Properties of ^{16}C(6.11 MeV) and its mirror in ^{16}Ne

H. T. Fortune
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

(Received 11 May 2016; published 11 July 2016)

From previous data for the reaction ^{14}C$(t,p)^{16}$C, I have extracted a width of 32.6(5) keV for the strong state at $E_x = 6.11$ MeV. Here, I examine its likely J^π and configuration. The predicted width of its mirror in ^{16}Ne is estimated to be about 260 keV.

DOI: 10.1103/PhysRevC.94.014305

I. INTRODUCTION

In the reaction ^{14}C$(t,p)^{16}$C, the only state above the known 4^+ at 4.14 MeV with any appreciable strength is a narrow state at $E_x = 6.109$ MeV [1]. Its maximum cross section is larger than that for all but the first 0^+, 2^+, and 4^+ states, implying likely natural parity. Its angular distribution is not sufficiently well fitted to ascertain an L value, but at these negative Q values, 2^+ and 3^- shapes are very similar. The original experiment reported a width of less than or about 25 keV. I have taken another look at this state in an attempt to understand its structure.

II. RESULTS AND CALCULATIONS

The portion of the spectrum containing this state is plotted in Fig. 1. At this excitation energy, a plate distance of 1/4 mm corresponds to an energy of 2.38 keV. The resolution width (full width at half maximum) in this experiment was approximately 19 keV as evidenced by the widths of peaks corresponding to bound states at lower excitation energy. Thus, the resolution width here is about 8.0 channels. (I use channel and 1/4 mm interchangeably.) The full width of this state is observed to be significantly larger, about 17.5 channels—corresponding to 42 keV. Using a Gaussian shape for the resolution profile and a Breit-Wigner shape for the natural width of the state, a fit provides a value of 13.7(3) channels for the latter. Thus, the natural width is 32.6(5) keV.

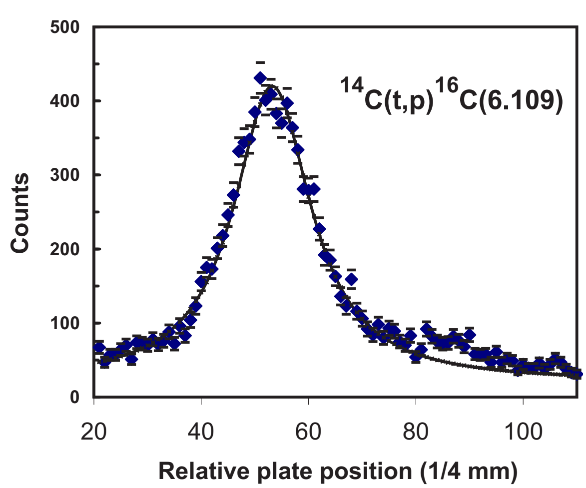

FIG. 1. Portion of the spectrum for the reaction ^{14}C$(t,p)^{16}$C containing the peak corresponding to the state at 6.11 MeV. With a resolution width of 19 keV, the observed peak shape corresponds to a natural width of 32.6(5) keV.

