Widths in ^{15}C and ^{15}F

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Earlier data for the reaction ^{13}C(*t,p*) have been analyzed to extract widths for several states of ^{15}C. Results affect predictions of widths in ^{15}F.

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I. INTRODUCTION

Several investigators [1–5] are interested in the possibility of narrow resonances in ^{15}F. Two recent predictions [1,2] differed considerably for both energies and widths. In one of the approaches [2], the widths in ^{15}F depend (through isospin invariance) on widths of the mirror states in ^{15}C. In some instances, the ^{15}C widths are of interest in their own right. Because several states of ^{15}C have not had their widths determined, we were motivated to attempt to extract widths from earlier data for the ^{13}C(t,p) reaction. The results of that analysis are presented here.

II. WIDTHS IN ^{15}C

Data in Ref. [6] were recorded on nuclear emulsion plates in the focal planes of a multiangle spectrograph. For a state with no natural width, the intrinsic line shape of the spectrograph has linear leading and trailing edges, with a flattening at the top caused primarily by energy loss and straggling in the target. The middle of Fig. 1 displays the peak corresponding to the first-excited state at 0.74 MeV. Excitation energy increases to the right. Unless stated otherwise, data in the examples are all for a laboratory angle of 11.25 deg. Data were analyzed at three forward angles and averaged to get the results quoted. Dispersion varies smoothly along the focal plane. For conditions of the present experiment, it changes from $\delta E_x/\delta x = 8.43$ keV/mm for the 0.74-MeV state to 12.47 keV/mm for a (hypothetical) state at $E_x = 8$ MeV. In Fig. 1, the full width at half maximum (FWHM) of the 0.74-MeV data is 1.96 mm, corresponding to a resolution of 16.5 keV. The FWHM of the triangle formed by the linear leading and trailing edges is even smaller. The figure also displays a symmetric Gaussian shape $Y = N\exp(-a^2x^2)$, where $x = E - E_0$, and the resolution width is given by $\Gamma = 1.66/a$. In the present example, χ-squared minimization leads to a width of 1.89 mm, $\Gamma = 16.0$ keV. If this state had natural width, the natural line shape would be represented by a Breit-Wigner shape

$$Y = N(\Gamma^2/4)/[(E - E_0)^2 + \Gamma^2/4],$$

and the experimental line shape would involve the convolution of this shape with the Gaussian resolution shape.

We turn now to other excited states. Prior investigations of the levels have involved the reactions ^{9}Be($^7Li,p$) [7] and ^{14}C(d,p) [8,9]. Some of the data are summarized in the compilation [10]. The $1/2^-$ state at 3.10 MeV [10] clearly has natural width. Literature values are <40 [7] and ∼42 keV [8]. As this state is thought to be primarily an $(sd)^2$ excitation, viz. ^{13}C(gs)$\times(sd)^2_{0+}$, it likely gets its width by decaying to the ^{12}C(gs)$\times(sd)^2_{0+}$ component in the ^{14}C (gs). (Here, gs stands for ground state.) The ^{14}C(*d,p*) results [8] gave a spectroscopic factor of $S = 0.021$ or 0.018. Our analysis [2] with $\Gamma = 42$ keV led to $S = 0.033$. Here the state is partially resolved (top of Fig. 1) from the 6.73-MeV state of ^{14}C, which is present because of a ^{12}C impurity in the ^{13}C target, but that state is bound and has no natural width. And the peak shape for bound states is well known from target thickness and intrinsic line shape for the spectrograph. Under present conditions, the experimental resolution (see above) is 15–17 keV, depending somewhat on outgoing proton energy. Using a Gaussian shape for the ^{14}C state, and a Breit-Wigner shape convoluted with the Gaussian resolution shape for the 3.10-MeV state, provides a natural width of 29(3) keV for the latter. This width is smaller than the one in Ref. [8], but the resulting spectroscopic factor of 0.023 is closer to their value. The effect of this new width on the predicted width of the mirror in ^{15}F is discussed in a later section.

The 4.22-MeV state has been assigned $J^\pi = 5/2^-$ and has been suggested to have the dominant configuration ^{13}C(gs) $\times$ $(sd)^2_{2+}$. In ^{14}C(*d,p*) this state was analyzed as $7/2^+$ or $9/2^+$, because the fit for $5/2^-$ was poorer. Reference [7] had placed limits on J of 5/2 or 7/2 and had suggested $5/2^-$. This state has no discernible width (bottom of Fig. 1). Reference [10] gives $\Gamma < 14$ keV. Reference [1] calculated its width to be 2 keV, but some of their other widths are suspect. We find that fitting this peak assuming a width of zero gives the best fit. Adding any appreciable width, even 2 keV, worsens the fit. Of course, as the state is neutron unbound, it must have some width, but the decay is hindered by a centrifugal barrier and by the expected lack of $1f5/2$ single-particle (sp) strength this low in excitation. This would be a great state to investigate in ^{14}C(*n,n*).

