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Survey of ^{17}O excited states selectively populated by five-particle transfer reactions

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The highly selective reactions ^{12}C(^{7}Li, d)^{17}O and ^{12}C(^{6}Li, p)^{17}O have been used to populate high-lying excited states in ^{17}O up to 16 MeV in excitation. Several of the states are newly observed, and the existence of others in a previous study of ^{12}C(^{6}Li, p)^{17}O is confirmed. The observed spectra show a clear gap of about 3 MeV, indicating an energy gap between 3p-2h and 5p-4h states in ^{17}O. Differential cross section angular distributions have been extracted from the data for both reactions and they have been compared with finite-range DWBA calculations by assuming a "^{5}He" cluster transfer. Possible spins and parities are reported for states at 11.82 MeV ($7/2^+$), 12.00 MeV ($9/2^+$), 12.22 MeV ($7/2^-$), and 12.42 MeV ($9/2^+$).

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I. INTRODUCTION

According to the single-particle shell model, the structure of the ^{17}O nucleus should be among the easiest nuclei to understand. The single-particle shell model implies that ^{17}O is composed of a doubly-magic ^{16}O nucleus as a core and a single neutron in the s-d shell. Only certain low-lying states, namely the ground state ($5/2^+$), the 0.87-MeV ($1/2^+$), and the 5.08-MeV ($3/2^+$) states, are known to have significant single-particle strength [1,2] and fit this simple picture. As early as the 1960s, it was experimentally observed that this model provided an incomplete description of the structure of the ground and excited states of ^{17}O [3] because other states with seemingly more complicated configurations were observed.

The structure of most of the states in ^{17}O below 10-MeV excitation has been studied extensively with inelastic electron scattering [4] and by particle transfer reactions of various types. The particle transfer experiments have observed through the use of two-, three-, and four-particle transfer reactions that states in ^{17}O with underlying 2p-1h [5,6], 3p-2h [7–9], and 4p-3h [10,11] structure, respectively, are selectively populated. The angular distributions of the differential cross sections of these measurements have also been reproduced with distorted wave Born approximation (DWBA) calculations that led to spin and parity assignments as well as measurements of the spectroscopic strengths. The results of these experiments have shown that, in general, the reactions transferring one to four nucleons selectively populate ^{17}O states below 10 MeV and that, as more nucleons are transferred, the reactions tend to favor states with higher excitation energy. Thus, one would expect states of structure like 5p-4h to lie above 10 MeV in excitation energy, which is the purpose of the present work.

Studies of the 5p-4h strength in ^{17}O were first suggested by Brown and Green [12], where it was remarked that states with 5p-4h strength would result from excited states built on deformed 4p-4h excitations of the ^{16}O core. In their model, which is based on the Nilsson model, the p shell and sd shell at high prolate deformation would be closer in energy, allowing several nucleons to be excited simultaneously from the ^{16}O core to form the high-lying excited states.

Despite this early theoretical suggestion, there have been relatively few corresponding five-particle transfer experimental studies for ^{17}O to investigate the proposed 5p-4h structure. The first experimental measurements of possible five-particle transfer reactions leading to ^{17}O were conducted by Meier-Ewert *et al.* with the ^{12}C(^{6}Li, p)^{17}O reaction at $E(^6\text{Li}) = 20$ MeV [13]. The energy of their measurements did not allow high-lying states to be investigated, but they selectively populated many states including, in particular, the 8.46-MeV state. They were able to show with Hauser-Feshbach (HF) formalism [14] that the angular distribution of the 8.46-MeV state could be explained by nondirect, compound nuclear processes. Also, Johnson and Waggoner [15] have conducted similar studies of the ^{12}C(^{6}Li, p) reaction at energies between 9 and 14 MeV and found that the differential cross sections at these lower energies could also be explained by assuming the reaction was a compound nuclear process. However, a further study of the ^{12}C(^{6}Li, p) reaction was conducted at $E(^6\text{Li}) = 28$ MeV by Smithson *et al.* [16], where it was observed that although some of the selectively populated states could be explained with HF formalism as at lower beam energies, there were certain states whose differential cross section angular distributions were much larger than HF predicted at forward angles. With this observation, they were

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able to explain the angular distribution of $^{17}O_{g.s.}$ with a DWBA calculation up to $\theta_{c.m.} = 50^\circ$, suggesting that the reaction was direct at forward angles. They concluded that there were many states that appeared to have angular distributions that were populated by some direct component at forward angles, but DWBA calculations for the excited states were not carried out.