If the state has $J^\pi = 3^-$, decay to the ground state (g.s.) would require $\ell = 3$, but decay to $5/2^+$ could proceed by $\ell = 1$ or 3. The lowest 3^- state expected in ^{16}C is a three-hole-three-particle (3h-3p) with the configuration ^{13}C(g.s.) $\otimes\, \nu(sd)^3_{5/2}$. It could decay to the $5/2^+$ state via $\ell = 1$ to the 4h-3p component of the latter—estimated to be 0%−9% [2]. The p-wave single-particle (sp) width for this configuration is about 1.4 MeV. The relevant spectroscopic factor is $S = (0\text{–}0.09)0.61$ where the second factor is S for ^{13}C(g.s.) $\rightarrow$ ^{12}C(g.s.) [3]—giving an expected width of 38(38) keV. This is clearly consistent with the experimental width. However, from a p-shell ^{14}C, this state could not be reached in a one-step direct $2n$ transfer experiment. But, ^{14}C is known to have an admixture of the configuration ^{12}C$\otimes\nu(sd)^2$, estimated to be in the range of 0.08 [4] to 0.12 [5]. From this component, the 3^- could be populated in $(t,\ p)$ by transfer of a $p_{1/2}d_{5/2}$ pair. This is the same pair transfer that populates the $5/2^+$ state of ^{15}C in the reaction ^{13}C$(t,p)^{15}$C [6]. So, if this state in ^{16}C is 3^-, we might expect its cross section to be related to the one in ^{15}C by the relation $\sigma[^{16}\mathrm{C}(6.11)] = (0.08\text{–}0.12)\sigma[^{15}\mathrm{C}(0.74)]$. A more detailed calculation reduces the expected ^{16}C(3^-) cross section even further. In the ^{13}C(t,p) reaction, the maximum of the angular distribution for the $5/2^+$ state has a cross section of 3.33 mb/sr, whereas in the ^{14}C(t,p) reaction, the 6.11-MeV state has $\sigma_{\max} = 4.0$ mb/sr—much too strong to have the configuration under discussion. Therefore, the 6.11-MeV state of ^{16}C is much too strong in $(t,\ p)$ to be 3^-. For the remainder of the present discussion, I assume its J^π is 2^+. With the ^{13}C(^{12}C$\,,^{9}$C) ^{16}C reaction, Bohlen *et al.* [7] concluded that the lowest 3^- state is at $E_x = 7.74$ MeV with a width of 0.20(4) MeV.

If the state has $J^\pi = 2^+$, the sp width for $d_{5/2}$ decay is 437 keV for decay to the g.s. of ^{15}C and 136 keV for decay to the $5/2^+$ at 0.74 MeV. The sp width for an s-wave neutron

TABLE I. Single-particle widths (keV) for decay of ^{16}C(6.11 MeV) $\rightarrow$ ^{15}C $+n$.

Final state	E_n (MeV)	$\Gamma_{\rm sp}(\ell = 2)$	$\Gamma_{\rm sp}(\ell = 0)$
$5/2^+$	1.12	136	∼1100
$1/2^+$	1.86	437	

TABLE II. Expected energies and decay strengths for ^{16}C(6.11 MeV) $\to$ ^{15}C $+n$ for the configurations listed.

Label	Configuration	E_x (calc.) (MeV)	Decay to $5/2^+$		Decay to $1/2^+$
			S_s	S_d	S_d
1	^{12}C(0) $\otimes$ $\nu(sd)^4_{21}$	5–7	0.007(7)	0.032(32)	0.006(6)
2	^{14}C(2) $\otimes$ $\nu(sd)^2_{01}$	7.6	0.16(2)	0.0074(74)	0.004(4)
3	^{14}C(2) $\otimes$ $\nu(sd)^2_{21}$	9.4	0.002(2)	0.24(11)	0.012(12)
4	^{14}C(0) $\otimes$ $\nu(sd)^2_{23}$	8.8	0.012(1)	0.020(2)	0.015(2)

is difficult to calculate but is probably more than 1 MeV for these decay energies. These are listed in Table I. Near this excitation energy, several 2^+ states could exist, including the four configurations listed in Table II. I estimated the energy of state 1 with the weak-coupling formalism of Bansal-French [8] and Zamick [9]. For state 2, I adopted the suggestion of long ago [10] that the first two 2^+ states of ^{14}C at energies of 7.01 and 8.32 MeV are approximately equal admixtures of two basis states—the p-shell 2^+ and the lowest $(sd)^2$ 2^+ state. The energy of the p-shell basis state is thus the average of the two energies, and this is the energy of state 2. For state 3, the 2×2 coupling produces a multiplet of states with $J = 0$–4 at a centroid energy of 1.76 MeV above state 2 because this is the energy of the first 2^+ state in ^{16}C. State 4 is just the third 2^+ state in an $(sd)^2$ shell-model calculation [11] with an inert ^{14}C core. The first two 2^+ states of this type are at 1.76 and 3.99 MeV.

