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^{12}C(t,p) and the ground state of ^{14}C

H. T. Fortune and G. S. Stephans

Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104

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The reaction ^{12}C(t,p) leading to the ground and 6.59-MeV 0^+ states of ^{14}C provides a quantitative measure of 0.35 ± 0.02 for the amplitude of *sd*-shell excitation in ^{14}C (g.s.).

[NUCLEAR REACTIONS ^{12}C (t,p), E = 18 MeV, measured σ (θ), DWBA analysis, determined ^{14}C (g.s.) wave function components.]

The amount of 2*s*-1*d* shell occupation in the ground state of ^{14}C has long been of interest. The presence of such core excitation affects the strong cancellation necessary to explain the severely inhibited β decay of ^{14}C. However, so many effects go in to make up this cancellation that it is not possible to determine the *sd*-shell admixture solely from the β-decay lifetime.

Estimates of this admixture from shell-model calculations have varied from about 4% to about 20%. Lie's[1] result for ^{14}C(g.s.) is 4%, while True[2] gets 10%, and Freed and Ostrander[3] quote a value of 18−20%. Experimental determinations of this number have also shown a great deal of variation. Perhaps the best number to date comes from an analysis of data from the reaction ^{14}C(p,d) to the low-lying $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states of ^{13}C.[4] That work yielded *s-d* shell admixtures of 7% or 10% using two different assumptions about their absolute normalization and the distribution of single neutron pickup strength. However, that work suffers from having ignored the mixing into these states of ^{13}C of configurations containing ^{12}C in its first-excited 2^+ state. Such admixtures are not accurately known, but are not negligible. Also, angular-distribution fits in Ref. 4 were somewhat poor and their analysis depends on application of a sum rule, or on knowing an absolute normalization.

We believe the reaction ^{12}C$(t,p)^{14}$C provides the best method for determining the sought admixture. First, there is no evidence from any data of any *sd*-shell component in ^{12}C(g.s.). Second, in the (t,p) reaction, $L = 0$ transfer into the *sd*-shell is about 5−10 times stronger than transfer into the *p* shell, thus giving a magnification effect.

We assume the wave functions

$$\psi(\text{g.s.}) = A\psi_{\text{CK}} + \epsilon\psi(sd)^2_{0^+}$$

and

$$\psi(6.59) = -\epsilon\psi_{\text{CK}} + A\psi(sd)^2_{0^+} ,$$

where ψ_{CK} is the wave function of ^{14}C(g.s.) in the calculation of Cohen and Kurath,[5] $\psi(sd)^2_{0^+}$ is the wave function of the lowest theoretical *sd*-shell state of ^{14}C,[6] and $A = (1-\epsilon^2)^{1/2}$. The (t,p) transfer amplitudes are then simply

$$\beta(\text{g.s.}) = A\beta(\text{CK}) + \epsilon\beta(sd)^2 ,$$

$$\beta(6.59) = -\epsilon\beta(\text{CK}) + A\beta(sd)^2 .$$

The pure transfer amplitudes are listed in Table I along with amplitudes for $|\epsilon| = 0.35$. We return later to the question of applicability of a two-state model.

Because the pure CK 0^+ level is predicted to be significantly weaker than the $(sd)^2_{0^+}$ level (see Fig. 1), whereas experimentally the g.s. and 6.59-MeV states have comparable cross sections (see Fig. 2), it is necessary to pick the sign of ϵ to be negative to correspond to constructive interference for the g.s. and destructive interference in the 6.59-MeV level. Constructive interference requires a negative sign of ϵ due to a relative phase between the *p*- and *sd*-shell two-neutron transfer amplitudes. With the above model, we have calculated cross sections for a range of $|\epsilon|$ from 0 to 0.55 using the code DWUCK.[7]

Optical-model parameters were standard and are

TABLE I. Two-neutron transfer amplitudes for lowest two 0^+ levels of ^{14}C.

State	Two-neutron amplitudes $(1p_{3/2})^2$	$(1p_{1/2})^2$	$(1d_{5/2})^2$	$(2s_{1/2})^2$
CK	0.4474	0.7057		
$(sd)^2$			0.6765	0.7364
$\lvert\epsilon\rvert = 0.35,\ E_x = 0.0$	0.4191	0.6611	−0.2368	−0.2577
$\lvert\epsilon\rvert = 0.35,\ E_x = 6.59$	0.1566	0.2470	0.6337	0.6898

