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PHYSICAL REVIEW C VOLUME 2, NUMBER 2 AUGUST 1970

Level Structure of ^{17}O and the ^{13}C(^{6}Li,d) and ^{13}C(^{7}Li,t) Reactions*

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(Received 16 April 1970)

The reactions ^{13}C(^{7}Li,t)^{17}O and ^{13}C(^{6}Li,d)^{17}O have been studied at 17 and 18 MeV, respectively. Both reactions are selective in the states they populate, although this is more evident in the (^{7}Li,t) case. Angular distributions were extracted for 15 levels below 8.5-MeV excitation. These exhibit pronounced structures and are generally indicative of direct-reaction mechanisms. Transitions to the negative-parity states at 3.06, 3.85, and 4.55 MeV are the strongest observed below 7-MeV excitation. These levels are discussed within the framework of the weak-coupling model and the transitions compared with those from the ^{12}C(^{7}Li,t) and ^{12}C(^{6}Li,d) reactions leading to the first $K=0$ rotational band in ^{16}O. Strong transitions are also observed to levels at 7.38, (8.46, 8.49), (8.87, 8.95), and (9.14, 9.20) MeV.

I. INTRODUCTION

The level structure of ^{17}O has been the subject of many experimental and theoretical studies.[1-12] The simple shell model which treats the ^{16}O core as inert is unable to account for the low-lying negative-parity states or the multiplicity of positive-parity states which lie just above 5-MeV excitation. These states originate from excitations of the core and a number of calculations have been performed for ^{17}O within the framework of an excited-core model.[8-12]

In order to investigate the particle-hole configurations of ^{17}O, it is convenient to employ transfer reactions in which the "hole" component is already present in the target nucleus. In this respect, ^{6,7}Li-induced reactions offer a convenient means for studying ^{17}O. In particular, recent studies[13,14] of the α-transfer reactions (^{6}Li, d) and (^{7}Li, t) with nuclei in the $2s$-$1d$ shell have shown them to be rather selective in the states they populate and that a direct-reaction mechanism plays an important role. It was therefore of interest to determine whether the ^{13}C(^{6}Li, d) and ^{13}C(^{7}Li, t) reactions would also show similar selectivity, and in particular it was hoped that the negative-parity states in ^{17}O having predominantly 4p-3h configurations could be identified. For purposes of comparison, the latter also prompted a study of the ^{12}C(^{6}Li, d) and ^{12}C(^{7}Li, t) reactions leading to the first $K=0$ rotational band in ^{16}O.

II. EXPERIMENTAL TECHNIQUES AND RESULTS

The ^{13}C(^{6}Li, d) and ^{13}C(^{7}Li, t) reactions were studied using 18-MeV ^{6}Li-ions and 17-MeV ^{7}Li-ions from the University of Pennsylvania tandem accelerator. Self-supporting ^{13}C targets were employed with 60 ± 14 μg/cm^2 thickness, as determined from a differential weighing measurement. The deuterons and tritons were momentum-analyzed in a multiangle spectrograph over an angular range $3\frac{3}{4}$ to $172\frac{1}{2}°$ and detected in nuclear emulsions. The angular interval with which distributions could be measured in a single exposure was $7\frac{1}{2}°$. However, by rotating the spectrograph through $3\frac{3}{4}°$ and performing two exposures for each reaction, angular distributions were obtained in $3\frac{3}{4}°$ intervals.

A deuteron spectrum measured at 30° and a triton spectrum at $7\frac{1}{2}°$ are shown in Fig. 1. The overall energy resolutions (full width at half maximum) were 60 and 85 keV for the (^{6}Li, d) and (^{7}Li, t) studies, respectively, determined mainly by the target thicknesses. Groups corresponding to states in ^{17}O are indicated by their corresponding excitation energies and those to states in ^{16}O are shown cross hatched. The latter arise from ^{12}C impurity in the ^{13}C targets, and from carbon buildup during the exposures. The relative strengths of groups ^{16}O$_6$ and ^{16}O$_7$, indicated by the broken lines in the spectra, were determined from a separate study of the (^{6}Li, d) and (^{7}Li, t) reactions on ^{12}C (see below).

