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^{12}C(^{6}Li, d)^{16}O reaction in the 20–34 MeV incident energy range

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The reaction ^{12}C(^{6}Li,d)^{16}O has been studied in the 20–34 MeV incident energy range. Angular distributions have been taken at 28 MeV and 34 MeV incident ^{6}Li energies; the data have been analyzed in terms of Hauser-Feshbach and exact finite range distorted-wave Born-approximation theories. The extracted α spectroscopic strengths are compared with the predictions of SU(3) shell model.

[NUCLEAR REACTIONS ^{12}C(^{6}Li, d)$E = 20-34$ MeV; measured $\sigma(E,\theta)$; ^{16}O levels deduced S. HF and EFR-DWBA analysis.]

I. INTRODUCTION

The (^{6}Li, d) reaction has been the object of increasing interest in the last few years since the original work of Ogloblin,[1] who suggested that the reaction mechanism is reasonably well described as a direct α transfer to the target nucleus.

More recently a systematic investigation was performed,[2-6] on nuclei of sd and fp shells allowing the following observations: (i) The shapes of the angular distributions of the emitted deuterons are characteristic of a well defined value of the transferred angular momentum L confirming the direct character of the reaction mechanism. (ii) Exact-finite-range distorted-wave–Born-approximation (EFR)-(DWBA) calculations reproduce the shapes of angular distributions in several cases; it is remarkable that practically the same set of ^{6}Li optical model parameters is able to account for different nuclei at different incident energies. (iii) Attempts have been made to relate the deduced α-spectroscopic strengths to nuclear structure information.[6-7]

For lighter nuclei, an important compound nucleus (CN) mechanism generally contributes to the reactions[7,8]; for this reason an analysis of the data in terms of direct transfer is not straightforward.

The present work concerns the ^{12}C(^{6}Li, d)^{16}O reaction, which was investigated at an incident energy of 20 MeV by Meier-Ewert *et al.*[8] We extended the measurements to higher energies where direct effects are expected to be more important.

In particular we have measured
(a) angular distributions of deuterons emitted between 5° and 90° (c.m.) at $E_{^6\text{Li}} = 28$ MeV,
(b) angular distributions from 5° to 35° (c.m.) at $E_{^6\text{Li}} = 34$ MeV, and
(c) excitation functions from 20 to 34 MeV at $\theta_{\text{lab}} = 15°$ in steps of 1 MeV. Previous results have been published elsewhere.[9,10]

Section II of the present work concerns the experimental procedure; Sec. III is devoted to the analysis of data in terms of Hauser-Feshbach and EFR-DWBA formalisms; Sec. IV gives a comparison with the shell model SU(3) predictions of Ichimura *et al.*[11]

II. EXPERIMENTAL PROCEDURE AND RESULTS

A ^{6}Li^{+++} beam was produced by the CEN-Saclay FN tandem Van de Graaff with intensity of the order of 100 nA. As targets we used self-supporting natural C foils of thicknesses in the range from 40 to 100 μg/cm^2, selected according to the different measurements.

The excitation function and the 28 MeV angular distributions were obtained in experiments detecting the emitted deuterons by means of ΔE-E silicon counter telescopes ($\Delta E = 80-120$ μm, $E = 5000$ μm). The 34 MeV data were obtained using a ΔE_1-ΔE_2-E silicon telescope ($\Delta E_1 = 80$ μm, $\Delta E_2 = 120$ μm, $E = 5000$ μm).

The particles were identified by analog processing of the E and ΔE signals. Identification and total energy ($\Delta E + E$) signals were stored on magnetic tape for off-line analysis. The overall energy resolution was about 80 keV. To determine the relative contributions in the 6.06 (0^+)–6.13 (3^-) and 6.92 (2^+)–7.11 (1^-) doublets, high resolution (30 keV) forward angular distributions were ob-

