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Levels of ^{15}C from a study of ^{9}Be(^{7}Li, p)^{15}C

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The ^{9}Be(^{7}Li, p)^{15}C reaction has been studied at $E(^{7}\text{Li}) = 20$ MeV using the Penn multiangle spectrograph. In addition to ^{15}C*(0.0, 0.74), proton groups are observed to at least 25 excited states with $E_x < 12$ MeV. Angular distributions are reported for many of these groups. $J^{\pi} = (\frac{1}{2}^-)$ and $(\frac{5}{2}^-)$ are suggested for the states ^{15}C*(3.11) and ^{15}C*(4.22), respectively. It is concluded from the small reduced width for neutron decay of suggested 2p-1h neutron states in ^{15}C that the ^{14}C(g.s.) has only a small 2p-2h neutron component.

[NUCLEAR STRUCTURE ^{9}Be(^{7}Li, p), $E = 20$ MeV; measured $\sigma(\theta)$, Γ. ^{15}C levels deduced J, π. Calculated Γ_n deduced l_n, S. Resolution 35 keV: $\theta = 3.75-168.75°$; $\Delta\theta = 7.5°$.]

I. INTRODUCTION

The ^{9}Be(^{7}Li, p) reaction [$Q_0 = 9094.2 \pm 1.4$ keV (Ref. 1)] at an incident energy of 20 MeV has been used to study the states of ^{15}C below an excitation of 12 MeV. When this study was initiated and the preliminary results reported[2] little information was available[3] concerning the level structure of ^{15}C. Early studies of the ^{9}Be(^{7}Li, p) (Refs. 4–6) and of the ^{14}C(d,p) reactions (Ref. 7) produced quite different energy level schemes for ^{15}C. A summary of these results is contained in Table I. The results of a subsequent study[8] of the ^{14}C(d,p) reaction also are presented in Table I.

Previous studies[9–12] of the Li induced proton producing reactions on light nuclei have concluded that such reactions proceed through an intermediate compound system, and it has been shown[9–12] that the measured total cross sections are proportional to $2J_f + 1$. In the present work the $2J_f + 1$ variation of total cross sections is used together with a comparison of the measured experimental total widths and widths predicted from neutron penetration of a centrifugal barrier to suggest J^{π} assignments for certain excited states of ^{15}C.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A self-supporting ^{9}Be foil, 40 μg/cm^2 thick, was bombarded by 20 MeV ^{7}Li ions accelerated in the University of Pennsylvania tandem Van de Graaff accelerator. The outgoing protons were detected in a multiangle spectrograph at 24 angles to the beam. Ilford K-5 nuclear track plates, covered with 0.032 to 0.051 cm Mylar foil to stop particles other than protons from reaching the emulsions, were used to detect the protons. Two separate exposures were made at magnetic fields of 10.687 and 8.455 kG (NMR frequencies of 45.5 and 36 MHz) because of the large kinematic shifts at large angles. Total electric charges of 6.0 and 4.0 mC were collected for the 10.687 and 8.455 kG runs, respectively.

Figure 1 shows a typical spectrum for this reaction. The groups labeled 4 and 6 on Fig. 1 each correspond to at least two closely spaced states (see Table I). Groups 9 and 10, 12 and 13, and 17 and 18 were better resolved at angles other than 11.3°. The shapes and location of the maxima of groups 14, 16, and 19 suggest that these groups correspond to unresolved and/or broad states. The states reported in this study all have $\Gamma_{\text{c.m.}} \lesssim 100$ keV. Broad or weakly populated states might not have been observed over the rising background due to multiparticle breakups.

Table I gives the measured values of E_x and $\Gamma_{\text{c.m.}}$ from the present study and compares these results with results of previous ^{9}Be(^{7}Li, p) studies[3–6] and a recent high resolution study[8] of the ^{14}C(d,p)^{15}C reaction. The present (^{7}Li, p) study populates all the levels reported from the ^{14}C(d,p)^{15}C reaction plus at least five additional levels below $E_x = 7.4$ MeV. Thus the ^{9}Be(^{7}Li, p) reaction appears to be less selective than the ^{14}C(d,p) reaction consistent with the suggested compound reaction mechanism for the (^{7}Li, p) reaction.

Angular distributions of the protons corresponding to 20 states of ^{15}C with $E_x < 8.6$ MeV are shown in Figs. 2–5. In addition, partial angular distributions have been obtained for the protons to ^{15}C*(9.79, 10.25, 11.13, and 11.83). The shapes of the angular distribution at $E(^7\text{Li}) = 20$ MeV are similar to those observed[10] at $E(^7\text{Li}) = 5.6-6.2$ MeV. Such generally featureless angular distribution shapes with approximate symmetry about 90° are consistent with the assumed compound reaction mechanism. It is noted, however, that the angular distributions corresponding to the transitions to the levels at 8.50 and 8.56 MeV clearly lack the 90° symmetry (see Fig. 5). This may be the result of a statistical fluctuation or of some other competing reaction mechanism. The total cross sections extracted from these angular distributions are presented in Table I.

