$^{13}C(^6Li,t)^{16}O$ reaction in the 20–32 MeV incident energy range

A. Cunsolo, A. Foti, G. Immè, G. Pappalardo, G. Raciti, and F. Rizzo
Istituto Nazionale di Fisica Nucleare Sezione di Catania, Centro Siciliano di Fisica Nucleare e di Struttura della Materia, Istituto di Fisica and Scuola di Specializzazione in Fisica, Università di Catania, Corso Italia, 57, 95129 Catania, Italy

N. Saunier
Département de Physique Nucléaire, Centre d'Etudes Nucléaire de Saclay, Boîte Postale No. 2, 91190 Gif-sur-Yvette, France
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The reaction $^{13}C(^6Li,t)^{16}O$ has been studied in the 20–32 MeV incident energy range. Angular distributions have been measured at $E_{^6Li} = 28$ MeV; the data have been analyzed in terms of Hauser-Feshbach and exact finite range distorted-wave Born-approximation theories. The extracted relative ^3He spectroscopic strengths show a satisfactory independence from the optical model parameters.

[NUCLEAR REACTIONS $^{13}C(^6Li,t)$ $E = 20–32$ MeV; measured $\sigma(E,\theta)$; ^{16}O levels deduced S. HF and EFR-DWBA analysis.]

I. INTRODUCTION

The study of trinucleon cluster states in light nuclei has been the object of many experimental and theoretical investigations.[1] Experimentally, the $(^6Li,t)$ and $(^6Li,^3He)$ nuclear reactions have been the most extensively used for heavy-ion three-nucleon transfer reactions.[2-9] The reason for this originates in the following arguments: (i) the ^6Li nucleus shows, in the ground state, a large[10] ^3He–t cluster component. (ii) The $(^6Li,t)$ and $(^6Li,^3He)$ reactions strongly populate only few of the known final nucleus states.[2-9] (iii) The angular distributions are forward peaked and the excitation functions[6] are rather flat.

On this basis, the ^6Li-induced three-nucleon transfer reactions have been sought to proceed through a direct mechanism and some spectroscopic information has been extracted. In fact, a zero-range DWBA analysis has been done[4-6] for the $(^6Li,t)$ and $(^6Li,^3He)$ reactions induced on ^{16}O at $E_{^6Li} \leq 24$ MeV. Recently the same reactions induced on ^{12}C at $E_{^6Li} = 60$ MeV have been analyzed, assuming a direct transfer of a ^3He or triton cluster with $0S$ internal motion, in the exact-finite range (EFR) distorted-wave Born-approximation (DWBA) framework. A similar analysis has been done[11] for the inverse reaction $^{19}F(^3He,^6Li)$ ^{16}O at $E_{^3He} = 11$ MeV.

Theoretically, such states may be predicted by a simple cluster folded potential model.[12] In particular, Buck and Pilt[13] have recently reported a study in which a number of low-lying negative parity states in ^{18}F and ^{18}O nuclei are successfully described as $(^{15}N$–$^3He)$ and $(^{15}N$–$t)$ cluster states, respectively. From the shell model point of view, as a very large basis of states is needed in order to describe many-particle many-hole configurations, only a few calculations have been done.[14-16] Furthermore, the trinucleon spectroscopic amplitudes have been calculated only for a few states of some light nuclei using the SU(3) shell model.[17]

In the present work, we report the study of the $^{13}C(^6Li,t)$ ^{16}O reaction in the incident energy range $E_{^6Li} = 20–32$ MeV, which was done in order to complete the information on the many-particle many-hole configurations for the ^{16}O nucleus states previously[18] obtained via the $^{12}C(^6Li,d)$ ^{16}O reaction. Section II deals with experimental procedures and results. In Sec. III the analysis of the data is done describing the reaction mechanism in terms of statistical compound nucleus and direct ^3He-cluster transfer incoherent contributions. The DWBA calculations were carried out taking into account, for each final state, only the main configuration suggested by Zucker, Buck, and McGrory (ZBM).[15] Preliminary results[19] have been published elsewhere.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The experiments were performed at F. N. tandem Van de Graaff laboratory of the Centre d'Etudes Nucléaires, Saclay. A $^6Li^{+++}$ beam, with intensity of the order of 100 nA and self-supporting ^{13}C targets, enriched to 80% and of thicknesses in the range from 80 to 200 $\mu g/cm^2$, have been used. The reaction products were detected by a cooled ΔE-E telescope made of two silicon detectors ($\Delta E = 150$ μ; $E = 5000$ μ) and the particle identification was obtained in a standard analogical way.[20]