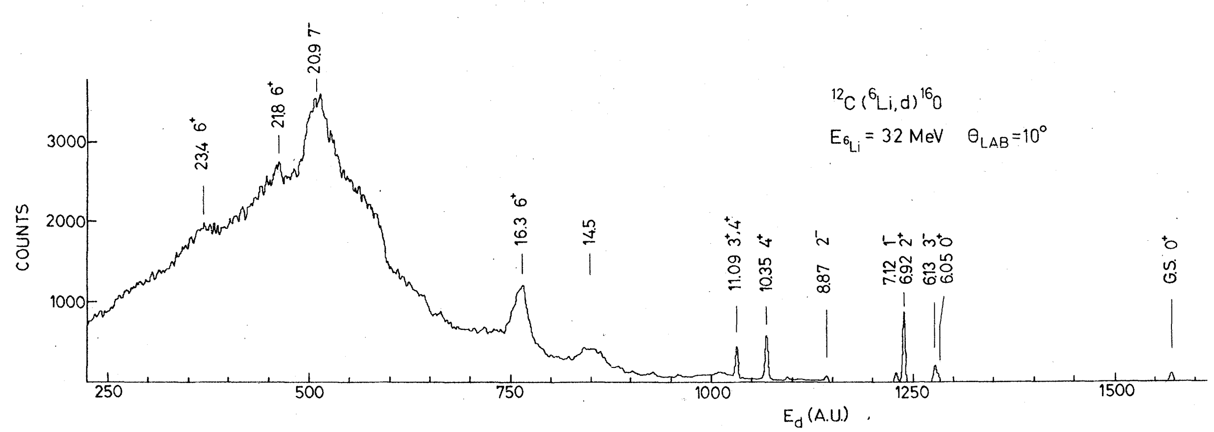

FIG. 1. Deuteron energy spectrum from the ^{12}C(^{6}Li, d)^{16}O reaction; the doublets at (6.92–7.11) MeV and (6.13–6.06) MeV have been analyzed by means of a magnetic spectrograph (see text).

tained with the Brown-Buechner magnetic spectrograph equipped with a (50× 14) mm^2 position sensitive detector in its focal plane. Because of the statistical errors in the experimental measurements of the 6.05 MeV 0$^+$ transition, we can give only an upper limit (about 10%) for its contribution to the 6.13 MeV 3$^-$ transition.

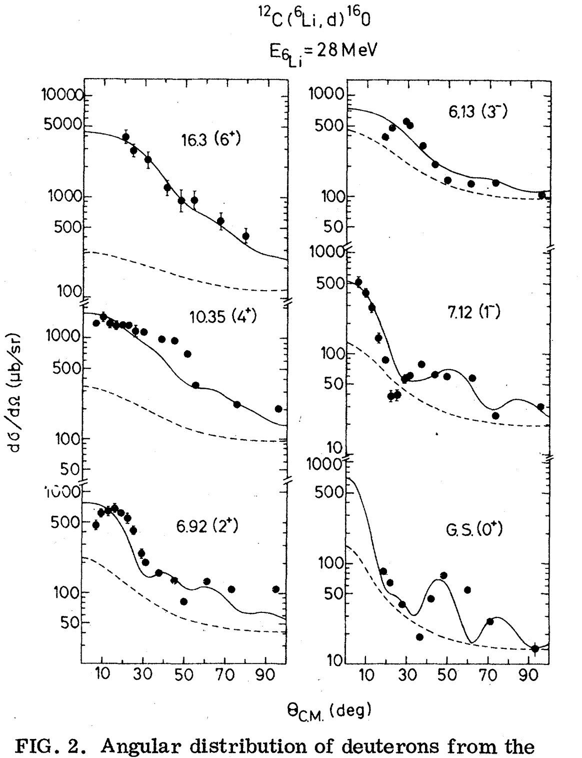

FIG. 2. Angular distribution of deuterons from the ^{12}C(^{6}Li, d)^{16}O reaction at $E_{^6\mathrm{Li}}$ =28 MeV. The dashed curves represent HF calculations, the full ones represent the incoherent sum of HF and EFR-DWBA (set I) contributions. In the left side are shown the levels belonging to the 4p-4h rotational band based on the missed 6.05 MeV 0$^+$ state; in the right side the other levels in order of excitation energy.

