reduced α-width, γ_{α}^2, of the sub-threshold $J^{\pi} = 1^{-}$ level at $E_x = 7.112$ MeV in ^{16}O. Most nucleo-synthesis calculations [1–6]) fit the existing high-energy $^{12}C(\alpha, \gamma)^{16}O$ data by treating $\gamma_{\alpha}^2(7.1)$ as a free parameter. The $\gamma_{\alpha}^2(7.1)$ values deduced [2,6]) are often rather small, e.g. much smaller than the single-particle (Wigner) limit, γ_{W}^2. Typically $\theta_{\alpha}^2 \equiv \gamma_{\alpha}^2/\gamma_{W}^2 \ll 0.1$ has been inferred for this level whereas the nearby known α-cluster levels in ^{16}O($J^{\pi} = 2^{+}$ and 4^{+}) have $\theta_{\alpha}^{2} \approx 1$.

In principle $\gamma_{\alpha}^{2}(7.1)$ or at least $\theta_{\alpha}^{2}(7.1)$ can be determined from a direct α-stripping reaction such as (^{6}Li, d) or (^{7}Li, t). While the latter appears [11,12] to be a relatively direct reaction, at least for $E(^{7}\text{Li}) \gtrsim 30$ MeV, the former is complicated by non-direct reaction components even at relatively high bombarding energies *viz.* $E(^{6}\text{Li}) \approx 30$ MeV [refs. [13,14]]. Recent studies [11,12] of ^{12}C(^{7}Li, t)^{16}O at $E(^{7}\text{Li}) = 38$ and 34 MeV and ^{12}C(^{6}Li, d)^{16}O at $E(^{6}\text{Li}) = 42$ MeV [ref. [15]] indicate $\theta_{\alpha}^{2}(7.1) \approx 0.1$ to 0.4, which could have important implications for the astrophysical models used to extrapolate the (α, γ) reaction rate.

In this experiment we have extended the study of ^{12}C(^{6}Li, d)^{16}O to $E(^{6}\text{Li}) \approx 90$ MeV. The data include both low-excitation ($E_x \lesssim 12$ MeV) and high-excitation ($E_x > 12$ MeV) regions in ^{16}O. These regions are of interest in view of recent α-cluster model [8,10] calculations for ^{16}O. In addition, data from angular correlation measurements [16,17] indicate the presence of several high-spin ($J^{\pi} = 6^{+}, 7^{-}, 9^{-}, 8^{+}$) members at $E_x \gtrsim 20$ MeV of the well known α-cluster rotational levels in ^{16}O.

The elastic scattering of ^{6}Li+^{12}C (and other nuclei) were measured in a separate experiment at $E(^{6}\text{Li}) = 99$ MeV and will be reported in detail elsewhere. A preliminary analysis of these data appears in ref. [18] and will be utilized here.

2. Experiment

The data were obtained at the Indiana University Cyclotron Facility (IUCF) with a 90.2±0.2 MeV $^{6}\text{Li}^{3+}$ beam. The targets consisted of natural carbon foils (98.9 % ^{12}C, 1.1 % ^{13}C) with $\rho x = 390 \pm 40\ \mu\text{g/cm}^{2}$. Beam centering was monitored with left-right solid-state monitor detectors, which also served to check the beam current integrator. The reaction products were detected and identified with a QDDM magnetic spectrometer [19] utilizing a helical-cathode proportional counter [20] backed by a pair of plastic scintillators. The energy resolution was 80 to 120 keV (FWHM). The spectrometer aperture was $d\Omega = 2.31$ msr ($\Delta\theta = \pm 1.3°$) for the angular distribution measurements, and $d\Omega = 3.34$ msr ($\Delta\theta = \pm 1.3°$) for the $\theta_{\text{lab}} = 5°$ spectrum. Measurements at $\theta_{\text{lab}} = 0°$ were obtained by employing an internal beam stop inside the spectrometer and using calibrated monitor detectors for beam integration.

The known levels in ^{16}O, $E_x < 12$ MeV, were used to calibrate the spectrometer-detector system and provide excitation energies ($E_x > 12$ MeV) accurate to $\lesssim \pm 100$ keV. This was sufficient to identify most of the groups observed in the deuteron spectra.

The estimated uncertainties in relative cross sections are ±10 %, and ±20 % for absolute cross sections.

3. Data

3.1. SPECTRA

Spectra obtained at $\theta_{lab} = 5°$ are shown in figs. 1 and 2. Deuteron groups which could be identified with known levels, $E_x < 21$ MeV, are labeled by their accepted E_x and J^π values [21].

In addition broad structures above background are observed at $E_x \approx 20.7$, 21.6, 23.8 and 26.9 MeV. An expanded portion of this region is displayed in fig. 3, along with computer-generated lorentzian peak shape fits to the observed structures [22]. Values of $\Gamma_{c.m.}$ for these fits are displayed in table 1. Structures at $E_x \approx 21.6$ MeV and 23.8 MeV have also been observed [15] in (^{6}Li, d) at $E(^6\text{Li}) = 42$ MeV and appear in (^{7}Li, t) measurements [11] at $E(^7\text{Li}) = 38$ MeV.

A striking feature of the spectrum displayed in fig. 1 is the preferential population of known α-cluster levels in ^{16}O including the $J^\pi = 0^+$ and 3^- levels at $E_x \approx 6.1$ MeV. Although these levels are not completely resolved, relative intensities could be inferred using the known excitation energies and employing a computer peak-fitting program [22].