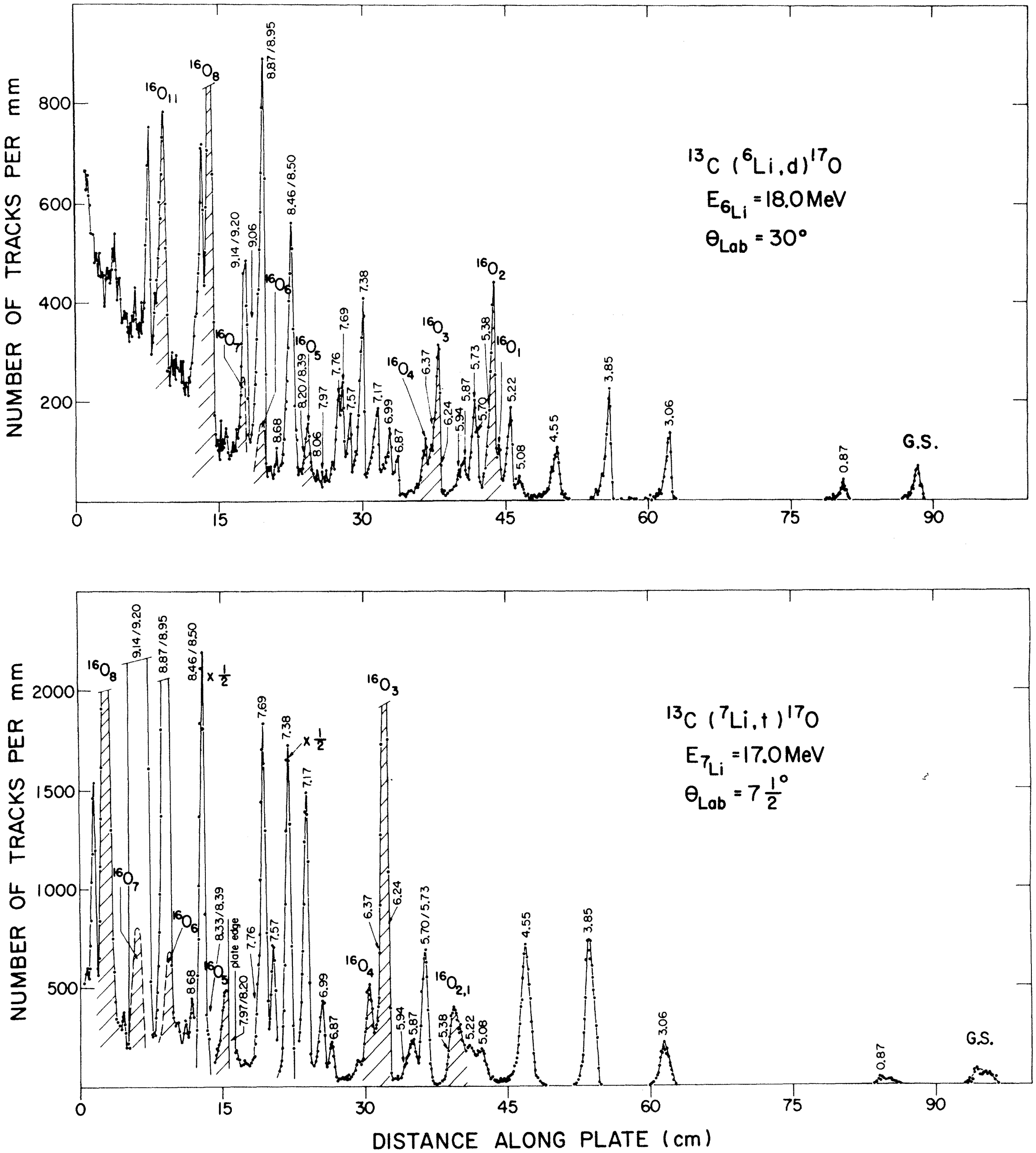

FIG. 1. Deuteron and triton spectra from the $^{13}C(^{6}Li, d)$ and $^{13}C(^{7}Li, t)$ reactions. Groups corresponding to states in ^{17}O are indicated by the corresponding level energies. Those corresponding to states in ^{16}O are shown cross hatched and arise from ^{12}C contaminant in the target.