Using published wave functions for the relevant nuclei [2,12,13], the spectroscopic factors for the various decays are as listed in Table II. Resulting computed widths ($\Gamma_{\text{calc}} = S\Gamma_{\text{sp}}$) are listed in Table III.

From these predicted widths, we see that only the last two configurations have total widths consistent with the experimental value of 32.6(5) keV. Configuration 3 has a total predicted width of 40(16 keV). However, its structure would not allow population in a one-step process. The fact that it is built on the excited 2^+ state might indicate a reaction route of inelastic scattering accompanied by $2n$ transfer. In the reaction ^{12}C(t,p) ^{14}C [13], the 2^+ state at 10.42 MeV was observed to be much stronger than expected for the second $(sd)^2$ 2^+ state. The cross sections for the 6.11-MeV state in ^{16}C and the 10.42-MeV state in ^{14}C are approximately equal. So, the latter might be the 2^+ state built on ^{12}C(2^+) expected in this energy region and thus populated by a similar two-step reaction. Cross sections for 2^+ states in the ^{12,14}C(t,p) ^{14,16}C reactions are plotted in Fig. 2.

The fourth configuration is the third 2^+ $(sd)^2$ state. The predicted total width from the table is 23(2) keV. But, this state is primarily of the structure $d_{5/2}d_{3/2}$ and $d_{3/2}s_{1/2}$, and it would thus have large widths for $d_{3/2}$ decay to both states. Estimates of these widths are 165 keV to the g.s. and 55 keV to the $5/2^+$ state. It appears, then, that this state is not a candidate for the observed 6.11-MeV state.

TABLE III. Predicted widths (keV) for decay of ^{16}C(6.11 MeV) $\to$ ^{15}C $+n$.

Label	Decay to $5/2^{+\text{b}}$		Decay to $1/2^+$
	Γ_{calc} (s)	Γ_{calc} (d)	Γ_{calc} (d)
1	8(8)	4(4)	3(3)
2	176(22)	1(1)	2(2)
3	2(2)	33(15)	5(5)
4[a]	13(1)	2.7(3)	7(1)

[a]Also has large predicted widths for $d_{3/2}$ decays to both $5/2^+$ and $1/2^+$ states. (See text.)
[b]Measured width is 32.6(5) keV.

III. MIRROR IN ^{16}Ne

A narrow 2^+ state has been reported [14,15] in ^{16}Ne at $E_x = 6.18$ MeV. It would be surprising if the only strong narrow state at similar energies in these two nuclei were not mirrors. I have discussed elsewhere [16] the fact that none of the expected 2^+ states in ^{16}Ne that should be strong in proton removal have a width consistent with the small limit of <100 keV [14]. If ^{16}C(6.11) is the mirror of ^{16}Ne(6.18), we expect $\Gamma(\text{Ne})/\Gamma(\text{C}) = \Gamma_{\text{sp}}(\text{Ne})/\Gamma_{\text{sp}}(\text{C})$ or $\Gamma(\text{Ne}) = 32.6\,\text{keV}(1100/136) = 264$ keV. These are for $d_{5/2}$ decay to $5/2^+$, which is the decay path reported [10] for ^{16}Ne. This width is considerably larger than the reported limit of <100 keV [14]. In the experiment that produced that limit, the resolution width at the relevant energy was 1.4 MeV FWHM. So, such a small limit may be overly optimistic. I note that another experiment gave a width limit of <500 keV [15]. Therefore, if the decay is indeed primarily to the $5/2^+$ state, I expect an accurate width measurement in ^{16}Ne will result in a value near 260 keV.