Early attempts to locate the $d3/2$ sp state in ^{15}C were unsuccessful. At the time of publication of the ^{13}C(*t,p*) reaction results, it had still not been located. A later attempt [9] with the ^{14}C(*d,p*) reaction gave definitive evidence of its energy and width, and also observed a weaker $3/2^+$ state at higher E_x that interfered with it. The two energies [9] were 4.78(10) and 5.81(2) MeV. We had not noticed the broad $3/2^+$ state in our (*t,p*) data, but later inspection showed that it is clearly present under the 4.66-MeV state. Data for this complex of states are displayed in Fig. 2. We have removed three narrow peaks; those corresponding to the 4.22-MeV state, to ^{14}C(8.32), and

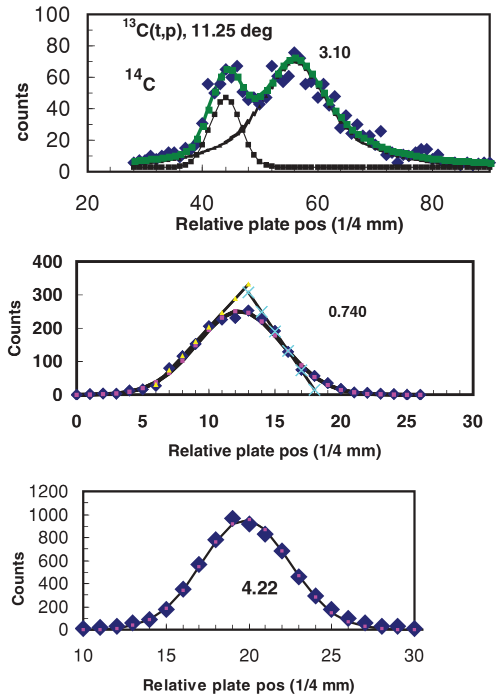

FIG. 1. (Color online) Peaks for three states of ^{15}C: the middle shows $E_x = 0.740$, which is bound, the top is 3.105, which has natural width, and the bottom has 4.22, which is unbound but narrow. Curves are explained in the text.

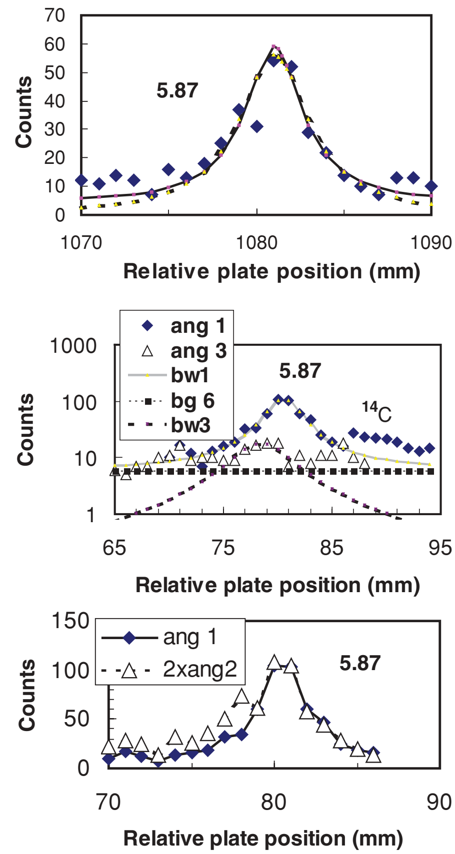

FIG. 3. (Color online) Data for 5.87-MeV region of ^{15}C at three forward angles. Top is for angle 2, bottom compares angles 1 and 2, and middle has angles 1 and 3. See the text.

to knock-on protons from hydrogen in the target. Then the counts were coarsely binned and converted to center-of-mass (cm) cross sections. The ordinate in Fig. 2 is 100 times the cross section, in millibarns per steradian. The abscissa is neutron cm energy. We have fitted the energy dependence of this cross section with two wide resonances, one near 4.66 MeV and the other very wide and centered just above it. For the latter, we performed two fits, one with a constant width (top) and one with an energy-dependent width (bottom) as determined from a potential model. Both fits used the Breit-Wigner shape for both resonances. The fit in the top of Fig. 2 assumes the width to be independent of energy. Energy, width, and normalization were allowed to vary for both resonances.