The rapid increase in background observed at higher excitations in the $(^{6}Li, d)$ spectrum of Fig. 1 is probably due to ^{6}Li breakup in the nuclear and Coulomb fields of the target nucleus.

Angular distributions have been extracted from both reaction studies on ^{13}C and these are shown in Figs. 2 and 3. They include the first seven states in ^{17}O and eight higher states which were clearly resolved or were fed by relatively strong transitions. Owing to the rapid kinematic shift with angle, particle distributions over the full angular range were only possible for the first two

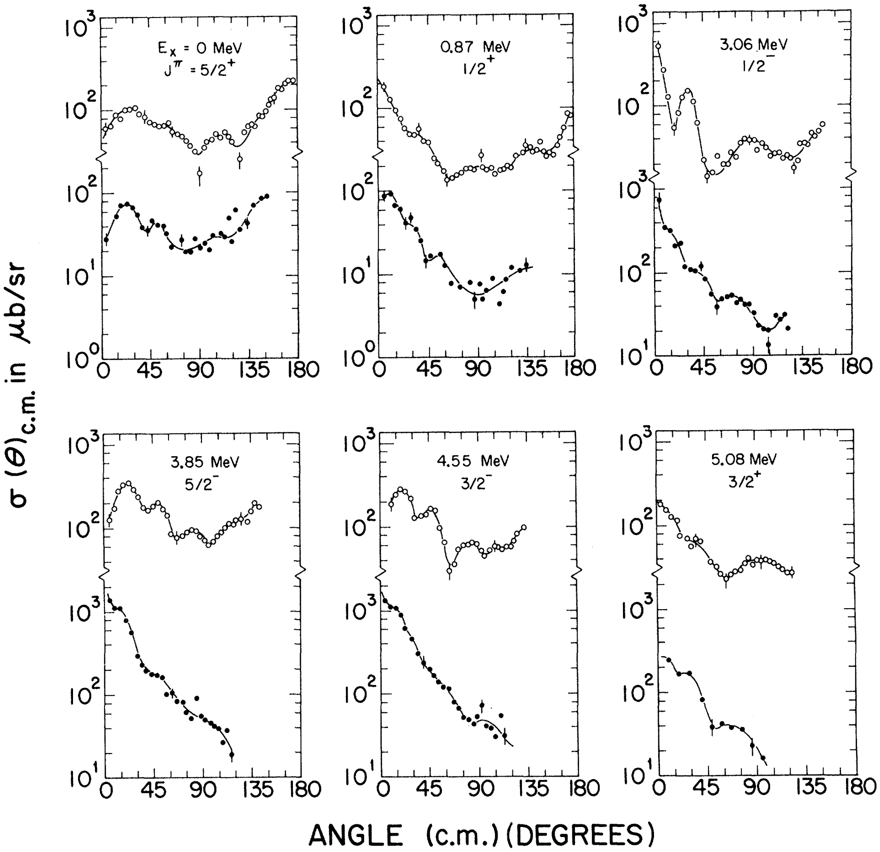

FIG. 2. Particle distributions from the ^{13}C(^{6}Li, d) reaction (open circles) and the ^{13}C(^{7}Li, t) reaction (filled circles) leading to the first six states of ^{17}O. For clarity, representative errors only are shown. The spin-parity assignments are from Table I.

states in the (^{6}Li, d) study. Since states above 8.5-MeV excitation were observed in only a very limited angular range, their distributions are not presented here. The energy resolution from the second of the two ^{13}C(^{7}Li, t) exposures was significantly worse than that from the first, and data could only be reliably extracted from this exposure for the first few isolated levels.