The $J^\pi = 1^-$ level at 7.1 MeV is populated with an intensity about 50 % of that of the broad $J^\pi = 1^-$ level at $E_x = 9.6$ MeV and greater than that of the non-α-cluster levels (2^-, $E_x = 8.87$ MeV and 2^+, $E_x = 9.85$ MeV). The cross sections for such non-α-cluster levels, including the unresolved $J^\pi = 3^+ + 4^+$ doublet at

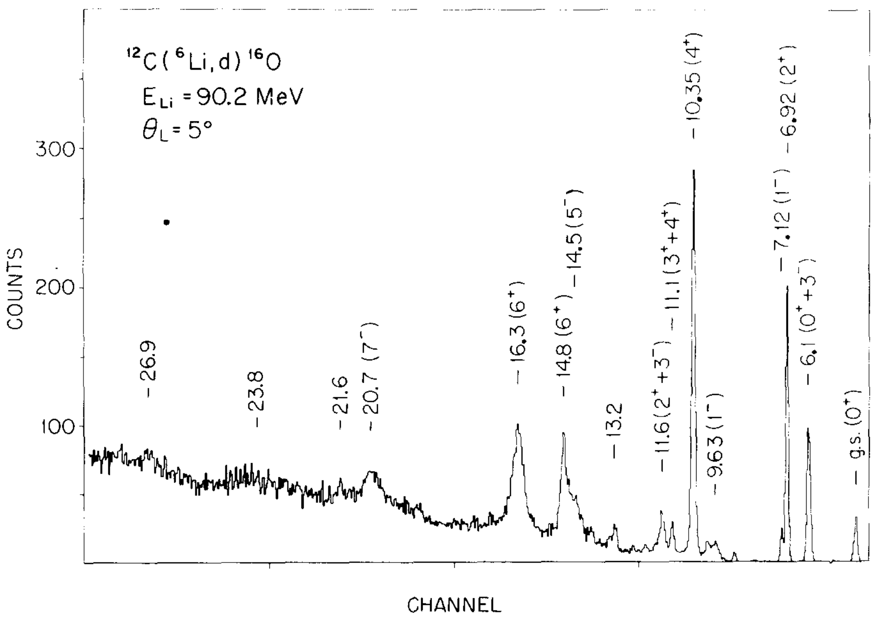

Fig. 1. Spectrum obtained at 5°. Known levels are indicated by E_x (MeV) and J^π values while other groups are indicated by E_x values only. The spectrum is a composite of several overlapping spectra.

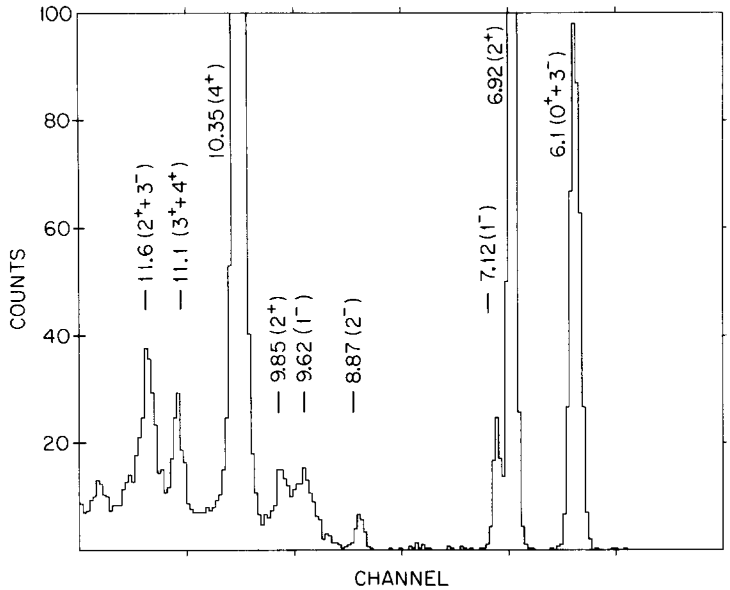

Fig. 2. An expanded portion of fig. 1 in the region of the $J^\pi = 1^-$ levels of astrophysical interest.

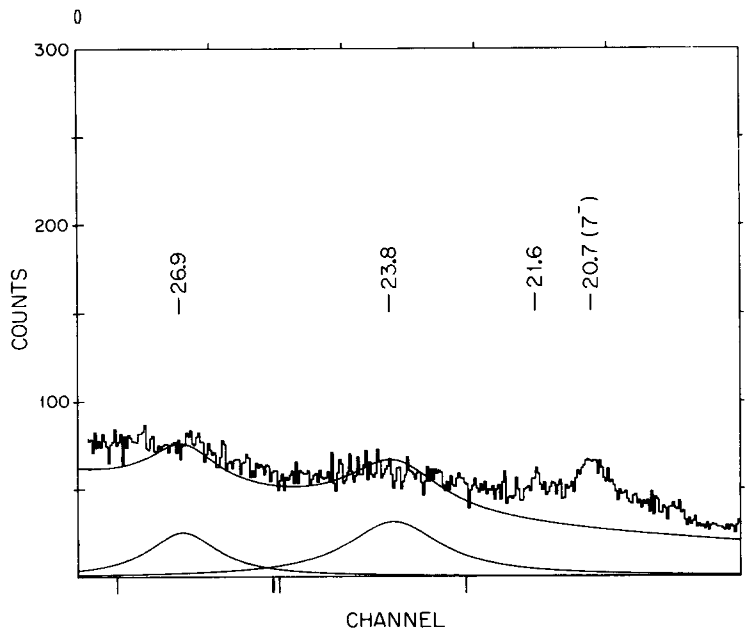

Fig. 3. A portion of the spectrum for $\theta_l = 5°$ (fig. 1) at large excitation energy. The curves and E_x values are the result of computer fits to the data between the cursor markers indicated under each lorentzian line fit.