A typical deuteron spectrum is displayed in Fig. 1. The main features are in agreement with previous observations,[1,8] in particular the following: (i) The 6.92 (2$^+$), 10.35 (4$^+$), and 16.30 (6$^+$) MeV levels belonging to the first rotational band are strongly populated. (ii) The 11.09 MeV peak is strongly seen, as observed also in a 32 MeV experiment.[12] (iii) The structure centered at about 14.5 MeV containing a 5$^-$ level[13] and the 20.9 MeV (7$^-$) level, both belonging to the negative (K = 0$^-$) rotational band, are selectively populated.

Figures 2, 3, 4, and 5 show the angular distribution of the deuteron groups leading to different ^{16}O levels, for the 28 and 34 MeV measurements, respectively. The shape of the angular distributions in most cases is typical of a given L transfer, suggesting qualitatively that at these energies a direct α-transfer mechanism dominates.

The differential excitation functions shown in Fig. 6 exhibit an overall smooth behavior with wide oscillations that cannot be of statistical nature because of the large number of incoherently contributing channels.[8]

III. ANALYSIS OF THE DATA

A. Hauser-Feshbach calculations

In order to estimate the contribution to the measured cross section of the CN statistical mechanism, we carried out calculations of the Hauser-Feshbach (HF) formula[14]

$$\frac{d\sigma(\alpha,\alpha')}{d\Omega}=\frac{\lambdabar^2}{4}\sum_{lsl's'JL}\frac{(-1)^{s'-s}}{(2I+1)(2i+1)}\overline{Z}(l'Jl'J;sL)\times\overline{Z}(l'Jl'J;s'L)P_L(\cos\theta)\,\frac{T^{(J)}_{\alpha l s}\,T^{(J)}_{\alpha' l' s'}}{\sum_c T^{(J)}_c}\,, \tag{1}$$

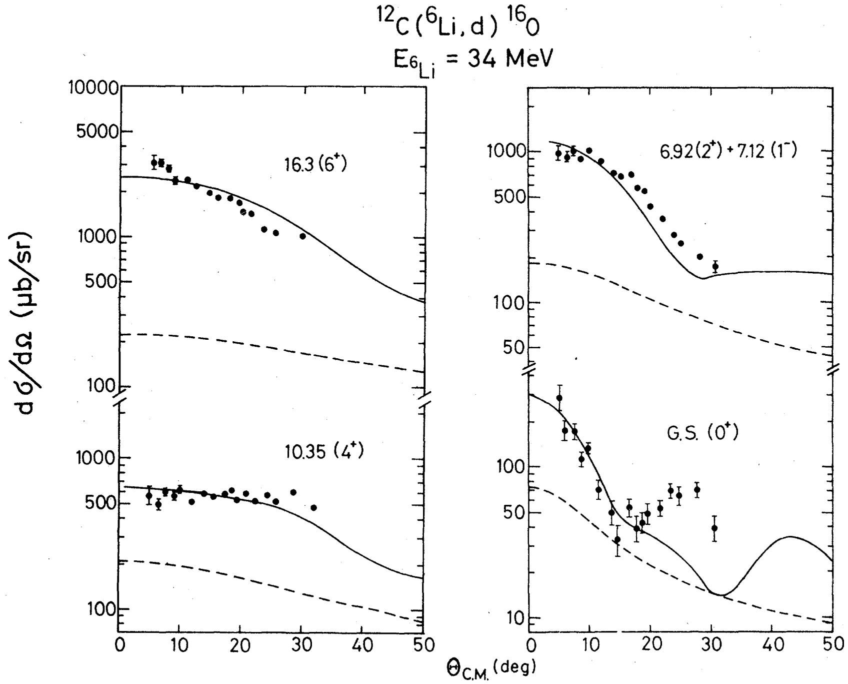

FIG. 3. Angular distribution of deuterons from the $^{12}C(^{6}Li, d)^{16}O$ reaction at $E_{^6Li}$ =34 MeV.

