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Neutron widths and configuration mixing in ^{11}Be

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We use known widths and branching ratios in ^{11}Be to discuss J^{π} and configuration admixtures. Analysis favors $3/2^-$ for the 3.96-MeV state and three-state mixing for this J^{π}.

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I. INTRODUCTION

A variety of experiments have been used to establish the properties of the low-lying states of ^{11}Be. Most of the results are from one- and two-nucleon transfer experiments and from β decay. These include ^{10}Be(d,p), ^{9}Be(t,p), ^{9}Be(^{16}O,^{14}O), β decay of ^{11}Li, and neutron decays following the last two. Early information concerning levels of ^{11}Be is summarized in a series of compilations [1–3]. The reaction ^{10}Be(d,p) has been studied at bombarding energies of 12 MeV [4] and 25 MeV [5]. The ^{9}Be(t,p) reaction has been performed at energies of 5 MeV [6], 15 MeV [7], 20 MeV [8], and 23 MeV [9]. Early β decay of ^{11}Li was discussed in Ref. [10]. Much of the J^{π} information in Refs. [1–3] is incorrect and has been superceded [7,11–13]. There is now general agreement on most values of J^{π} and dominant configurations of states up to 5.5 MeV. Data for levels at excitation energies below 6 MeV are summarized in Table I, where the J^{π} values are the most recent ones, most now considered firm [13]. The $3/2^+$ suggestion for the 3.89-MeVstate in Ref. [12] was based on incomplete information and J^{π} has since been determined to be $5/2^-$ from β decay. Some information is available from the reaction ^{13}C(^{6}Li,^{8}B) [14]. Early theoretical work was done by Cohen-Kurath (CK) [15] for the p-shell states and by Teeters-Kurath [16] for positive parity. Other calculations involve an SU(3) cluster model [12]. Additional experimental information is available in Refs. [17–22]. In the present paper, we discuss quantitatively the quality of agreement between the known properties and the supposed structure.

II. WIDTHS AND SPECTROSCOPIC FACTORS

Unless indicated otherwise, the widths we use (Table II) are the weighted average of those from the compilation and from results of the ^{9}Be(t,p) reaction [7]. For the $5/2^+$ state at 1.778 MeV, the majority of its configuration is a $d_{5/2}$ single particle (sp) coupled to the ground state (gs) of ^{10}Be. Presumably most of the remaining strength is $^{10}\mathrm{Be}(2^+)\times 2s_{1/2}$. The width of 102(14) keV, combined with the $\ell = 2$ sp width of 175 keV, gives a spectroscopic factor of $S = \Gamma/\Gamma_{\mathrm{sp}} = 0.58(8)$. Values from ($d$,$p$) are similar: $S = 0.50$ in Ref. [5].

The state at 2.69 MeV has been identified as having $J^{\pi} = 3/2^-$, and is predominantly the lowest p-shell $3/2^-$ state. The cross section in (t,p) is consistent with this interpretation. (However, see below.) Its total width is 213(15) keV. The p-wave sp width for this energy is ~ 1.8 MeV, yielding $S{\sim}0.12$, to be compared with the expected value of 0.106 [12] or 0.168 [15].