The level scheme for ^{17}O up to 9-MeV excitation is summarized in Table I. Below 7.9 MeV, the excitation energies are from Ajzenberg-Selove and Lauritsen[1] except for the level at 7.76 MeV. This state has not previously been reported but is seen in both the present work and in the ^{15}N(^{3}He, p)^{17}O reaction.[15] With some exceptions (see footnotes to Table I), the spin-parity assignments in this excitation range are also from Ref. 1. Above 7.9 MeV the level energies and J^{π} assignments are those reported by Barnes, Belote, and Risser[2] from measurements of the ^{13}C(α, α) and ^{13}C(α, n) reactions.

In Fig. 4 are shown particle distributions from the ^{12}C(^{6}Li, d) and ^{12}C(^{7}Li, t) reactions leading to the 6.06-, 6.92-, and 10.35-MeV states in ^{16}O. The incident energies were again 18 and 17 MeV, respectively, and the measurements were made with natural methane gas and a differentially pumped gas cell with a windowless beam entry port. The gas pressure was maintained close to 15 Torr, equivalent to about 9-μg/cm^2 target thickness. The (6.01, 6.12)-MeV doublet in ^{16}O was clearly resolved in both reactions. The full curves shown in Fig. 4 are experimental distributions for the 3.06- and 4.55-MeV states of ^{17}O. These comparisons are discussed in the following section.

III. DISCUSSION

Many of the characteristics of the (^{6}Li, d) and (^{7}Li, t) reactions which have been observed with heavier nuclei[13,14] are also exhibited in the present work. Thus, whereas the (^{6}Li, d) reaction appears to be only moderately selective, the (^{7}Li, t) reaction is highly so, as is evident from the spectra of Fig. 1. The cross sections are generally higher in the (^{7}Li, t) reaction, and the angular distributions exhibit more pronounced forward maxima but have less oscillatory structures than those