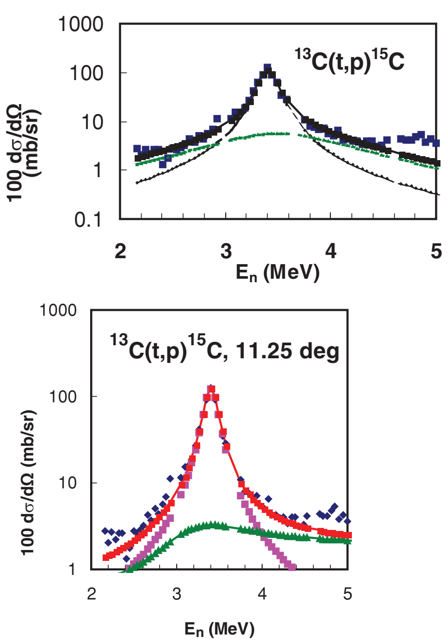

FIG. 2. (Color online) Peaks corresponding to the broad $3/2^-$ and $3/2^+$ states of ^{15}C, compared to Breit-Wigner shapes and their sum. Gaps are at locations where narrow states have been removed. Top: fit with both widths independent of energy. Bottom: fit with energy-dependent width for $3/2^+$, as given by a potential model.

Above the n breakup threshold (1.218 MeV), a real three-body continuum produces background counts. So the background is never zero, but it is small enough to be ignored for all but the weakest states. In the present case, the quality of the fit was improved if a small background was included, but the improvement was very slight. Final parameters are insensitive to whether background was included. For the fit in the top of Fig. 2, the narrower peak corresponds to an n cm energy of 3.40(1) MeV, with a width of 176(15) keV. The neutron energy of the wide state is 3.52(8) MeV, with a width of 1.54(8) MeV. In Ref. [9], a second, weaker $3/2^+$ state was observed, and interfered with the broader one. We see no evidence for an interference dip, and information on this second $3/2^+$ state is unclear (but see further discussion later). Perhaps it has destructively interfering amplitudes for $2n$ transfer. Our

TABLE I. Energies (MeV) and widths (keV) of unbound states in ^{15}C.

Literature[a]			^{13}C(t,p)[b]		
E_x	J^π	Width	E_x	J^π	Width[c]
3.103(4)	$1/2^-$	<40	3.100(6)	$1/2^-$	29(3)
4.220(3)	$5/2^-$	<14	4.215(9)	$5/2^-$	Narrow
4.657(9)	$3/2^-$	–	4.62(1)[c]	$3/2^-$	176(15)
4.78(10)	$3/2^+$	1740(400)	4.74(8)[c,d]	$3/2^+$	1540(80)
			4.64(10)[c,e]	$3/2^+$	1510(100)
5.833(20)	$(3/2^+)$	64(8)	(5.844(30))	–	(61(10))
5.866(8)	$1/2^-$	–	5.861(8)[c,f]	$1/2^-$	29(4)[i]
6.358(6)	$(5/2, 7/2^+, 9/2^+)$	<20	6.356(6)	–	Narrow
6.417(6)	(3/2 to 7/2)	∼50	6.415(9)[c,g]	–	42(4)[j]
6.449(7)	(9/2, 11/2)	<14	6.450(9)[c,h]	–	Narrow[j]
6.536(4)	–	<14	6.529(6)	–	12(4)
6.626(8)	(3/2)	20(10)	6.622(9)	–	Narrow
			6.785(9)[c]	–	Narrow
6.841(4)	–	<14	6.835(6)	$9/2^-$ (or $7/2^-$)	Narrow
6.881(4)	(9/2)	<20	6.876(7)	–	Narrow
7.095(4)	(3/2)	<15	7.093(6)	–	Narrow
			(7.195(15))[c]	–	105(15)
7.352(6)	(9/2, 11/2)	20(10)	7.341(8)[c]	–	Narrow
7.414(20)	–	–	7.387(7)	$7/2^-$(or $9/2^-$)	32(3)

[a]Reference [10].
[b]Reference [6], unless noted otherwise.
[c]Present.
[d]With constant width.
[e]With energy-dependent width.
[f]Fitting (5.844) and 5.861 as a single state gives $E_x = 5.867(8)$, $\Gamma = 44(6)$.
[g]Reference [6] had 6.404(7).
[h]Reference [6] had 6.440(6).
[i]Angle 1 only.
[j]Fitting 6.415 and 6.450 as a single state gives $E_x = 6.425(10)$, $\Gamma = 45(5)$.

excitation energy for the $3/2^+$ state is 4.74(8) MeV, compared with 4.78(10) in Ref. [9]. For the $3/2^+$ fit with constant width, after correcting for the gaps where narrow states were removed, the $3/2^+$ cross section at 11.25 deg is 3.2 mb/sr. For comparison, the $3/2^-$ cross section is 7.48 mb/sr.

