Angular distribution measurements for $^{14}C(d,p)^{15}C$ and the level structure of ^{15}C†

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A 14 MeV deuteron beam was used to measure the angular distributions for the $^{14}C(d,p)$-^{15}C reaction leading to the two bound states and eight of the unbound states of ^{15}C. Vector-analyzing powers were measured for the elastic scattering and for the two bound states. Distorted wave Born approximation calculations were performed and spectroscopic factors were obtained for the two bound states. Calculations for stripping to unbound states using a resonance form factor and following the approach of Vincent and Fortune were compared with the angular-distribution data of the unbound states to obtain values of J, π, and neutron width Γ_n. A strong J dependence occurs in the calculated cross sections for stripping to unbound states.

[NUCLEAR REACTIONS $^{14}C(d,p)$, $(\vec{d},p)$, $(\vec{d},d)$, $E_d=14.0$ MeV: measured $\sigma(\theta)$, $iT_{11}(\theta)$. ^{15}C levels deduced J, π, S, and/or $\Gamma_n/\Gamma_{s.p.}$.]

I. INTRODUCTION

Within the last few years there has been increased interest in the study of stripping reactions leading to unbound states since the observable resonance phenomena contain valuable information pertaining to nuclear dynamics. The study of ^{15}C is particularly interesting since the ^{15}C nucleus appears to possess only two bound states and to provide one of the few nuclear systems wherein resonance features are dominant but amenable to a simple yet relatively complete microscopic analysis. Philpott[1] recently published a continuum shell-model calculation, based upon a microscopic treatment of the internal structure of ^{15}C which predicts a wide range of resonance phenomena. Reehal and Wildenthal[2] have also published shell-model calculations for ^{15}C. There has until recently, however, been a paucity of experimental information on the level structure of ^{15}C. In one recent study of the $^{14}C(d,p)^{15}C$ reaction[3] nine states were identified in ^{15}C. Another recent effort employed the $^{9}Be(^{7}Li,p)^{15}C$ reaction.[4] In the latter work the authors identified more than 27 states in ^{15}C and utilized the statistical assumption of a $2J_f+1$ variation of the total cross section to suggest spin assignments for many of these levels.

Except for low energy ($E_d=3.4$ MeV) measurements of the ground and first excited state proton groups,[5] no angular-distribution data have been previously published for the $^{14}C(d,p)^{15}C$ reaction. In the present paper we will present angular-distribution data for the $^{14}C(d,p)^{15}C$ reactions leading to 10 final states of ^{15}C. We also measured the vector-analyzing power for deuteron elastic scattering and for the (d,p) reactions leading to the two bound states of ^{15}C. These data will be compared to the predictions of a conventional distorted wave Born approximation (DWBA) calculation. The angular-distribution data for the unbound states will be compared to the predictions of the DWBA for stripping to unbound states calculated using the method of Vincent and Fortune.[6]

II. EXPERIMENTAL

The target used for this experiment was ≈70% enriched ^{14}C deposited on a thin (0.12 μm) Ni foil and was approximately 14 keV thick to 14 MeV deuterons. The deuteron bombarding energy used for all measurements was 14.0 MeV. The experiment was run in two stages. In the first stage four $\Delta E-E$ solid state detector systems were used. Spectra were accumulated in 5° steps from 15° to 65° and at 90°. These data were stored in a two-dimensional array and the appropriate proton peaks were summed on line. For this stage of the experiment a vector-polarized beam produced by the Notre Dame polarized ion source was employed. Data were taken with the beam alternately polarized up and down along the direction normal to the scattering plane. Further details of this technique have been discussed previously.[7] Vector-analyzing powers for the proton groups leading only

to the ground and first excited states of ^{15}C resulted from these measurements. The relatively poor resolution of the solid state detectors along with the high continuum background and the small cross sections made it impossible to extract data for the other proton groups.

In the second stage of the experiment angular distributions for the unbound states were measured. The Notre Dame 100-cm broad-range magnetic spectrograph with a 40-cm long position-sensitive proportional counter mounted at the focal surface was used to analyze and detect the reaction protons. Typical proportional counter spectra for the $^{14}C(d,p)^{15}C$ reactions are shown in Fig. 1. The decrease in the background at each end of a spectrum marks the ends of the proportional counter. Because of the length of the counter, only a small region of excitation could be studied at a time and these regions are shown in Fig. 1. Notice also that the spectra shown are for different angles and for different amounts of collected charge. Clearly evident are the large continuum background and the ^{13}C and ^{17}O contaminant peaks. ^{15}C groups were identified by kinematics and from our previous study of this reaction.[3]

Proton yields were extracted from the spectra by two methods. In the first method, yields were extracted by summing counts under the peaks after estimating the magnitude of the background. In the second method, the data in the region of interest were fitted by computer using Gaussian peak shapes and a quadratic background. Results obtained using the two methods agreed within statistics, but the uncertainties are less for the computer-fitted data. These data are shown in Figs. 2 thru 6. For the unbound states the statistical uncertainties are $\geq 10\%$.

Angular-distribution data were taken in the spectrograph for proton groups corresponding to the ground and first excited state, and to eight unbound states in the region of excitation up to 7 MeV. The levels reported at 5.84, 5.86, 6.64 MeV, and the possible level at 4.55 MeV by Garrett, Ajzenberg-Selove, and Bingham[4] in their study of $^{9}Be(^{7}Li,p)^{15}C$ were not observed in the present work. The 6.64-MeV level is evidently very weakly populated in the $^{14}C(d,p)$ reaction under our experimental conditions (see Fig. 1). A search was made for the 5.84- and 5.86-MeV levels as well as for the possible level at 4.55 MeV, but without success.