III. DISCUSSION

A. $2J_f+1$ variation of the total cross section

It is known[9,13,14] that if a compound system is populated at a sufficient excitation energy and with a distribution of large angular momenta, and spread over enough states to eliminate correlations between the compound and final states, then the total cross section in a particular light particle decay channel is proportional to $2J_f+1$. (J_f is the angular momentum of the state populated in the final system.) The conditions[9,14] for the $2J_f+1$ dependence of the reaction cross section are apparently satisfied for ^{9}Be(^{6}Li,p) transitions[9] to low-lying states in ^{14}C measured with 20 MeV incident ^{6}Li's and for ^{13}C(^{7}Li,p) transitions[12] to low-lying states in ^{19}O at 16 MeV bombarding energy. Since the reaction mechanism is expected to be similar[15] for (^{6}Li,p) and (^{7}Li,p) transitions on the same target at the same incident energy, it might be expected that the ^{9}Be(^{7}Li,p) cross sections for populating states in ^{15}C also would be proportional to $2J_f+1$. [The energetics of the (^{6}Li,p) and (^{7}Li,p) reactions on ^{9}Be and the ^{13}C(^{7}Li,p) study[12] are compared in Table II.]

Spins and parities were known previously[3] only for the ground and first excited states of ^{15}C ($\frac{1}{2}^+$ and $\frac{5}{2}^+$, respectively). Directly comparing the total cross sections corresponding to these two levels of known J with the next two excited states at 3.11 and 4.22 MeV suggests J of $\frac{1}{2}$ and $\frac{5}{2}$, respectively, for these two levels. Based on the total cross section corresponding to ^{15}C*(0.74) $J^\pi = \frac{5}{2}^+$, the predicted values of $2J_f+1$ are given in Table III.

B. Widths of unbound states of ^{15}C

Additional information may be obtained for the spins and parities of the unbound levels of ^{15}C. The narrow widths of several of the states unbound only to neutron decay[16] to the ^{14}C ground state ($E_b = 1.218$ MeV) indicate hindrance for neutron emission. Such hindrances may result from either a reduced penetrability due to the angular momentum of the decay or from a configuration having a small overlap with a ^{14}C core plus a neutron.

The neutron decay width is related to the penetrability of the angular momentum barrier $P_n(l)$

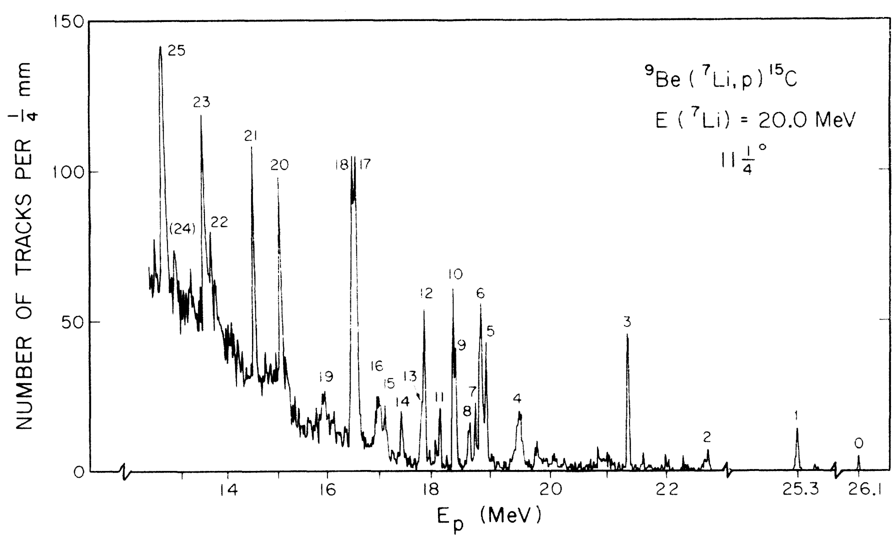

FIG. 1. Proton spectrum from the ^{9}Be(^{7}Li, p)^{15}C reaction at $E(^7\text{Li}) = 20.0$ MeV, $\theta = 11.25°$. The ordinate shows the number of proton tracks in a 250 μm wide bin of the photographic emulsion, the abscissa the proton energy in MeV. The numbers identifying the peaks correspond to the states displayed in Table I. The binding energies for breakup into ^{14}C + n and ^{13}C + 2n are 1.218 and 9.395 MeV, respectively. Thus only the groups labeled 0 and 1 [corresponding to ^{15}C*(0.0, 0.74)] are bound. Much of the low-intensity sharp structure above the continuum background can be accounted for by the reaction ^{12}C(^{7}Li, p) to excited states of ^{18}O.

and the neutron reduced width θ_n^2 by

$$\Gamma_n = 2\gamma_n \theta_n^2 P_n(l),$$

where γ_n is the neutron Wigner limit (taken to be 2.73 MeV in the present case). Neutron penetrabilities of the angular momentum barrier have been calculated assuming a Woods-Saxon nuclear geometry using the code ABACUS[17] and neutron optical-model parameters obtained from experiment.[18] The penetrabilities, shown in Fig. 6, were

TABLE I. Energy levels of ^{15}C.