The fit with an energy-dependent width is slightly worse (bottom of Fig. 2), and requires a small shift in resonance energy to $E_n = 3.42$ MeV. At this energy, the potential-model width has the value 1.51 MeV. The fact that the potential-model width fits the data without reduction implies a spectroscopic factor near unity. This is perhaps surprising, because Ref. [9] has $S \sim 0.5(3)$, but they have a much larger sp width, ∼3.5 MeV. We do not know why the sp widths are so different. Their resonance width is 1.74(40) MeV, the large uncertainty arising from the large continuum breakup cross section. In our fits, changing the background from zero to the preferred value changes the width by only 40 keV. The $3/2^-$ width must arise from a small portion of the $2p3/2$ sp state, which lies considerably higher in ^{15}C. A similar mixture into the lowest $3/2^-$ state was observed in ^{17}N [11]. The present cross section for the $3/2^-$ state of 7.48 mb/sr is slightly larger than the 6.55 mb/sr in Ref. [6], because the peak summation region there was too narrow. The new value improves both the $(3/2^-)/(5/2^-)$ and ^{15}C/^{16}C ratios.

The next state is the one at 5.87 MeV. This state presents a bit of a puzzle. It has a clear $L = 0$ angular distribution, and therefore $J^\pi = 1/2^-$. Similarity to the second 0^+ in ^{16}C was noted in Ref. [6]. The compilation lists two states near here, the other presumably being the second $3/2^+$ state found at 5.81 MeV in Ref. [9] and mentioned earlier. Our data at angle 2 are consistent with domination by a single state (top of Fig. 3), but because of the presence of another nearby state, we have looked very closely at the peak shape for different angles. These are presented in Fig. 3. Because of its $L = 0$ angular distribution, the $1/2^-$ state is strongest at the most forward angle, 3.75 deg. It has a deep minimum near the third angle, 18.75 deg. So, we have compared the peak shape at the first three angles. In the bottom of Fig. 3 we compare the peaks at angles 1 and 2, with the latter corrected for a small kinematic shift. If we multiply the angle-2 data by a factor of 2, the right-hand sides of the two peaks agree perfectly, but the left-hand sides differ. In the middle of Fig. 3, the peak shape at angle 3 (again shifted for kinematics) shows that the 5.87-MeV peak is almost totally absent, but counts remain at slightly lower excitation energy. These counts may correspond to the missing second $3/2^+$ state. The dotted curve is calculated for a state at 5.84 MeV with a width of 61 keV.

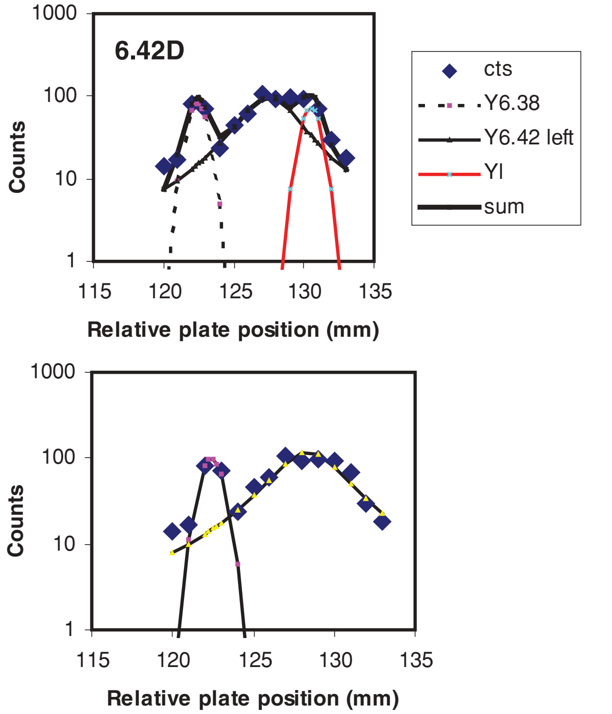

FIG. 4. (Color online) Region near 6.4 MeV, fitted with two states (bottom) and three states (top).