The $^{13}C(^{6}Li,t)$ ^{16}O measurements consist of

(i) Angular distributions at $E_{^{6}Li}$ = 28 MeV, from θ_{lab} = 15° to θ_{lab} = 140°, in steps of 5° for forward angles and 10° for backward angles.

(ii) Excitation functions taken at θ_{lab} = 15°, from 20 to 32 MeV incident energy and in 1 MeV steps.

A triton energy spectrum, obtained in an excitation run, is shown in Fig. 1. The overall energy resolution [full width at half maximum (FWHM)] is about 80 keV. The spectrum is dominated by the 11.09 (4^+, 3^+) peak and by the complex structure lying in the 14–15 MeV ^{16}O excitation energy range. In order to better investigate this structure, we have measured, in a high resolution experiment (FWHM 30 keV) done at $E_{^{6}Li}$ = 25 MeV and θ_{lab} = 15°, the energy spectrum of tritons leading to this ^{16}O excitation energy region by means of two position sensitive detectors placed in the focal plane of a Brown-Buechner magnetic spectrograph. The obtained data are shown in Fig. 2 and clearly demonstrate the population of a ^{16}O level at 14.30 ± 0.02 MeV. The other components, the 14.39 and 14.82 MeV levels, are strongly populated in $^{14}N(\alpha,d)$ ^{16}O experiments,[21,22] and have been interpreted as the $[d_{5/2}^2(5^+,0)p_{1/2}^2(1^+,0)]J = 5^+, 6^+$ ^{16}O states predicted by ZBM.[15]

As the 14.30 MeV state is only noticeable[22] in (α,d) spectra and it is not seen at all in the $(^{6}Li,d)$ or $(^{7}Li,t)$ experiments,[18,23] one can infer that its structure is a highly pure (3p-3h) configuration.

Due to the thickness of the ^{13}C target used in angular distribution runs, the triton energy resolution was ≃150 keV. This fact prevents us from resolving the 6.92 MeV 2^+ and 7.12 MeV 1^- doublet, and limits the extraction of data.

The angular distributions and differential excitation functions obtained are displayed in Figs. 3 and 4, respectively.

III. ANALYSIS OF THE DATA

The main features of the present data are in good agreement with a previous lower energy investigation.[3] The angular distributions are generally forward peaked and the excitation functions exhibit a smooth decreasing behavior, suggesting for the most populated transitions a dominant direct transfer reaction mechanism. Moreover, the backward angle shapes of the 28 MeV angular distributions (see Fig. 3) suggest some contributions

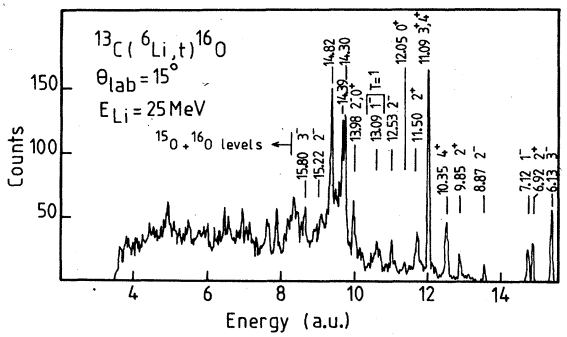

FIG. 1. Triton energy spectrum from the $^{13}C(^{6}Li,t)^{16}O$ reaction at $E_{^{6}Li}$ = 25 MeV.