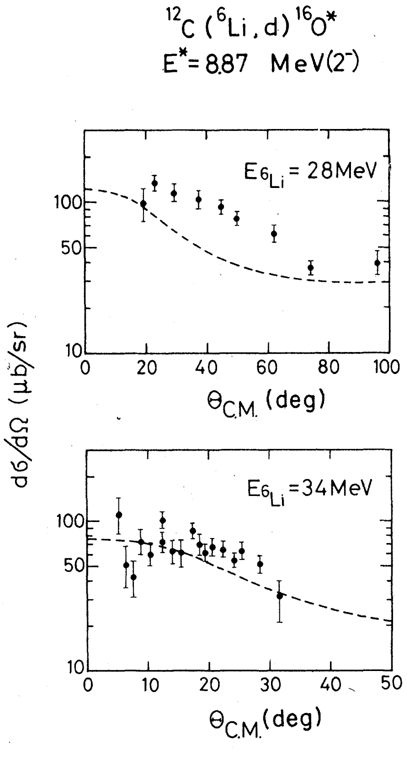

FIG. 4. Angular distribution of deuterons leading to the 8.87 MeV (2−) ^{16}O level.

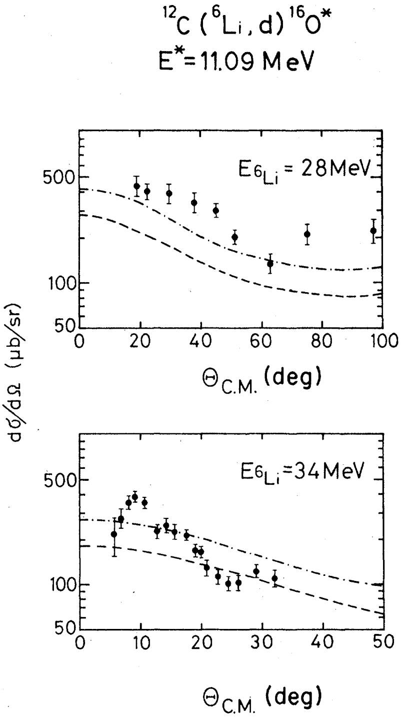

FIG. 5. Angular distribution of deuterons leading to the 11.09 MeV peak. The curves represent the HF predictions, the dashed one assuming contribution from a 4^+ level, the dot-dashed one assuming contribution from a 4^+ and a 3^+ level.

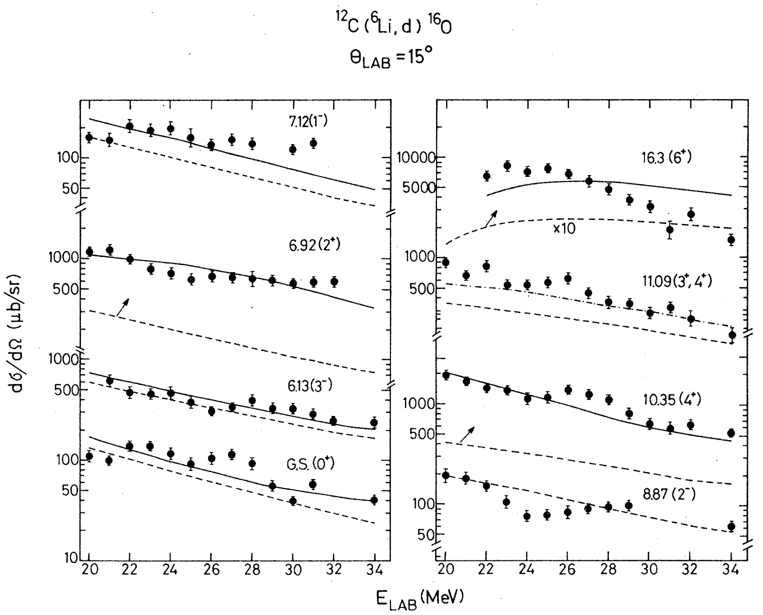

FIG. 6. Differential excitation functions for the ^{12}C(^{6}Li, d)^{16}O reaction at $\theta_{\rm lab}$ =15°.