TABLE 1

Levels in ^{16}O

E_x [a]) (MeV)	J^{π} [a])	$\Gamma_{c.m.}$ (keV) this work [a])	$\Gamma_{c.m.}$ (keV) 42 MeV [b])	$\Gamma_{c.m.}$ (keV) accepted [c])	σ_{exp} [d]) (μb)	σ_{CN} [e]) (μb)	σ_{dir} [f]) (μb)
g.s.	0^+				8.8	0.8	8.0 ± 0.9
6.049	0^+				5.4	0.8	4.6 ± 0.5
6.130	3^-				54.2	5.9	48.3 ± 5.4
6.917	2^+				66.7	4.2	62.5 ± 6.7
7.117	1^-				6.9	2.5	4.4 ± 0.7
8.872	2^-		<20		4.2	4.2	$\equiv 0$
9.63	1^-	330 ± 30	400 ± 50	510 ± 60	16.6	2.5	14.1 ± 1.7
9.847	2^+		< 30	0.9 ± 0.3	5.9	4.2	1.6 ± 0.6
10.353	4^+		34 ± 5	27 ± 4	147.1	7.6	139.6 ± 14.7
10.952	0^-						
11.080	3^+			<12	} $\lesssim 20$	14	$\lesssim 6$
11.095	4^+		< 30	0.28 ± 0.05	}		
11.26	0^+						
11.521	4^+						
11.60	3^-	620 ± 100	770 ± 90	800 ± 10			
13.02	2^+			150 ± 11			
13.09	1^-	≈ 230		130 ± 5			
13.13	3^-			130 ± 30			
14.67	5^-	450 ± 75	520 ± 50	560 ± 75			
14.815	(6^+)	< 90	45 ± 10	67 ± 8			
16.29	(6^+)	320 ± 65	300 ± 50	370 ± 40			
20.88	(7^-)	440 ± 70	600 ± 100	650 ± 75			
21.6 [g])		$\lesssim 100$	≈ 100				
23.0	(6^+)		≈ 200	$\lesssim 500$			
23.8 [g])	(6^+)	1980 ± 250	≈ 1300				
26.9 [g])		1700 ± 250					

[a]) Excitation energies and J^{π} values are from the compilation of ref. [21]), unless noted otherwise. Uncertain J^{π} values are given in parentheses. The Γ values listed are the FWHM of the fitted lorentzian line shape and do not include α-penetrabilities [see ref. [24])].

[b]) Ref. [15]). [c]) Ref. [21]).

[d]) Integrated cross section, $\theta_{c.m.} = 0°$ to $50°$. Absolute uncertainties $\pm 20\,\%$; relative uncertainty, $\pm 10\,\%$.

[e]) Estimated non-direct cross section, assumed to arise from compound-nuclear reactions, normalized to σ for the 8.872 (2^-) level.

[f]) Direct α-transfer cross section where $\sigma_{dir} \equiv \sigma_{exp} - \sigma_{CN}$.

[g]) This work: Estimated error in E_x is ± 100 keV.

$E_x \approx 11.1$ MeV, scale approximately as $2J+1$, as expected for a statistical, non-direct process such as a compound-nuclear reaction. They are also weakly populated, in contrast to the situation at lower bombarding energies [23]).

The data at $\theta_{lab} = 5°$ and other angles, were analyzed with a least-squares multi-peak-fitting computer program employing both gaussian and lorentzian peak shapes and various background curves [22]). The observed line-widths, $\Gamma_{c.m.}$, for α-unbound levels are given in table 1.

They are discussed further in a separate paper investigating the reaction-dependence of nuclear decay widths [24]). The value of $\Gamma_{c.m.}$ (1^-, E_x = 9.6 MeV) = 330±30 keV obtained here confirms the value [15]) obtained at $E(^6Li)$ = 42 MeV, which is less than the presently accepted [21]) value (510 keV). The other $\Gamma_{c.m.}$ values agree within quoted uncertainties with accepted values and those obtained at $E(^6Li)$ = 42 MeV. [Note that the $\Gamma_{c.m.}$ quoted in table 1 do not include corrections for α-penetrabilities or other effects; see ref. [24]) for more details.]

The broad structures observed in this experiment at $E_x \approx 21.6$ and 23.8 appear to correspond to groups also observed [11]) in (^{7}Li, t) and other [14, 16]) (^{6}Li, d) experiments. Angular correlation measurements [16]) suggest $J^\pi = 6^+$ for these groups.

A recent study [17]) of (^{12}C, ^{8}Be) suggests $J^\pi = 8^+$ for a group observed at $E_x = 22.5 \pm 0.5$ MeV, which is close in excitation energy for the predicted 8^+ α-cluster band member. This group is absent or weak in $^{12}C(^6Li, d)^{16}O$ even at $E(^6Li)$ = 90 MeV whereas the $J^\pi = 7^-$ α-cluster level at E_x = 20.7 MeV is still prominent (fig. 1). The former does not appear in (^{6}Li, dα) angular correlation data [16]).