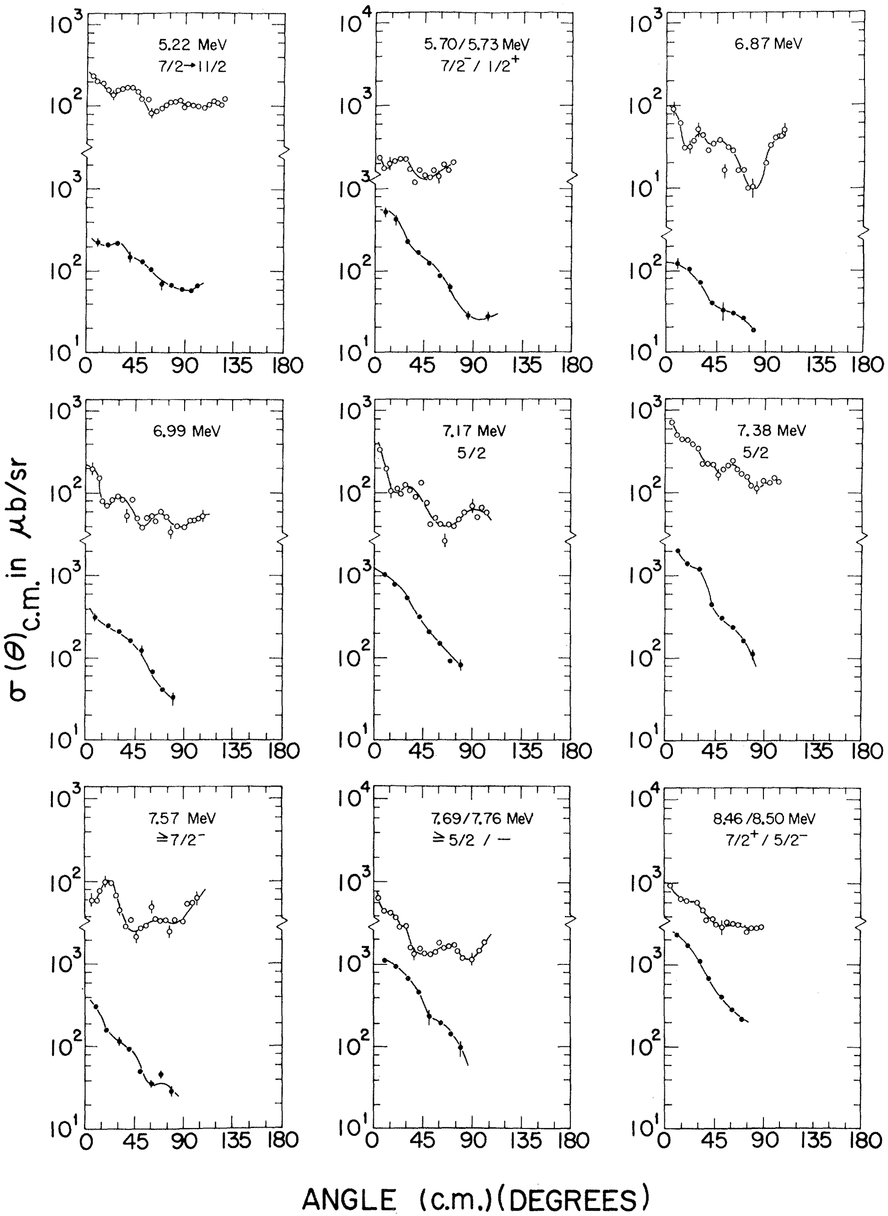

FIG. 3. Particle distributions from the $^{13}C(^{6}Li, d)$ reaction (open circles) and $^{13}C(^{7}Li, t)$ reaction (filled circles) leading to states of ^{17}O between 5- and 8.5-MeV excitation. Representative errors only are shown. The spin-parity assignments are from Table I.

from $(^{6}Li, d)$.

The angular distributions from both reactions, however, appear to be characteristic of a direct mechanism. In the transitions to the 0.87- and 5.08-MeV states, the α-particle should be captured with the same orbital angular momentum (i.e., $L=1$) and the corresponding angular distributions (Fig. 2) are indeed seen to be very similar. The same applies to the states at 3.85 and 4.55 MeV, for which the angular momentum of the captured α particle in the final state should be $L=2$. If the ground and 3.06-MeV distributions are also considered, which correspond to $L=3$ and $L=0$ capture, respectively, it is evident that the distributions exhibit progressively broader forward peaks with increasing L value in both the $(^{6}Li, d)$ and $(^{7}Li, t)$ reactions.

Of particular interest in the present study are the strong transitions to the three negative-parity states at 3.06 MeV ($\frac{1}{2}^-$), 3.85 ($\frac{5}{2}^-$), and 4.55 ($\frac{3}{2}^-$). Since it is known that in ^{16}O the 4p-4h state lies lower than the 2p-2h state,[12,16] it has been suggested[9] that the first $\frac{1}{2}^-$ state in ^{17}O should contain mostly

TABLE I. Differential cross sections from the ^{13}C(^{6}Li,d)^{17}O and ^{13}C(^{7}Li,t)^{17}O reactions.