Group No.[d]	Present work E_x (MeV ± keV)	σ[a] (μb)	$\Gamma_{c.m.}$ (keV)	Previous work E_x[b] (MeV ± keV)	E_x[c] (MeV ± keV)
0	g.s.	28	Bound	g.s.	g.s.[e]
1	≡0.744	115	Bound	0.7441 ± 2.0	0.747 ± 7[e]
					(2.48 ± 50)[f]
2	3.10 ± 30	38	<40	3.1053 ± 5.0[g]	3.08 ± 40
3	4.227 ± 15	128	<15	4.2211 ± 3.0	4.21 ± 30
	(4.55 ± 30)				(4.60)
4	5.837 ± 20, 5.862 ± 20	101			5.93 ± 30
5	6.374 ± 15	120	<20		6.38 ± 30
6	6.440 ± 20, 6.465 ± 20	200		6.4281 ± 7.0[h]	
7	6.546 ± 15	77	<20	6.5398 ± 5.0	
					6.58 ± 40
8	6.643 ± 15	62	20 ± 10		
9	6.851 ± 15	245	<20	6.8449 ± 5.0	(6.84)
10	6.898 ± 15	162	<20	6.8824 ± 5.0	
11	7.104 ± 15	90	<15	7.0972 ± 6.0	(7.06)
12	7.358 ± 15	202	20 ± 10	7.3513 ± 6.0	7.32 ± 30
13	7.418 ± 20				
14	7.75 ± 30[i]				(7.69)
15	8.01 ± 30				(8.00)
16	8.13 ± 30[i]				8.12 ± 60
17	8.495 ± 15	230	40 ± 15		(8.47)
18	8.563 ± 15	220[j]	40 ± 15		
19	9.00 ± 30[i]				
	(9.73 ± 30)				
20	9.793 ± 20	250[j]	20 ± 15		
21	10.252 ± 20	160[j]	20 ± 15		
22	11.019 ± 25				
23	11.127 ± 20	300[j]	30 ± 20		
24	(11.68 ± 30)				
25	11.829 ± 20	450[j]	70 ± 30		

[a] Obtained by integrating full angular distributions, except where indicated. Absolute values ±20% except group 17 (±30%).

[b] From ^{14}C$(d,p)^{15}$C: See Ref. 8.

[c] From early studies of ^{9}Be$(^{7}$Li$,p)^{15}$C and ^{14}C$(d,p)^{15}$C: See Ref. 3.

[d] See Fig. 1.

[e] $J^\pi = \frac{1}{2}^+$ and $\frac{5}{2}^+$, respectively, for ^{15}C*(0, 0.74): See Ref. 3.

[f] This previously reported (Ref. 4) tentative level probably does not exist. See Sec. III E for discussion. $\sigma < 5$ μb assuming that this angular distribution is similar to that for ^{15}C*-(0.74).

[g] $\Gamma_{c.m.} \approx 42$ keV.

[h] $\Gamma_{c.m.} \approx 61$ keV.

[i] Broad or unresolved states.

[j] Obtained by integrating angular distributions from 0° to 90° c.m. and doubling the result. Absolute values ±30% except group 25 (±40%).

TABLE II. Comparison of kinematics for (^{6}Li,p) and (^{7}Li,p) studies on ^{9}Be and on ^{13}C.

Reaction	E(Li) (MeV) lab	c.m.	Ref.	Q_0 (MeV)	Compound nucleus excitation (MeV)	Compound nucleus ang. mom. limit	Ground-state c.m. decay energy (MeV)
$^{9}Be(^{6}Li,p)^{14}C$	20	12.00	9	15.127	37.33	$\sim\frac{21}{2}$	27.13
$^{9}Be(^{7}Li,p)^{15}C$	20	11.25	Present	9.094	31.82	~11	20.34
$^{13}C(^{7}Li,p)^{19}O$	16	10.40	12	7.412	28.45	~11	17.81

TABLE III. Summary of suggested spins and parities for unbound levels of ^{15}C.