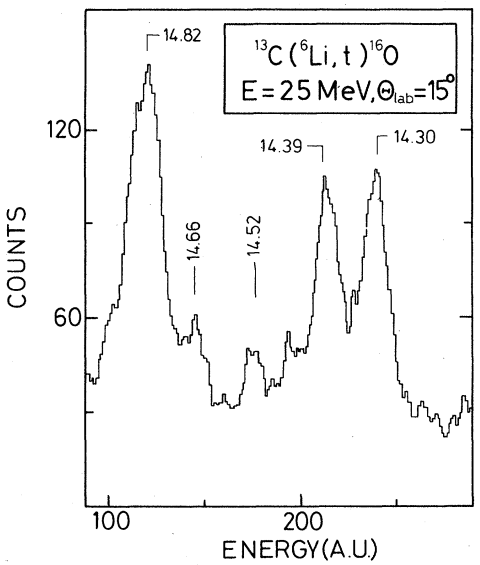

FIG. 2. High resolution (FWHM ~ 30 keV) energy spectrum of tritons populating the ^{16}O in the 14–15 MeV excitation energy region.

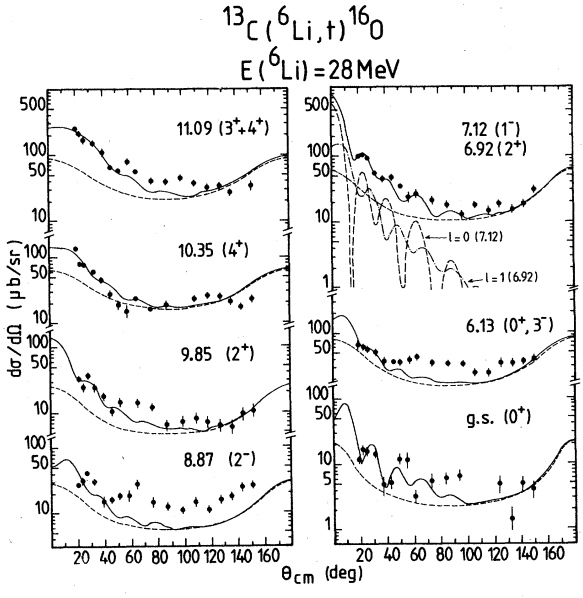

FIG. 3. Angular distribution of triton from $^{13}C(^{6}Li,t)^{16}O$ reaction at $E_{^{6}Li}$ = 28 MeV. The dashed curves represent HF calculations, the full ones represent the incoherent sum of HF and EFR-DWBA (set I) contributions.

TABLE I. Optical model parameters for HF calculations. Potential depths are in MeV, lengths in fm, and the radii dependence is $R = rA^{1/3}$. 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}Li + ^{13}C	644.1	0.75	0.79	9.08 [a]	2.23	0.75	2.5		26
n + ^{18}F	c	1.337	0.66	b, d	1.273	0.48	1.337		35
p + ^{18}O	e	1.25	0.65	7.86 [b]	1.25	0.47	1.25	8.5	36
d + ^{17}O	85.3	1.1	0.902	8.975 [b]	1.6	0.509	1.3	9.41	38
t + ^{16}O	146.8	1.4	0.551	18.4 [a]	1.4	0.551	1.3		32
α + ^{15}N	45.1	1.787	0.586	15.1 [a]	1.787	0.5	1.787		39

[a] Form factor: Woods-Saxon.
[b] Form factor: Woods-Saxon derivative.
[c] Energy dependence: $V(E) = 47.01 - 0.267E - 0.00118E^2$.
[d] Energy dependence: $W(E) = 9.52 - 0.53E$.
[e] Energy dependence: $V(E) = 57.5 - 0.55E$.

from a nondirect reaction mechanism. This leads us to describe the (^{6}Li, t) reaction in terms of incoherent contributions from the direct transfer of the ^{3}He-cluster and the statistical compound nucleus reaction mechanism. Such a procedure is expected to be accurate.[18]

A. Hauser-Feshbach calculations

The statistical compound nucleus contributions have been evaluated following the Hauser-Feshbach (HF) formulation.[24] In Table I are reported the optical model parameters used for HF calculations. The details for such calculations have been reported elsewhere.[18] In order to check the absolute value of the calculated HF cross sections, we compared the theoretical values with the backward angle experimental data of all the transitions observed. The normalized HF cross sections are shown as dashed curves in Fig. 3 for the 28 MeV data and in Fig. 4 for the differential excitation functions. In general, the statistical contributions are not negligible in the presently investigated incident energy range.