listed in Table II. We plot in Fig. 3 the calculated cross section for the two states at the second maximum of the angular distribution as a function of $|\epsilon|$. Also shown there is their ratio, which experimentally is 0.9. The value of $|\epsilon|$ that reproduces this ratio is $|\epsilon| = 0.35$. In Fig. 4, we display the same quantities, but for 0°, at which the extrapolated experimental ratio is 0.44. Again, a value of $|\epsilon| = 0.35$ is required. In Fig. 2, we show the two experimental angular distributions and those calculated with this value of ϵ. The fits appear satisfactory. The fit to the absolute magnitude requires $N = 400$, which is the value used in constructing all figures. Of course, the cross section ratios are independent of this number. This value of ϵ corresponds to an $(sd)^2$ admixture of 12%. The uncertainty in $|\epsilon|$ due solely to experimental considerations is approximately ± 0.02 (or 5%). This range neglects any contributions due to the assumptions that were used in calculating the transfer amplitudes. The validity of those assumptions is discussed at greater length later in the text.

We can use the derived wave functions to calculate the Hamiltonian that gives rise to them:

$$H = U^T E U ,$$

where U is a unitary matrix whose rows are the eigenfunctions and E is the diagonal eigenvalue matrix (0, 6.59 MeV). The result (in MeV) is

$$H = \begin{bmatrix} 0.81 & 2.16 \\ 2.16 & 5.78 \end{bmatrix} .$$

The off-diagonal matrix element of 2.16 MeV is quite large, but still reasonable. The $(sd)^2_{0_1^+}$ state contains nearly all of the $(sd)^2$ $L = 0$ two-neutron strength[6] and hence is a good "cluster" state, with

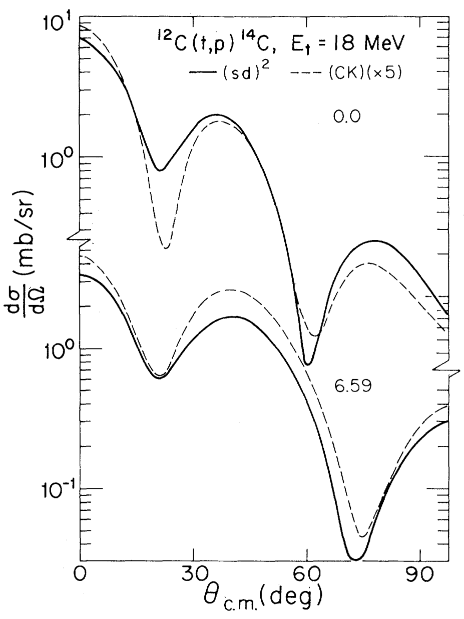

FIG. 1. A plot of DWBA calculations for both the g.s. and 6.59 MeV states, using the pure CK (dashed) and $(sd)^2$ (solid) transfer amplitudes from Table I. The $(sd)^2$ cross section has been multiplied by the normalization factor $N = 400$. The CK cross section has been multiplied by a factor of 5, in addition to the factor of 400.

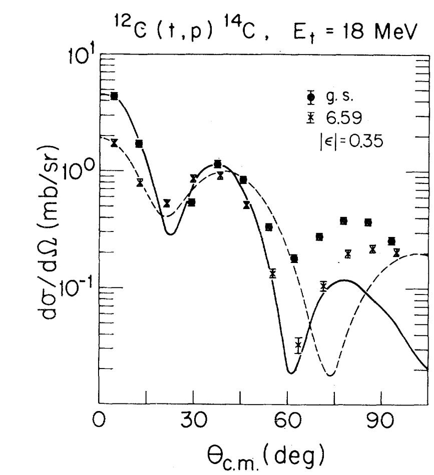

FIG. 2. Angular distributions plus DWBA calculations for the g.s. (circles plus solid line) and 6.59 MeV state (crosses plus dashed line). DWBA curves were calculated using the transfer amplitudes listed in Table I for $|\epsilon| = 0.35$ and have both been multiplied by the same normalization factor, $N = 400$.

TABLE II. Optical-model parameters used in analysis of $^{12}C(t,p)^{14}C$. (Strengths in MeV, lengths in fm.)

	V	r_0	a	W	r_0'	a'	$W'=4W_D$	r_0'	a'	r_C	V_{so}	r_{so}	a_{so}
t	177.	1.138	0.724	18	1.602	0.769				1.40	20	1.138	0.724
p	59(61)[a]	1.131	0.570				72(60)[a]	1.131	0.50	1.131	22	1.131	0.57
n	b	1.26	0.60							1.26			

[a]Values in parenthesis are for the 6.59 MeV state due to the energy dependence of the potentials.
[b]Varied to give the correct neutron separation energy.

