Core Excitation in $^{14}\text{C}$ and Two-proton Pickup

H Terry Fortune

University of Pennsylvania, fortune@physics.upenn.edu

Follow this and additional works at: http://repository.upenn.edu/physics_papers

Part of the Physics Commons

Recommended Citation


© 2012 American Physical Society

This paper is posted at ScholarlyCommons. http://repositoryupenn.edu/physics_papers/267

For more information, please contact libraryrepository@pobox.upenn.edu.
Core Excitation in $^{14}$C and Two-proton Pickup

Abstract
In two-proton pickup from $^{14}$C, the calculated cross-section ratio for the first two 0$^+$ states of $^{12}$Be depends on the configuration mixing in these two states and on the amount of core excitation in the ground state (g.s.) of $^{14}$C. Using the $^{12}$Be wave functions that are reasonably well known, I have calculated this ratio as a function of the core excitation in $^{14}$C(g.s.). A measurement of this ratio should allow an independent determination of the $^{14}$C mixing—previously estimated to be about 12%.

Disciplines
Physical Sciences and Mathematics | Physics

Comments

© 2012 American Physical Society

This journal article is available at ScholarlyCommons: http://repository.upenn.edu/physics_papers/267
Core excitation in $^{14}$C and two-proton pickup

H. T. Fortune

Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania, 19104

(Received 13 August 2012; revised manuscript received 27 September 2012; published 7 December 2012)

In two-proton pickup from $^{14}$C, the calculated cross-section ratio for the first two 0$^+$ states of $^{12}$Be depends on the configuration mixing in these two states and on the amount of core excitation in the ground state (g.s.) of $^{14}$C. Using the $^{12}$Be wave functions that are reasonably well known, I have calculated this ratio as a function of the core excitation in $^{14}$C(g.s.). A measurement of this ratio should allow an independent determination of the $^{14}$C mixing—previously estimated to be about 12%.

DOI: 10.1103/PhysRevC.86.067303  PACS number(s): 21.60.Cs, 25.55.Hp, 25.70.Hi, 27.20.+n

Introduction. The ground state (g.s.) of $^{14}$C contains some core excitation. The predominantly p-shell wave function has, in addition, an amplitude of $^{12}$C x $\nu$ (sd)$^2$. The intensity of this configuration has been estimated from an analysis of the $^{12}$C(t,p) cross sections to the g.s. and excited 0$^+$ state (called 0$^+$ here). In a two-state model, the (sd)$^2$ component in the g.s. is the same as the p-shell component in 0$^+$. The result is 0.12(3) [1]. Of course, $^{14}$C has more than two 0$^+$ states. The appropriateness of a two-state model in this case is demonstrated by the obvious nonparticipation of the next (third) 0$^+$ state in $^{14}$C, as can be seen clearly [2] by the fact that its [the second (sd)$^2$ 0$^+$ state] behaves nearly identically to the second 0$^+$ state in $^{16}$C, which has no p-shell state. (Their cross-section magnitudes and angular-distribution shapes are the same.)

In a theoretical calculation in connection with the analysis of $^{14}$C($\pi^+\pi^0$) inelastic scattering, Hayes et al. [3] obtained an estimate of 8% (sd)$^2$ in the $^{14}$C(g.s.) and 13% p-shell component in the excited 0$^+$ state. These are different because the shell-model calculation is not a two-state model, as was the other analysis mentioned above, where these two percentages were equal. These estimates are summarized in Table 1. Here I investigate the possibility of another experimental determination of this mixing.

1$^{12}$Be, the two 0$^+$ states (g.s. and 2.251(1) MeV [4]) are thought to be linear combinations of two basis states—the normal p-shell $^{12}$Be(g.s.) and an intruder with two neutrons in the sd shell. It is now widely accepted from several different analyses [5–9] that the latter is about 68% of the $^{12}$Be(g.s.). A calculation [6] of the $^{12}$Be-$^{12}$O Coulomb energy difference gave an $s^2$ parentage of 0.53(3) in the g.s. A simple (sd)$^2$ shell-model calculation [6] gave a $d^2/s^2$ ratio of 0.22/0.78 and hence 0.68(4) for the (sd)$^2$ component [6]. A very recent measurement [10] of the Gamow-Teller (GT) strengths of the two 0$^+$ states from the $^{1}$+ g.s. of $^{12}$B was made using the reaction $^{12}$B($^3$Li, $^7$Be) in inverse kinematics. This experiment is the first to directly measure the p-shell component of the excited 0$^+$ state. Other investigations had inferred it from orthogonality with the g.s. or through destructive interference in (t,p) and $B(E2)$. These new results have clearly indicated that the commonly accepted wave functions are approximately correct: Their intensities of 0.25(5) and 0.60(5) for the p-shell component of the g.s. and excited 0$^+$ state, respectively, are to be compared to our 0.32(4) and 0.68(4). This uncertainty is from the combined shell-model and Coulomb-energy calculations [6]. However, considering the wide variety of processes (see Summary in Ref. [9]) that have confronted these wave functions and the remarkable agreement between experiments and calculations, the actual uncertainty is probably smaller than this.

