PHYSICAL REVIEW C VOLUME 50, NUMBER 3 SEPTEMBER 1994

$(sd)^2$ states in ^{12}Be

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(Received 17 February 1994)

The ^{10}Be$(t,p)^{12}$Be reaction has been studied with 15- and 17-MeV triton beams. At 17 MeV, angular distributions were measured for five low-lying states, and distorted-wave Born-approximation calculations were used to analyze the data. Contributions from ^{10}Be (g.s.) $\otimes(sd)^2$ and complete $1p$-shell wave functions were investigated. Comparison is made with $(sd)^2$ states in ^{14}C and ^{16}C.

PACS number(s): 21.10.Hw, 21.60.Cs, 25.55.Hp, 27.20.+n

I. INTRODUCTION

The ^{12}Be nucleus is very difficult to reach, and thus has been the object of only a few studies [1–5]. The ^{10}Be(t,p) reaction [1] populates four definite states of ^{12}Be, and one additional tentative one. In ^{10}Be$(t,p\gamma)$, an excited state at 2.110±0.015 MeV was assigned [3] $J = 2$. Its strength in (t,p) forbids unnatural parity, and hence $J^\pi(2.1) = 2^+$. For other states of ^{12}Be, no J^π assignments were suggested. The reaction ^{14}C(^{14}C,^{16}O) [5] populates three states of ^{12}Be: $E_x = 0$, 2.10, and 2.68 ± 0.03 MeV. The latter is weak, but the authors discuss the possibility that it has $J^\pi = 0^+$. It is likely the same as the state at 2.712 ± 0.020 MeV that was only tentatively assigned to ^{12}Be in Ref. [1].

Low-lying levels of ^{12}Be are expected to be either two sd-shell neutrons coupled to the ground state (g.s.) of ^{10}Be [i.e., ^{10}Be (g.s.) $\otimes(sd)^2$] or $1p$-shell states as calculated, e.g., by Cohen and Kurath [6] (CK)—or mixtures of the two configurations. The measured β decay half life [3,7,8] of ^{12}Be has an average value of 23.6 ± 0.9 fs [9]—a value which corresponds to a reduction in strength of more than a factor of 2 compared with the prediction of the $1p$-shell calculation of CK. Barker [10] pointed out that considerable evidence exists to support the view that (non-p-shell) configuration mixing plays a significant role in the low-lying $T = 2$ states of $A = 12$ nuclei.

As we know, all low-lying states of ^{16}C [11] are of $(sd)^2$ character, including two 0^+ states, two 2^+, one 3^+, and one 4^+. For ^{14}C, all low-lying positive-parity states are $(sd)^2$ except for the 0^+ g.s. and one 2^+ level. The physical ground state is dominantly of p-shell character, but contains a small component [12] of $(sd)^2_{0_1}$. Undoing the mixing suggests the unperturbed 0_1^+ $(sd)^2$ state lies at 5.78 MeV. The first two 2^+ states are nearly equal mixtures [13] of p shell and $(sd)^2_{2_1}$. The unmixed 2_1^+ $(sd)^2$ state thus has an excitation energy of 7.66 MeV.

In all three of these nuclei (^{12}Be, ^{14}C, and ^{16}C), the 4^+ level is not "contaminated" by p-shell admixtures, and hence we expect the 4_1^+ states in all three nuclei to be similar. The (t,p) reaction should be an ideal tool to identify $(sd)^2$ excitations in ^{12}Be, as it was for ^{14}C and ^{16}C [11,12,14].

II. EXPERIMENTAL PROCEDURE

The experiment was performed with 15.0- and 17.0-MeV triton beams from the University of Pennsylvania tandem accelerator. The target was 94% enriched ^{10}Be in the form of a 112 ± 25 μg/cm^2 deposit of ^{10}BeO onto a 1.0 mg/cm^2 Pt backing. Targets were prepared by D. Goosman. Outgoing protons were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsion plates. Absorber foils placed directly in front of the focal plane stopped all particles more massive than protons. Data were recorded in 7.5° steps, beginning at 3.75°. To aid in peak identification, data were also collected for an identical Pt backing that had no Be deposited onto it.