Recently, there has been renewed interest in multiparticle transfer reactions as a way to populate states of different structures in light nuclei with the possibility of determining the presence of possible molecular cluster configurations [17]. For example, Milin and von Oertzen [18] and von Oertzen *et al.* [19] have made extensive studies of the $^{13-14}C$ isotopes using four- and five-particle transfer reactions on ^{9}Be. Through measurements with several different reactions, including $^{9}Be(^{7}Li, d)^{14}C$, they have obtained an almost complete spectroscopy for ^{14}C up to 18-MeV excitation, revealing interesting structure phenomena such as α-clustering and rotational bands. They remark in their experimental results that the $(^{7}Li, d)$ reaction selectively populated different states in ^{14}C than the other reactions they studied. The structure and spin of the high-lying excited states in these nuclei was investigated with coupled reaction channel (CRC) calculations by assuming a multistep, sequential transfer of an α particle followed by a neutron, and vice versa. Also, Jarczyk *et al.* [20,21] have shown that, for the $^{12}C(d, ^{7}Li)^{7}Be$ reaction, the α particle and the neutron are simultaneously transferred as a correlated ^{5}He cluster. Thus, it seemed reasonable that $^{12}C(^{6}Li, p)$ and $^{12}C(^{7}Li, d)$ could also have a five-particle direct transfer reaction mechanism, provided the energy was sufficiently high.

To test the conclusion of Smithson *et al.* [16], as well as to add to the available spectroscopic information for ^{17}O at high excitation energy, measurements of five-particle transfer reactions leading to ^{17}O were conducted with the $^{12}C(^{7}Li, d)$ reaction at $E(^{7}Li) = 34$ MeV and the $^{12}C(^{6}Li, p)$ reaction at $E(^{6}Li) = 32$ MeV. The lithium beam energies were chosen such that a direct component to the reactions at forward angles could be observed as in the previous work. Recent studies of the structure of the ^{9}Be ground state [22] have shown that although the ^{5}He nucleus is particle unbound, ^{5}He clustering could exist within heavier nuclei. Following this idea, the possibility that the selectively populated states observed in five-particle transfer reactions leading to ^{17}O excited states are populated by direct, single-step ^{5}He transfer is investigated by comparing the experimental data with DWBA calculations.

The paper is organized as follows. In Sec. II, the experimental procedure used for measuring the absolute differential cross section angular distributions for the states selectively populated in $^{12}C(^{7}Li, d)^{17}O$ and $^{12}C(^{6}Li, p)^{17}O$ is reported. In Sec. III, a detailed explanation of the DWBA calculations carried out in this study is provided. In Sec, IV, the experimental angular distributions measured in this work are compared with the DWBA calculations by assuming a single-step ^{5}He cluster transfer. Also, the L transfer, spin, and parity of the states suggested by the calculations are reported. Finally, in Sec. V, some general conclusions are made about the ^{17}O states studied in this work.

II. EXPERIMENTAL PROCEDURE

The $^{12}C(^{7}Li, d)^{17}O$ and $^{12}C(^{6}Li, p)^{17}O$ angular distributions were measured in two separate experiments. The Florida State University Super FN Tandem accelerator was used to accelerate ^{7}Li and ^{6}Li beams to $E(^{7}Li) = 34$ MeV and $E(^{6}Li) = 32$ MeV, respectively. The beams impinged on a self-supporting, natural carbon target with an areal density of 100 μg/cm^2.

The outgoing particles from the reactions were measured by using two ΔE-E silicon surface barrier telescopes composed of a 300-μm ΔE detector and a 5-mm E detector. An experimental resolution of around 110 keV was obtained. Although the 5-mm E detector was thick enough to stop all of the deuterons coming from the $^{12}C(^{7}Li, d)^{17}O$ reaction, it was not thick enough to stop all of the protons coming from $^{12}C(^{6}Li, p)^{17}O$. Thus, the ^{17}O states were identified by starting with a ^{6}Li beam at 26 MeV, where the protons coming from the ^{17}O ground and first excited states were fully stopped in the detector telescopes. The ^{6}Li beam energy was then raised in steps of 2 MeV until the final energy of 32 MeV was reached. It was found for $^{12}C(^{6}Li, p)$ at $E(^{6}Li) = 32$ MeV that the 5-mm E detectors were able to stop all the protons resulting from ^{17}O states above the 4.554-MeV, $3/2^-$ state.

Each detector was collimated with a polar angle width of 0.5°. The telescopes were placed 7.5° apart on the same side of the beam axis and were rotated about the center of the scattering chamber to measure the angular distributions. The angular calibration of the telescopes was established with the $^{6}Li + ^{12}C$ elastic scattering reaction by using a 30-MeV ^{6}Li beam to match the highly structured elastic scattering cross section to the data of Vineyard *et al.* [23].

A telescope composed of a 75-μm ΔE detector and a 500-μm E detector was placed on the opposite side of the beam axis at a stationary angle to monitor the target for carbon buildup and for inconsistencies in the beam charge accumulation during the experiments by monitoring the $^{6}Li + ^{12}C$ and $^{7}Li + ^{12}C$ elastic scattering peaks. It was observed that the target thickness was constant during the experiment.