In two-proton pickup from $^{14}$C, both components will contribute to the reaction, even though all the pickup will still be from the p shell, as demonstrated previously [11]. The pickup reaction amplitude to the excited 0$^+$ state will be destructive, causing a large decrease in the excited state/g.s. ratio from the value it would have for a pure p-shell $^{14}$C(g.s.). Because of the sensitivity of this destructive interference to the magnitudes and phases of these mixings, the excited state/g.s. cross-section ratio expected in two-proton pickup from $^{14}$C(g.s.) as a function of the assumed core excitation in the latter.

The model. I use the subscript CK to denote pure p-shell states, as in Cohen and Kurath [12]. Wave functions are then

$$^{14}$C(g.s.) = $u^{14}$CC + $v^{14}$CC(x(sd)$^2$),

$^{12}$Be(g.s.) = $a^{10}$BeCK(g.s.)x(sd)$^2$ + $b^{12}$BeCK(g.s.), and

$^{12}$Be(exc) = $-b^{10}$BeCK(g.s.)x(sd)$^2$ + $a^{12}$BeCK(g.s.).

The two-proton pickup amplitudes are

$$A(\text{exc}) = uaA^{(14}$CC$\rightarrow^{12}$BeCK),$$

$$A(\text{g.s.}) = ubA^{(14}$CC$\rightarrow^{12}$BeCK) + vaA^{(12}$CC$\rightarrow^{10}$BeCK).$$

In both cases, the second term needs to be multiplied by a factor of $(\sqrt{5})/3$ for isospin uncoupling and recoupling. If we take the individual amplitudes from Cohen and Kurath [12], then the squares of the A’s above are equal to their $S_{\text{mag}}$’s, where $S_{\text{mag}}$ is the L = 0 two-nucleon cluster spectroscopic factor. These are listed in Table II. The quantity $D_{\text{mag}}$ is for $L = 2$. Then with $x = v/u$, y = $b/a$, and $r^2 = \sigma(\text{exc})/\sigma(\text{g.s.)}$, we have

$$r = (1.336 - 1.235xy)/(1.336y + 1.235x).$$

Results. Using $a^2 = 0.68$ and $b^2 = 0.32$, the dependence of this ratio ($r^2$) on the $^{14}$C(g.s.) admixture is plotted as a solid curve vs $v^2$ in Fig. 1. The short-dashed curves above and below
TABLE I. Estimates of core excitation in $^{14}$C(g.s.).

<table>
<thead>
<tr>
<th>Source</th>
<th>Core excitation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C($t,p$) $^{14}$C</td>
<td>12(3)%</td>
<td>[1]</td>
</tr>
<tr>
<td>$^{14}$O($p,t$) $^{12}$O</td>
<td>$&gt;$6%</td>
<td>[14], present work</td>
</tr>
<tr>
<td>Hayes et al. 3</td>
<td>8%, 13%</td>
<td>[3]</td>
</tr>
</tbody>
</table>

*The first number is the 2 $h\omega$ mixture in the g.s.; the second number is the amount of 0 $h\omega$ in the first excited 0$^+$ state.

With good isospin, the wave functions of $^{14}$C and $^{14}$O are equal, as are those for $^{12}$Be, $^{12}$O, and $^{12}$C ($T = 2$). With isospin conservation, the excited state/g.s. ratio will be the same in $^{14}$C → $^{12}$Be, $^{14}$O → $^{12}$O, and $^{14}$C → $^{12}$C ($T = 2$). In the reaction $^{14}$C($p,t$), the 0$^+$, $T = 2$ state at $E_x = 27.595$(3) MeV was clearly observed [13], with an $L = 0$ angular distribution, as expected. This state is the double analog of the ground state (g.s.) of $^{12}$Be. Another peak was observed [13] at an excitation energy of 29.630(50)–2.035(50) MeV above the lowest 0$^+$, $T = 2$ state. This peak probably contains both the first 2$^+$ $T = 2$ state and the second 0$^+$ $T = 2$ state—double analogs of the $^{12}$Be first two excited states.

In an experimental tour-de-force, the $^{14}$O($p,t$) reaction was performed, in reverse kinematics [14]. Here, too, the g.s. was clearly observed with an $L = 0$ angular distribution, but the 2$^+$ and 0$^{+'}$ states were not resolved. A single excited-state peak was seen at $E_x = 1.8$(4) MeV [14]. Resolution in that experiment was about 1 MeV. There is some difference of opinion [15,16] as to whether these excited peaks in $^{12}$C and $^{12}$O are predominantly 0$^+$ or mostly 2$^+$, or a more nearly equal combination of the two. In $^{12}$O, the angular distributions of the excited peak and the g.s. were virtually identical, and the ratio of cross sections was $\sigma$(exc)/$\sigma$(g.s.) ≈ 0.86.