Typical spectra of protons are displayed in Fig. 1. The resolution is about 28 keV [full width at half maximum (FWHM)]. Much of the background arises from the Pt backing, but a number of impurity peaks are apparent. Five narrow low-lying states of ^{12}Be are identified. The impurity peaks are labeled by final nucleus and excitation energy. We performed three separate exposures—two at 15 MeV and one at 17 MeV. Data have been analyzed for five angles at 15 MeV and seven angles at 17 MeV. We thus have 17 different measurements of the g.s. Q value. These values span a range of 9 keV, with a standard deviation of 2.6 keV. The presence of known [13,15,16] impurity peaks from ^{9}Be, ^{12}C, and ^{16}O allowed an accurate determination of a minor adjustment to the absolute

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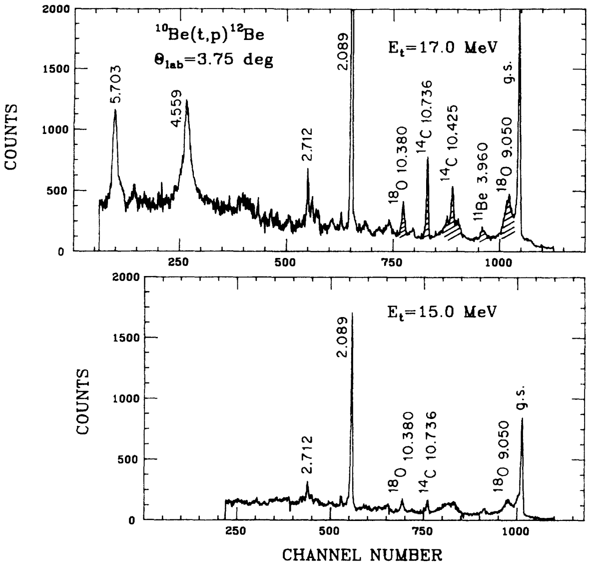

FIG. 1. Spectra of protons from the reaction ^{10}Be$(t,p)^{12}$Be, at a laboratory angle of 3.75°, and E_t = 17.0 MeV (top) and 15.0 MeV (bottom). States in ^{12}Be are labeled by their excitation energies. Peaks from impurities in the target are hatched and labeled by final nucleus and their excitation energy.

calibration [amounting to a shift of 17 keV for the ^{12}Be (g.s.)]. Propagation of uncertainties in reference peak energies and standard deviations in our measurement provide our quoted uncertainty of 4.2 keV in the g.s. Q value (-4808.3 ± 4.2).

Because of the possibility [2] of an excited state below 1.0 MeV, a careful subtraction of the backing spectrum was done. Subtraction of the backing spectrum (not shown) removes virtually all of the smooth background, but leaves the peaks from O and C. However, because the backing *does* contain some oxygen, it is possible to oversubtract the backing spectrum and thereby eliminate the oxygen peaks. We did this by normalizing to one of the known oxygen peaks, subtracting 1.6 times the backing spectrum, and then adding back in a constant 35 counts/mm to get back near zero in the nonpeak regions. The result is displayed in Fig. 2 for the g.s. region. A small carbon contaminant peak remains, suggesting that the ^{10}BeO target contains significantly more C contamination than does the backing. No low-lying state of ^{12}Be is seen. Below 6 MeV excitation energy, our data allow us to set an upper limit of 30 μb/sr cross section for any possible missing narrow state of ^{12}Be. (For comparison, this value is ~ 1% of the g.s. cross section.)