The state at 3.41 MeV was assigned $J^{\pi} = 3/2^-$ from an apparent $L = 0$ angular distribution in (t,p), and suggested [7] to be the lowest $(\mathrm{sd})^2_{0+}$ state: $^{9}\mathrm{Be\,(gs)} \times (\mathrm{sd})^2_{0+}$. However, the absolute (t,p) cross section is only $\sim$ 28% of the value expected for this configuration. Morrissey *et al.* [11], based on its nonobservation in β decay, suggested it might be a $3/2^+$ state. Its width is 113(13) keV. An $\ell = 1$ sp width is difficult to calculate at this energy, but is $\sim$2.1 MeV, implying $S{\sim}0.05$ if $3/2^-$. The $\ell = 2$ sp width is 1.1 MeV, giving $S = 0.10(1)$ if $3/2^+$—close to the upper limit for the amount of $d_{3/2}$ strength expected this low in excitation energy. Of course, a $3/2^-$ state with configuration $^{9}\mathrm{Be\,(gs)} \times (\mathrm{sd})^2_{0+}$ would have no gs width either, except through mixing in the initial or final state. If we add this S to the one for the 2.69-MeV $3/2^-$ state, we get $S_{\mathrm{tot}} = 0.17$, close to the CK value of 0.168 for the p-shell $3/2^-$. Another possibility is mixing in the ^{10}Be(gs). A small component ε of $^{8}\mathrm{Be\,(gs)} \times (\mathrm{sd})^2_{0+}$ in ^{10}Be(gs) would produce a gs decay spectroscopic factor of $\varepsilon^2\ S[^{9}\mathrm{Be(gs)} \to {}^{8}\mathrm{Be(gs)} + n]$. In CK, the second factor is 0.58, requiring $\sim$10% mixing in ^{10}Be(gs) if this is the sole explanation. Undoubtedly, several effects combine to produce the observed strength. For the 2.69-MeV state, the $L = 0 + 2$ distorted wave Born approximation (DWBA) curve displayed with the data has the $L = 0,2$ mixture appropriate for the p-shell $3/2^-$ state. The excess of experimental cross section over the DWBA curve at small angles indicates that the $L = 0$ component is stronger than expected for the p-shell state. The $(\mathrm{sd})^2_{0+}$ $3/2^-$ state should have pure $L = 0$, and the 3.41-MeV state has only $\sim$30% of the expected cross section. If the p-shell and $(\mathrm{sd})^2_{0+}$ $3/2^-$ states mix, the lower one will acquire a constructive sum of amplitudes and the higher state a destructive sum. So, mixing of these two states could explain both the (t,p) results and the decay widths. Also, as ^{11}Li undoubtedly has a constructive sum of $(\mathrm{sd})^2_{0+}$ and p-shell neutrons, β decay to the 3.41-MeV state would involve a small overlap, producing a small branch. Thus, this mixing could also explain the β decay. The $3/2^+$ possibility is discussed further in Sec. III.

Beginning with the state at 3.89 MeV, states of ^{11}Be can decay to the 2^+ first-excited state of ^{10}Be at 3.368 MeV. For 3.89 MeV, the neutron decay energy is very small—only

TABLE I. Properties of low-lying states of ^{11}Be.

Compilation[a]		(t,p)[b]			Dominant
E_x (MeV)	Γ(keV)	E_x (MeV)	Γ(keV)	J^{π}[c]	configuration[b]
0	–	−0.004(3)	–	$1/2^+$	^{10}Be(gs)$\times 2s_{1/2}$
0.32004(10)	–	0.320(2)	–	$1/2^-$	p shell
1.778(12)	100(20)	1.748(4)	104(21)	$5/2^+$	^{10}Be(gs)$\times 1d_{5/2}$
2.69(2)	200(20)	2.642(9)	228(21)	$3/2^-$	p shell
3.41(2)	125(20)	3.398(6)	104(17)	$3/2^-$ $3/2^+$	^{9}Be $\times$ (sd)$^2_{0+}$ ^{10}Be(2^+)$\times 2s_{1/2}$
3.887(12)	<10	3.888(1)	–	$5/2^-$	p shell
3.956(15)	15(5)	3.955(1)	–	$3/2^-$	^{9}Be $\times$ (sd)$^2_{2+}$
5.240(21)	45(10)	5.255(3)	29(8)[d]	$5/2^-$	^{9}Be $\times$ (sd)$^2_{2+}$
(5.86)	~300	5.849(10)	139(17)	$(5/2^-)$?	?

[a] Reference [3].

[b] Reference [7].

[c] References [7,11–13].

[d] Subsequent analysis of data of Ref. [7].

19 keV—and yet a 2^+ decay is observed. Following β decay of ^{11}Li, a branching ratio (BR) of $\Gamma(2^+)/\Gamma_{\rm tot} = 0.62^{+0.14}_{-0.21}$ is reported [13]. (See Table III.) As this state is thought to be $5/2^-$, this 2^+ decay is understandable, because gs decay is hindered by a large centrifugal barrier and by a small amount of expected $f_{5/2}$ sp strength. For $\ell = 1$ and $E_n = 19$ keV, we have $\Gamma_{\rm sp} = 2.9$ keV. In CK, the spectroscopic factor for the first $5/2^-$ state to decay to 2^+ is 0.66. (Millener has 0.574.) With the CK value and our sp width, we have $\Gamma(2^+) = 1.9$ keV as the width expected for decay to 2^+. The BR would then give $\Gamma_{\rm tot} = 3.1^{+1.5}_{-0.6}$ keV, leaving 1.2(7) keV for decay to the gs. This total width is consistent with the one given in the compilation as <10 keV. An $\ell = 3$ sp width for gs decay at this energy is 170 keV—implying $S(f_{5/2}) = 0.007(4)$, quite an acceptably small value.