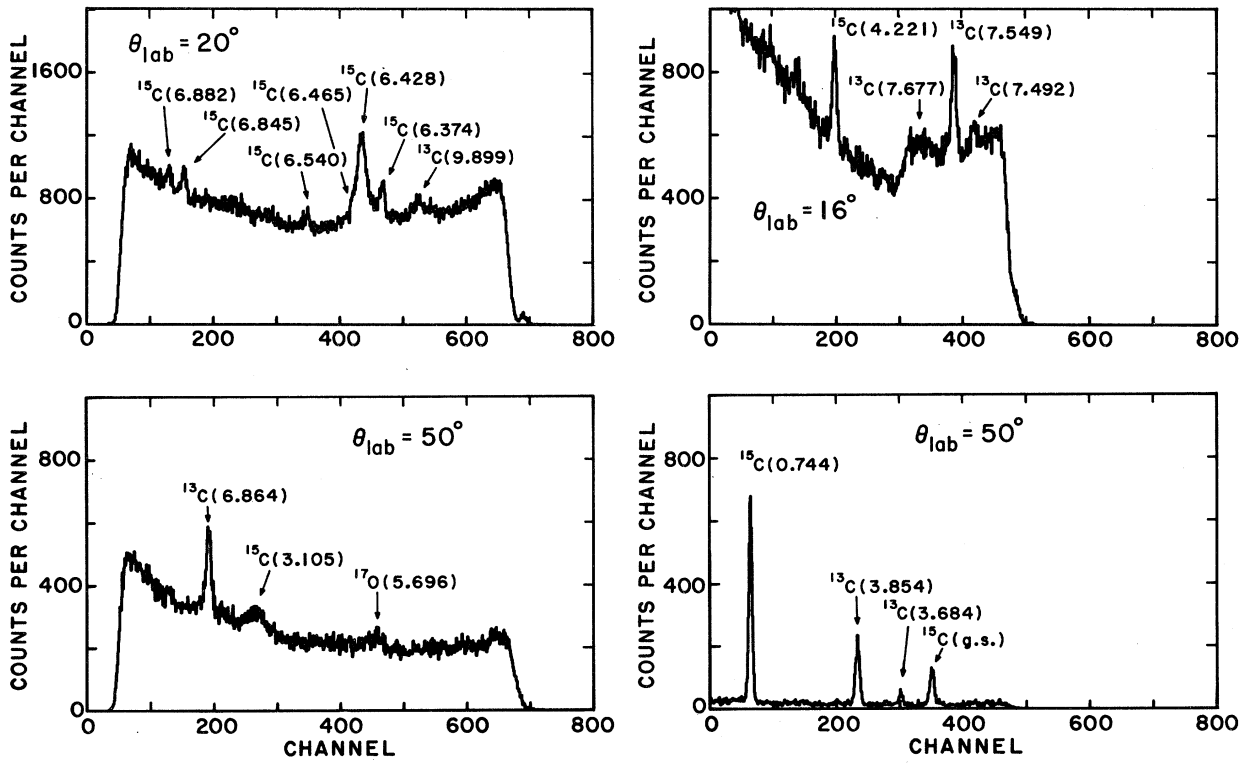

FIG. 1. Typical spectra for the $^{14}C(d,p)^{15}C$ reaction taken with a 40-cm long position sensitive proportional counter in the focal plane of the 100-cm spectrograph. Note more than one angle is shown. Groups are labeled by the final nucleus and state energy. The large background arises because residual nuclei are unbound for the target and most contaminants.

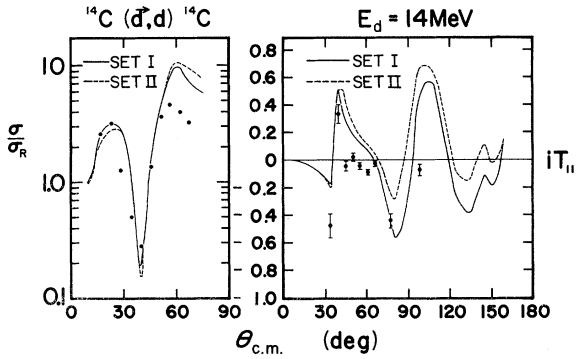

FIG. 2. Angular distribution of the cross section and analyzing power for elastic scattering of deuterons by ^{14}C. Optical-model fits for two parameter sets, Table I, are shown. Set I is the preferred set.

Possible reasons for the failure to observe these states are discussed below. Angular distributions were measured for proton groups to the levels reported at 6.374 and 6.465 MeV in Ref. 4 but not identified in our earlier work.[3]

Absolute cross sections were obtained by measuring ^{14}C$(p,p)^{14}$C cross sections with the spectrograph as a function of energy from E_p = 10.0 to 10.8 MeV. These results were normalized to cross sections measured previously[8] at these energies. The uncertainties involved in this normalization procedure lead to an estimated maximum error of 20% in the absolute cross sections reported here.