E_x [a] (MeV)	J^π [b]	$d\sigma/d\omega$ in μb/sr [c] (^{6}Li,d)	(^{7}Li,t)	E_x [a] (MeV)	J^π [b]	$d\sigma/d\omega$ in μb/sr [c] (^{6}Li,d)	(^{7}Li,t)
0	$5/2^+$	105	75	7.28	$3/2^+$	i	i
0.871	$1/2^+$	180	92	7.382	5/2	720	2000
3.058	$1/2^-$ [d]	560	750	7.569	$7/2^-$ [g]	98	310
3.846	$5/2^-$ [d]	340	1400	7.685	⩾5/2 }		
4.551	$3/2^-$	285	1350	7.72	$3/2^-$ }	620	1100
5.082	$3/2^+$	180	250	7.76	}		
5.215	7/2 – 11/2 [e]	245	230	7.970	$1/2^-$	i	i
5.377	$3/2^-$	h	h	8.064	$3/2^+$	h	h
5.695	$7/2^-$ }	230	530	8.197	$3/2^-$	i	i
5.731	$1/2^+$ [f] }			8.332	$1/2^+$	i	i
5.866	$3/2^+$ [f] }	90	150	8.393	$5/2^+$	i	i
5.936	$1/2^-$ }			8.460	$7/2^+$ }	940	2400
6.24		h	h	8.498	$5/2^-$ }		
6.37	$1/2^+$	h	h	8.679	$3/2^-$	50	200
6.869		92	125	8.873	$3/2^+$ }		
6.99		200	320	8.884	$7/2^-$ }	1400	2000
7.170	5/2	350	1050	8.945	$7/2^-$ }		

[a] Below 7.9-MeV excitation the level energies are from Ref. 1, except for the 7.76-MeV state, which has not previously been reported. Above 1.9 MeV, the energies are from Ref. 2.

[b] Except where otherwise indicated, spin-parity assignments are from Ref. 1 for levels below 7.9-MeV excitation and from Ref. 2 for levels above 7.9 MeV.

[c] In the case of states for which angular distributions are shown (Figs. 2 and 3), the differential cross sections are the maximum (center-of-mass) values in the distributions and have estimated uncertainties of ±25%. For other states, the differential cross sections are the values measured at 30°.

[d] See Ref. 6.

[e] See Ref. 7.

[f] S. R. Salisbury and H. T. Richards, Phys. Rev. 126, 2147 (1962).

[g] See Ref. 5.

[h] Level obscured by ^{16}O contaminant group.

[i] Level unobserved in these reactions.

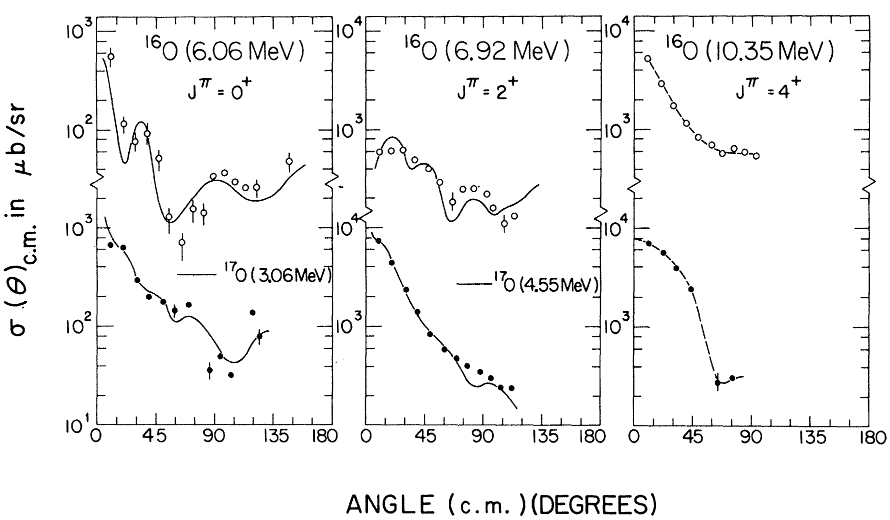

FIG. 4. Particle distributions from the ^{12}C(^{6}Li, d) reaction (open circles) and ^{12}C(^{7}Li, t) reaction (filled circles) leading to the 6.06-, 6.92-, and 10.35-MeV states of ^{16}O. The full curves are the experimental distribution shapes from the ^{13}C-(^{6}Li, d) and ^{13}C(^{7}Li, t) reactions leading to the 3.06- and 4.55-MeV levels of ^{17}O. They are not normalized to the same absolute cross-section scales shown in the figure. The dashed curves are drawn through the experimental points to guide the eye.