E_x [a] (MeV)	$2J_f+1$ [d]	J [b] consistent with $2J_f+1$	$\Gamma_{c.m.}$ [a] (keV)	l_{max} [c] from Γ_n	Comments
3.11	2.0	$\frac{1}{2}$	40 ± 10	3	$J^\pi=(\frac{1}{2}^-)$ see Sec. IIIC
4.22	6.7	$\frac{5}{2},\frac{7}{2}$	<15		$J^\pi=(\frac{5}{2}^-)$ see Secs. IIIC & D
5.84, 5.86	5.3	Sum = 2			
6.37	6.3	$\frac{5}{2}$	<20		
6.43, 6.46	10.4	Sum = 4, 5 or 6	68 ± 10		
6.54	4.0	$\frac{3}{2}$	<20		See Secs. IIIB & C
6.64	3.2	$\frac{3}{2}$	20 ± 10	5	See Secs. IIIB & C
6.84	12.8	$\frac{11}{2},\frac{13}{2}$	<20		
6.88	8.5	$\frac{7}{2},\frac{9}{2}$	<20		
7.10	4.7	$\frac{3}{2}$	<15		
7.35	10.5	$\frac{9}{2},\frac{11}{2}$	20 ± 10	6 [e]	
8.50	12.0 [f]	$\frac{9}{2},\frac{11}{2},\frac{13}{2}$ [f]	40 ± 15	g	
8.56	11.5 [f]	$\frac{7}{2}-\frac{13}{2}$ [f]	40 ± 15	g	
9.79	13.0	$\frac{9}{2}-\frac{15}{2}$	20 ± 15	g	
10.25	8.3	$\frac{5}{2},\frac{7}{2},\frac{9}{2}$	20 ± 15	g	
11.13	15.7	$\frac{11}{2}-\frac{19}{2}$	30 ± 20	g	
11.83	23.5	$\frac{13}{2}-\frac{31}{2}$	70 ± 30	g	

[a] See Table I. Values from present study used except where values from (d,p) study (Ref. 8) judged to be more accurate.

[b] Includes errors for total cross section as given in Table I, and assumes strength corresponds to a single state except for 5.84-5.86 and 6.43-6.46 MeV doublets.

[c] Determined from a comparison of predicted neutron width Γ_n with total observed width requiring that $\theta_n^2 \le 1.0$. A factor of ±50% was included in the predicted widths to reflect expected uncertainties in the penetrability calculations and in the Wigner limit (Ref. 19).

[d] Based on total cross section for $^{15}C^*(0.74)$ $J^\pi=\frac{5}{2}^+$ —see Table I.

[e] Level also unbound to neutron decay to $^{14}C^*(6.09)$ by $l=0$ or 1 decay.

[f] Angular distributions are not symmetric about 90°. See Fig. 5.

[g] Levels unbound to neutron decay to several excited states in ^{14}C.

calculated using the low-energy approximation

$$T(l) \cong \frac{4}{KR} P(l) .$$

This relationship is good when $k \ll K$. [$T(l)$ is the transmission coefficient for the lth partial wave, R, the nuclear radius, was taken to be 4.95 fm, and K and k are the neutron wave numbers inside and outside the nucleus, respectively.]

Since the neutron reduced width, θ_n^2, can never be greater than ~1.0,[19] the experimental total decay width (when neutron decay is the only allowed particle decay) of a specific state restricts the l value of the neutron decay to be less than some maximum value l_{max}. These l_{max} are listed in Table III for the levels of ^{15}C populated in the present study. Ideally states could be completely inhibited from neutron decay, i.e. $\theta_n^2 = 0$. It is expected, however, that most states should have some width for neutron emission. Indeed in a similar analysis[9] of the neutron widths of unbound levels in ^{14}C all known J^π and the J's determined from the $2J_f+1$ rule were consistent with reduced neutron widths $\theta_n^2 \gtrsim 0.01$. In the present study, however, the $J=\frac{3}{2}$ suggested from the $2J_f+1$ variation of total cross sections (Table III) for the levels at 6.54 and 6.64 MeV disagree with the restriction on l_n ($l_n \geq 3$) determined from the predicted penetrabilities requiring that $\theta_n^2 \gtrsim 0.01$.

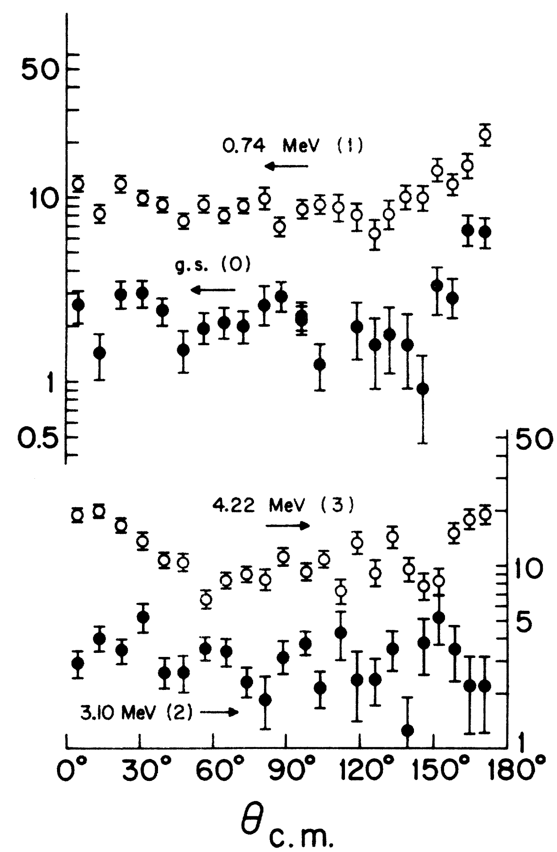

FIG. 2. Angular distributions of the protons in the c.m. system to the states identified by the E_x designations. The ordinates show the differential cross section in μb/sr. The number in parentheses refers to the group number shown in Table I, where the total cross sections are also listed. The arrows designate the appropriate ordinate scale. The errors indicated are statistical.