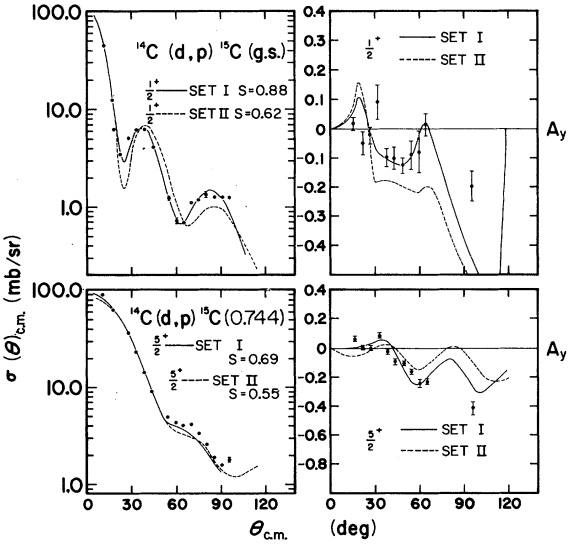

FIG. 3. Cross sections and analyzing powers for the two bound states of ^{15}C. The lines are DWBA predictions using the optical-model parameters from Table I. Set I was adjusted to give an acceptable fit to these data as well as the elastic scattering.

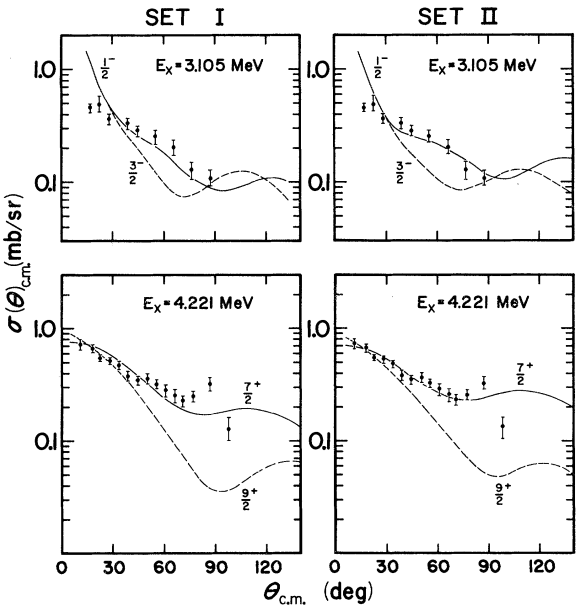

FIG. 4. Angular distributions to unbound states of ^{15}C. Lines are DWBA calculations for stripping to unbound states calculated using DOXY. Note the strong J dependence of the angular distributions which is evident for both sets of optical-model parameters. The fits for other l values are unacceptable.

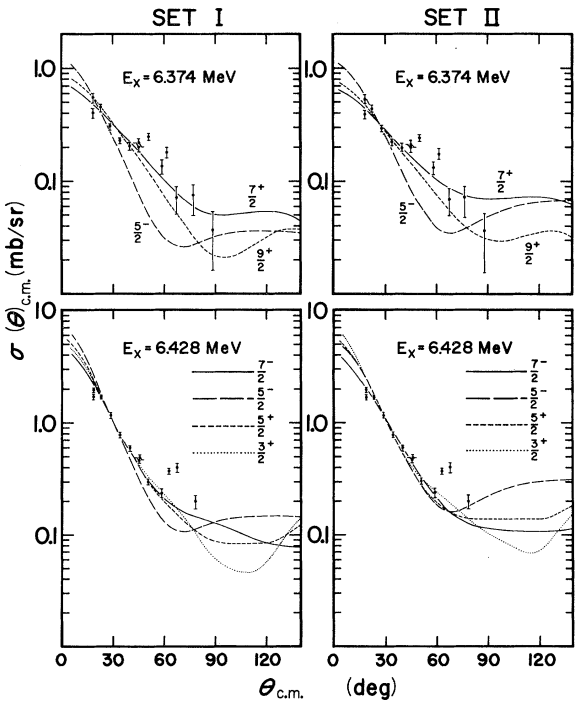

FIG. 5. Angular distributions for unbound states of ^{15}C. The calculations shown include the acceptable DWBA predictions.

III. ANALYSIS

The analysis of the $^{14}C(d,p)^{15}C$ cross sections was performed in two parts. The analysis of the bound state data was carried out using the DWBA program DWUCK[9] and the analysis of the unbound state data using the method of Vincent and Fortune[6] and the program DOXY.[10] Two sets of deuteron and proton optical-model parameters were used in both calculations. The deuteron parameters of the first set (Set I) were obtained by fitting the $^{14}C(\vec{d},d)^{14}C$ cross-section and analyzing-power data using an optical-model search program,[11] employing as initial parameters those recently used by Huby and Kelvin[12] to fit data on $^{12}C(d,p)^{13}C$. These parameters were then varied slightly to give a reasonable account of the vector-analyzing power of the ground and first excited states. The proton parameters of Set I are parameters (Set EN) previously used to fit data on $^{16}O(d,d)^{16}O$ and $^{16}O(d,p)^{17}O$.[13] A second set (Set II) of optical-model parameters was also used in our calculations to test the sensitivity of the results to the optical-model parameters. The second set differs only slightly from the deuteron and proton Set HD given in Ref. 13. The DWBA calculations of the cross section and analyzing power for the $^{14}C(\vec{d},d)^{14}C$ reaction are shown in Fig. 2; for Set I (solid curve) and Set II (dashed curve).