If the g.s. of $^{14}$C and $^{14}$O were pure $p$ shell, the second 0$^+$, $T = 2$ state in $^{12}$C and the excited 0$^+$ state in $^{12}$O would be significantly stronger than the $A = 12$, $T = 2$ g.s. (by a factor of about 0.68/0.32) in both of the ($p,t$) reactions mentioned above. Yet, in both, the sum of the 0$^+$ and 2$^+$ cross sections is less than that of the lower 0$^+$ (by a factor of about 0.8 to 0.9). Therefore, these reactions make it clear that $^{14}$C(g.s.) must contain an $(sd)^2$ admixture. The horizontal dashed line in Fig. 1 is the upper limit on $r^2$ from $^{14}$O($p,t$). This limit clearly eliminates any $v^2$ less than about 0.06 and therefore requires some core excitation in $^{14}$C.

A good measurement of this ratio in either $^{14}$C($p,t$)$^{12}$C ($T = 2$) or $^{14}$O($p,t$)$^{12}$O probably requires better resolution than is obtainable in either case. Good resolution might not even resolve the two states because of the natural width expected for the second 0$^+$, $T = 2$ state. However, in $^{12}$Be the two states are well separated (by 144 keV [4]), and they have no natural width. Thus, the best reaction to measure this ratio is probably two-proton pickup from $^{14}$C to form $^{12}$Be. Two previous such experiments gave conflicting results. Neither of them resolved the 2$^+$ and 0$^+$ states. In the reaction [17] $^{14}$C($^{14}$C, $^{12}$Be$^*$)$^{16}$O, the summed yield to the two states was about 31% of that for the g.s. Resolution for the g.s. was 180(20) keV, and the doublet width was 240(30) keV. In the reaction [18] $^{14}$C($^{11}$B, $^{13}$N)$^{12}$Be, the 1$^-$ state was also not resolved, and the ratio of all three states to the g.s. was close to unity. However, in Ref. [17], the 1$^-$ state in $^{12}$Be was only about 6% of the g.s. In a ($^{12}$C, $^{14}$O) or ($^{14}$C, $^{16}$O) reaction, the nuclear structure requires $L = 0$ at the projectile/ejectile vertex and hence a single $L$ value at the target/residual vertex (also $L = 0$ for 0$^+$ states). This is not the case for the ($^{11}$B, $^{13}$N) reaction, where other values of $L$ can contribute. This difference might be responsible for the conflicting results in the two reactions mentioned above.

We need a good resolution two-proton pickup experiment on $^{14}$C, i.e., $^{14}$C($^{14}$C, $^{12}$O), $^{14}$C($^{15}$C, $^{14}$O), or $^{14}$C($^{15}$C, $^{16}$O). The $^{13}$C($^{12}$C, $^{14}$O) reaction [19] has been done, with angular distributions that were well characterized by distorted-wave calculations. So, $^{13}$C($^{12}$C, $^{14}$O) might be the best choice.

The first 2$^+$ state of $^{12}$Be is dominated by the intruder $(sd)^2 s^2$ configuration [5], with a small amount ($\sim 20\%$) of the 2$^+$ $p$-shell state [6]. Thus, a bonus of such a two-proton pickup experiment would be the determination of the normal-intruder mixing in the first 2$^+$ state.

**TABLE II. Two-nucleon transfer strengths within the 1p shell [12].**

<table>
<thead>
<tr>
<th>Initial state</th>
<th>Final state</th>
<th>$S_{\text{mag}}$</th>
<th>$D_{\text{mag}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C(g.s.)</td>
<td>$^{12}$Be(g.s.)</td>
<td>1.784</td>
<td>—</td>
</tr>
<tr>
<td>$^{14}$C(g.s.)</td>
<td>$^{12}$Be(2$^+$)</td>
<td>—</td>
<td>2.761</td>
</tr>
<tr>
<td>$^{12}$C(g.s.)</td>
<td>$^{10}$Be(g.s.)</td>
<td>2.747a</td>
<td>—</td>
</tr>
<tr>
<td>$^{12}$C(g.s.)</td>
<td>$^{10}$Be(2$^+$)</td>
<td>—</td>
<td>1.215a</td>
</tr>
</tbody>
</table>

*aThese must be multiplied by a factor $(5/9)$ from isospin uncoupling and recoupling for input into the present analysis.

FIG. 1. For two-proton pickup from $^{14}$C to the first two 0$^+$ states of $^{12}$Be, the solid curve is a plot of the calculated cross-section ratio as a function of the assumed core excitation in $^{14}$C(g.s.). The dashed lines surrounding it correspond to the uncertainty from uncertainties in the $^{12}$Be amplitudes. The vertical line, and the surrounding dashed lines, indicate the estimate of 12(3)% from Ref. [1]. The horizontal dashed line is the limit from $^{14}$O($p,t$) (Ref. [14] and present work).