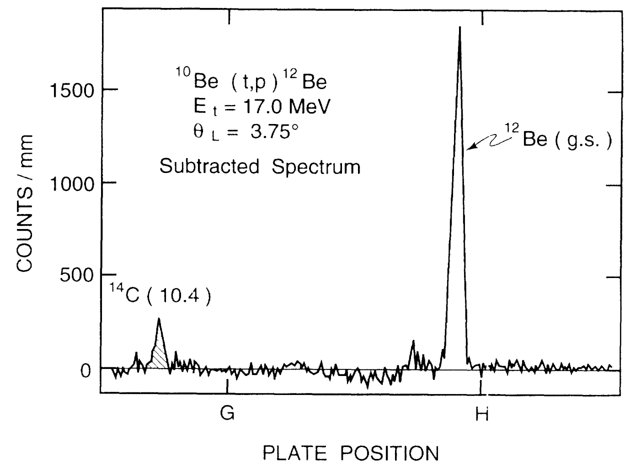

FIG. 2. Subtracted spectrum: Data from Fig. 1 (top) minus 1.6 times backing spectrum plus 35 counts/mm.

III. RESULTS AND ANALYSIS

In Table I, the extracted excitation energies, assigned (or suggested, see below) J^π, level widths, and maximum cross sections are listed for five states of ^{12}Be. The angular distributions of the five states are displayed in Fig. 3, together with smooth curves drawn through the data points. At the bottom of the right-hand column of Fig. 3, we present data for the 10.74-MeV 4^+ state of ^{14}C from the ^{12}C (t,p) reaction [13].

Microscopic distorted-wave Born-approximation (DWBA) calculations, using the code DWUCK4 [17], were performed for the five states. The optical-model parameters used in the calculations are listed in Table II. They are similar to those of Ref. [16], but with some adjustments to the real parts of the potential for both t and p. At least part of the increase in V_p arises from the large value of $(N-Z)/A$ for ^{12}Be. For bound states, each neutron had one half of the $2n$ separation energy. For unbound states, a binding energy of 100 keV was assumed. Because of the large negative Q value in the present reaction, the angular distributions are nearly featureless, but subtle differences do exist for L = 0, 2, and

TABLE I. Experimental results of ^{10}Be(t,p) reaction.

E_x(MeV ± keV)[a]	E_x(MeV ± keV)[b]	J^π	Γ (keV)	$(d\sigma/d\Omega)_{\max}$ (mb/sr)	r_{12}[c]
0.0	$Q = -4808.3 \pm 4.2$	0^+	—	2.78	1.57±0.16
2.102±12	2111±3	2^+	—	3.79	1.27±0.13
2.702±17	2730±3	(0^+)	—	0.41	1.69±0.17
4.56±25	4580±5	(2^+)	107±17	2.20	1.21±0.12
5.70±25	5724±6	$(2^+,3^-,4^+)$	86±15	1.15	1.24±0.12

[a] Reference [9].
[b] This work.
[c] Ratio of cross sections at 3.75° and 11.25°.

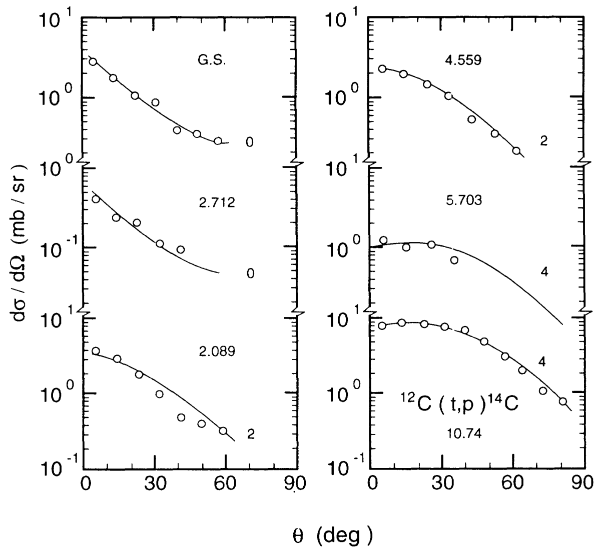

FIG. 3. The angular distributions and smooth curve passing through the data points for the five states of ^{12}Be and 10.74-MeV 4^+ state from the ^{12}C$(t,p)^{14}$C reaction.