The next state in ^{15}C is at 6.356 MeV. In this region of excitation, the ^{13}C(t,p) reaction populates five states, all of which can be fitted with a Gaussian shape of width 18.5–18.8 keV. These energies are 6.356, 6.621, 6.785, 6.835, and 6.876 MeV. It is very unlikely that all these states just happen to have the same natural width, so we conclude that the resolution width is slightly worse at this region of E_x, and the Gaussian width of 18.5–18.8 keV represents the resolution width here. We list these states as narrow in Table I. Upper limits on natural width depend on strength of the state (statistics), background assumed, and the nearness of other states, but we expect Γ 2–4 keV for all of them.

The state at 6.356 MeV has no discernible width, as mentioned previously. Its peak is well fitted with a Gaussian shape (Fig. 4). If we treat the broad peak just above it as a single state (bottom of Fig. 4), its energy is 6.425(10) MeV, and the width is 45(5) keV. However, the compilation lists a broad state at 6.417(6) MeV with a width of ∼50 keV and a narrow state at 6.449 (7) MeV, with $\Gamma < 14$ keV. Putting both states into our fit (top of Fig. 4) leads to energies and widths of 6.415(9), 42(4), and 6.450(7), narrow, respectively. These energies differ slightly from those of 6.404(7) and 6.440(6) in Ref. [6].

The portion of the spectrum from about 6.5 to 7.5 MeV is plotted in the bottom of Fig. 5. Data for some of these states are displayed on expanded scales in subsequent figures. From Fig. 5, for the two strongest states, it appears that the upper one has natural width and the lower one does not. We return to this point later. Also, several weaker states appear to be narrow, as mentioned previously.

The state at 6.529 MeV (Fig. 6) clearly has natural width, whereas the 6.621-MeV level appears to be narrow. The lower one is weak enough that its extracted width depends on the

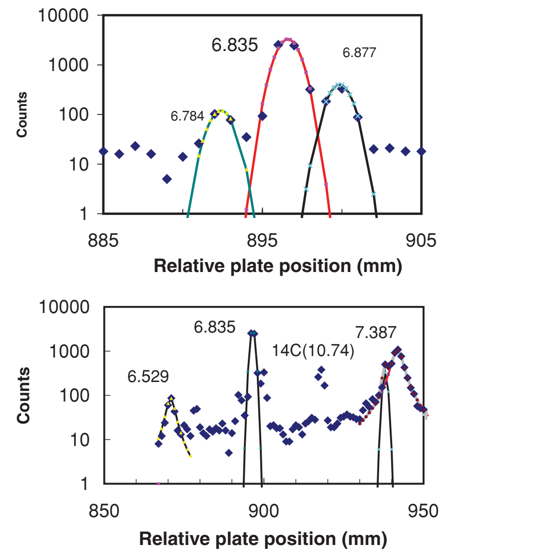

FIG. 5. (Color online) The bottom displays the excitation region from about 6.5 to 7.5 MeV and the top shows three narrow states near 6.8 MeV, compared with Gaussian shapes.

background level assumed. With no background (bottom of Fig. 6), the width is 15 keV; allowing the background to vary (top of Fig. 6) leads to a value of 4 counts/mm and a width of 9 keV. We quote $\Gamma = 12(4)$ keV.

As mentioned above, the strong $L = 4$ state at 6.835 MeV and the peaks on either side appear to be narrow. They are compared with Gaussian resolution shapes in the top of Fig. 5.

The spectrum exhibits a wide, weak peak that was not analyzed in Ref. [6]. If it is a state in ^{15}C, its energy is 7.195(15) MeV and its width is 105(15) keV (bottom of Fig. 7). It is certainly not the state at 7.093 MeV, which is only partially

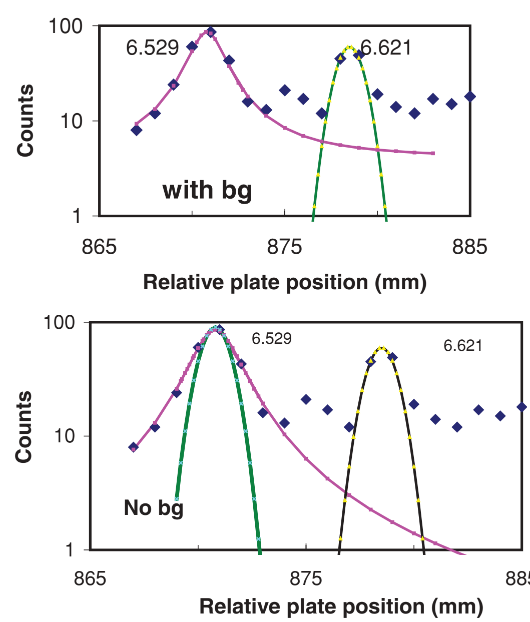

FIG. 6. (Color online) Two states just above 6.5 MeV, fitted with (top) and without (bottom) background. Lower-energy peak clearly has natural width.

