Core excitation in ^{14}C and two-proton pickup

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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%.

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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 $v(sd)^2$. 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 $0^{+'}$ herein). 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 it [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(π, π') 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 I. Here I investigate the possibility of another experimental determination of this mixing.

In ^{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(^{7}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. ratio can provide a strong constraint on the small intruder admixture in ^{14}C(g.s.). If we take the ^{12}Be 0^+ mixing to be the value mentioned above, we can estimate 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

$$^{14}\mathrm{C(g.s.)} = u\,^{14}\mathrm{C_{CK}} + v\,^{12}\mathrm{C_{CK}}\mathrm{x}(sd)^2_0,$$
$$^{12}\mathrm{Be(g.s.)} = a\,^{10}\mathrm{Be_{CK}(g.s.)x}(sd)^2_0 + b\,^{12}\mathrm{Be_{CK}(g.s.)}, \quad \text{and}$$
$$^{12}\mathrm{Be(exc)} = -b\,^{10}\mathrm{Be_{CK}(g.s.)x}(sd)^2_0 + a\,^{12}\mathrm{Be_{CK}(g.s.)}.$$

The two-proton pickup amplitudes are

$$A(\mathrm{exc}) = uaA(^{14}\mathrm{C_{CK}} \to {}^{12}\mathrm{Be_{CK}}) - vbA(^{12}\mathrm{C_{CK}} \to {}^{10}\mathrm{Be_{CK}}),$$
$$A(\mathrm{g.s.}) = ubA(^{14}\mathrm{C_{CK}} \to {}^{12}\mathrm{Be_{CK}}) + vaA(^{12}\mathrm{C_{CK}} \to {}^{10}\mathrm{Be_{CK}}).$$

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_{mag}'s, where S_{mag} is the $L = 0$ two-nucleon cluster spectroscopic factor. These are listed in Table II. The quantity D_{mag} is for $L = 2$. Then with $x = v/u$, $y = b/a$, and $r^2 = \sigma(\mathrm{exc})/\sigma(\mathrm{g.s.})$, 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.).

Source	Core excitation	Reference
^{12}C(t,p) ^{14}C	12(3)%	[1]
^{14}O(p,t) ^{12}O	>6%	[14], present work
Hayes *et al.* [a]	8%, 13%	[3]

[a]The first number is the $2\,\hbar\omega$ mixture in the g.s.; the second number is the amount of $0\,\hbar\omega$ in the first excited 0^+ state.

it correspond to the uncertainty caused by the uncertainties in a^2 and b^2. The vertical solid line surrounded by two dashed lines corresponds to the estimate of 12(3)% core excitation in ^{14}C(g.s.) from Ref. [1]. We thus see that a measurement of this ratio in two-nucleon pickup provides a sensitive test of the amount of core excitation in ^{14}C.

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 $\rightarrow$ ^{12}Be, ^{14}O $\rightarrow$ ^{12}O, and ^{14}C $\rightarrow$ ^{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 $\sigma(\mathrm{exc})/\sigma(\mathrm{g.s.}) \sim 0.86$.

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

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

Initial state	Final state	S_{mag}	D_{mag}
^{14}C(g.s.)	^{12}Be(g.s.)	1.784	—
^{14}C(g.s.)	^{12}Be(2^+)	—	2.761
^{12}C(g.s.)	^{10}Be(g.s.)	2.747[a]	—
^{12}C(g.s.)	^{10}Be(2^+)	—	1.215[a]

[a]These must be multiplied by a factor (5/9) from isospin uncoupling and recoupling for input into the present analysis.

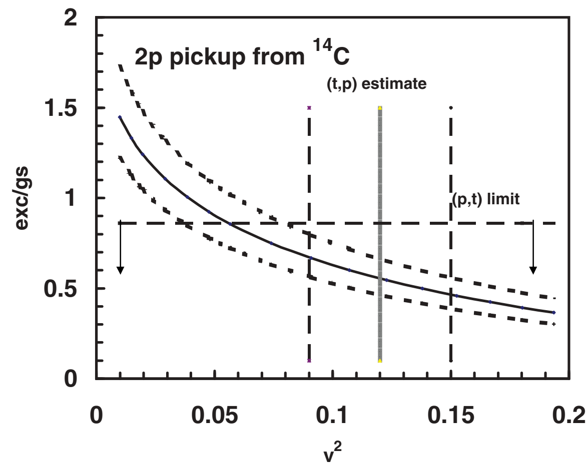

FIG. 1. For two-proton pickup from ^{14}C to the first two 0^+ states of ^{12}Be, the solid curve is a plot of the calculated cross-section ratio as a function of the assumed core excitation in ^{14}C(g.s.). The dashed lines surrounding it correspond to the uncertainty from uncertainties in the ^{12}Be 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).

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(^{13}C, ^{15}O), ^{14}C(^{12}C, ^{14}O), or ^{14}C(^{14}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, ^{14}C(^{12}C, ^{14}O) might be the best choice.

The first 2^+ state of ^{12}Be is dominated by the intruder $(sd)^2{}_2$ configuration [5], with a small amount (∼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.

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