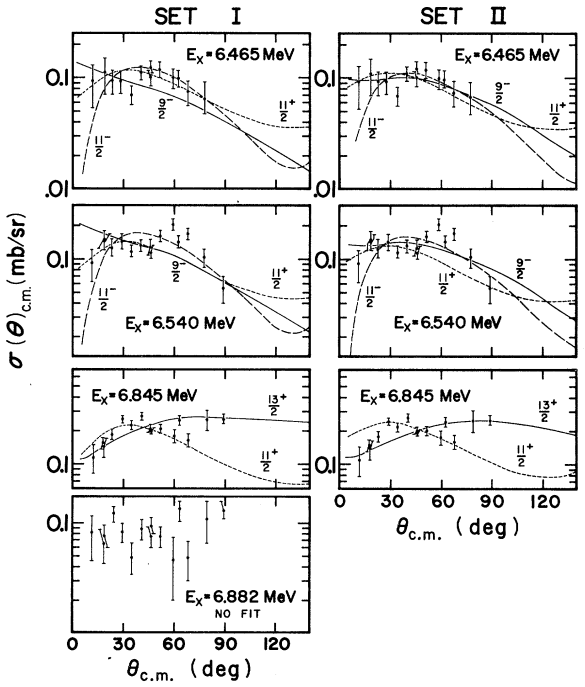

FIG. 6. Angular distributions for unbound states of ^{15}C showing the acceptable DWBA predictions.

A. DWBA analysis of bound states

For the bound state calculations, the form factors for the $2s_{1/2}$ and $1d_{5/2}$ neutrons were obtained in the usual way by varying the depth of a real Woods-Saxon well ($r_0 = 1.3$ fm, $a_0 = 0.7$ fm) to reproduce the neutron separation energies. All DWBA calculations were performed with no radial cutoff and the integrals extended to 40 fm. Nonlocality and finite-range corrections were included in the calculations with corresponding parameters as listed in Table I. The DWBA calculations for the cross section and analyzing power of the ground state and first excited state are shown in Fig. 3 for Set I (solid curve) and Set II (dashed curve). The spectroscopic factors were obtained from the relation:

$$\sigma(\theta)_{exp} = 1.53 S \sigma_{DWBA}(\theta) \text{ (mb/sr)}.$$

B. DOXY analysis of unbound states

The resonance scattering wave functions which are used as input to the DOXY program were generated by the optical-model program JUPITOR[14] employing a Woods-Saxon potential containing real central and spin-orbit terms. A radius parameter $r_0 = 1.25$ fm, a diffuseness of 0.6 fm, and a spin-orbit potential depth $V = 6$ MeV were used. In each case, the depth of the central potential was varied to reproduce the observed resonance energy for the unbound state of interest. In performing the DOXY calculations, the radial integration was carried out along the real axis in the complex r plane to $r_t = 12.5$ fm (Ref. 6) and then along a line parallel to the imaginary axis far enough to ensure convergence. All the calculations were done in the zero-range local approximations. The results obtained using optical-model parameter Sets I and II are shown in Figs. 4, 5, and 6.

A measure of the spectroscopic factor for an unbound state is provided by the ratio of the measured neutron width to the width of a single-particle resonance occurring at the same energy. The single-particle widths $\Gamma_{s.p.}$ were extracted from the energy dependence of the scattering phase shifts generated by the optical-model program JUPITOR. In calculating these phase shifts, the optical-model parameters were taken to be the same as those used to generate resonant wave functions. A single-level approximation to the phase shifts generated by the optical-model program was used to extract the resonance energies and single-particle widths. In this approximation the phase shift is written:

$$\delta_l^{\pm}(E) = \Phi_l(E) + \tan^{-1}[\Gamma(E) / 2(E_\lambda + \Delta_\lambda - E)],$$

where Φ_l is an energy-dependent potential phase which was taken to be equal to the hard-sphere phase, Δ_λ is the shift function, and $\Gamma(E)$ is $2P_l(E)\gamma^2$, where γ^2 is the reduced width and $P_l(E)$ is the penetrability. P_l and Δ_λ were taken to be the usual functions of F_l and G_l. The resonance energy E_R was taken to be that energy for which $E_R = E_\lambda + \Delta_\lambda(E_R)$ and $\Gamma_{s.p.}$ was taken to be the width $\Gamma(E)$ evaluated at $E = E_R$. For narrow levels for which the phase shift $\delta_l^{\pm}(E)$ changes by 180° as the resonance is traversed, the width and resonance energy can be easily obtained by inspection of a plot of phases. However, for broad levels one usually finds that the phases $\delta_l^{\pm}(E)$ do not pass through 180° and that the resonance energy does not occur at $\delta_l^{\pm}(E) = 90^0$. In such cases it is necessary to evaluate the above expression.

The neutron width of the unbound state can be determined from the ratio of the cross-section values calculated by DOXY to the experimental cross-section values. The details of the extraction of the neutron width have been discussed previously in Refs. 6 and 7. Values of $\Gamma_{s.p.}$ and Γ_n are given in Table II in keV and are in the center of mass sytem.

IV. RESULTS

Table II presents the results of the present investigation. The widths given in column two were obtained from the spectra. Neutron widths given in columns five and seven were obtained from the cross-section data using Eq. (30) of Ref. 6.