The broad group observed here at $E_x \approx 27$ MeV may correspond to the $J^\pi = 7^-$ level (E_x = 27.7 MeV) assigned by the (^{6}Li, dα) angular correlation work of Artemov *et al.* [16]).

3.2. ANGULAR DISTRIBUTIONS

Angular distributions, including $\theta_{lab} = 0°$, for most levels $E_x < 11$ MeV are displayed in fig. 4. The curves are finite-range distorted-wave calculations (FRDW) and will be discussed in subsect. 4.1.

The experimental angular distributions for known α-cluster levels (g.s., 6.92 MeV and 10.35 MeV) are sharply forward-peaked but otherwise exhibit little angular structure. The unnatural parity $J^\pi = 2^-$ level (E_x = 8.87 MeV) and the non-α-cluster 2^+ level (E_x = 9.85 MeV) should not be populated by a direct α-transfer and indeed the angular distributions for these levels are much less forward-peaked than those for other levels.

Based upon data obtained at lower bombarding energies [13–15]), we assume the formation of the $J^\pi = 2^-$ level proceeds dominately via a compound nuclear (CN) reaction. With this assumption and assuming $\sigma_{CN} \propto 2J+1$ as indicated by Hauser-Feshbach calculations [15]), one can obtain estimates of σ_{CN} for the other levels. These estimates are sufficient to account for most or all of the observed cross sections for the $J^\pi = 2^+$ (9.85 MeV) and $J^\pi = 3^+ + 4^+$ (11.1 MeV) groups while the forward angle $J^\pi = 1^-$ (7.12 MeV) cross section is much larger (×4) than the CN estimate.

Integrated experimental cross sections, denoted σ_{exp}, and the corresponding CN estimates, σ_{CN}, are given in table 1. We also define the direct α-transfer cross sections as $\sigma_{dir} = \sigma_{exp} - \sigma_{CN}$. This neglects possible coherent interference between various reaction mechanisms.

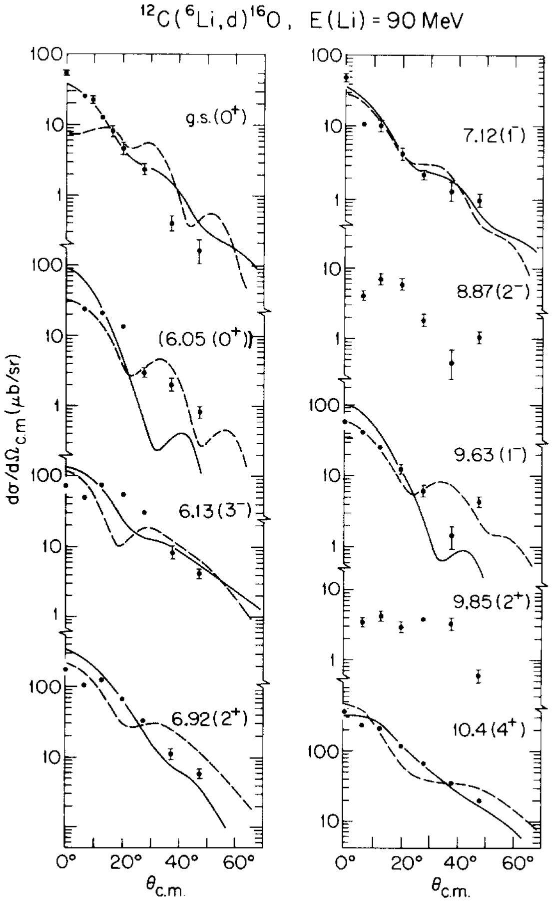

Fig. 4. Experimental and calculated (FRDW) angular distributions. The solid curves employ parameters IUI, WSC, OI and H and the broken curves, UM, WSC, OI and H.

4. Analysis

4.1. ANGULAR DISTRIBUTIONS

Finite-range distorted-wave calculations have been performed in the post representation with a k-space expansion program [25]. The FRDW parameter sets employed are listed in table 2. The ^{6}Li = α+d, bound state parameter set WSC is an $(N, L) = (0, 0)$ wave function consisting of an attractive Woods-Saxon central potential and a repulsive soft core ($R = 1.25$ fm). This is based upon a ^{6}Li wave function determined by Watson *et al.* [26]) in fitting α+d elastic scattering and α-knockout reactions from ^{6}Li. It simulates a properly antisymmetrized $(N, L) = (1, 0)$ wave function. The potentials K1 and K2 which correspond to $(N, L) = (1, 0)$ and