4. As indicated by the hand-drawn curves in Fig. 3, the g.s. 0^+ angular distribution is rising more steeply near 0° than is that for the 2.1-MeV 2^+ state. We quantify this difference in the right-hand column of Table I, where we list the ratios of cross sections at the first two angles. With this comparison, the 2.7-MeV state appears to be 0^+, while the 4.6-MeV level is probably 2^+. The 5.7-MeV state has some features of 0^+, but may in fact (see below) have $J^\pi = 4^+$.

Figure 4 displays angular distributions for the first four states compared with a variety of DWBA curves. For 0^+ these are pure $(2s\frac{1}{2})^2$, pure $(1d\frac{5}{2})^2$, and Cohen-Kurath $(1p)^2$, and for 2^+ they are pure $(2s\frac{1}{2})(1d\frac{5}{2})$, pure $(1d\frac{5}{2})^2$, and CK $(1p)^2$. Curves have been normalized to the data. Very little difference in shape is noted, but magnitudes are quite different. Cross sections for transfer into the *sd* shell are larger than those for CK by factors of about 7 and 20 for 0^+ and 2^+, respectively.

The solid curves in Fig. 5 are $L = 0$ mixed-configuration DWBA curves, while the dashed curve su-

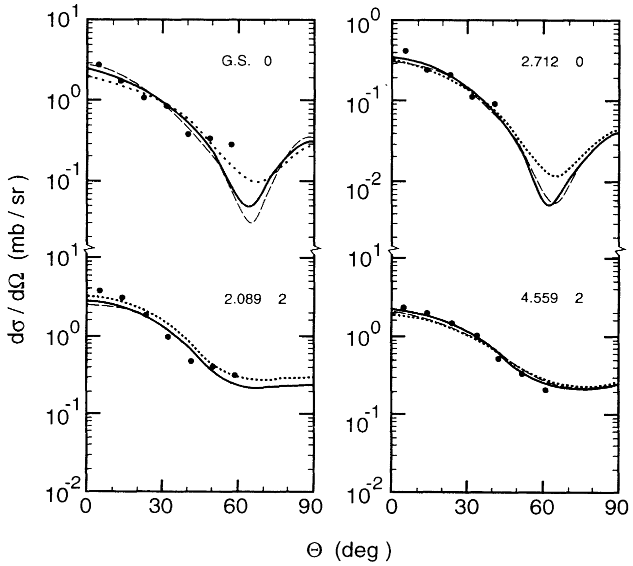

FIG. 4. Angular distributions for the four lowest states, compared with DWBA curves calculated with simple configurations: $(1d\frac{5}{2})^2$ (solid), CK (dotted), and (dashed) $(2s\frac{1}{2})^2$ for 0^+, $(1d\frac{5}{2})(2s\frac{1}{2})$ for 2^+.

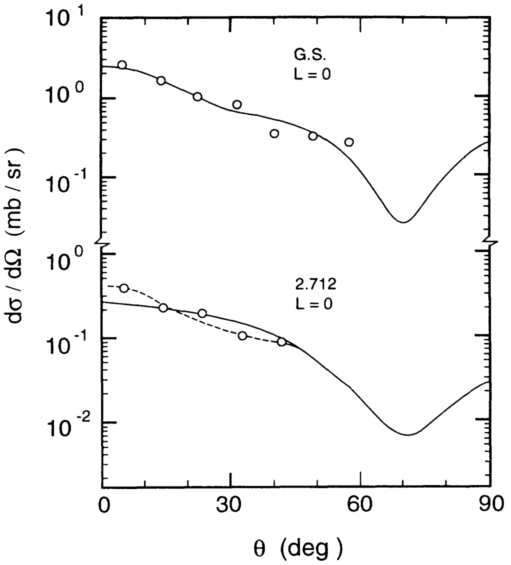

FIG. 5. Angular distributions for the ground and 2.7-MeV states of ^{12}Be from the ^{10}Be(t,p) reaction, together with $L = 0$ DWBA curves (solid). The dashed curve shown for the 2.7-MeV data is a smooth curve drawn through the g.s. data.