Ground state of ^{15}C. The ground-state spin of ^{15}C is known[15] to have $J^\pi = \frac{1}{2}^+$. It can be seen in Fig. 3 that a good fit to the cross-section data is obtained with the DWBA calculation employing parameter Set I. A spectroscopic factor of 0.88 is obtained using this parameter set. The vector-analyzing power (VAP) is also fairly well reproduced. Set II gives a visibly poorer fit to both the cross-section and VAP data, and yields a spectroscopic factor of 0.62. The only previously published DWBA fits to (d,p) data for this level were obtained at deuteron energies below 4 MeV.[5]

0.744-MeV level. For the first excited state data, the calculations using parameter Set I provide the better over-all fit to the cross section and analyzing-power data. The spin of this level is known to be $\frac{5}{2}^+$, and the fit to the data verify this assignment. Sets I and II yield spectroscopic factors of 0.69 and 0.55, respectively. The corresponding ratios of these values to the ground-state spectroscopic factors are 0.78 and 0.89. For $^{16}O(d,p)^{17}O$ the spectroscopic factor for stripping to the $\frac{5}{2}^+$ ground state has been reported[16] to be 0.81 and for the $\frac{1}{2}^+$ first excited state to be 0.71. Our present results are quite close to these values. From the shell-model calculations of Philpott[1] and Reehal and Wildenthal[2] the spectroscopic factors for both the ground and first excited states are predicted to be very close to one. Our result for the first excited state is somewhat lower then this prediction.

3.105-MeV level. In our previous study of the $^{14}C(d,p)^{15}C$ reaction,[3] we reported this level to have a natural width in the center-of-mass system

TABLE I. Optical-model parameters used in the DWBA and DOXY calculations. The parameters are given in the same format as in Ref. 13.

	Particle	V (MeV)	r_0 (fm)	A_0 (fm)	W_d (MeV)	r_i (fm)	A_i (fm)	V_{so} (MeV fm^2)	r_{so} (fm)	a_{so} (fm)
Set I	d	107.9	1.03	0.60	8.0	1.99	0.39	8.0	0.99	0.45
	p	53.0	1.175	0.75	9.0	1.32	0.55	6.2	1.01	0.75
Set II	d	112.0	1.03	0.60	5.3	1.87	0.45	8.2	0.99	0.45
	p	53.0	1.175	0.75	9.0	1.32	0.45	6.2	1.01	0.45

Bound state parameters

	V (MeV)	r (fm)	a (fm)
$2s_{1/2}$	46.5	1.3	0.7
$1d_{5/2}$	45.0	1.3	0.7

Nonlocal parameters

PNLOC = 0.54 (deuterons)
PNLOC = 0.85 (protons)

Finite-range parameters

FNRN 6 = 0.621

of approximately 42 keV. Except for γ decay, the only decay channel open to the unbound states in ^{15}C below 7.3 MeV is neutron decay to the ground state of ^{14}C. As a consequence, for most of the states investigated the neutron width and total width are the same. A useful comparison can thus be made between the experimental natural widths and the neutron widths obtained from the analysis of the stripping data for various assumed J^π values. These widths are listed in Table II. Any assumed J^π value which yields a width much larger or much smaller than the measured natural width, can be excluded. In a recent study[7] of the reliability of neutron widths extracted from data by comparision with DOXY, it was shown that in most cases the widths are probably correct to

TABLE II. Results of present work. Arrows indicate preferred choices.

				Set I		Set II	
E_x (MeV)	Γ_{exp} [a] (keV)	J^π	$\Gamma_{s.p.}$ (keV)	Γ_n (keV)	$\Gamma_n/\Gamma_{s.p.}$	Γ_n (keV)	$\Gamma_n/\Gamma_{s.p.}$
g.s.	Bound	$\frac{1}{2}^+$			0.88 [b]		0.63 [b]
0.744	Bound	$\frac{5}{2}^+$			0.69 [b]		0.55 [b]
3.105	≈42	$\frac{1}{2}^-$	4500	96	0.021	79	0.018 ←
		$\frac{3}{2}^-$	4500	36	0.008	31	0.007
		$\frac{3}{2}^+$	1010			2.6	0.003
		$\frac{5}{2}^+$	1010			1.6	0.002
		$\frac{5}{2}^-$	60			0.3	0.006
		$\frac{5}{2}^-$	60			0.2	0.003
4.221	≤14	$\frac{7}{2}^+$	11	0.31	0.028	0.24	0.022 ←
		$\frac{9}{2}^+$	11	0.17	0.015	0.14	0.013
6.374	≤14	$\frac{5}{2}^-$	1430	5.8	0.004	4.9	0.003
		$\frac{7}{2}^+$	152	1.3	0.009	1.0	0.007 ←
		$\frac{9}{2}^+$	152	0.8	0.005	0.6	0.004 ←
6.428	≈50 [c]	$\frac{1}{2}^-$	10 700	1370	0.129	1693	0.159
		$\frac{3}{2}^-$	10 700	617	0.058	729	0.069
		$\frac{3}{2}^+$	7300	176	0.024	158	0.022 ←
		$\frac{5}{2}^+$	7300	85	0.012	70	0.010 ←
		$\frac{5}{2}^-$	1430	24	0.017	26	0.018 ←
		$\frac{7}{2}^-$	1430	14	0.010	11	0.008 ←
		$\frac{7}{2}^+$	152	5	0.033	4.5	0.030
		$\frac{9}{2}^+$	152	2.7	0.018	2.5	0.016
6.465	≤14	$\frac{9}{2}^-$	7.8	0.082	0.011	0.066	0.008
		$\frac{11}{2}^-$	7.8	0.054	0.007	0.040	0.005
		$\frac{11}{2}^+$	0.224	0.004	0.018	0.003	0.013 (←)
6.540	≤14	$\frac{9}{2}^-$	8.1	0.127	0.016	0.097	0.012
		$\frac{11}{2}^-$	8.1	0.074	0.009	0.068	0.008 (←)
		$\frac{11}{2}^+$	0.245	0.005	0.020	0.003	0.012
6.845	≤14	$\frac{11}{2}^+$	0.390	0.016	0.041	0.010	0.026
		$\frac{13}{2}^+$	0.390	0.024	0.062	0.020	0.051