where α and α' are the entrance and exit channels, respectively; I and i are the spins of the target nucleus and of the incident particle, respectively; s and l are the channel spin and the relative angular momentum; J is the total angular momentum; $T_{\alpha ls}$ are the optical model penetrabilities and the $\overline{Z}$'s are related to the W Racah coefficients by

$$\overline{Z}(l_1J_1l_2J_2;sL)=[(2l_1+1)(2J_1+1)(2l_2+1)(2J_2+1)]^{1/2}(l_1l_200|L0)W(l_1J_1l_2J_2;sL)\,.$$

An equivalent expression has been sometimes used (see, for example, Ref. 15) in which the summation in the denominator of (1) is replaced by an integral over the residual nuclei level densities:

$$\sum_c T_c^{(J)}=\sum_\nu \sum_{l_\nu s_\nu I_\nu}\int_0^{E_{\nu_{\max}}} T_{l_\nu}(E_\nu)\rho(E_\nu^*,I_\nu)dE_\nu\,, \tag{2}$$

where ν refers to a given residual nucleus (to which the CN can decay) and $\rho(E_\nu^*,I_\nu)$ is the density of the spin I_ν levels at the excitation energy E_ν^*.

The expression

$$\rho(E^*,I)=\frac{\hbar^3}{24\sqrt{8}}(2I+1)\exp\left[-\frac{I(I+1)}{2\sigma^2}\right]a^{1/2}\mathcal{I}^{-3/2}\times\frac{\exp[2(aU)^{1/2}]}{(U+t)^2}\,, \tag{3}$$

given by Lang *et al.*[16] on the basis of the Fermi gas model, has been used to estimate the above quantity.

In expression (3) $\sigma=\mathcal{I}^2t/\hbar^2$ is the spin cutoff factor, $\mathcal{I}$ is the nuclear moment of inertia, t is the nuclear temperature, and a is a parameter related to the spacing of the levels at the Fermi energy. In order to obtain the HF cross section in its absolute value, we used for (3) the same parameters that give a reasonable fit for the ^{12}C (^{6}Li,p)^{17}O reaction.[15] That is,

$a=0.127A$ (MeV^{-1}),

$\mathcal{I}=0.7\mathcal{I}_R$ (with $r_0=1.5$ fm),

$U=E^*-\Delta+70/A$ (Δ is the pairing energy[17]).

In Table I are listed the parameters for the calculations of formula (1).

We normalized the obtained absolute values of the HF calculations so as to reproduce the experimental point at $E_{^6\rm Li}$ =20 MeV $\theta_{\rm lab}$ =15° of the 8.87 (2⁻) MeV transition; at this incident energy Mayer-Ewert *et al.* suggest[8] that the CN mechanism is dominant. The normalization factor was found to be $(d\sigma/d\Omega)_{\rm exp}/d\sigma/d\Omega_{\rm HF}=0.70$.

The resultant HF values are displayed as dashed curves in Figs. 2, 3, 4, 5, and 6. In general the contribution of the HF cross section is sensibly smaller than the experimental cross section except for the 8.87 (2⁻) and 11.09 (4⁺) cases where they are comparable.

Equation (1) gives the energy averaged statistical CN cross section in its *absolute* value, and

TABLE I. Optical model parameters for HF calculations. Potential depths are in MeV, lengths in fm, and the radii dependence is $\boldsymbol{R} = rA_t^{1/3}$. For the spin-orbit potential we used the same radius and diffuseness as in the real part.

Channel	V^{a}	r_v	a_v	W	r_w	a_w	r_c	V_{so}^{b}	Ref.
$^6\text{Li} + ^{12}\text{C}$	241	1.75	0.55	14.5[a]	2.27	0.23	2.5	···	21
$n + ^{17}\text{F}$	c	1.309	0.66	b,e	1.26	0.48	1.309	···	32
$p + ^{17}\text{O}$	d	1.25	0.65	7.70[b]	1.25	0.47	1.25	7.5	33
$d + ^{16}\text{O}$	101.4	1.0	0.717	8.75[b]	1.589	0.625	1.3	···	34
$t + ^{15}\text{O}$	146.8	1.4	0.551	18.4[a]	1.4	0.551	1.3	···	35
$\alpha + ^{14}\text{N}$	195	1.28	0.654	21[a]	1.28	0.654	1.3	···	36

[a] Form factor: Woods-Saxon.