The absolute differential cross section normalization was obtained in the following way. The signal from the ΔE detector preamplifier was split into two signals and shaped with two separate amplifiers. The gain for the first amplifier was set to measure the energy loss from deuterons or protons passing through the ΔE detector. The gain for the second amplifier was set to measure the $^{7}Li + ^{12}C$ or $^{6}Li + ^{12}C$ elastic scattering, since ^{7}Li and ^{6}Li from the elastic scattering are stopped in the ΔE detector at these energies. These separate amplifier signals were then measured by the data acquisition computer with separate ADCs. This allowed simultaneous measurement of $^{12}C(^{7}Li,^{7}Li)^{12}C$ and $^{12}C(^{7}Li, d)^{17}O$ [and $^{12}C(^{6}Li,^{6}Li)^{12}C$ and $^{12}C(^{6}Li, p)^{17}O$] at the same angle. Since a previous measurement of the absolute differential cross section for $^{12}C(^{7}Li,^{7}Li)^{12}C$ at 34 MeV was available [23], the absolute differential cross sections for $^{12}C(^{7}Li, d)^{17}O$ were found by normalizing the angular distributions of the reactions to the elastic scattering data. A similar procedure was used to find the absolute differential cross sections for $^{12}C(^{6}Li, p)^{17}O$.

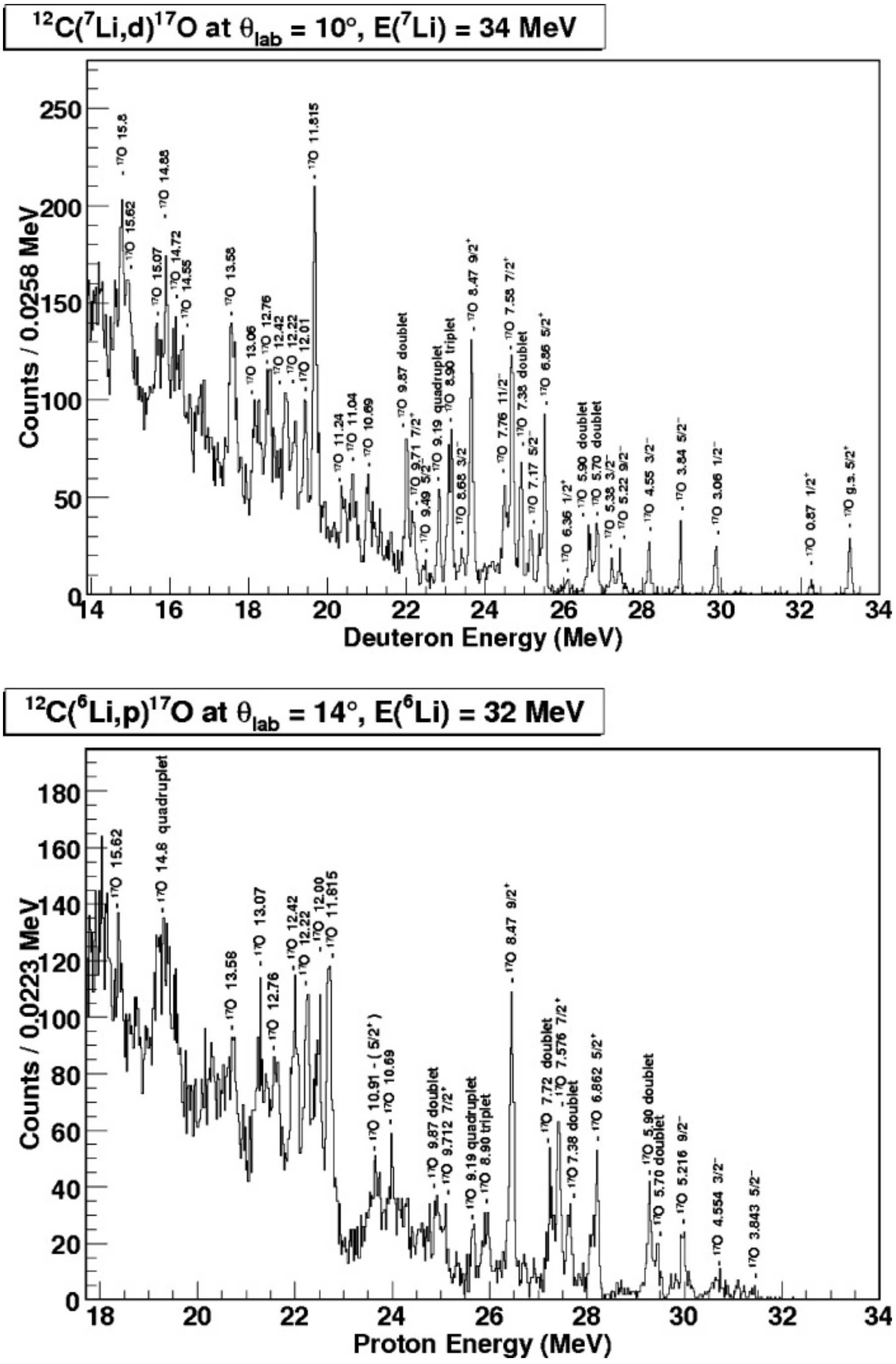

FIG. 1. Sample spectra measured in the experiments.

The statistical errors in the cross-section measurements shown are the size of the data points unless otherwise indicated by error bars. The absolute uncertainty in the normalization of the cross section is ±7% and arises from uncertainties from beam current integration (3%), repeatability (3%), angle setting (2%), and counting statistics (<1%). These uncertainties are the same as the those given for the ^{7}Li $+ ^{12}$C elastic scattering data [23].