[a] Widths in center-of-mass system.
[b] The quantity given is the spectroscopic factor.
[c] See text for discussion.

at least within a factor of 2. A study of Table II, shows that the neutron width changes by almost a factor of 10 for a change in l of 1 and thus, although the widths extracted from the cross section are only approximate, they are quite useful in limiting J. For the 3.105-MeV level, it can be seen that only $l=1$ gives a neutron width within the acceptable range, all higher l's giving too small a width. The DOXY calculations for $\frac{1}{2}^-$ and $\frac{3}{2}^-$ for parameter Sets I and II are shown in Fig. 4. One sees a large difference in the shape of the angular distributions for $l+\frac{1}{2}$ and $l-\frac{1}{2}$, and the $\frac{1}{2}^-$ calculations definitely reproduce the data better than the $\frac{3}{2}^-$ curve. This is true for both parameter Sets I and II. None of the predicted angular distributions for $l_n \neq 1$ resemble the data. Values of $\Gamma_n / \Gamma_{\text{s.p.}}$ are also given in Table II and for $\frac{1}{2}^-$ Set I yields a value of 0.021 and Set II, a value of 0.018. The width obtained (96 or 79 keV) is approximately a factor of 2 larger than our estimated natural width of 42 keV. However, the value of $\Gamma_n / \Gamma_{\text{s.p.}}$ is in basic agreement with a recent determination[17] of a 3% intensity of a 2p-2h admixture of the $(2s_{1/2}{}^2, sp^{-2})_n$ configuration in the ground state of ^{14}C. The assignment of $\frac{1}{2}^-$ for the 3.105-MeV level is also in agreement with the suggestions of Garrett, Ajzenberg-Selove, and Bingham,[4] and the shell-model predictions of Refs. 1 and 2. Philpott[1] in his continuum shell-model calculation, predicts that the third excited state of ^{15}C should be a $\frac{1}{2}^-$ state at approximately 2.2 MeV and have a natural width of about 30 keV. He also predicts that the three active neutrons outside the ^{12}C core are $(s_{1/2}{}^2)_0 p_{1/2}$. Except for the 0.9 MeV difference in excitation energy, our results are in good agreement with these predictions. Reference 2 predicts the $\frac{1}{2}^-$ state to be at 2.68 MeV, which is also a little lower than the actual experimental value. In the study of the $2J_f+1$ variation of total cross section in the ^{9}Be(^{7}Li, p)^{15}C reaction,[4] the spin of the 3.105-MeV level was limited to $\frac{1}{2}$. From a comparison with the level structure of ^{17}O, these authors suggested that the 3.105-MeV state may have a neutron configuration similar to that of the $\frac{1}{2}^-$ state at 3.06 MeV in O.[17] From our results this suggestion appears to be correct.

4.221-MeV level. In our previous paper[3] on this reaction, we reported the 4.221-MeV level to have a width less than or equal to our resolution of about 14 keV. Since we have only an upper limit on the width, we can rule out only $l=1$ for this level on the basis of width alone. The best fit, for either Set I or Set II (Fig. 4), is obtained for a $\frac{7}{2}^+$ assignment. Again, a large J dependence is present in the DOXY predictions. A $\frac{5}{2}^-$ calculation (not shown) gives a worse fit to the data than the $\frac{9}{2}^+$ calculation. Using the $2J_f+1$ criterion, Garrett, Ajzenberg-Selove, and Bingham[4] limited the spin to be $\frac{5}{2}$, $\frac{7}{2}$, and from a comparison with the level structure of ^{17}O, these authors suggest that J^π may be $\frac{5}{2}^-$. Philpott[1] predicts a $\frac{5}{2}^-$ state near 3.86 MeV. The state should be narrow and the major shell-model component should be $(p_{1/2}, s_{1/2})_1 d_{5/2}$. We would not expect to populate this configuration in a single-step transfer reaction, so either the 4.22-MeV level is not the suggested $\frac{5}{2}$ state, or it is not excited in simple stripping and therefore the DOXY calculations should not be expected to reproduce the data. It is surprising to find an $l=4$ state so low in the spectrum. Neither Philpott[1] nor Reehal and Wildenthal[2] have included the g orbital in their calculations, but Reehal and Wildenthal[2] predict the lowest $\frac{7}{2}^+$ state (mixed configuration) to be near 5.75 MeV which is about 1.5 MeV higher than the 4.221-MeV level. If the ^{14}C(d,p)^{15}C reaction to this level proceeds by single-step transfer, however, the $\frac{7}{2}^+$ assignment is strongly favored over $\frac{5}{2}^-$. A possible explanation of such a low lying $\frac{7}{2}^+$ state is given in the next section.