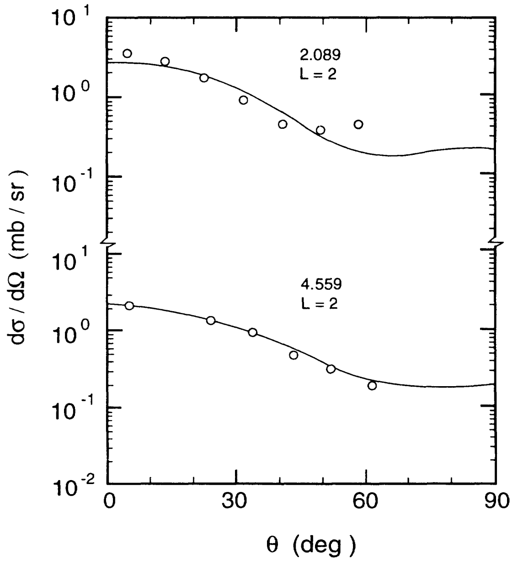

FIG. 6. As Fig. 5, but for a known 2^+ state at 2.1 MeV and a suspected 2^+ level at 4.6 MeV, compared with $L = 2$ DWBA curves.

TABLE II. Optical-model parameters used in analysis of ^{10}Be$(t,p)^{12}$Be (strengths in MeV, lengths in fm).

Channel	V	r_0	a_0	W	$4W'$	r'_0	a'_0	V_{SO}	r_c
t	195.00	1.29	0.58	18.90		1.37	0.96		1.29
p	90.00	1.13	0.57		34.20	1.13	0.50	5.50	1.13
Bound state		1.26	0.60	$\lambda = 25.0$					1.20

TABLE III. Hamiltonian matrix elements in $d\frac{5}{2}$ $s\frac{1}{2}$ space (Ref. [18]).

	Matrix element	Value (MeV)
0^+	$\langle s^2 \vert V \vert s^2 \rangle$	-1.54
	$\langle s^2 \vert V \vert d^2 \rangle$	-1.72
	$\langle d^2 \vert V \vert d^2 \rangle$	-2.78
2^+	$\langle ds \vert V \vert ds \rangle$	-0.59
	$\langle ds \vert V \vert d^2 \rangle$	-0.59
	$\langle d^2 \vert V \vert d^2 \rangle$	-1.02
s.p.e.[a]	s	-0.503
	d	1.275

[a] From ^{11}Be.

TABLE IV. Calculated energies and two-nucleon transfer amplitudes for $(sd)^2$ and p-shell states in ^{12}Be.

	E_x (MeV)	Transfer amplitudes
0+	0.158	$0.760s^2$, $0.650d^2$
	3.640	$-0.650s^2$, $0.760d^2$
	1.095	-0.563 $(p\frac{3}{2})^2$, $-0.740(p\frac{1}{2})^2$
2^+	3.633	$0.936ds$, $0.352d^2$
	5.425	$-0.352ds$, $0.936d^2$
	5.465	$0.061(p\frac{3}{2})^2$, $0.142(p\frac{3}{2})(p\frac{1}{2})$
4^+	5.82	$1.0d^2$

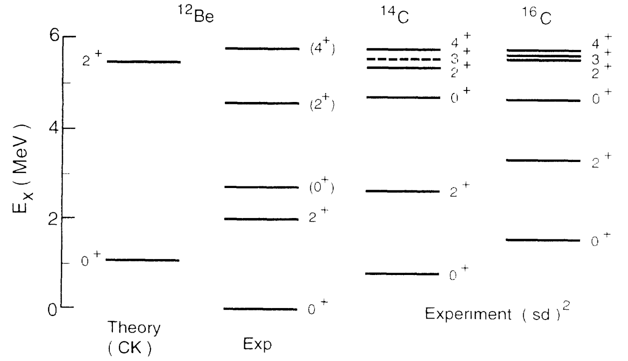

FIG. 7. Energy levels of ^{12}Be (p shell, left column; experimental, second column) and of $(sd)^2$ states in ^{14}C (third column) and ^{16}C (fourth column). 4^+ levels of ^{14}C and ^{16}C have been aligned with ^{12}Be (5.7). Experimental and p-shell ^{12}Be states are on same absolute energy scale.

perimposed on the 2.7-MeV data is a smooth curve drawn through the g.s. data. We only give a tentative (0^+) suggestion for the 2.7-MeV level.