Sample spectra from the ^{12}C(^{7}Li, d)^{17}O and ^{12}C(^{6}Li, p)^{17}O measurements are shown in Fig. 1. Whereas the states at low excitation energy are, in general, weakly populated, there are several states at excitation energies above 6 MeV that appear to be selectively populated in both reactions. Of these states, only the 6.86-MeV, $5/2^{+}$ and 7.58-MeV, $7/2^{+}$ states currently have suggested spin and parity assignments. The spin and parity of the 8.47-MeV state have been reported as either $7/2^{+}$ [8] or $9/2^{+}$ [4]. The present work confirms the existence of the 10.69- and 12.00-MeV states that were previously observed by Smithson *et al.* [16]. Although the 10.69-MeV state does not appear in the most recent ^{17}O compilation [24], it has been observed in ^{14}N(^{6}Li,^{3}He)^{17}O [9]. These states, in addition to the strongly populated states at 11.82, 12.22, and 12.42 MeV, do not have spin and parity assignments, and among these states, only the 11.82-MeV state was investigated by a previous DWBA analysis [8].

Figure 1 shows that there are other strongly populated levels in ^{17}O going up to ≈16 MeV excitation. Perhaps the most striking feature seen in the spectra is the clear 3-MeV gap between the selectively excited states at 8.47 and 11.82 MeV. The levels marked in Fig. 1 were observed in both reactions, although ^{12}C(^{7}Li, d) had better resolution (about 110 keV) and allowed for better separation of the states at high excitation energy. The high level density of previously reported levels above 9 MeV in ^{17}O makes it difficult to correlate the levels observed in this work with those currently known. Previously determined level widths have been used to either confirm or correlate the levels with those in the compilation [24]. For excitation energies above 12.5 MeV, the levels observed at 12.76, 13.07, 13.58, 14.72, and 15.8 MeV correspond to those in the compilation. However, although ^{17}O levels have been previously reported near 14.55, 14.88, 15.07, and 15.62 MeV, either the widths of these levels have not been reported or they have experimental widths that are too wide to be the same levels that were populated in the current work. Note that for states above 14.5 MeV, the exact determination of the width was not possible because of the background from the continuum. The energies and widths of the ^{17}O levels observed in this work are reported in Table I.

Several other measurements were made during the course of this study. The first was to determine whether the high-lying levels selectively excited in the five-particle transfer reactions could also have some single-particle strength by using the ^{16}O(d, p) reaction with a 16-MeV deuteron beam. This measurement agreed with (d, p) studies at lower energies [1,2] that showed the major s-d single-particle strength to be exhausted by 5.7-MeV excitation in ^{17}O.

TABLE I. ^{17}O states selectively populated in five-particle transfer reactions.

^{17}O state (MeV ± keV)[a]	Width (keV)
6.86 ± 13	<0.1[c]
7.58 ± 13	<0.1[c]
8.47 ± 13	2.13 ± 0.11[c]
10.69 ± 26[e]	<40[d]
11.82 ± 13	12 ± 3[c]
12.00 ± 26[e]	<50[d]
12.22 ± 26	⩽ 20[c]
12.42 ± 26	<50[d]
12.76 ± 26[e]	<70[b]
13.06 ± 26	16 ± 4[c]
13.58 ± 26	68 ± 19[c]
14.55 ± 26[e]	
14.72 ± 26	35 ± 11
14.88 ± 26[e]	
15.07 ± 26[e]	
15.62 ± 26[e]	
15.8 ± 26	⩽ 30[c]

[a] This work (see Fig. 1).

[b] This work. Width reported is estimated based on the FWHM of the peak in the ^{12}C(^{7}Li, d) data.

[c] Width taken from Tilley *et al.* [24].

[d] Width taken from Smithson *et al.* [16]. Width measurement limited by detector resolution of the ^{12}C(^{6}Li, p) measurement.

[e] New level in ^{17}O.

The second measurement was to obtain a spectrum for ^{13}C(^{6}Li, d)^{17}O with good energy resolution (≈40 keV) to confirm the weak population of the 6.86- and 7.58-MeV levels in four-particle transfer reactions. The measured spectrum was similar to those observed in previous measurements [10,11,25].

A third set of measurements was designed to look for possible rapid fluctuations in the population of ^{17}O levels by the ^{12}C(^{7}Li, d) reaction that could be caused by possible strong resonances in the compound system. As already noted, the selective population of the same levels with roughly the same relative strengths was found for data taken between 26 and 32 MeV in the ^{12}C(^{6}Li, p) reaction. The same result was found for ^{12}C(^{7}Li, d) for ^{7}Li bombarding energies between 32 and 35 MeV.

III. DWBA CALCULATIONS

DWBA calculations were performed with the code FRESCO [26] to study the structure of states that were selectively populated in ^{12}C(^{6}Li, p) and ^{12}C(^{7}Li, d). For all the calculations in this work, it was assumed the five particles were transferred directly onto ^{12}C$_{\mathrm{g.s.}}$ as a ^{5}He cluster. All the calculations presented here include the full complex remnant term [27] that ensures good agreement between the post and prior formulations of DWBA. Overall, the method of calculation was similar to that used in Ref. [28].