6.374-MeV level. The 6.374-MeV level has had only an upper limit of about 14 keV placed on its width.[3] The DOXY calculations for the transition to this state are shown in Fig. 5. The $\frac{5}{2}^-$ calculations give definitely poorer fits to the data than the $\frac{7}{2}^+$ and $\frac{9}{2}^+$ calculations. The data however, are not good enough to allow a choice between $\frac{7}{2}^+$ and $\frac{9}{2}^+$. This l_n assignment is in disagreement with the limit of $\frac{5}{2}$ placed on J in Ref. 4.

6.428-MeV level. In Ref. 3, this level was reported to have a width of about 61 keV. In the data of that publication the 6.465-MeV level was not resolved from the 6.428-MeV level. However, in the present work, we have separated the two levels and the 6.428-MeV level is observed to have a width of approximately 50 keV. This limits l to 2 or 3 for this level. The DOXY calculations for $\frac{3}{2}^+$, $\frac{5}{2}^\pm$, $\frac{7}{2}^-$ are shown in Fig. 5. In this case no clear choice is possible between the four curves. Since the DOXY calculation for the 3.105-MeV level overpredicted the width by a factor of 2, it would appear that the $\frac{3}{2}^+$ or $\frac{5}{2}^+$ assignment is preferred over a $\frac{5}{2}^-$ or $\frac{7}{2}^-$ assignment. Philpott[1] predicts the second $\frac{5}{2}^+$ state in ^{15}C to be at about 6.62 MeV of excitation and to have a major shell-model component of $(s_{1/2}{}^2)_0 d_{5/2}$. In the present work $\Gamma_n/\Gamma_{\text{s.p.}}$ for the $\frac{5}{2}^+$ assignment is 0.010 which seems to be in accord with the 3% intensity of a $(2s_{1/2}{}^2, sp^{-2})_n$ configuration in the ground state of ^{14}C recently reported in Ref. 17. The first $\frac{3}{2}^+$ state is predicted in Ref. 1 to have a width of about 500 keV and an excitation energy of about 3.16 MeV, and to have a major shell component of $(p_{1/2}{}^2)_0 d_{3/2}$. The next $\frac{3}{2}^+$ state which would be populated in a

stripping reaction is predicted to be at approximately 9 MeV with a width of 500 keV.[1] The major shell-model configuration of this state would be $(s_{1/2}{}^2)_0 d_{3/2}$. Thus it appears that a $\frac{5}{2}^+$ assignment is probably to be preferred over the $\frac{3}{2}^+$ assignment for the 6.428-MeV level, but one cannot definitely rule out the possibility that this state is populated in a $l=3$ transition.

6.465-MeV level and 6.540-MeV level. Both of these states have widths less than 14 keV.[3] Calculations for $\frac{9}{2}^-$, $\frac{11}{2}^-$, and $\frac{11}{2}^+$ transitions are shown in Fig. 6. The $\frac{9}{2}^-$ curves provide somewhat poorer representations of the data than those for either $\frac{11}{2}^-$ or $\frac{11}{2}^+$. Because of the poor statistics it is difficult to make a choice between $\frac{11}{2}^-$ or $\frac{11}{2}^+$ but the $\frac{11}{2}^+$ fit may be a little better for the 6.465-MeV state, whereas the $\frac{11}{2}^-$ seems to be a little better for the 6.540-MeV state. None of the possible assignments presented here for the 6.540-MeV state are in agreement with the upper limit of $J=\frac{3}{2}$ suggested in Ref. 4.

6.845-MeV level. Again only an upper limit has been placed on the width of this level.[3] Calculations for $\frac{11}{2}^+$ and $\frac{13}{2}^+$ are shown in Fig. 6 with the $\frac{13}{2}^+$ being slightly preferred over the $\frac{11}{2}^+$. Both of these assignments are consistent with the limit of $J=\frac{11}{2}$ or $\frac{13}{2}$ given in Ref. 4.

6.882-MeV level. The statistics for this state are so poor that no DOXY calculations are shown for the level. The data are consistent with $\frac{9}{2}^-$, $\frac{11}{2}^+$, and $\frac{13}{2}^+$. The spin has been limited to $\frac{7}{2}$ or $\frac{9}{2}$ in Ref. 4.

V. DISCUSSION

A comparison of the present results with the shell-model calculations of Philpott,[1] and Reehal and Wildenthal[2] is presented in Fig. 7 together with the limits on J suggested by Garrett, Ajzenberg-Selove, and Bingham.[4] One would not expect most of the shell-model states presented in these calculations to be seen with the $^{14}C(d,p)^{15}C$ reaction if it proceeded by single-step neutron transfer. One might expect to see unbound states having