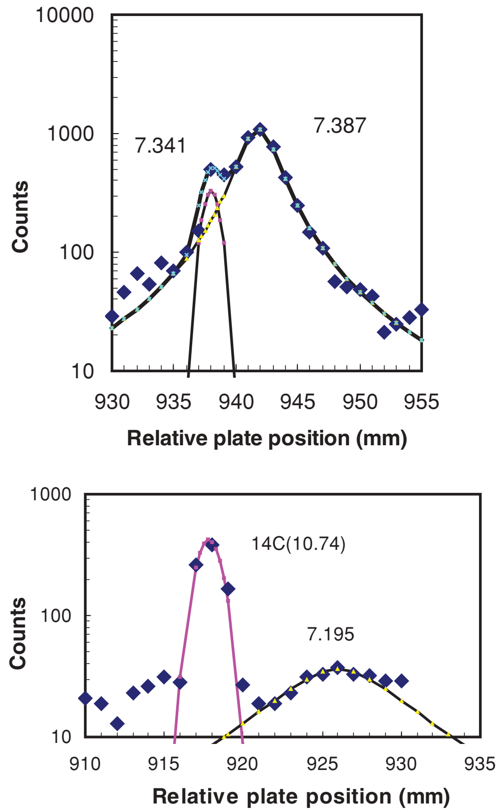

FIG. 7. (Color online) Top: the states at 7.341 and 7.387 MeV. Bottom: spectrum of ^{14}C(10.74), unresolved from ^{15}C(7.093) and apparent new wide state at 7.195 MeV.

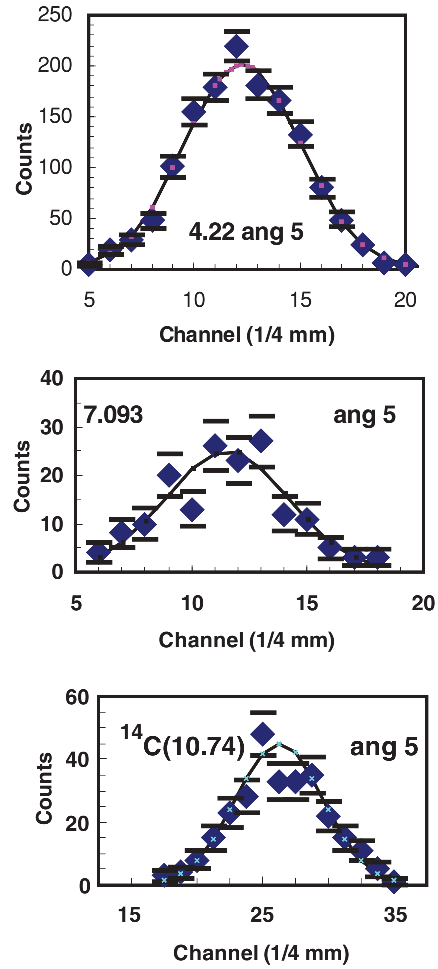

FIG. 8. (Color online) From angle 5 (33.75 deg), plots of peaks for $E_x = 4.22$, 7.093, and ^{14}C(10.74), with Gaussian fits. All appear narrow.

resolved from ^{14}C(10.74) and appears to be narrow. The ^{14}C(10.74) peak in Fig. 7 is wider than the resolution width. Fitting it with a Gaussian shape requires a width of 22.3 keV, rather than the 18.5–18.8 keV expected here. This state is thought [10] to have natural width and is only partially resolved from a ^{15}C state at 7.093 MeV. For this reason, we have examined this region at larger angles. By angle 5 (33.75 deg), the two states are totally resolved, but, of course, much weaker by then. The peaks for those two states and for the 4.22-MeV level are plotted in Fig. 8, in steps of 1/4 mm. All three are well fitted by Gaussian shapes, with FWHM corresponding to 18.7 keV for 4.22 and 20.1 keV for ^{14}C(10.74), both reasonably close to the 18.8-keV resolution width encountered earlier at this outgoing energy, but perhaps indicating some natural width for the ^{14}C state. Earlier work has reported a natural width of 20(7) keV [12] or ∼15 keV [13] for ^{14}C(10.74), but the present result would cast doubt on those values. The 20(7)-keV value is from the ^{9}Be(^{6}Li, p) reaction [12], which also reported a width of 22(6) keV for ^{14}C(8.318), whose width is now given as 3.4(6) keV [10]. Further investigation here would be worthwhile.