$2N+L = 4$. The CK 0^+ level has a similarly good overlap, this time with the $L = 0$ cluster for $2N+L = 2$.

Of course, any $(sd)^2$ 0^+ level will contain some amount of the configurations $(1d_{3/2})^2$, but this has been ignored in Ref. 6 and in the above analysis. Putting it in will only extremely slightly affect the results through a renormalization of the *sd*-shell wave function component. This is so because any reasonable interaction puts only about 10% of $(1d_{3/2})^2$ into the lowest 0^+ level, with the majority of this configuration lying about 14 MeV higher.

We have repeated the calculations of Fig. 3 with an $(sd)^2$ wave function containing an arbitrary 6% admixture of $(1d_{3/2})^2$. The new wave function retained the same ratio of $(2s_{1/2})^2$ to $(1d_{5/2})^2$ but both components were reduced to normalize the final state. With this $(sd)^2$ wave function, it was possible to obtain a best fit to the two angular distributions for $|\epsilon| = 0.37$. This latter value falls within the uncertainty range of the value obtained using no $(1d_{3/2})^2$. Thus, it is clear that the neglect of $(1d_{3/2})^2$ components does not significantly affect the conclusions of the present work.

Concerning the applicability of a two-state model, we note that the third 0^+ level of ^{14}C, which was discovered in this experiment at 9.75 MeV excitation, is observed—and predicted—to be extremely weak. If the $(sd)^2_{0_2^+}$ level mixed appreciably with either the CK or $(sd)^2_{0_1^+}$ states, the third experimental level would acquire a significant (t,p) cross section. Thus, the experimental result favors

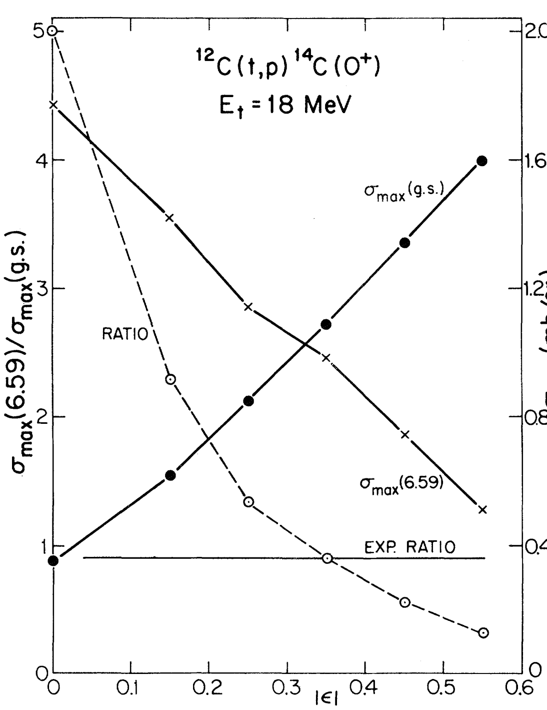

FIG. 3. A plot of DWBA cross section for the second maximum at 38° for the g.s. (solid circles) and 6.50 MeV state (crosses) as a function of $|\epsilon|$ (scale at right). Also plotted is the ratio of the two (open circles, scale at left), and the experimental value.

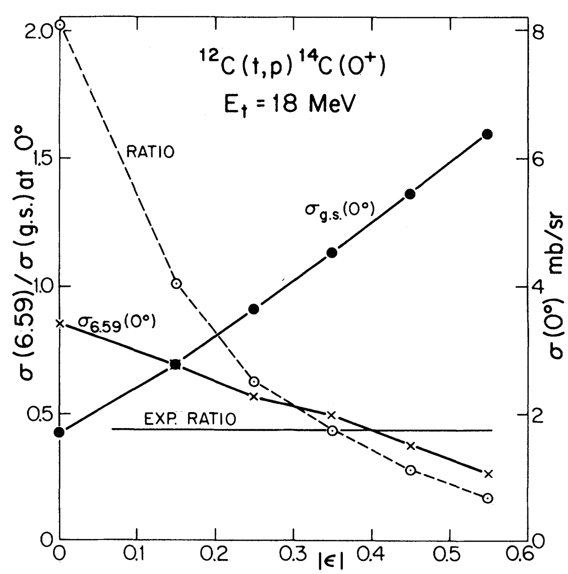

FIG. 4. Same as Fig. 3 except for 0°. The experimental ratio is obtained by extrapolation.

no mixing of the third state. The absence of mixing is also expected on theoretical grounds, since the $(sd)^2_{0_2^+}$ state is an "anticluster" state and hence has a spatial symmetry that is not favorable for mixing with $L = 0$ cluster states.

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