We come now to the 3.96-MeV $3/2^-$ state. Following β decay its BR for 2^+ decay is given [13] as $\Gamma(2^+)/\Gamma_{\rm tot} = 0.78^{+0.65}_{-0.31}$. In the ^{9}Be(^{16}O,^{14}O) reaction [20], this ratio is 0.54(7), though this state is not resolved from the 3.89-MeV state. In ^{9}Be(t,p) the 3.89-MeV state is approximately half as strong (angle-integrated cross sections) as 3.96 MeV. A similar ratio might be expected in the heavy-ion-induced $2n$ transfer. Reference [20] points out that no amount of combined 3.89 + 3.96 yield will make their data consistent with those of Ref. [13]. The total width [3] of this state is 15(5) keV. For gs decay, the sp width is difficult to calculate, but we estimate it to be ~2.3 MeV. The gs branch for the 3.96-MeV state is 0.22(4) in Ref. [13] and 0.48(6) in Ref. [20], leading to $S(\text{gs}) = 1.4(5)\times 10^{-3}$ or $3.1(11)\times 10^{-3}$. These are small enough to arise from small, neglected components in the wave function. For decay to the 2^+ state, the decay energy is 98 keV, for which $\Gamma_{\rm sp}$ is 36 keV. Thus, if we use the β decay BR, we have $S = 0.32(17)$ for 2^+ decay, quite a large value (though with a large uncertainty) for a state thought to be dominated by the configuration ^{9}Be(gs) $\times$ (sd)$^2_{2+}$. The BR from Ref. [20] gives $S = 0.22(8)$, still quite large. Millener has $S = 0.864$ for the p-shell $3/2^-$ to decay to 2^+, but this is presumably the 2.69-MeV state. The next p-shell $3/2^-$ has $S = 0.123$, but it is expected above 5 MeV. It is very likely that mixing occurs among the lowest three $3/2^-$ states: p-shell, ^{9}Be $\times$ (sd)$^2_0$, and ^{9}Be $\times$ (sd)$^2_2$. In (t,p) there is a hint of an $L = 0$ contribution to the 3.96-MeV angular distribution (as can be seen by comparing data for 3.96 and 5.24 MeV—the latter is pure $L = 2$). Also, 3.96 is slightly (~15%) weaker than it should be, in comparison with 5.24, if they are both ^{9}Be $\times$ (sd)$^2_{2+}$. The situation is discussed further in Sec. III. Clearly, we need smaller uncertainties here—both in $\Gamma_{\rm tot}$ and BR—and a better understanding of the discrepancy between results of Refs. [13] and [20].

The next state is at 5.24 MeV, and has been assigned $J^{\pi} = 5/2^-$ and suggested to have the configuration ^{9}Be $\times$ (sd)$^2_{2+}$. Its width is given in the compilation [3] as 45(10) keV.

TABLE II. Widths (keV) and spectroscopic factors for three lowest unbound states of ^{11}Be.

E_x (MeV)	J^{π}	$\Gamma_{\rm exp}$[a]	ℓ	$\Gamma_{\rm sp}$	$S = \Gamma_{\rm exp}/\Gamma_{\rm sp}$	$S_{\rm th}$
1.78	$5/2^+$	102(14)	2	175	0.58(8)	0.67[b]
2.69	$3/2^-$	213(15)	1	~1800	~0.12	0.168[c]
3.41	$3/2^-$	113(13)	1	~2100	~0.05	–
	$3/2^+$		2	1100	0.10(1)	–

[a] Weighted average of values in Table I.

[b] Reference [12].

[c] Reference [15].

TABLE III. Branching ratios of states in ^{11}Be for neutron decays to ^{10}Be.