The strong state at 7.387 MeV clearly has natural width (top of Fig. 7). Our analysis yields $\Gamma = 32(3)$ keV. On the low-E_x side is a weak state at 7.341 that has no apparent width. It is possible that the 7.352-MeV state in the compilation, with a width of 20(10) keV, contains both states. In (t,p) the 6.835- and 7.387-MeV states were both strong and were reached by $L = 4$ transfer, implying $J^\pi = 7/2^-$ for one and $9/2^-$ for the other. The fact that the lower of the two has no discernible width and the upper one has a clear natural width might argue for $7/2^-$ for the upper one. The $7/2^-$ state can decay to ^{14}C(gs) via $\ell = 3$, whereas $9/2^-$ would require $\ell = 5$. The upper one is above the threshold for decay to the 1^- of ^{14}C at $E_x = 6.09$ MeV, to which it could decay via $\ell = 2$. Thus, our width values provide a clear preference of $7/2^-$ for 7.387 and $9/2^-$ for 6.835. In Ref. [6], the narrow state at 7.341 MeV was not separated from the 7.387-MeV level. With the current fit, its cross section is 0.53 mb/sr, causing a reduction to 5.09 mb/sr for 7.387. It is then slightly weaker than 6.835, strengthening the argument of $7/2^-$ for 7.387.

III. CONSEQUENCES FOR ^{15}F

The low-lying negative parity states of ^{15}C are dominated by the configuration ^{13}C(gs) $\times\ \nu(sd)^2$, where $\nu(sd)^2$ represents two neutrons in the sd shell. For ^{15}F, the corresponding states are ^{13}N(gs) $\times\ \pi(sd)^2$, where $\pi(sd)^2$ is two protons. We assume the wave-function amplitudes for mirror states in ^{15}C and ^{15}F are the same, and the Coulomb interaction affects only the radial wave functions. We have taken wave functions from Ref. [14]. With these wave functions, the Coulomb energies

TABLE II. Energies (MeV) and widths (keV) in ^{15}C and ^{15}F.

	^{15}C			^{15}F		
J^π	E_x	Source	Γ	Source	E_p	Γ
$1/2^-$	3.10	Ref. [1]	2	Ref. [1]	5.49	5
		Present	29(3)	Present	4.63	38
				Expt (Refs. [4,5])	4.9(2)	200(200)
$5/2^-$	4.22	Ref. [1]	2	Ref. [1]	6.88	10
		Present	Narrow	Present	5.92	6
				Expt (Refs. [4,5])	–	–
$3/2^-$	4.66	Ref. [1]	90	Ref. [1]	7.25	40
		Present	176(15)	Present	6.30	350
				Expt (Refs. [4,5])	6.4(2)	200(200)

in ^{15}F were computed for a Woods-Saxon potential having r_0, $a = 1.25$, 0.65 fm, plus the Coulomb potential of a uniform sphere. Coulomb energies were then combined with the known excitation energies in ^{15}C to obtain the ^{14}O(gs) + p energies listed in Ref. [2] and Table II.

Given the computed proton energies, single-particle (sp) widths were calculated using the same potential for proton decay to ^{14}O(gs). Within our model the spectroscopic factors in ^{15}C and ^{15}F are equal, so the ratio of experimental widths should be the same as the ratio of sp widths, that is,

$$\Gamma_{\rm calc}(^{15}\mathrm{F}) = [\Gamma_{\rm sp}(^{15}\mathrm{F})/\Gamma_{\rm sp}(^{15}\mathrm{C})]\Gamma_{\rm expt}(^{15}\mathrm{C}).$$

These are the widths listed in Table II. Reference [2] states that a width of 42 keV for ^{15}C(3.10) leads (via isospin invariance) to a $1/2^-$ state in ^{15}F at a proton resonance energy of 4.63 MeV and a width of about 55 keV. With our new width of 29 keV, this prediction changes to 38 keV. Of course, if the proton energy of the resonance is different, then the width will also be slightly different. We plot in Fig. 9 the expected width for a range of energies. References [4,5] observed two states in the decay of ^{16}Ne* that they suggest as $1/2^-$ and $3/2^-$ mirrors of the 3.10- and 4.66-MeV states of ^{15}C. Their widths for both are 0.2(2) MeV, and the energies are $E_p = 4.9(2)$ and 6.4(2) MeV. In Ref. [2], our predicted $3/2^-$ energy was 6.30 MeV. For a width of 90 keV in ^{15}C, the predicted width in ^{15}F was 180 keV. With our new ^{15}C width of 176(15) keV, the predicted width in ^{15}F would be about 350 keV. The energy dependence of this predicted width is also displayed in Fig. 9. Predictions of Ref. [1] are given for comparison.