B. EFR-DWBA calculations

The direct contributions have been calculated in the ^{3}He-cluster approximation, using the Saturn-Mars EFR-DWBA code of Tamura and Low.[25] As the relative t–^{3}He cluster motion in the ^{6}Li ground state is a 2S state,[10] the following final

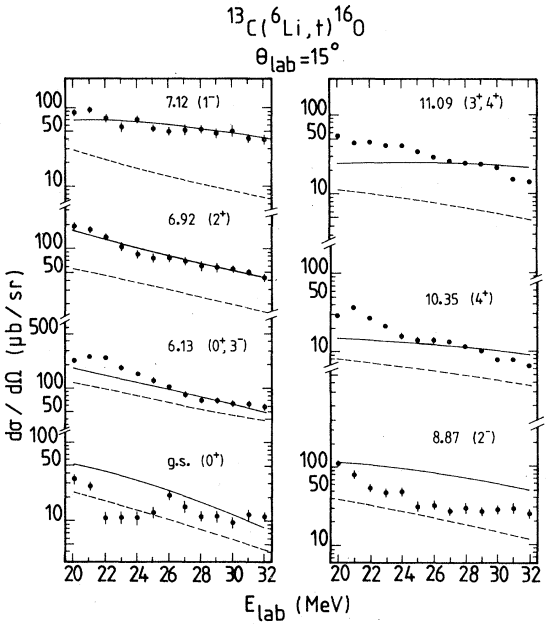

FIG. 4. Differential excitation functions for the ^{13}C(^{6}Li, t)^{16}O reaction at $\theta_{lab} = 15°$.

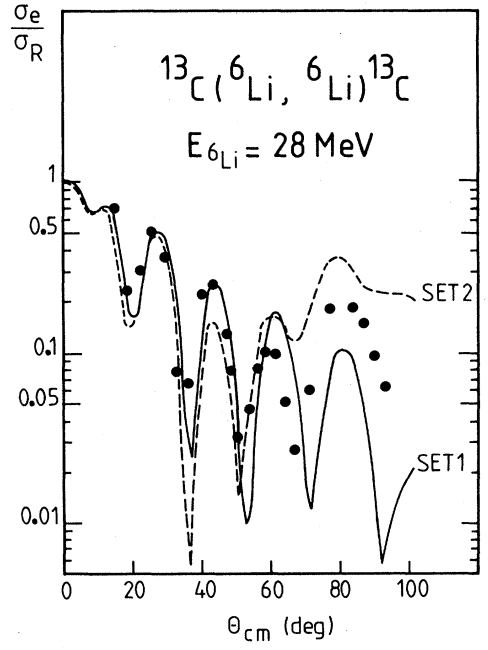

FIG. 5. Elastic scattering cross section of ^{6}Li on ^{13}C at $E_{^6\mathrm{Li}} = 28$ MeV compared with the theoretical predictions obtained using the ^{6}Li + ^{13}C OMP of Table II.

state parity π_f, l-selection rule holds:

$$\pi_f = (-)^{l+1}, \quad (1)$$

where l is the transferred angular momentum. Unfortunately, two transferred angular momenta are allowed for many transitions, even if the hypothesis that the reaction proceeds without spin flip is made.

The bound state wave functions were generated using Saxon-Woods potential, with depth adjusted to reproduce the known ^{3}He-core separation energy, the principal (N) and orbital (L) quantum numbers being given by the usual Talmi-Moshinsky rule

$$2N+L = \sum_{i=1}^{3} (2n_i + l_i), \quad (2)$$

where n_i and l_i are the harmonic oscillator quantum numbers of each transferred nucleon. The configurations assumed for the description of the reached ^{16}O states are tabulated in Table III.