C. Suggested J^π assignments

3.11 MeV level. The $2J_f+1$ variation of cross sections suggests $J=\frac{1}{2}$ for this level. J^π of $\frac{1}{2}^+$ and $\frac{1}{2}^-$ would be consistent with $l_n=0$ and 1 and neutron reduced widths[20] of 0.005 ± 0.001 and 0.0075 ± 0.0015, respectively, for the decay of this state to ^{14}C(g.s.). Both these values of θ_n^2 are small and would indicate a poor overlap between $^{15}C^*(3.11)$ and ^{14}C(g.s.) plus a neutron. Small neutron reduced widths are expected for the decay of states in ^{15}C with neutron holes in the p shell to ^{14}C(g.s.) with a closed neutron p shell. The lowest such state in ^{15}C would be a $\frac{1}{2}^-$ state having two neutrons in the s-d shell and a $p_{1/2}$ neutron hole (2p-1h). A

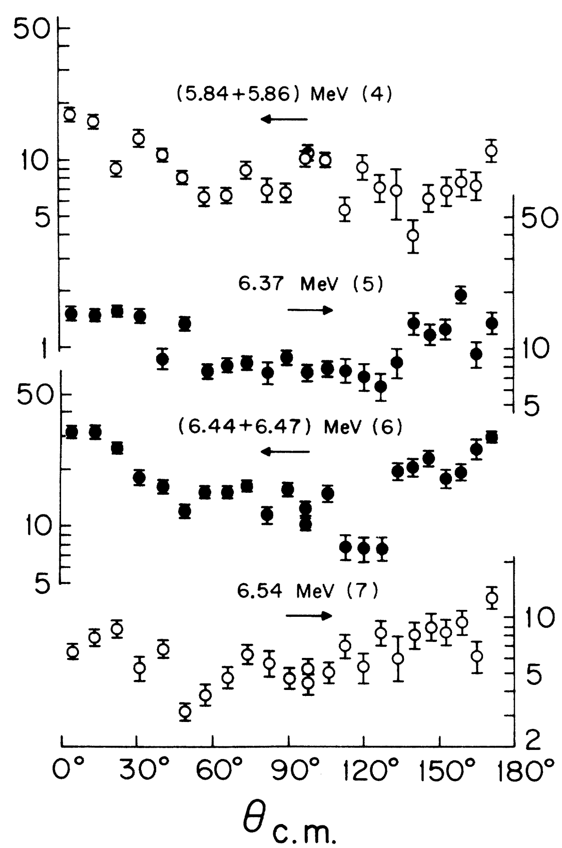

FIG. 3. See caption of Fig. 2.

state of this neutron configuration is observed at 3.06 MeV in the $N=9$ nucleus ^{17}O (see Fig. 7 and Ref. 21). It would be difficult to explain the very small neutron width $\theta_n^2 = 0.005 \pm 0.001$ that a positive parity assignment would require. Therefore $J^\pi = \frac{1}{2}^-$ is preferred for ^{15}C*(3.11). A $J^\pi = \frac{1}{2}^-$ state of this configuration is predicted[22] at an excitation of 2.37 MeV. The neutron reduced width corresponding to $l_n = 1$ ($\theta_n^2 = 0.0075 \pm 0.0015$) indicates[20] that the ^{14}C ground state contains little 2p-2h neutron configuration.

4.22 MeV level. The $2J_f+1$ variation of the cross sections predicts either $J=\frac{5}{2}$ or $\frac{7}{2}$ for this state (Table III). No maximum l_n for the neutron decay can be determined since only an upper limit is known for the width of this state. The upper limit for the total width, 15 keV, gives limits of $\theta_n^2 < 0.003$, <0.045, and <0.55 for $l_n = 2$ ($J^\pi = \frac{5}{2}^+$), 3 ($J^\pi = \frac{5}{2}^-$ and $\frac{7}{2}^-$), and 4 ($J^\pi = \frac{7}{2}^+$), respectively. A $J^\pi = \frac{5}{2}^-$ assignment is preferred again by comparison with the low-lying level spectra of the $N=9$ nucleus ^{17}O and with the low-lying predicted[22] spectrum for ^{15}C.

Other levels. Spins consistent with the $2J_f+1$ variation in cross sections are given in Table III for the other unbound states of ^{15}C that were observed in this study. For most of these levels below the excitation (7.311 MeV) where the states can neutron decay to the excited states of ^{14}C only an upper limit is known for the $\Gamma_{\text{c.m.}}$; therefore no restrictions can be placed on the J^π from $l_{\max}$ that are more stringent than the J derived from the $2J_f+1$ rule.