The entrance channel potentials for both the ^{6}Li + ^{12}C and ^{7}Li + ^{12}C systems were taken from Vineyard *et al.* [23]. The p + ^{17}O exit channel potential was taken from the p + ^{16}O potential of van Oers and Cameron [29], as was also assumed in the DWBA calculations of Smithson *et al.* [16]. The d + ^{17}O exit channel potential was that of Li *et al.* [30]. Becuase of the lack of ^{5}He + ^{12}C binding potentials, a binding potential for α + ^{13}C [28] was assumed. The calculations were found to be most sensitive to the choice of the ^{6}Li and ^{7}Li bound-state potentials that describe the binding of the ^{5}He cluster to ^{6}Li and ^{7}Li. For ^{6}Li → p + ^{5}He, the binding potential developed by Y. Kudo *et al.* [31] for describing the reaction ^{12}C(p, ^{6}Li) was used. For ^{7}Li → d + ^{5}He, the binding potential previously employed by Refs. [20,32] was used. The potentials, once established for the two reactions, were then kept constant for all the calculations presented. The potentials used in the calculations are summarized in Table II.

Although the measured angular distributions are rather structureless, they are sufficiently different that it was possible to extract L transfers from them, which would then suggest possible spin values for these selectively excited states. The first calculations carried out were for states that had been previously observed. States that appear strong in five-particle transfer but are weak in other reactions are at 6.86 and 7.58 MeV. The 8.47-MeV state could not be separated from

TABLE II. Parameters of the potentials for the reaction channels considered in the DWBA calculations. Radius parameters are given as $R_x = r_x \times (A_{\text{proj}}^{1/3} + A_{\text{tar}}^{1/3})$.

Entrance channel system	Type[a]	V_0 (MeV)	r_R (fm)	a_r (fm)	W_0 (MeV)	r_I (fm)	a_I (fm)	Ref.
^{6}Li + ^{12}C	WSV	244	0.65	0.75	9.95	1.16	0.78	[23]
^{7}Li + ^{12}C	WSV	290	0.64	0.64	10.71	1.22	0.97	[23]
Exit channel system								
^{17}O + p	WSV	48.43	1.142	0.726				[16,29]
^{17}O + p	GS				7.28	1.268	0.676	[16,29]
^{17}O + p	SO	−5.63	1.114	0.585				[16,29]
^{17}O + d	WSV	85.14	1.15	0.74	3.7[b]	1.55	1.04	[30]
^{17}O + d	SO	2.29[b]	0.92	0.74				[30]
Bound-state potential system	Type[a]	V_0 (MeV)	r_R (fm)	a_r (fm)	r_c (fm)	E_B (MeV)		
^{6}Li → p + ^{5}He	WSV	81.51	1.11	0.65	1.11	4.59		[31,33]
^{7}Li → d + ^{5}He	WSV	85.2	0.85	0.65	0.85	9.61		[20,32]
^{12}C + ^{5}He → ^{17}O	WSV	68.32	0.85	0.65	0.85	0.01[c]		[28][d]

[a] WSV = Woods-Saxon volume; GS = Gaussian shape surface; SO = spin orbit.

[b] The well depths were adjusted to account for the difference in beam energies.

[c] Weak binding is assumed here even though final states are unbound.

[d] Because of the lack of ^{12}C + ^{5}He binding potentials, an α + ^{13}C binding potential was used in the calculations.

its nearby neighbor at 8.50 MeV in the current work, but the much higher resolution work of Smithson *et al.* shows that the 8.47-MeV state is stronger in the (^{6}Li, p) reaction. The angular distributions for these three states were chosen to determine whether the data could be explained by DWBA calculations because it was believed that their spins and parities were well established. However, this is not the case. The 6.86-MeV state has a tentative assignment of ($5/2^+$), and this appears to be largely based on the firm assignment of a proposed mirror state in ^{17}F. The 7.58-MeV state has a tentative assignment of ($7/2^+$) in the 1993 ^{17}O data evaluation [24], but in the current NNDC database of ^{17}O levels it is listed as $7/2^-$. The $7/2^-$ assignment appears to be based on the assignment of $7/2^-$ to a state at 7.55 MeV in ^{17}F, but there are states around 7.4 MeV in ^{17}F with no spin and parity assignment that could also easily be compared with that of the 7.58-MeV state in ^{17}O. The 8.47-MeV state has a tentative assignment of ($9/2^+$) in the 1993 data evaluation [24], but it appears as $7/2^+$ in the NNDC level listing. Given these disagreements in the spin assignments for these levels, the DWBA analysis in this work attempts to clear up these discrepancies.

The L and J^π values for the selectively populated excited states in ^{17}O with undetermined spin were selected in the following way. DWBA calculations for $0 \leqslant L \leqslant 6$ were performed for a given J^π to determine the L transfer that gave the best description of the data. In general, the best L and J^π values for each state were able to describe the angular distributions obtained for both reactions.