4p-3h configuration rather than 2p-1h. This is consistent with the large transition strengths to the 3.06-MeV state observed in this study. The next $\frac{1}{2}^-$ state at 5.94 MeV cannot be completely resolved from the 5.87-MeV level, but it is clearly much less strongly excited than the first $\frac{1}{2}^-$ state.

Further insight into the particle-hole nature of these two states can also be had from a study of the $^{15}N(^3He, p)^{17}O$ reaction, which should readily excite the 2p-1h states but not those of 4p-3h character. This reaction has recently been investigated in this laboratory[15] and the 5.94-MeV level is observed to be more strongly excited, by a factor of 2 in cross section, than the level at 3.06 MeV. Thus, although some 2p-1h configuration must be mixed into the lower $\frac{1}{2}^-$ state, this level probably has mostly a 4p-3h configuration, whereas the level at 5.94 MeV is mainly of 2p-1h character. This is also consistent with the recent shell-model calculations of Zuker,[17] who finds a mixture of approximately 75% 4p-3h and 25% 2p-1h configurations in the 3.06-MeV state.

The first $\frac{1}{2}^-$ level can be pictured as formed mainly by coupling a $1p_{1/2}$ particle to the first excited 0^+ state at 6.06 MeV in ^{16}O, since this latter state is the head of a $K^\pi = 0^+$ rotational band strongly dominated by 4p-4h components.[16] Thus, if these reactions proceed mainly by direct α capture, the angular distributions for the 3.06-MeV state in ^{17}O should be identical to those for the 6.06-MeV state of ^{16}O excited by the $^{12}C(^6Li, d)$ and $^{12}C(^7Li, t)$ reactions at the same incident energies. This comparison is made in Fig. 4 wherein, except for an apparent phase shift in the $(^6Li, d)$ reactions, the identity of shapes is well demonstrated.

Higher members of the $K = 0$ rotational band in ^{16}O occur at 6.92 MeV (2^+) and 10.35 MeV (4^+). If the coupling of a $1p_{1/2}$ particle to this band is weak, we may expect a $\frac{5}{2}^-$, $\frac{3}{2}^-$ doublet centered at about 3.9 MeV in ^{17}O, formed by coupling to the 2^+ member of the band. The ratio of transition intensities to these two states should be as $(2J+1)$, i.e., 1.5. The angular distributions for the 3.85- and 4.55-MeV states are indeed seen to be quite similar in shape to those for the 6.92-MeV level of ^{16}O (Fig. 4) and their center of gravity lies between 4.1 and 4.2 MeV, in reasonable agreement with the weak-coupling prediction. The integrated cross sections for these states are given in Table II. From this, the measured ratio of cross sections in the $(^6Li, d)$ study for the 3.85- and 4.55-MeV states is 1.3, again in reasonable agreement with the expected value. The agreement is less satisfactory, however, in the $(^7Li, t)$ reaction, where the cross-section ratio is close to unity.

Further discrepancies arise between these two reactions if absolute cross sections are compared. Thus, in the weak-coupling description for these odd-parity states, the cross sections for forming the 3.06 ($\frac{1}{2}^-$) state of ^{17}O and the 6.06 (0^+) state of ^{16}O should be equal, as also should be the summed cross sections for the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states of ^{17}O and the 6.92 (2^+) state of ^{16}O. From Table II it is apparent that, within the experimental uncertainties, reasonable agreement is obtained from the $(^6Li, d)$ study, whereas in the $(^7Li, t)$ measurements the cross sections for forming the ^{16}O states are three to four times greater than those for the corresponding ^{17}O levels.