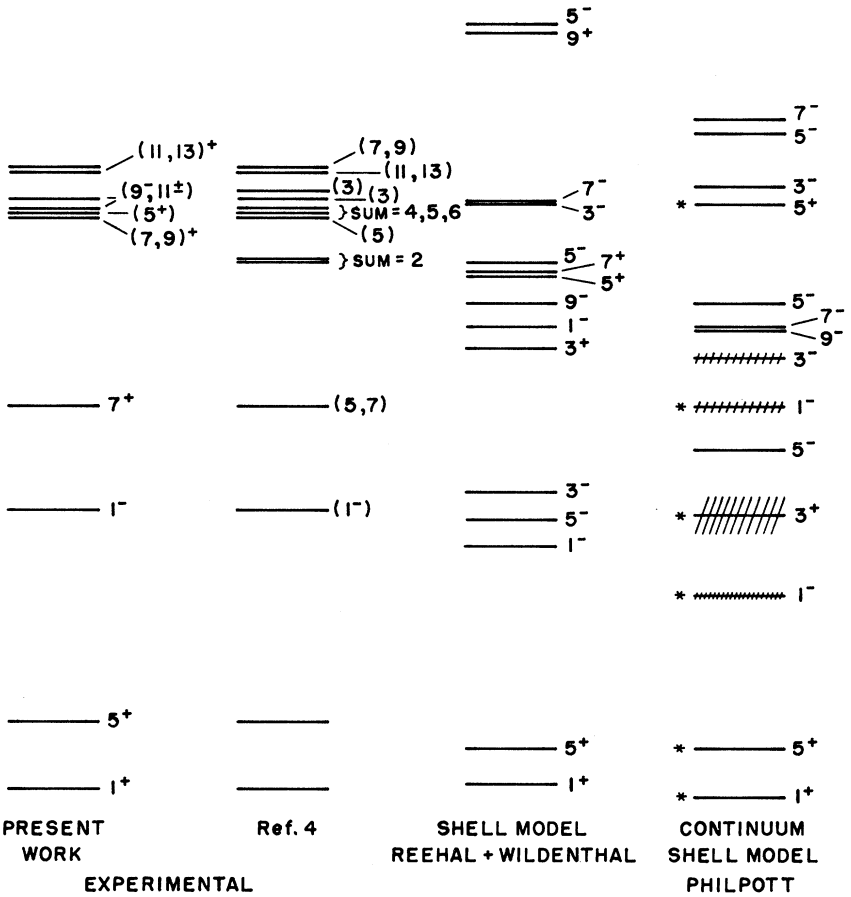

FIG. 7. Comparison of experimental data and shell-model predictions for ^{15}C. States are labeled by $2J^\pi$ and cross hatching indicates the width of levels calculated in the continunm shell model. For that model asterisks mark those levels that have large single-particle components which one would expect to see in ^{14}C (d,p) ^{15}C.

the following J^π and major neutron shell-model configuration[1]: $\frac{1}{2}^-$, $(s_{1/2}{}^2)_0 p_{1/2}$; $\frac{3}{2}^+$, $(p_{1/2}{}^2)_0 d_{3/2}$; $\frac{1}{2}^-$, $(d_{5/2}{}^2)_0 p_{1/2}$; and $\frac{5}{2}^+$, $(s_{1/2}{}^2) d_{5/2}$. From the present work we have identified the 3.105-MeV level as the lowest $\frac{1}{2}^-$ level predicted and suggest that the 6.428-MeV level may be the $\frac{5}{2}^+$ level with the configuration given above. It is surprising and a little disappointing that we were unable to locate the single-particle $d_{3/2}$ state. If Philpott is correct that the width of this state is about 500 keV, it would be very difficult to find in our $^{14}C(d,p)$ spectra unless it were strongly populated which evidently it is not. We also did not observe the predicted second $\frac{1}{2}^-$ state, but if it is less strongly populated than the 3.105-MeV level it is clear that we would not see it in our present data. What appears to be somewhat surprising in the present results is the many states with apparently high spin, like the $\frac{7}{2}^+$ at 4.221 MeV and the $\frac{11}{2}^+$ or $\frac{13}{2}^+$ states at 6.845 MeV. These high spin assignments may be erroneous if indeed they are populated predominantly by two-step processes. However, the spin of the 6.845-MeV level has previously been limited to a value of $\frac{11}{2}$ or $\frac{13}{2}$,[4] in agreement with the present results. In the shell-model calculations of Philpott[1] and Reehal and Wildenthal[2] the ^{12}C core was considered to be inert. Also higher orbits such as f, g, and h, were not considered. It is possible that single-particle admixtures with core-excited states may be responsible for some of the states observed in the present work. It is interesting to speculate as to whether the major configuration of the states at 4.221 and 6.370 MeV may be a 2^+ excitation of the ^{12}C core coupled to the $d_{5/2}$ neutron.

As mentioned earlier we also were not able to observe the 5.84- and 5.86-MeV states in ^{15}C reported in Ref. 4. The sum of the spins of these two levels is limited to 2 in Ref. 4, which implies that the spins of the levels are limited to $\frac{1}{2}$ and $\frac{3}{2}$. The 6.64-MeV level, which we also do not observe, has been limited to $\frac{3}{2}$. It appears either that low spin states are not strongly populated in the $^{14}C(d,p)^{15}C$ reaction, or that these states have shell-model configurations which are not populated in a simple stripping reaction.

The other surprising result of the present work is the strong J dependence in the cross section predicted by the DOXY calculations. Our investigation of this behavior show that the J dependence is not a strong function of the resonant wave function used. In fact, it is present when the same wave function is used for both J. It does not show any simple dependence on l_n. The J dependence is also evident in the published calculations for P_9 and P_{11}, in the $^{12}C(d,p)$ work of Ref. 7, and is evident for other values of l_n in our own calculations on this reaction. We have also made DOXY calculations for the $^{16}O(d,p_6)^{17}O$ reaction for the case of $l_n = 5$, which showed a strong J dependence at forward angles in the $^{14}C(d,p)^{15}C$ reaction. However, in the $^{16}O(d,p_6)$ case the differences in the calculated cross sections are very small. We have investigated the J dependence as a function of excitation energy but were unable to observe a strong correlation. Further investigation of the J dependence is necessary for a better understanding of the effect; however, in the present work it has been very useful in assigning J^π.

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