Once the values of L and J^π were determined, the number of nodes, N, was chosen according to the oscillatory energy conservation relation $2(N-1) + L + 1 = \Sigma_{i=1}^{5} 2(n_i - 1) + l_i$ [34], where (n_i, l_i) are the single-nucleon shell quantum numbers resulting from the placement of the five nucleons above the ^{12}C$_{g.s}$ core. The convention where the number of radial nodes is $N \geqslant 1$ is adopted as it is in FRESCO. To conserve parity in the calculations, the final choice of L limits the number of possible configurations. For example, following the aforementioned relation, the three-particle configuration $^{12}\text{C}_{\text{g.s.}} + (1p_{1/2})^2(1d_{5/2})^3$ (parity +) is only possible for L odd and the two-particle configuration $^{12}\text{C}_{\text{g.s.}} + (1p_{1/2})^3(1d_{5/2})^2$ (parity −) is only possible for L even.

The N value chosen for the calculations corresponds to the mp-nh configuration suggested by previous transfer reaction experiments that have also selectively populated the states studied. The results of the previous experiments are summarized in Table III. The spectra in Fig. 1 show a 3-MeV gap between the strongly excited states at 8.47 and 11.82 MeV. Consequently, the states above 11.82 MeV were assumed to have 5p-4h configuration with the five transferred particles going into the s-d shell. The exception was the 12.22-MeV state, where only calculations that resulted in a negative-parity state (even L) described the data. However, in all of the calculations changing the N value only affected the normalization of the calculations with respect to the data and did not change the shape of the predicted angular distribution. Thus, the choice of N was somewhat arbitrary, depending on the structure assumed for each state.

IV. RESULTS OF THE DWBA CALCULATIONS

The 6.86-MeV excited state in ^{17}O has been given a tentative spin assignment of $J^\pi = (5/2^+)$ [24]. A good description of the angular distributions of both reactions was obtained with an $N = 3$, $L = 3$ calculation by assuming $J^\pi = (5/2^+)$. Thus, these results support the spin and parity assignment of the data evaluation. The comparison of the DWBA calculations to the measured data is shown in Fig. 2.

For the $^{17}\text{O}^*_{7.58}$ data, agreement between the two reactions was obtained with an $N = 2$, $L = 5$ calculation by assuming $J^\pi = 7/2^+$. This result supports the data evaluation of Tilley *et al.* [24] but does not agree with the NNDC listing. Note also

TABLE III. States in ^{17}O selectively populated in five-particle transfer reactions compared with other transfer reactions.[a]

Level (MeV)	2 particle[b]		3 particle[c]		4 particle[d]		5 particle[e]	
	^{15}N(α, d)	^{15}N(^{3}He,p)	^{14}N(^{6}Li,^{3}He)	^{14}C(^{6}Li,t)	^{13}C(^{6}Li,d)	^{13}C(^{7}Li,t)	^{12}C(^{6}Li,p)	^{12}C(^{7}Li,t)
6.86		weak	X		weak	weak	X	X
7.58		X			weak	weak	X	X
8.47 + 8.50	X	X	X	X	X	X	X	X
10.69		weak	X				X	X
11.82				X	weak	X	X	X
12.00			X	weak			X	X
12.22	X			X			X	X
12.42						X	X	X

[a] X = selectively populated; weak = weakly populated; blank = not observed.
[b] References [5,6].
[c] References [7–9].
[d] References [10,11].
[e] Reference [16] and this work.

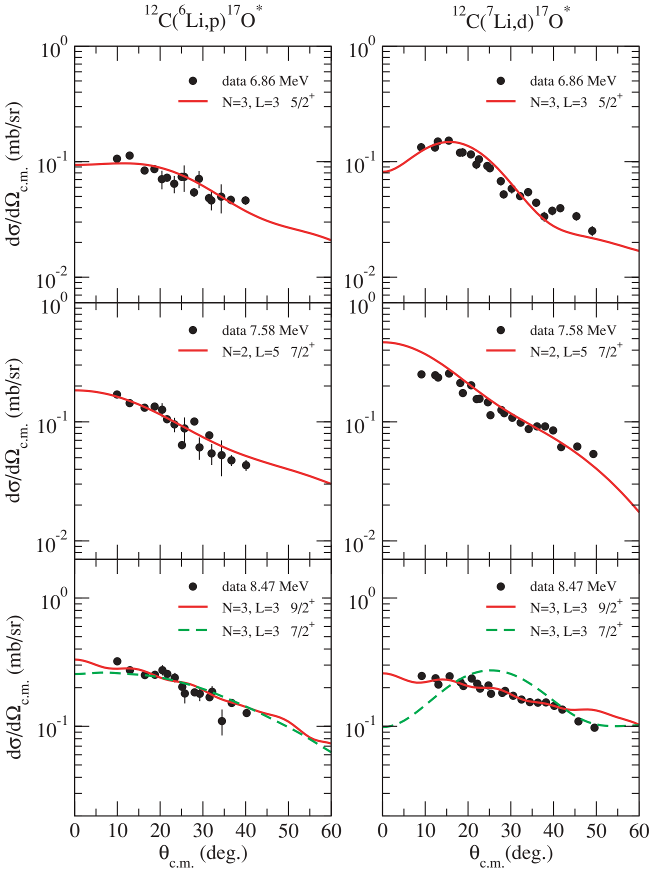

FIG. 2. (Color online) Angular distributions measured in this work for the ^{17}O*6.86−, 7.58−, and 8.47-MeV states. The data measured in this work from ^{12}C(^{6}Li, p) are shown on the left and the data from ^{12}C(^{7}Li, d) are shown on the right. The solid lines show the results of the DWBA calculations. Note that for the 8.47-MeV state, the $J^\pi = 9/2^+$ calculations give the best description overall for both reactions (see text for discussion).

that, to change the parity in the calculations in this work, it is necessary to also change the L value in the DWBA calculation. An even L value that reproduced the measured angular distributions was not found. It follows then that the results of this work support that this state has $J^\pi = 7/2^+$.