Some departure from the weak-coupling predictions is to be expected, since it is known from the $^{15}N(^3He, p)^{17}O$ reaction[15] that some 2p-1h components are also mixed into all three states. Furthermore, the splitting of the doublet members is comparable to their separation from the $\frac{1}{2}^-$ level, which is inconsistent with the weak-coupling assumption. However, the apparent differences between the $(^6Li, d)$ and $(^7Li, t)$ reactions probably stem from the reaction mechanisms and may be due, for example, to the different kinematical conditions. Nevertheless, the cross sections for the transitions to the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states, and the overall similarity between their angular distributions and those for the collective 2^+ state of ^{16}O (Fig. 4) suggest a close correspondence between them, and point again to a large 4p-3h component for these ^{17}O levels. Birkholz and Beck,[8] working within the framework of an excited-core model, have also predicted predominantly 4p-3h configurations for these two states.

TABLE II. Integrated cross sections.

E_x (^{16}O) (MeV)	σ in mb[a] $^{12}C(^6Li,d)$	σ in mb[a] $^{12}C(^7Li,t)$	E_x (^{17}O) (MeV)	σ in mb[a] $^{13}C(^6Li,d)$	σ in mb[a] $^{13}C(^7Li,t)$
6.06	0.39	1.43	3.06	0.43	0.49
			3.85	1.15	1.01
			4.55	0.88	1.12
6.92	2.68	8.30	3.85+4.55	2.03	2.13

[a]These values were obtained by integrating the differential cross sections over the angular interval 0 to 120° in the center-of-mass system. The estimated uncertainties are ±25%.

Brown and Green[12] have described the positive-parity states of ^{17}O as arising from mixing the usual shell-model 1p-0h states with states having 3p-2h and 5p-4h configurations, obtained by exciting particles out of a deformed core. In principle, it should be possible to excite the first two components by means of the ^{13}C(^{7}Li, t) and ^{13}C-(^{6}Li, d) reactions. In those cases where these states are well resolved, however, they appear to be only very weakly excited, which would suggest that the four transferred nucleons cannot readily enter different major shells. This is also consistent with the weak transition to the predominantly 2p-1h $\frac{1}{2}^-$ state at 5.94 MeV, discussed earlier. Such a conclusion is at variance, however, with results obtained from the (^{6}Li, d) and (^{7}Li, t) reactions on nuclei in the $2s$-$1d$ shell, in which transitions involving the capture of one or more nucleons into the $1f_{7/2}$ shell are among the strongest observed.[13]

Above 7-MeV excitation, strong transitions are observed to the levels at 7.38, (8.46, 8.50), (8.87, 8.95), and (9.14, 9.20) MeV. In this region a $\frac{7}{2}^-$, $\frac{9}{2}^-$ doublet may be expected, centered around 8 MeV and formed by coupling a $1p_{1/2}$ particle to the 4^+ member of the rotational band in ^{16}O. The only known $\frac{7}{2}^-$ states among these strongly excited levels are those at 8.88 and 8.95 MeV (Table I), which could not be resolved in this work. None of the remaining levels is known to be $\frac{9}{2}^-$, although the distributions for the (8.46, 8.50)-MeV doublet are rather similar to those for the 10.35-MeV state of ^{16}O.

To conclude, it seems that some of the features of the low-lying negative-parity states of ^{17}O can be rather well described by the coupling of the motion of the extra nucleon to the low-lying collective states of the ^{16}O core. Furthermore, the present investigation shows that these features can be conveniently investigated by means of "α"-transfer reactions induced by ^{6,7}Li ions, for which, at energies around 18 MeV, a direct-reaction mechanism appears to play an important role. Further investigations with these reactions, however, are still essential to their better understanding.

ACKNOWLEDGMENTS

The authors are indebted to Dr. A. P. Zuker for communicating his results ahead of publication. It is also a pleasure to acknowledge the assistance of T. A. Caldwell and J. Powers with the data analysis. The ^{13}C targets were prepared by L. Csihas and the nuclear plates were carefully scanned by Mrs. M. Barnet, Mrs. V. Adams, and Mrs. K. Coliukos.

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*Work supported by the National Science Foundation.

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