TABLE 2

FRDW bound-state and optical-model parameter sets

System	Set	Parameter values [a]	Ref. [b]
$^{6}Li = \alpha + d$ (bound state)	WSC	$(N, L) = 0, 0$, $V = -26.0$, $R = 1.95$, $a = 0.70$, $R_C = 1.90$, plus soft-core repulsion (see text): $V = +26.0$, $R = 1.25$, $a = 0.0$	[26]
	K1	$(N, L) = (1, 0)$, $V = -77.8$, $R = 1.90$, $A = 0.65$, $R_C = 1.90$	[27]
	K2	Same as K1 but $(N, L) = (0, 0)$ and $V = 20.1$	[27]
$^{16}O = \alpha + ^{12}C$	O1	(N, L) – see table 3 $R = 2.98$, $a = 0.73$, V adjusted to fit α-separation energy, or 0.4 MeV if unbound (see text).	[15]
$^{6}Li + ^{12}C$	UM	$V = -214.0$, $R_R = 2.98$, $a_R = 0.70$, $R_C = 2.98$, $W = -40.0$, $R_I = 3.89$, $a_I = 0.90$	[15]
	IU1	$V = -94.0$, $R_R = 2.98$, $a_R = 0.81$, $R_C = 2.98$, $W = -40.5$, $R_I = 2.89$, $a_I = 1.16$	[30]
	IU2	$V = -160.0$, $R_R = 2.98$, $a_R = 0.84$, $R_C = 2.98$, $W = -35$, $R_I = 3.48$, $a_I = 1.01$	[31]
	IU3	$V = -255$, $R_R = 2.15$, $a_R = 0.81$, $R_C = 2.15$, $W = -56.2$, $R_I = 2.45$, $a_I = 1.16$	[32]
	IU4	$V = -94$, $R_R = 2.98$, $a_R = 0.81$, $R_C = 2.98$, $W_D = 35$, [c] $R_I = 1.17$, $a_I = 1.23$	[32]
$d + ^{16}O$ (optical potential)	N	$V = -92.0$, $R_R = 2.62$, $a_R = 0.78$, $R_C = 3.27$, $W_D = 8.9$, [c] $R_I = 3.43$, $a_I = 0.73$	[33]

[a]) The potentials listed correspond to standard Wood-Saxon forms. Potentials (V, W, W_D) are in MeV, radii and diffuseness parameters (R_R, R_I, R_C, a_R, a_I) are in fermis.

[b]) The potentials are based upon similar parameters obtained in the references listed but in some cases (WSC, IU1, IU2, UM) certain parameters have been modified (see text).

[c]) Surface-derivative form.

(0, 0) respectively are based upon those suggested by Kubo and Hirata [27]). We have adopted the set WSC as our preferred $\alpha + d$ potential as it yields a ^{6}Li wave function which reproduces a wide range of physical data.

The $^{16}O = \alpha + ^{12}C$ bound-state potential is that used in our previous analysis [15]) at $E(^{6}Li) = 42$ MeV. It satisfactorily reproduces the correct r.m.s. radius of the relative $\alpha + ^{12}C$ motion one infers from the measured charge radii of ^{4}He, ^{12}C and ^{16}O. This procedure is discussed elsewhere [28]).

Levels above $E_x = 7.2$ MeV in ^{16}O are α-unbound. We have employed an α-binding energy of a few hundred keV for these levels as most are quasi-bound (narrow). The exception is the broad $J^{\pi} = 1^{-}$ level ($E_x = 9.6$ MeV). Here we have extrapolated the FRDW cross sections versus α-binding energy and applied [15] an appropriate correction factor (× 1.3).

The $^{6}Li + ^{12}C$ optical parameter set UM is based upon potentials determined [29] at $E(^{6}Li)$ = 50.6 MeV, with W adjusted slightly (increased) to fit measured 99 MeV ^{6}Li elastic data. Set IU1 is a "best-fit" potential determined [30] in an analysis of a set of elastic data at $E(^{6}Li)$ = 99 MeV while IU2 is an extrapolation of a set determined [31] by fitting $^{6}Li + ^{28}Si$ data at $E(^{6}Li)$ = 154 MeV, again with W adjusted slightly (decreased) to fit $^{6}Li + ^{12}C$ at $E(^{6}Li)$ = 99 MeV. The latter potential is thought to be more uniquely determined than those obtained at lower ^{6}Li bombarding energies. Potentials IU3 and IU4 are alternate sets determined [32] by fitting the data used to establish set IU1. Sets UM, IU1, IU2, IU3 have volume absorption while set IU4 has surface absorption although with a much reduced radius.

The $d + ^{16}O$ potential is that determined by Newman *et al.* [33]. It is similar to the global set established by Childs and Daehnick [34], except we do not include the spin-orbit coupling as a computer economy measure. It is found that the choice of the deuteron optical potential is not overly crucial, nor is the inclusion of spin-orbit coupling [28].

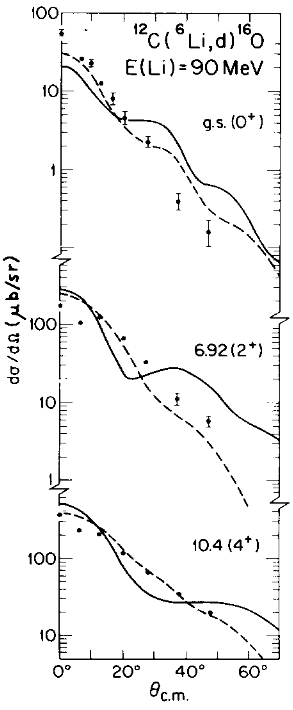

Fig. 5. Experimental and calculated (FRDW) angular distributions. The solid curves employ parameters IU2, WSC, OI and N and the broken curves, IU4, WSC, OI and N.