In transfer reaction measurements such as those of Ref. [8], $J^\pi = (7/2^+)$ is reported for the $^{17}\mathrm{O}^*_{8.47}$ state. However, this spin assignment results from an $L = 4$ transfer of a ^{3}He, which implies that the spin of this state could also be $J = L + 1/2 = 9/2$. Recent measurements of inelastic electron scattering [4] have also suggested that the spin for this state should be $(9/2^+)$. In addition, the strong population of the $^{17}\mathrm{O}^*_{8.47}$ state in five-particle transfer reactions, which are highly angular momentum mismatched, favors the higher spin assignment. A search of L values was conducted by assuming both possible spin values for the 8.47-MeV state. It was found that if $J^\pi = 7/2^+$ was assumed, no satisfactory description of the (^{7}Li, d) angular distribution could be obtained. However, for $J^\pi = 9/2^+$, both data sets could be described with an $N = 3$, $L = 3$ calculation. We present the DWBA calculations for the two reactions for the $^{17}\mathrm{O}^*_{8.47}$ state, assuming both $J^\pi = 7/2^+$ and $9/2^+$, in Fig. 2.

The angular distributions for the $^{17}\mathrm{O}^*_{11.82}$ state were most similar in shape to those of the $^{17}\mathrm{O}^*_{7.58}$, $J^\pi = 7/2^+$ state for both reactions. Thus, $J^\pi = 7/2^+$ was also assumed for the DWBA calculations of this state. The results of these calculations are shown in Fig. 3, and a good description of the data for both reactions was obtained.

The angular distribution of the $^{17}\mathrm{O}^*_{12.00}$ state measured in this work was observed to be less forward-peaked than the 11.82-MeV state, and the data for the (^{7}Li, d) reaction most closely resembled that of the 8.47-MeV state. Given the result just described for the 8.47-MeV state, $J^\pi = 9/2^+$ was also tried for the 12.00-MeV state calculations. Reasonable descriptions of both data sets were found with $N = 3$, $L = 3$. Similar calculations were also carried out for the $^{17}\mathrm{O}^*_{12.42}$ state,

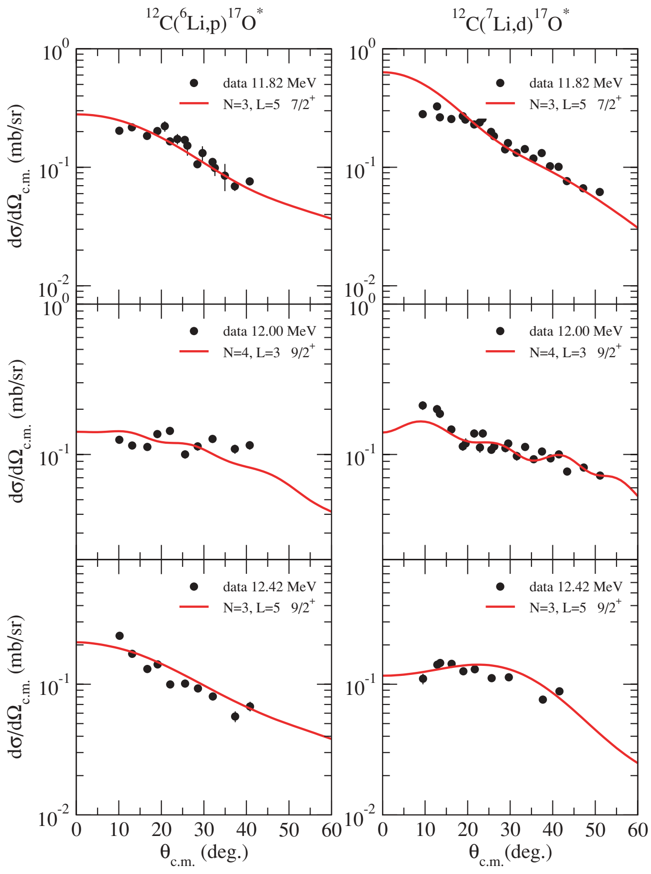

FIG. 3. (Color online) Angular distributions measured in this work for the ^{17}O* 11.82-, 12.00-, and 12.42-MeV states. The data measured in this work from ^{12}C(^{6}Li, p) are shown on the left and the data from ^{12}C(^{7}Li, d) are shown on the right. The solid lines show the results of the DWBA calculations. In these DWBA calculations, the 5p-4h particle configuration is assumed (see text for discussion).