E_x (MeV)	J^{π}	0^+	2^+	Ref.
3.890	$5/2^-$	0.38(9)	$0.62^{+0.14}_{-0.21}$	[13]
3.969	$3/2^-$	0.22(4)	$0.78^{+0.65}_{-0.31}$	[13]
		0.48(6)[a]	0.54(7)[a]	[20]
5.24	$5/2^-$	–	1.00	[13]
		<0.27	0.81(16)	[20]
5.96	$(5/2^-?)$	<0.13	0.97(16)	[20]

[a] Contains contributions from both 3.89 and 3.96.

No width is listed for this state in the (*t*,*p*) paper, but subsequent analysis of those data yields $\Gamma = 29(8)$ keV, giving an average of 35(6) keV. The only observed *n* decays are to the 2^+. With an energy of 1.38 MeV, the $\ell = 1$ sp width is 1.45 MeV, giving $S = 0.024(4)$. This *S* is small enough that it could easily be acquired by mixing with the *p*-shell $5/2^-$—which is predicted to have $S = 0.66$. The limit of BR < 0.27 [20] for the gs branch corresponds to $S(f_{5/2}) < 0.02$.

The state at 5.96 MeV may or may not be the same as the 5.849(10)-MeV state seen in (*t*,*p*), with a width of 139(17) keV. The compilation lists a questionable state at (5.86) MeV with a width of ∼300 keV. The 5.96-MeV state in Ref. [20] has $\Gamma = 400$ keV and only a 2^+ branch.

III. CONFIGURATION MIXING

If the 3.41-MeV state has $J^\pi = 3/2^+$, then the lowest $(\mathrm{sd})^2$ state is the one at 3.96 MeV. The strength of the latter in (*t*,*p*) indicates very little mixing (∼1%–2%) between it and the first $3/2^-$ *p*-shell state. Its small gs spectroscopic factor (Sec. II) is also consistent with very little mixing. The weakness of its $L = 0$ component and the strong decay of the 3.96-MeV state to the 2^+ of ^{10}Be may be more difficult to understand. If J^π (3.41) is $3/2^+$, its $d_{3/2}$ spectroscopic factor of ∼0.10 (see above) is large enough that it should exhibit a clear $\ell = 2$ stripping pattern in ^{10}Be(*d*,*p*). Reference [5] states that they investigated the range of excitation energy up to $E_x = 7.0$ MeV with the ^{10}Be(*d*,*p*) reaction, but their published spectrum goes only to just above 3 MeV. They state that they did not observe the 3.41-MeV state. However, they also state that the 2.69-MeV state was not excited with measurable strength. The present analysis gives a value of $S{\sim}0.12$ for the latter.

We now consider the possibility that J^π (3.41) is $3/2^-$, and summarize the arguments for three-state mixing among the $3/2^-$ states: The 2.69-MeV state has excess $L = 0$ strength over that expected for the *p*-shell $3/2^-$.The 3.41-MeV state has only 28% of the cross section expected for the lowest $^9\mathrm{Be} \times (\mathrm{sd})^2_0$ state, and it has appreciable width for decay to the gs. The 3.96-MeV state has 15% less strength than that expected for the $^9\mathrm{Be} \times (\mathrm{sd})^2_2$ configuration, and its angular distribution contains a hint of $L = 0$ (not present for that configuration). Also it has an appreciable *S* for decay to the 2^+ state (although with a large uncertainty). Recall that the *p*-shell $3/2^-$ state has a large $S(2^+)$. If only the lowest two states had mixed, 12% of the *p*-shell $3/2^-$ state mixed into the 3.41-MeV level is enough to explain the (*t*,*p*) results, while the decay widths suggest 28%, with some uncertainty. For the 3.96-MeV state, the 2^+ decay suggests ∼25% mixing of the *p*-shell state, whereas only ∼15% of the (*t*,*p*) strength is lacking. It might appear that the absence of any appreciable $L = 2$ strength in the 3.41-MeV angular distribution might argue against all this. But, this fact actually argues against two-state mixing and for all three states to mix. If the second $3/2^-$ state mixed with only one of the others, it would necessarily acquire some $L = 2$ strength. But, with three states, the $L = 2$ admixtures from the other two states could be destructive for the 3.41-MeV state.

For the $5/2^-$ states: The 3.89-MeV state is predicted (and observed) to be weak, but it is stronger than expected. As its angular distribution is not a clear $L = 2$ shape, it could contain some nondirect (e.g., compound nucleus) contribution. If it receives its extra strength from the much stronger 5.24-MeV state, the mixing would have a negligible effect on the latter.

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