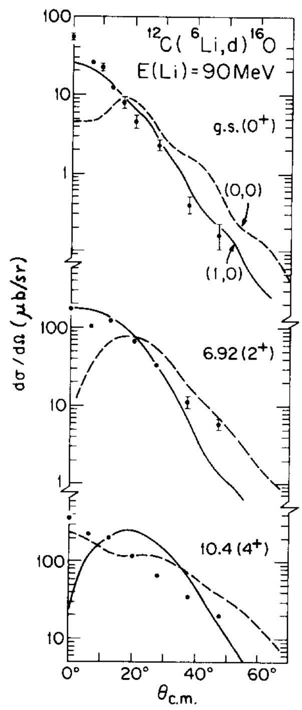

Fig. 6. Same as fig. 5 except ^{6}Li wave functions K1 (N, L = 1, 0; solid curves) and K2 (N, L = 0, 0; broken curves) are used.

Calculations with our adopted parameter sets (WSC, O1, IU1, and N) are shown in fig. 4 (solid curves). Except for the $J^{\pi} = 0^{+}$ (6.05 MeV) and the $J^{\pi} = 1^{-}$ (9.6 MeV) data, which however are computer-unfolded from other data and hence less reliable, the calculations reproduce the observed angular distributions, especially the 0^{+} (g.s.) and 1^{-} (7.12 MeV) levels. Calculations employing the ^{6}Li optical model set UM (broken curves) are not as satisfactory as are those for IU1. Calculations with sets IU2 and IU4 are displayed in fig. 5. The angular distributions for set IU4 are not significantly different than those displayed in fig. 4 for set IU1 while those for set IU2 are less satisfactory. We find that the IU global parameter sets determined by fitting a range of ^{6}Li elastic data at E(Li) = 99 MeV give much better fits to our data than other, extrapolated, parameter sets such as UM and IU2.

Calculations utilizing different α+d wave functions (sets K1 and K2 with IU1, O1, and N) are shown in fig. 6. Neither set K1[$(N, L) = (1, 0)$] nor set K2 [$(N, L) = (0, 0)$] yields satisfactory results. The (^{6}Li, d) data at $E(^{6}\text{Li}) = 90$ MeV appears to be a surprisingly sensitive probe of the relative α+d wave function in ^{6}Li and the wave function given by the parameter set WSC appears to be preferable [28]).

The sensitivity of (^{6}Li, d) and (d, ^{6}Li) to various other FRDW parameters has been discussed in more detail elsewhere [15, 28, 35]) and appears to be similar in the present analysis.

4.2. SPECTROSCOPIC INFORMATION

Alpha spectroscopic factors, S_{α}, for $^{16}\text{O} \rightarrow \alpha + {}^{12}\text{C}$ have been determined via the relation

$$\frac{d\sigma^{\text{exp}}}{d\Omega} = S'_{\alpha} S_{\alpha} (2J+1) \frac{d\sigma^{\text{FRDW}}}{d\Omega}, \qquad (1)$$

where S'_{α} is the $^{6}\text{Li} \rightarrow \alpha + \text{d}$ spectroscopic factor (here taken as unity) and J is the spin of the final state. A single l-transfer (= J) is allowed for an s-state ^{6}Li projectile and a $J^{\pi} = 0^{+}$ target. In this case one has $\Delta\pi = (-1)^{l}$ only.

Values of S_{α} determined for our adopted FRDW parameter sets are given in table 3. These are based on the fits shown in fig. 1. As noted in other analyses [15, 28, 36]), the absolute S_{α} values are very model-dependent and vary by $\times 10$ or more between various parameter sets and/or assumed (N, L) values. The relative S_{α} values are less model dependent and these indicate $S_{\alpha}/S_{\alpha}(4^{+}, 10.35\text{ MeV}) \approx 1$ for the known α-cluster levels in ^{16}O, except for the 0^{+} g.s. The latter, as at $E(^{6}\text{Li}) = 42$ MeV, indicates $S_{\alpha}/S_{\alpha}(4^{+}) > 1$ if one assumes $(N, L) = (2, 0)$. This is reduced to $S_{\alpha}/S_{\alpha}(4^{+}) \approx 1$ if one has $(N, L) = (4, 0)$. Extended cluster-model calculations [10]) generally indicate more radial nodes (N) than the leading SU(3) or shell-model terms would indicate. A comparison of the observed relative S_{α} values with recent cluster-model calculations is displayed in fig. 7a. The agreement is at least qualitatively

TABLE 3

Alpha spectroscopic factors and reduced widths for levels in ^{16}O

J^{π} [a]	E_x (MeV)	(N, L) [b]	$S_\alpha/S_\alpha(4^+)$ [c]	$\theta_\alpha^2/\theta_\alpha^2(4^+)$ [d]	$\theta_\alpha^2/\theta_\alpha^2(2^+)$ [e]
0^+	g.s.	(2, 0)	1.96	0.39	0.18
		(4, 0)	(0.5)	(0.50)	(0.24)
0^+	6.0	(4, 0)	0.92	2.33	1.10
3^-	6.1	(1, 3)	0.94	0.46	0.22
2^+	6.9	(3, 2)	1.06	2.12	1.00
1^-	7.1	(2, 1)	0.67	0.83	0.39
		(4, 1)	(0.25)	(0.63)	(0.30)
1^-	9.6	(4, 1)	0.61 [f]	1.28	0.60
2^+	9.8	(2, 2)	$\lesssim 0.01$	$\lesssim 0.02$	$\lesssim 0.01$
4^+	10.3	(2, 4)	1.00	1.00	0.47
4^+	11.1	(2, 4)	$\lesssim 0.05$	$\lesssim 0.05$	$\lesssim 0.03$

[a]) Spin, parity and excitation energies are from ref. [21]).