Curves in Fig. 6 are both for $L = 2$. The 2.1-MeV state is known to have $J^\pi = 2^+$, and its data are somewhat more poorly fitted by $L = 2$ than are the data for 4.6 MeV. We suggest a tentative (2^+) for the latter.

Data for the 5.7-MeV state are limited in angular range, and are in reasonable agreement with either $L = 0$, 2, 3, or 4 curves, as well as with the 4^+ smooth curve displayed with these data in Fig. 3. As we see below, we expect both 0^+ and 4^+ states near 5 MeV, and our 5.7-MeV level may contain contributions from both. However, primarily because of its large cross section, we prefer (4^+) for the 5.7-MeV state. (The g.s. should contain most of the L = 0 strength.) Spins of $(2^+,3^-)$ can also not be ruled out. (See, however, discussion below.)

We can estimate the positions of $(sd)^2$ states in ^{12}Be with a simple computation. We take two-body residual matrix elements from Ref. [18], and we use single-particle energies for $2s\frac{1}{2}$ and $1d\frac{5}{2}$ from ^{11}Be [9]. These are listed in Table III. The calculation is not meant to be definitive, merely illustrative. The assumption of a p-shell ^{10}Be core should be somewhat reasonable for computing ^{10}Be $\rightarrow$ ^{12}Be $(sd)^2$ transfer. We note that the p-shell 0^+ T = 2 state of Cohen-Kurath lies 1.095 MeV above its experimental counterpart in ^{12}C [9]. Hence, on an absolute ^{12}Be excitation energy scale, the p-shell 0^+ is at 1.095 MeV and the p-shell 2^+ is at 5.465 MeV.

Energies and two-nucleon transfer amplitudes for $(sd)^2$ and p-shell states are listed in Table IV. We thus note that the low-lying states of ^{12}Be would be dominated by $(sd)^2$ components. We do not attempt mixing the two configurations. Our model is too simple for that to be realistic. A more serious shell-model calculation with proper mixing is needed.

In the right-hand column of Fig. 7 we plot the known energy levels of ^{16}C. The next column displays the $(sd)^2$ states of ^{14}C (after removing p-shell contributions), with ^{14}C(4^+) lined up with ^{16}C(4^+). The third column from the right contains all the known states of ^{12}Be, with the 5.7-MeV level lined up with the other 4^+ levels. The left-hand column displays the two p-shell states expected in ^{12}Be from CK—on the same energy scale as the experimental ^{12}Be levels.

The near degeneracy of the p-shell g.s. and $(sd)^2_{0^+_1}$ make it very likely that the physical ^{12}Be (g.s.) is a nearly complete mixture of these two configurations. The 2.7-MeV (0^+) level is then probably the other 0^+ state arising from these two configurations. The first 2^+ state would then appear to be mostly $(sd)^2_{2^+_1}$, with $(sd)^2_{2^+_2}$ and the CK 2^+ lying higher. If our suggestions are correct, there are missing states with 0^+ near 5 MeV, 3^+ near 5.5 MeV, and 2^+ at $E_x \gtrsim 6$ MeV.

IV. CONCLUSION

In the present study of ^{10}Be(t,p), at $E_t = 17.0$ MeV, we have measured angular distributions for five low-lying states of ^{12}Be. Consideration of several factors leads to J^π assignments (suggestions) of 0^+, 2^+, (0^+), (2^+), and (4^+) for states at $E_x = 0.0$, 2.1, 2.7, 4.6, and 5.7 MeV, respectively.

ACKNOWLEDGMENTS

We acknowledge informative discussions with John Millener, Dieter Kurath, and Alex Brown. Partial financial support was provided by the National Science Foundation and the U.S. Department of Energy.

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