In order to reproduce the well structured $^{16}O_{g.s.}$ angular distribution shape, we tested many sets of optical model parameters (OMP) for the entrance[26-31] and exit[32-34] channels. The best agreement was obtained using the two OMP sets reported in Table II that give both very similar shapes of EFR-DWBA angular distributions. In Fig. 5 the predicted ^{6}Li elastic cross sections at 28 MeV on ^{13}C are compared with the experimental data.[26]

Except for the single-l transitions, the extraction of the spectroscopic information is not straightforward. In fact, in the absence of spin-orbit interactions, the direct cross section has the following expression:

$$\sigma^{DWBA} \propto |A_{2S}(^{6}Li;t)|^2 \sum_k |A_{N_k L_k}(^{16}O;^{13}C) B^{DWBA}_{N_k L_k; 2S}(\theta)|^2, \quad (3)$$

where the index k runs on all the l-allowed values, $A_{N_k L_k}$ are the spectroscopic amplitudes for the ^{16}O in a definite state, dissociating into a $^{13}C_{g.s.}$ nucleus and a ^{3}He with relative motion specified by $N_k L_k$ and the factor $B_{N_k L_k, 2S}(\theta)$ is the usual DWBA transition amplitude. In our case, the comparison with the data can be done as follows:

$$\sigma_{exp} - \sigma_{HF} = \sigma^{DWBA} = S_1 \sigma_{L_1} + S_2 \sigma_{L_2}. \quad (4)$$

The spectroscopic strengths S_1 and S_2 contain all the spectroscopic information, and can be extracted via a fitting procedure of the experimental data, based on a linear two parameters least square method. For the unresolved doublets $(2^+, 1^-)$ at 6.92 and 7.12 MeV, and $(3^+, 4^+)$ at 11.08 and 11.09 MeV, linear four and three least square procedures were done. When a deduced S_i parameter gave a negative value, a new best fit procedure was performed, neglecting the corresponding contribution. To check this procedure, independent best fits have been done for the excitation function data, especially for the resolved doublet 2^+, 1^-. In general, a good consistency has been found. In Figs. 3 and 4 the theoretical predictions for angular distributions and excitation functions are shown.

The overall agreement for the transitions to the positive-parity ^{16}O states is good, in contrast with those leading to the negative-parity states. In particular, the predicted angular distribution shape for the 2^-, 8.87 MeV level is out of phase with respect to the experimental one.

All these observations indicate that, at the energies presently investigated, the $^{13}C(^{6}Li,t)\,^{16}O$ populates essentially (2p-2h) configurations. This conclusion is in agreement with that deduced by a qualitative analysis[19,21] done comparing the selectivities shown by $^{14}N(\alpha,d)$, $^{13}C(^{6}Li,t)$, $^{12}C(^{6}Li,d)$, and $^{12}C(^{7}Li,t)$ reactions.[21-23]

The obtained spectroscopic strengths are reported in Table III. The relative spectroscopic strengths $S/S_{g.s.}$ obtained using OMP set 1 and set 2 are essentially the same, except for the 7.12, 1^- transition. Moreover, from inspection of Table III, it can be noted that essentially the lower l cross section contributes.

This spectroscopic $l_<$ effect, also seen in the

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

	Channel	V [a]	r_v	a_v	W	r_w	a_w	r_c	Ref.
Set I	^{6}Li + ^{13}C	250	1.354	0.65	30 [b]	1.354	0.65	2	31
	t + ^{16}O	146.8	1.4	0.55	19.3 [a]	1.4	0.55	1.3	32
Set II	^{6}Li + ^{13}C	159	1.23	0.780	7 [a]	2.15	0.8	2.5	4
	t + ^{16}O	162.9	1.14	0.5	11.84 [a]	1.82	0.56	1.25	34
	^{3}He − ^{13}C		2 [c]	0.65				2 [c]	8
	^{3}He − t		1.73 [c]	0.45				1.73 [c]	8

[a] Form factor: Woods-Saxon.
[b] Form factor: Woods-Saxon derivative.
[c] $R = r(A_1^{1/3} + A_2^{1/3})$.

TABLE III. ^{3}He-spectroscopic strengths from the ^{13}C(^{6}Li, t)^{16}O reaction.