[b]) The quantities N and L are the radial nodes and orbital angular momentum assigned to the c.m. motion of the α-cluster in ^{16}O. The first set of N- and L-values listed correspond to the dominant SU(3) components. Alternate N- and L-values used to determine S_α are shown in parentheses.

[c]) S_α relative to that of the 10.35 MeV (4^+) level. The first values shown correspond to parameter sets IU1, WSC, O1 and N of table 2 and correspond to an absolute value of $S_\alpha(4^+) = 3.9$.

[d]) Ratios of reduced α-widths at $s = 5.4$ fm relative to that of the 10.35 MeV (4^+) level. The FRDW $S_\alpha(4^+)$ corresponds to an absolute value of $\theta_\alpha^2(4^+) = 0.76$.

[e]) Ratios of reduced α-widths relative to that of the 6.9 MeV (2^+) level. The FRDW $S_\alpha(2^+)$ corresponds to an absolute value of 1.61 for $\theta_\alpha^2(2^+)$.

[f]) Includes a correction factor (× 1.3) for extrapolation to positive energy (see text).

good and comparable with that observed with (^{7}Li, t). As noted below comparisons of α-widths are much more meaningful.

The values of relative S_α given in table 3 for our preferred parameter sets are in fair agreement with those determined [15]) at $E(^6Li) = 42$ MeV, and with values determined from (^{7}Li, t) measurements [12]). We note the large relative S_α value observed for the 7.12 MeV, $J^\pi = 1^-$ level of astrophysical interest.

A comparison of relative S_α values for alternate ^{6}Li optical-model parameter sets (IU3 and IU4) is displayed in fig. 7b. Set IU3 gives results similar to those with set IU1 while those for set IU4 are somewhat different. We also display S_α values obtained from a reanalysis of the (^{6}Li, d) data at $E(^6Li) = 42$ MeV employing our preferred parameter sets (IU1, WSC, O1 and N). Results from (^{7}Li, t) at $E(^7Li) = 34$ MeV are included for comparison [12]). There appears to be a bombarding energy effect in the S_α values extracted which is likely due to the poor momentum-matching conditions ($|l_i - l_f| \approx 10$ to $20\hbar$) for reactions involving both light and heavy ions. This mostly affects comparisons between levels which differ greatly in both excitation energy and J^π values.

The absolute values of S_α vary × 20 between different FRDW calculations (fig. 7b) although the relative S_α values exhibit less variation (within × 2 or less for most levels). One must consider S_α as a very model-dependent quantity, therefore,

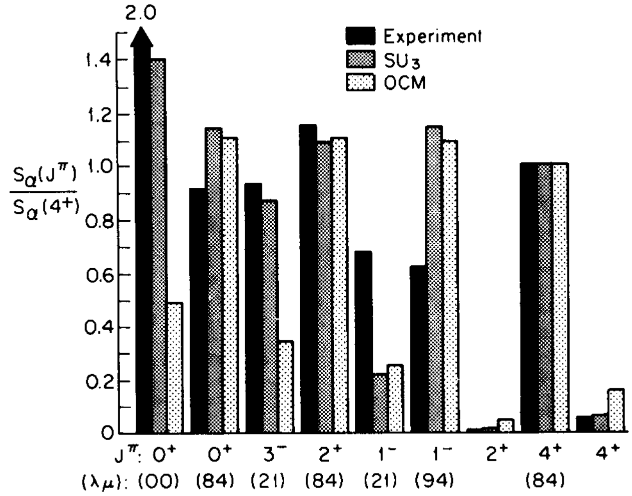

Fig. 7a (top). S_α values relative to those of the $J^\pi = 4^+$ (10.35 MeV) level, deduced from FRDW (1U1, WSC, O1 and N) compared with the SU(3) [ref. [8]] and OCM [ref. [10]] theoretical models. The absolute $S_\alpha(4^+)$ for FRDW is 3.9 and for SU(3) and OCM, 0.2 and 0.6 respectively.

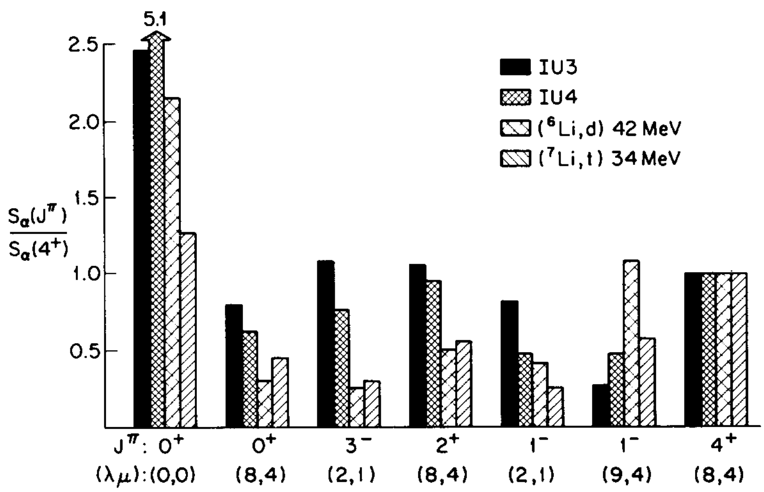

Fig. 7b (bottom). Relative S_α values inferred from the present expetiment using FRDW employing different ^{6}Li optical-model parameters (IU3 and IU4) compared with those obtained from (^{7}Li, t), ref. [12]), and a reanalysis (see text) of (^{6}Li, d) at $E(^6\text{Li}) = 42$ MeV.

especially if the appropriate ^{6}Li elastic scattering is not available. Also the absolute FRDW cross sections depend directly on the interaction $V_{d\alpha}$ which for an $(N, L) = (0, 0)$ ^{6}Li wave function, such as WSC, may be artifically small [28]) compared with the true effective interaction (see table 2).