The $J=\frac{3}{2}$ values for ^{15}C*(6.54) and ^{15}C*(6.64) suggested from the $2J_f+1$ variation of cross sections (Table III) require very small neutron reduced widths for these levels. This would be consistent with hole configurations in the ^{14}C core, and indeed ^{15}C*(6.64) is not observed[8] in ^{14}C(d,p). ^{15}C*(6.54), however, is observed[8] to be populated with considerable strength in ^{14}C(d,p) indicating either an overlap of ^{15}C*(6.54) with ^{14}C(g.s.) and a neutron, or a sizeable nondirect single-step neutron transfer[23] in the transition to this state. Other possible sources of discrepancies between the J consistent with the experimental and reduced widths of ^{15}C*(6.54) and that suggested by the $2J_f+1$ rule would be larger discrepancies in the calculation of the penetrability P_n than assumed or a breakdown of the $2J_f+1$ rule. In the present study the compound nuclear excitation energy and

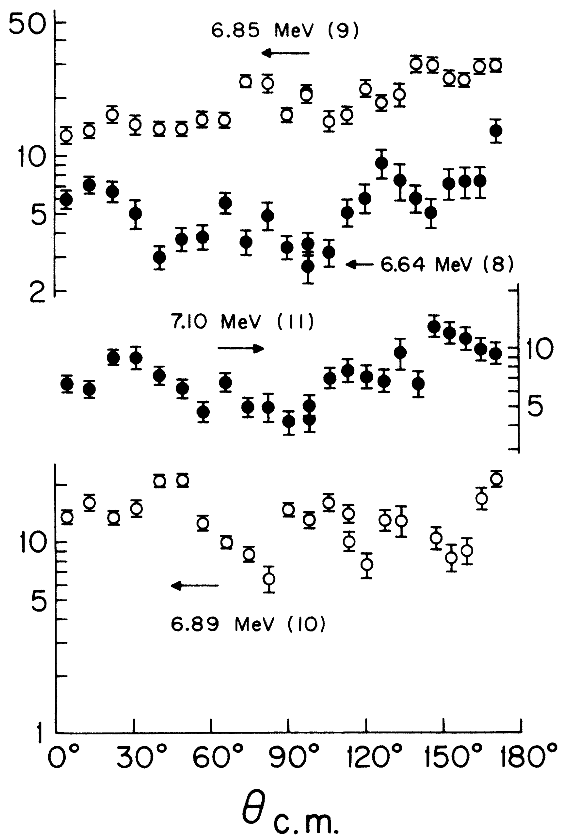

FIG. 4. See caption of Fig. 2.

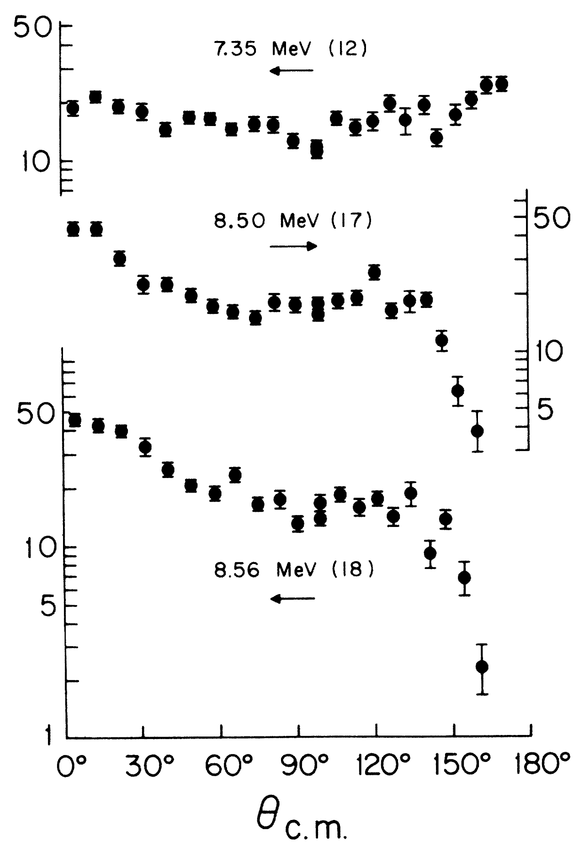

FIG. 5. See caption of Fig. 2.

the energy of the exiting protons are intermediate between those of the ^{9}Be(^{6}Li,p)^{14}C and ^{13}C(^{7}Li,p)^{19}O studies[9,12] (see Table II) for which the $2J_f+1$ rule has been studied more extensively.