Levels E^* (MeV)	J^π	Allowed l values	^{3}He-spectr. strengths [a] ($\times 10^2$) Set I	Set II	$S/S_{g.s.}$ Set I	$S/S_{g.s.}$ Set II	Main configuration (Ref. 15)
g.s.	0^+	1	3.51 ± 0.41	2.37 ± 0.28	1	1	0p-0h
6.13	3^-	2					1p-1h
		4	0.69 ± 0.23	0.40 ± 0.12	0.20 ± 0.07	0.17 ± 0.05	
6.92	2^+	1	0.60 ± 0.25	0.32 ± 0.17	0.17 ± 0.07	0.14 ± 0.08	2p-2h
		3					
7.12	1^-	0	1.57 ± 0.51	2.41 ± 0.54	0.45 ± 0.16	1.02 ± 0.26	1p-1h
		2					
8.87	2^-	2	0.31 ± 0.05	0.28 ± 0.04	0.09 ± 0.02	0.12 ± 0.02	1p-1h
9.85	2^+	1	0.39 ± 0.05	0.26 ± 0.06	0.11 ± 0.02	0.11 ± 0.03	2p-2h
		3		0.07 ± 0.03		0.03 ± 0.01	
10.35	4^+	3	0.27 ± 0.12	0.19 ± 0.08	0.08 ± 0.04	0.08 ± 0.03	2p-2h
		5	0.02 ± 0.35	0.06 ± 0.18	0.006 ± 0.11	0.03 ± 0.09	
11.09	4^+	3	0.33 ± 0.26	0.25 ± 0.08	0.09 ± 0.07	0.11 ± 0.04	2p-2h
		5	1.66 ± 0.56	1.01 ± 0.31	0.47 ± 0.17	0.43 ± 0.14	

[a] The quoted errors come from the assumed 30% ambiguity in the estimation of the CN cross section (Ref. 18) and from statistical errors.

^{15}N(^{3}He, d) ^{16}O reaction[37] and predicted by Kurath and Towner in the α-transfer case,[40] may be qualitatively understood in terms of the rule $2N+L$ = constant. This rule associates to the lower L value the higher N value, getting a bound state radial wave function more enhanced at the nuclear surface, where the clustering is expected to occur.

IV. CONCLUSIONS

The aim of the present work was to obtain information on the $^{13}C_{g.s.}$–^{3}He cluster structure of the ^{16}O states, via the investigation of the ^{13}C(^{6}Li, t) ^{16}O reaction in the incident energy range $E_{^6\mathrm{Li}}$ = 20–32 MeV. A qualitative analysis of the population of the ^{16}O states lying at $E_x \lesssim 15$ MeV, done comparing the ^{13}C(^{6}Li, t) data with two nucleons and α-transfer data, indicates that the direct ^{3}He transfer excites, in the ^{16}O nucleus, essentially $(1p)^1(2s\,1d)^2$ configurations. Another interesting result of such an analysis is the selective population of a state at 14.30 MeV for which an essentially (3p-3h) structure is suggested.

The quantitative analysis is done assuming that the contributions from statistical compound nucleus and from direct ^{3}He-transfer mechanisms add incoherently. The first contribution is carefully estimated normalizing the calculated HF cross sections to the backward angles data. The direct contribution is calculated in the cluster EFR-DWBA approximation. For many transitions, two angular momenta are allowed, and the DWBA cross sections appear as an incoherent sum of two single-l cross sections, in which [Eq. (4)] the spectroscopic information is contained as two weight factors. The extraction of these spectroscopic strengths is done via a linear multiparameters least square fitting. The results confirm the qualitative analysis:

(1) All the observed negative parity states having essentially (1p-1h) structure are badly reproduced.

(2) The positive parity states are well accounted for via the direct populations of (2p-2h) configurations.

Since the 14.30 MeV state is the only candidate for having a highly pure (3p-3h) structure lying below ~15 MeV excitation energy in the ^{16}O nucleus, one can infer that the other ^{3}He–^{13}C cluster states would lie at higher excitation energy, and hence the present investigation is to be extended at higher incident energies.

Finally, the present analysis indicates that the lower allowed l cross sections are the predominant contributors. This $l_<$ effect, which might be due to the major surface increase of the radial part of the relative motion cluster wave functions, is to be confirmed by spectroscopic amplitudes calculations based on more realistic wave functions. The validity of our conclusions is in some way restricted by the ambiguities present in a DWBA analysis (e.g., the OMP ambiguities, the bound state form factor, etc.). Further improvement in the analysis would be done by a microscopic treatment of the transferred ^{3}He particle. This work is now in progress.

The measurements reported in the present work started with the enlightening contribution of the late Dr. G. Bassani.

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