[b] Form factor: Woods-Saxon derivative.

[c] Energy dependence: $V(E) = 47.01-0.26\ 7E-0.00118E^2$.

[d] Energy dependence: $V(E) = 56.1-0.55E$.

[e] Energy dependence: $W(E) = 9.52-0.53E$.

it is valid when the statistical mechanism is the only one present in all channels; however, in some cases Eq. (1) can give an estimate of the statistical contribution to the energy averaged cross section[15,18,19] when direct processes are also present, as in our case. We added incoherently the HF and EFR-DWBA cross sections.

B. EFR-DWBA calculations

We analyzed the direct component of the cross section in terms of EFR-DWBA using the code Saturn-Mars of Tamura and Low[20] assuming a simple single-step α-cluster transfer from ^{6}Li to ^{12}C. The ^{6}Li is assumed to be an α-d cluster in a relative 2S state and the α- ^{12}C wave functions are generated in a Woods-Saxon potential with the depth adjusted to give the known α-separation energy, the number of nodes N being given by the usual Talmi-Moshinsky relationship.

$$2N + L = \sum_{i=1}^{4} (2n_i + l_i)\,.$$

In Table II the assumed configurations are reported.

We tested various sets of $^6\text{Li} + ^{12}\text{C}$ optical model parameters deduced from elastic scattering analysis[21,22-24]; however, they did not succeed in reproducing the general shape of our experimental angular distributions. Then we used the *same* optical model parameters that, in a systematic way, account for the (^{6}Li, d) reaction in nuclei of sd and fp shells[2-6]. The optical parameters that were used are listed in Table III as set I and set II.

Both sets give very similar shapes of EFR-DWBA angular distributions. In Fig. 7 is shown a comparison between the experimental elastic scattering data[21] and the theoretical values calculated

TABLE II. α-spectroscopic strengths from the $^{12}\text{C}(^6\text{Li},d)^{16}\text{O}$ reaction.

Levels E (MeV)	J^π	α-Spectr. str.[a] Set I	 Set II	S/So[b] exp.	S/So[c] th.	Suggested[d] main config.
0.0	0^+	0.159 ±0.014	0.104 ±0.010	1.00	1.00	0p-0h
6.13	3^-	0.054 ±0.006	0.055 ±0.006	0.34	0.15	1p-1h
6.92	2^+	0.036 ±0.002	0.044 ±0.002	0.23	0.79	4p-4h
7.12	1^-	0.062 ±0.006	0.049 ±0.005	0.39		1p-1h
10.35	4^+	0.062 ±0.002	0.079 ±0.003	0.40	0.70	4p-4h
16.30	6^+	0.018 ±0.003	0.044 ±0.006	0.11	0.54	4p-4h

[a] From the 28 MeV data. The quoted errors come from the assumed 30% ambiguity in the estimation of the CN cross section (Ref. 19) and from statistical errors.

[b] Set I

[c] Ref. 11.

[d] Refs. 30 and 31.

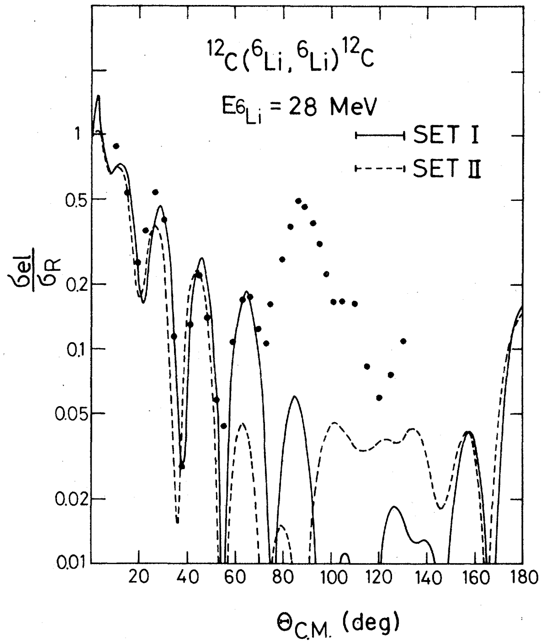

FIG. 7. Elastic scattering cross section of ^{6}Li on ^{12}C at $E_{^6Li}$ = 28 MeV compared with the theoretical predictions obtained using the ^{6}Li + ^{12}C optical model parameters of Table II; the agreement is limited to the forward angular region.

with sets I and II of optical parameters.