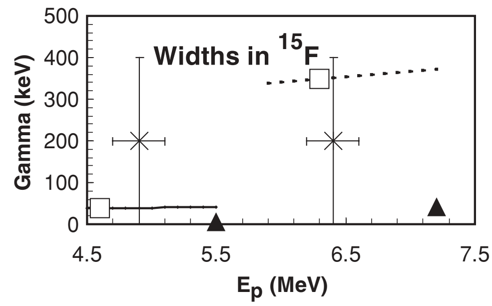

FIG. 9. Energies and widths in ^{15}F. Predictions of Ref. [2], amended by new ^{15}C widths, are shown as open squares, with the slight energy dependence attached. Closed triangles are predictions of Ref. [1]. Crosses are new experimental values [4,5].

We note that our widths for both $1/2^-$ and $3/2^-$ states are significantly larger than those predicted by Ref. [1]. Because their predicted energies are higher than ours, their widths would be even smaller if computed for our energies. At present, the experimental energies favor our description, but the uncertainties in the widths are too large for a definitive test. We note, however, that Ref. [1] has a smaller $3/2^-$ width in ^{15}F than in ^{15}C, a very surprising result. Clearly, more experimental work needs to be done.

The other state observed in Ref. [5] is at $E_p = 7.8(2)$ MeV. It should be the mirror of a state near 6 MeV in ^{15}C. Of the states near here, the second $1/2^-$ is perhaps most likely to be populated in the decay of ^{16}Ne*. In ^{15}C the width of this state is 29(4) keV, leading to a predicted width of about 35 keV for its mirror in ^{15}F for this decay branch. However, as pointed out in Ref. [5], a $1/2^-$ state could decay to the 1^- state of ^{14}O via $\ell = 0$, with a large width. Our estimate of the ^{15}F energy for the mirror of the $1/2^-$ state at 5.87 MeV in ^{15}C is $E_p = 7.1$ MeV, with a width for decay to ^{14}O(1^-) of about 0.8 MeV. Another possibility is the mirror of the second $3/2^-$, for which candidates exist at 6.417 and 6.622 MeV in ^{15}C. The lower is more likely because it has natural width. Its width for p decay to ^{14}O(1^-) could be even larger than for the second $1/2^-$.

In summary, we have extracted widths for several states of ^{15}C from earlier data for the reaction ^{13}C(t,p). Many of the states are very narrow. The $d3/2$ sp state is observed, with energy and width consistent with previous values. New values of some of the ^{15}C widths lead to slightly altered predictions for ^{15}F widths.

[1] L. Canton, G. Pisent, J. P. Svenne, K. Amos, and S. Karataglidis, Phys. Rev. Lett. **96**, 072502 (2006); **99**, 089202 (2007).
[2] H. T. Fortune and R. Sherr, Phys. Rev. Lett. **99**, 089201 (2007).
[3] A. Lepine-Szily (private communication).
[4] I. Mukha *et al.*, Phys. Rev. C **77**, 061303(R) (2008).
[5] I. Mukha *et al.*, Phys. Rev. C **79**, 061301(R) (2009).
[6] S. Truong and H. T. Fortune, Phys. Rev. C **28**, 977 (1983).
[7] J. D. Garrett, F. Ajzenberg-Selove, and H. G. Bingham, Phys. Rev. C **10**, 1730 (1974); J. D. Goss, A. A. Rollefson, C. P. Browne, R. A. Blue, and H. R. Weller, *ibid.* **8**, 514 (1973).
[8] J. D. Goss, P. L. Jolivete, C. P. Browne, S. E. Darden, H. R. Weller, and R. A. Blue, Phys. Rev. C **12**, 1730 (1975).
[9] S. E. Darden, G. Murillo, and S. Sen, Phys. Rev. C **32**, 1764 (1985).
[10] F. Ajzenberg-Selove, Nucl. Phys. A **523**, 1 (1991).
[11] H. T. Fortune, G. E. Moore, L. Bland, M. E. Cobern, S. Mordechai, R. Middleton, and R. D. Lawson, Phys. Rev. C **20**, 1228 (1979).
[12] F. Ajzenberg-Selove, H. G. Bingham, and J. D. Garrett, Nucl. Phys. A **202**, 152 (1973).
[13] S. Mordechai *et al.*, Nucl. Phys. A **301**, 463 (1978).
[14] H. T. Fortune, M. E. Cobern, S. Mordechai, G. E. Moore, S. Lafrance, and R. Middleton, Phys. Rev. Lett. **40**, 1236 (1978).