D. Comparison of low-lying levels of ^{15}C and ^{17}O

Both ^{15}C and ^{17}O have ground-state configurations of an unpaired neutron outside a filled p shell. The low-lying spectra (see Fig. 7 for a comparison) then is expected to be based on shell model states with the valence nucleon in the $d_{5/2}$ and $s_{1/2}$ orbits and at higher excitation energy in the $d_{3/2}$ orbit. Such states should be populated strongly in the ^{14}C(d,p) and ^{16}O(d,p) reactions. These $\frac{5}{2}^+$, $\frac{1}{2}^+$, and $\frac{3}{2}^+$ states are known[21,24] in ^{17}O at 0.0, 0.87, and 5.08 MeV, respectively. In ^{15}C the ordering of the $\frac{5}{2}^+$ and $\frac{1}{2}^+$ states are reversed relative to ^{17}O. The $2s_{1/2}$ orbit is known[25] to come lower in excitation for lighter nuclei. In ^{11}Be, for example, it is even below the $1p_{1/2}$ shell model orbit.[26] The different number of states observed in ^{15}C relative to ^{17}O above 5 MeV is a result of states based on three unpaired particles which should be different for ^{15}C and ^{17}O. Also ^{15}C is unbound lower in excitation than ^{17}O. Some states that are sharp in ^{17}O may be broad in ^{15}C, and therefore they have remained undetected. In fact the $1d_{3/2}$ particle state in ^{15}C may have suffered this fate, since it would have a large neutron reduced width for decay to ^{14}C(g.s.). In ^{17}O this state ^{17}O*(5.08) has a width[21] of 95 ± 5 keV and it is unbound by <1 MeV.

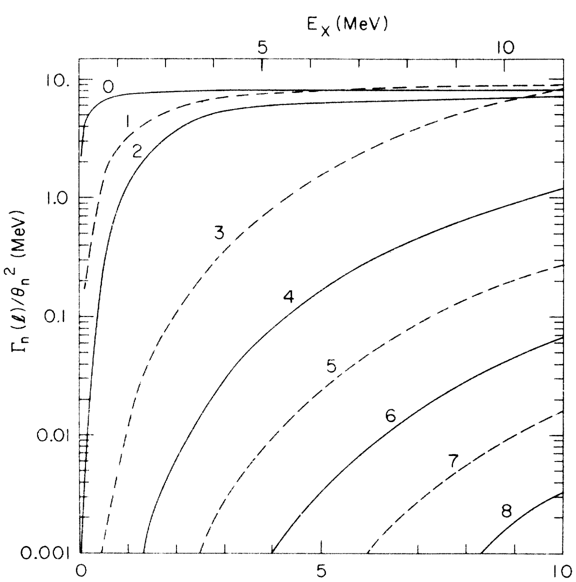

FIG. 6. Plot of Γ_n/θ_n^2 in MeV versus the neutron decay energy E_n as a function of l_n for the neutron decay of unbound states of ^{15}C. See Sec. III B for details of the penetrability calculation. Also shown is an excitation energy scale in ^{15}C assuming decay to the ^{14}C ground state. Values of $R=4.95$ fm and $\gamma_n=2.73$ MeV were used for the radius and Wigner limit, respectively, in the calculation.

E. Does the proposed level at 2.48 MeV ^{15}C really exist?

A level at 2.48 ± 0.05 MeV in ^{15}C was suggested in an earlier poor resolution study of the ^{9}Be(^{7}Li,p) reaction,[4] but was not observed in a later study of this reaction,[5] in the present work[27] or in any other experimental studies[3,7,8] of ^{15}C. All other known[3,8] levels of ^{15}C are populated by the present study (see Table I) consistent with the assumed compound mechanism for the ^{9}Be(^{7}Li,p) reaction. A level at 2.48 MeV in ^{15}C does not fit into the scheme of low-lying ^{15}C levels as interpreted in terms of the shell model or by comparison with ^{17}O (see Fig. 7). Neither is a $\frac{3}{2}^+$ state predicted[22]

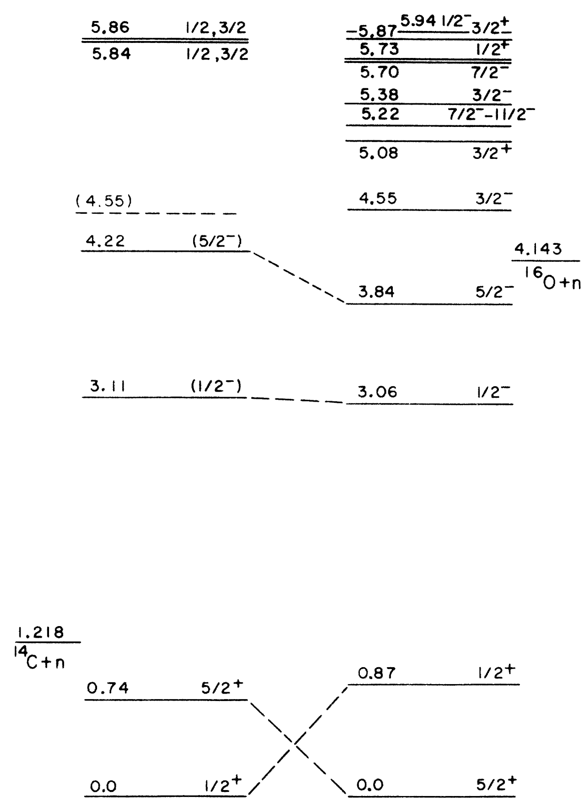

FIG. 7. Comparison of the low-lying level scheme of ^{15}C and ^{17}O. Both nuclei have nine neutrons and the low-lying levels are expected to be based on the various configurations of the valence neutrons. Levels suggested to be of similar configurations are connected with broken lines. Other possible identifications are discussed in Sec. III D of the text. A level previously suggested (Ref. 4) at 2.48 MeV in ^{15}C is not shown because it probably does not exist (see Sec. III E for discussion).