By comparison of EFR-DWBA calculations with the experimental data we extract a normalization constant S (spectroscopic strength) defined in our case as

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = S\left(\frac{d\sigma}{d\Omega}\right)_{\text{EFR-DWBA}} + \left(\frac{d\sigma}{d\Omega}\right)_{\text{HF}} .$$

The S values deduced from the 28 MeV angular distributions are shown in Table II. For the unbound levels at 10.35 (4^+) and 16.3 (6^+) MeV the theoretical EFR-DWBA cross sections were obtained by the binding energy extrapolation method.

The theoretical and experimental angular distributions are compared in Figs. 2 and 3. The agreement in shape is rather good in all cases except for the forward angles in 2^+, 3^-, and 4^+ levels. Varying[25] the form factor for the α-d system did not affect significantly the shape of the calculated angular distributions. From Table II we note that the ratio of the α-spectroscopic strengths for the 6.92 (2^+) and 10.35 (4^+) MeV ^{16}O levels ($R_{(^6Li,d)} = 0.58 \pm 0.04$) agrees with the one extracted from a similar analysis[26] of the (^{7}Li, t) reaction ($R_{(^7Li,t)} = 0.61$).

IV. CONCLUSIONS

At the energies of the present experiment the $^{12}C(^6Li,d)^{16}O$ reaction mechanism, for the transitions leading to the selectively excited ^{16}O levels, is well described by a direct α transfer. This conclusion is supported by the shape of the angular distributions and by the average trend of the excitation functions

The contribution of the compound nucleus statistical mechanism is important for the transition to the 8.87 (2^-) MeV level (see Fig. 4). In the case of the 11.09 MeV peak, if one considers the two terms of the 3^+, 4^+ doublet,[27] the HF calculation gives cross sections of the same order as the experimental ones (see Fig. 5); however, the shape of the 34 MeV angular distribution at forward angles is quite different from the HF predictions (see Fig. 5) suggesting that more complex mechanisms can contribute to this transition as it was remarked in Refs. 12, 28, and 29.

In columns 5 and 6 of Table II a comparison is made between relative α-spectroscopic strengths deduced in the present work and the theoretical values of Ichimura *et al.*[11] calculated for pure particle-hole configurations in the framework of the harmonic oscillator shell model with SU(3) classification.

Our conclusion is that, in spite of the uncertainties present in our analysis, a disagreement exists; this can be due to neglect of the role of the configuration mixing in the description of the ^{16}O

TABLE III. Optical model parameters for EFR-DWBA calculations.

	Channel	V^a	r_v	a_v	W	r_w	a_w	r_c	Ref.
Set I	$^6Li + ^{12}C$	250	1.354	0.65	30^b	1.354	0.65	2	3,5
	$d + ^{16}O$	95	1.127	0.8	10^b	1.332	0.8	2	
Set II	$^6Li + ^{12}C$	72.6	1.37	0.87	8^a	2.3	0.81	2.5	4
	$d + ^{16}O$	92.94	1.036	0.787	8.91^b	1.355	0.727	1.3	37
	$d - \alpha$		1.545^c	0.65				1.545^c	3
	$^{12}C - \alpha$		1.25^c	0.65				1.25^c	

[a] Form factor: Woods-Saxon.

[b] Form factor: Woods-Saxon derivative.

[c] $R = r(A_1^{1/3} + A_2^{1/3})$.

levels.[30,31]

Work including the configuration mixing effects in EFR-DWBA analysis is in progress.

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