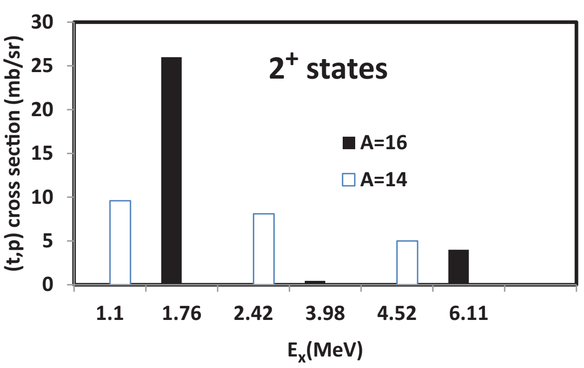

FIG. 2. Peak cross sections for 2^+ states in the reactions $^{A-2}$C$(t,p)^A$C [1,13]. For ^{16}C (solid rectangles), the abscissa is excitation energy; for ^{14}C (open rectangles), it is $E_x - 5.9$ MeV.

TABLE IV. Comparison of energies (MeV) and widths (keV) for suggested mirrors in ^{16}C and ^{16}Ne.

Nucleus	E_x (expt.)	E to $5/2^+$	Γ_{sp} [c]	E to $1/2^+$	Γ_{sp} [c]	Γ_{exp}
^{16}C	6.11 [a]	1.12	136	1.86	437	32.6(5) [c]
^{16}Ne	6.18 [b]	4.77	1100	6.17	2000	<100 [b], <500 [d]
Width ratio			0.12		0.22	$>0.33, >0.065$

[a]Ref. [1].
[b]Ref. [14].
[c]Present paper.
[d]Ref. [15].

IV. SUMMARY

Using previous data from the reaction ^{14}C$(t,p)^{16}$C, I have extracted the width of the strong state at $E_x = 6.11$ MeV. The result is $\Gamma = 32.6(5)$ keV. The state is much too strong to be 3^-. I conclude that its J^π is 2^+. I have investigated the widths to be expected for several 2^+ configurations. The only structure that has the appropriate width is a state built on the p-shell 2^+ state of ^{14}C. Using mirror symmetry, I expect that the mirror in ^{16}Ne of this state will have a width of about 260 keV, despite an earlier limit of <100 keV for the 2^+ 6.18-MeV state in that nucleus (see Table IV).

[1] H. T. Fortune, R. Middleton, M. E. Cobern, G. E. Moore, S. Mordechai, R. V. Kollarits, H. Nann, W. Chung, and B. H. Wildenthal, Phys. Lett. B **70**, 408 (1977).
[2] H. T. Fortune and R. Sherr, Phys. Rev. C **72**, 024319 (2005).
[3] S. Cohen and D. Kurath, Nucl. Phys. A **101**, 1 (1967).
[4] A. C. Hayes *et al.*, Phys. Rev. C **37**, 1554 (1988).
[5] H. T. Fortune and G. S. Stephans, Phys. Rev. C **25**, 1 (1982).
[6] S. Truong and H. T. Fortune, Phys. Rev. C **28**, 977 (1983).
[7] H. G. Bohlen *et al.*, Phys. Rev. C **68**, 054606 (2003).
[8] R. Bansal and J. B. French, Phys. Lett. **11**, 145 (1964).
[9] L. Zamick, Phys. Lett. **19**, 580 (1965).
[10] E. K. Warburton and W. T. Pinkston, Phys. Rev. **118**, 733 (1960).
[11] H. T. Fortune, M. E. Cobern, S. Mordechai, G. E. Moore, S. Lafrance, and R. Middleton, Phys. Rev. Lett. **40**, 1236 (1978).
[12] H. T. Fortune, R. Sherr, and B. A. Brown, Phys. Rev. C **85**, 054304 (2012).
[13] S. Mordechai, H. T. Fortune, G. E. Moore, M. E. Cobern, R. V. Kollarits, and R. Middleton, Nucl. Phys. A **301**, 463 (1978).
[14] J. Marganiec *et al.*, Eur. Phys. J. A **51**, 9 (2015).
[15] K. W. Brown *et al.*, Phys. Rev. C **92**, 034329 (2015).
[16] H. T. Fortune, Eur. Phys. J. A **52**, 119 (2016).