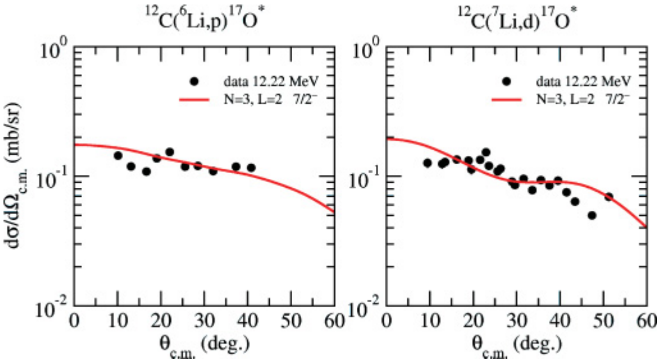

FIG. 4. (Color online) Angular distributions measured in this work for the ^{17}O* 12.22-MeV state. The data measured in this work from ^{12}C(^{6}Li, p) are shown on the left and the data from ^{12}C(^{7}Li, d) are shown on the right. The solid lines show the results of the DWBA calculations (see text for discussion).

although in this case a higher L transfer ($L = 5$) was required to reproduce the data.

Despite numerous searches with different values for J, it was difficult to find a good description of the angular distribution data for $^{17}\mathrm{O}^*_{12.22}$. No DWBA calculation with positive parity gave satisfactory results for both reactions. The results obtained from the $L = 1$ and $L = 3$ calculations seemed to suggest an L value that was in between the two, but, as was previously mentioned, to switch to an even L value required a parity change. Thus, when $J^\pi = 7/2^-$ was assumed, the $L = 2$ calculation produced a reasonable description of both data sets (Fig. 4).

The best values for N, L, and J^π obtained in this work for the DWBA calculations are summarized in Table IV.

V. CONCLUSION

The present work was undertaken to explore the high-lying structure of ^{17}O through multiparticle transfer reactions. Because ^{17}O should be an excellent nucleus to test nuclear structure models it would seem that the spins and parities of its low-lying (<10 MeV) states should be well established by now. However, this is not the case and this is due to the very low threshold for neutron emission (4.1 MeV), which makes traditional means for determining spins and parities through γ-ray measurements impossible. There have been very clear spin-parity assignments made through resonance

TABLE IV. Best values of N, L, J^π, and $C^2S_{(^5\mathrm{He})}$ used in the DWBA calculations.

State	^{12}C(^{6}Li, p)					^{12}C(^{7}Li, d)				
(MeV)	N	L	J^π	$C^2S_{(^5\mathrm{He})}$[d]	Config.	N	L	J^π	$C^2S_{(^5\mathrm{He})}$[d]	Config.
6.86	3	3	$5/2^+$	0.30	a	3	3	$5/2^+$	0.53	a
7.58	2	5	$7/2^+$	0.25	a	2	5	$7/2^+$	0.59	a
8.47	3	3	$9/2^+$	0.81	a	3	3	$9/2^+$	1.06	a
11.82	3	5	$7/2^+$	0.23	b	3	5	$7/2^+$	0.96	b
12.00	4	3	$9/2^+$	0.28	b	4	3	$9/2^+$	0.56	b
12.22	3	2	$7/2^-$	1.32	c	3	2	$7/2^-$	2.16	c
12.42	3	5	$9/2^+$	0.20	b	3	5	$9/2^+$	0.77	b

[a] Assumed ^{17}O particle configuration $^{12}\mathrm{C}_{\mathrm{g.s.}} + (1p_{1/2})^2, (1d_{5/2})^3$-(3p-2h).
[b] Assumed ^{17}O particle configuration $^{12}\mathrm{C}_{\mathrm{g.s.}} + (1p_{1/2})^0, (1d_{5/2})^5$-(5p-4h).
[c] Assumed ^{17}O particle configuration $^{12}\mathrm{C}_{\mathrm{g.s.}} + (1p_{1/2})^3, (1d_{5/2})^2$-(2p-1h).
[d] Values given are the squares of the spectroscopic amplitudes used in the FRESCO calculations.

reactions but the states populated by multiparticle transfer reactions are generally not seen in the resonance reactions. Consequently, the works to date including the present one have relied on theoretical transfer models such as the DWBA to extract information. It is therefore important to mention that the results reported in this work depend on the model used to interpret them, and that perhaps slightly different N, L, and J^{π} values would be found for these new states if a reaction model other than single-step direct transfer of five particles were chosen.

The present work selectively populates the same levels with the ^{12}C(^{7}Li, d) reaction as seen in an earlier ^{12}C(^{6}Li, p) experiment. Angular distributions have been obtained for the strongly excited states for both reactions and suggested spin-parity assignments are made under the assumption that both reactions can be described with the same reaction model. The data are consistent with ^{5}He cluster transfer, so these reactions can be added to the more commonly studied two-, three-, and four-particle transfer reactions. Whereas the level density in ^{17}O is high for excitation energies above 8 MeV, it has been possible to show that several of the strongly excited levels are not consistent with those appearing in the current ^{17}O compilations. The rich structures present in ^{17}O that can now be obtained from the multiparticle transfer reactions published to date should allow for this nucleus to be an excellent further test of molecular models such as have been applied previously to the carbon isotopes [17].

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