at this low an excitation in ^{15}C. Therefore, it is concluded that this suggested level[4] at 2.48 MeV in ^{15}C probably does not exist.

This doubtful level in ^{15}C has been used to support the suggestion[28,29] that the $J^{\pi}=\frac{3}{2}^{+}$ level at 13.42 MeV in ^{15}N is largely $T=\frac{3}{2}$. The appearance of a $J^{\pi}=\frac{3}{2}^{+}$, $T=\frac{3}{2}$ level at such a low excitation suggests[30] a large deformation for the $T=\frac{3}{2}$ levels of mass 15. Such a rotational description is contradictory to the explanation of ^{15}C in terms of the shell model presented above and in Ref. 22 and to the similarity of the low-lying level schemes of ^{15}C and ^{17}O (see Fig. 7). Furthermore, if the low-lying levels of ^{15}C are interpreted as members of this suggested rotational band, then the $\frac{3}{2}^{+}$ member should be populated with significant strength[30,31] in the ^{14}C(d,p) reaction. This level has never been observed in studies[3,7,8] of the ^{14}C(d,p) reaction.

IV. CONCLUSION

Excitation energies and angular distributions of ^{9}Be(^{7}Li,p) transitions at $E(^{7}\mathrm{Li})=20$ MeV have been measured for all of the known levels and several new states below $E_x=12$ MeV in ^{15}C. (The level suggested[4] at 2.48 MeV from an early study of this reaction probably does not exist—see Sec. III E.) The angular distribution shapes, the nonselectivity in populating final states, and the apparent $2J_f+1$ variation of the cross sections are consistent with an assumed predominant compound mechanism for this reaction. In one specific case, ^{15}C*(6.54), the $J=\frac{3}{2}$ suggested from the $2J_f+1$ variation of cross sections would require a very small neutron reduced width (to be consistent with the measured upper limit for the total width, $\Gamma_{\mathrm{c.m.}}<20$ keV), which is inconsistent with the sizeable ^{14}C(d,p) cross section observed[8] populating this state. Not enough data presently is available to distinguish between the possible explanations of this discrepancy, e.g., (i) sizeable nondirect single-step neutron transfer[23] in ^{14}C(d,p), (ii) larger errors in the calculated neutron penetrabilities than assumed, or (iii) a breakdown of the $2J_f+1$ variation of total cross sections. It would seem important to measure a complete ^{14}C(d,p) angular distribution for this as well as for other transitions to unbound ^{15}C states.

Spin and parities of ($\frac{1}{2}^{-}$) and ($\frac{5}{2}^{-}$) have been suggested for ^{15}C*(3.11) and ^{15}C*(4.22), respectively, and these two levels have been suggested to have similar configurations to ^{17}O*(3.06), $J^{\pi}=\frac{1}{2}^{-}$, and ^{17}O*(3.84), $J^{\pi}=\frac{5}{2}^{-}$, respectively. The very small reduced neutron width[20] (0.0075 ± 0.0015) for the 2p-1h ^{15}C*(3.11) indicates that ^{14}C(g.s.) contains little 2p-2h neutron strength. Such a suggestion contradicts previous neutron pickup measurements[32] from ^{14}C(g.s.) which show considerable $d_{5/2}$ strength. It has been suggested,[33] however, that this strength may be the result of processes other than direct single neutron pickup. Further studies of the neutron pickup reactions at higher bombarding energies would seem to be important. For comparison, the value of the (d,p) spectroscopic factor[21,34] for the ^{17}O*(3.06), $J^{\pi}=\frac{1}{2}^{-}$ state (assumed to be 2p-1h with respect to the $N=8$ closed neutron shell) is 0.032. Taking these numbers for the neutron reduced widths at face value, one could conclude that ^{14}C(g.s.) has a smaller 2p-2h neutron component than ^{16}O(g.s.). It must be pointed out, however, that large uncertainties exist in the extranction of both numbers; see, e.g. Sec. III B and Ref. 23 for discussions of significant sources of error in obtaining neutron reduced widths from Γ_n and from weak (d,p) transitions, respectively. In any case, if the tentative $J^{\pi}=(\frac{1}{2}^{-})$ assignment for ^{15}C*(3.11) proves to be correct, the present results suggest that the neutron configuration of ^{14}C(g.s.) has only a small particle-hole component.

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