As noted in previous analyses [15, 28, 36]) of α-transfer, the least model-dependent quantities determined with a (^{6}Li, d) or (d, ^{6}Li) experiment are the α-widths defined by

$$\gamma_\alpha^2(s) = \frac{\hbar^2 s}{2\mu_\alpha} |R_L(s)|^2, \quad (2)$$

where s is the channel radius (chosen close to the reaction radius), μ_α is the reduced mass, and $R_L(s) = \sqrt{S_\alpha} R_L^{\mathrm{DW}}(s)$ is the product of $\sqrt{S_\alpha}$ and the radial part of the FRDW $\alpha + {}^{12}$C model wave function, $R_L^{\mathrm{DW}}(s)$, used to describe ^{16}O.

The reduced α-width is then given by

$$\theta_\alpha^2(s) \equiv \gamma_\alpha^2(s)/\gamma_{\mathrm{w}}^2(s), \quad (3)$$

where

$$\gamma_{\mathrm{w}}^2(s) \equiv 3\hbar^2/2\mu_\alpha s^2 \quad (4)$$

is the Wigner limit. Also $\gamma_\alpha^2(s)$ is related to the α-decay width, for unbound levels,

$$\Gamma^\alpha_{\mathrm{c.m.}} = 2\gamma_\alpha^2(s) P_L^\alpha(s), \quad (5)$$

where $P_L^\alpha(s)$ is the $\alpha + {}^{12}$C penetrability.

Fortunately $\gamma_\alpha^2(s)$ [or $\theta_\alpha^2(s)$] are the quantities relevant to astrophysical calculations and extended cluster models since they represent a measure of the α-clustering probability at the nuclear surface. Again, however, relative values of $\gamma_\alpha^2(s)$ and $\theta_\alpha^2(s)$ are best determined, although in principle one can use the experimental $\Gamma^\alpha_{\mathrm{c.m.}}$ values as an absolute normalization of the FRDW calculations [28,36]).

Values of the α-widths deduced from FRDW for levels in ^{16}O are given in table 3. Only in special circumstances is $\theta_\alpha^2(s) \propto S_\alpha$. The FRDW analysis indicates

$$R_1 \equiv \theta_\alpha^2(7.1\ \mathrm{MeV})/\theta_\alpha^2(9.6\ \mathrm{MeV}) = 0.7 \pm 0.2,$$

$$R_2 \equiv \theta_\alpha^2(7.1\ \mathrm{MeV})/\theta_\alpha^2(6.9\ \mathrm{MeV}) = 0.4 \pm 0.2$$

for $s = 5.4$ fm. This is consistent with our previous (^{7}Li, t) and (^{6}Li, d) measurements [12,15]). As discussed [15]) in the analysis of the $E(^6\mathrm{Li}) = 42$ MeV data the ratio R_2 of $\theta_\alpha^2(7.1$ MeV) relative to the nearby 2^+ level ($E_{\mathrm{x}} = 6.92$ MeV) should be fairly reliable as it minimizes the dependence on the FRDW calculations. The ratio of $\theta_\alpha^2(7.1$ MeV) to the 4^+ level (table 3) is probably less reliable.

Alternately, one can assume $\sigma_{\mathrm{dir}} \propto (2J+1)\theta_\alpha^2(s)$ for levels close in E_{x} and J and employ the reaction cross sections (table 1). This procedure gives

$$R_1 = 0.31 \pm 0.05,$$

$$R_2 = 0.12 \pm 0.02,$$

which are less than given by the FRDW analysis. (Utilizing just forward angle data would give $R_2 \approx 0.2$.)

Both procedures thus appear to be consistent with $0.3 < R_1 < 0.6$ and $0.1 < R_2 < 0.4$. The larger value for R_1 may indicate a smaller θ_α^2(9.6 MeV) than generally assumed, which would also be consistent with the smaller Γ observed for this level [see ref. [15]) for a further discussion].

Since analysis [21]) of $\alpha + {}^{12}C$ data indicate θ_α^2(6.9 MeV) and θ_α^2(9.6 MeV) > 0.5, the above ratioes of R_1 and R_2 imply $0.05 < \theta_\alpha^2$(7.1 MeV) < 0.3. Thus analysis of the present data indicates that high-energy α-transfer reactions are not consistent with the small α-width [θ_α^2(7.1 MeV) $\ll 0.1$] deduced for the $J^\pi = 1^-$ level at $E_x = 7.1$ MeV from some astrophysical models [2]).

The values of θ_α^2 (and S_α) deduced here for the known α-cluster levels in ^{16}O (table 2) are generally much more self-consistent and in better agreement with expectations [7-10]) than those inferred from (^{6}Li, d) data [13, 14, 15]) obtained at lower energies. The 0^+ (g.s.), however, still appears to be enhanced (by $\times 2$ to $\times 5$) compared with other levels in ^{16}O. This is reminiscent of two-nucleon transfer where one observes large pairing correlations in the 0^+ g.s. of nuclei [37]). An analogous situation appears to exist for α-particle transfer.

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