Widths and structure of unbound states in ^{12}Be

H. T. Fortune
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
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I have estimated the energies of several unbound states of ^{12}Be and their spectroscopic factors for decay to the $1/2^+$ ground state and $1/2^-$ first-excited state of ^{11}Be. These are then used to estimate the expected widths for such decays. Results for likely 3^- and 4^+ states are good. I find that only 0^+ and/or 2^+ states can account for the width recently observed for a state decaying with a centroid neutron energy of 1.24 MeV.

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I. INTRODUCTION

Above an excitation energy of 3.171(2)(3.49) MeV, states of ^{12}Be can decay by $1n$ emission [1] to the $1/2^+$ ground state (g.s.) ($1/2^-$, 0.32-MeV state) of ^{11}Be. Above 3.672(2) MeV, $2n$ emission to the g.s. of ^{10}Be is allowed. Very few unbound states of ^{12}Be are known. Here, I compare their experimental widths with ones calculated using a variety of assumptions about their structure.

In the reaction ^{10}Be(t,p) [2,3], four states were strongly excited: the 0^+ g.s., 2^+ at 2.11 MeV, probable 3^- at 4.58 MeV, and likely 4^+ at 5.72 MeV. A weaker state at 2.70 MeV was later determined [4] to be 1^-, and an excited 0^+ state was discovered at 2.25 MeV [5]. In the (t,p) reaction, a weak broad state was observed near 5.4 MeV and a hint of another just below the 5.72-MeV peak....

Very recently, a state (or collection of states) was populated in proton removal from ^{13}B and observed to decay by $1n$ emission to the g.s. and/or first-excited state of ^{11}Be with a centroid decay energy of $E_{\rm n} = 1.243(21)$ MeV and an extracted width of 634(60) keV [6]. The large width required $\ell \leqslant 1$ if a single state and the peak shape appeared to eliminate $\ell = 0$. Experimental results thus require $J^\pi = 0^\pm, 1^\pm$, or $2^\pm$ for the state exhibiting the bulk of the decays. Reference [6] expressed a preference for $2^-(1^-)$. Because the identity of the final state could not be determined, the excitation of the ^{12}Be state is not known, but it is in the range of 4.4–4.8 MeV.

In an earlier paper [7], I discussed (in general terms) those results as they relate to widths expected for 2^+ and 2^- states. Here, I present calculated energies, spectroscopic factors, and widths for all the states expected in the energy region of the state observed in Ref. [6].

II. CALCULATIONS AND RESULTS

First, I have computed the widths to be expected for the 3^- and 4^+ states, and then for other unbound states expected in this energy region, I use a Woods-Saxon nuclear potential, having r_0, $a = 1.26, 0.60$ fm with the well depth adjusted to reproduce the energy of the state. The single-particle width is then computed from the phase shifts.

The state at 5.72 MeV has the energy and (t,p) strength appropriate to the lowest 4^+ state in this nucleus [3,8]. In a simple $(sd)^2$ shell-model calculation, its configuration is predominantly d^2 with a small amount of dd', where d and d' refer to $d_{5/2}$ and $d_{3/2}$, respectively. Thus, its allowed decay is to the $5/2^+$ state at 1.78 MeV in ^{11}Be. Decay to states of lower J would require the presence of neutrons in the $1f$ and/or higher orbitals and can thus be ignored. The observed width is 86(15) keV [2,3], and the neutron decay energy is 0.77 MeV for which the computed single-particle width for $\ell = 2$ decay is 54 keV, resulting in a spectroscopic factor of $S = \Gamma_{\rm exp}/\Gamma_{\rm sp} = 1.59(28)$. The rigorous upper limit on this spectroscopic factor is 2.0, and the S for $\ell = 2$ to a pure $d_{5/2}$ state is about 1.95 [8]. However, the 1.78-MeV state of ^{11}Be is not pure $d_{5/2}$. Its spectroscopic factor computed from its width is 0.58(8) [9] so that in the simplest model, the S for $4^+ \rightarrow 5/2^+$ would be 1.13(16), in reasonable agreement with the value deduced here.

The state at 4.58 MeV is now thought [10–12] to be the first 3^- state in ^{12}Be. In the reaction ^{10}Be(t,p) [3], it was suggested to have $J^\pi = 2^+$ or 3^- on the basis of the shape of its angular distribution. Millener [10] was the first to point out that it was much too strong to be 2^+ because nearly all the 2^+ strength expected in the *psd* space is exhausted by the first 2^+ state at 2.1 MeV. He suggested a 3^- or a $3^-/2^+$ doublet. A later calculation [11] demonstrated the correctness of his argument. Within a few percent, this state has the appropriate cross section for a 3^- state reached by stripping of a $p_{1/2}d_{5/2}$ pair. Its energy agrees very well [12] with that calculated in a simple model that treats it as being of the structure ^{11}Be$(1/2^-) \otimes d$. Thus, it should decay exclusively to the $1/2^-$ state with $S = 1$. Decay to the g.s. would require participation of the $1f$ orbital, which we can ignore. The single-particle width for this energy of 1.09 MeV is 118 keV, giving $S = 0.91(14)$—in good agreement with the model. The 3^- and 4^+ results are summarized in Table I.

Concerning the new unbound state [6] that decays with a neutron energy of 1.24 MeV, we need to consider several possibilities for its J^π and structure. Except for 0^-, no

TABLE I. Decays of first 3^- and 4^+ states in ^{12}Be (energies in MeV and widths in keV).

Initial state		Final state		Decay					
$E_{\rm x}$	J^π	$E_{\rm x}$	J^π	ℓ	$E_{\rm n}$	$\Gamma_{\rm exp}$	$\Gamma_{\rm sp}$	$S_{\rm exp} = \Gamma_{\rm exp}/\Gamma_{\rm sp}$	$S_{\rm th}$
4.58	3^-	0.320	$1/2^-$	2	1.09	107(17)	118	0.91(14)	1.0
5.72	4^+	1.78	$5/2^+$	2	0.77	86(15)	54	1.59(28)	1.13–1.95[a]

[a]See the text.

TABLE II. Dominant configurations and predicted excitation energies (MeV) and spectroscopic factors of relevant negative- and positive-parity states of ^{12}Be.

J^π	Dominant configuration	E_x	$S(1/2^+)$	$S(1/2^-)$
2^-	^{11}Be$(1/2^-)\otimes d$	5.12	0	$\sim$1.0
1_2^-	^{11}Be$(3/2^-)\otimes s$	5.09	$\sim$0	$\sim$0
2_2^+	^{10}Be$(2^+)\otimes(sd)_0^2$	4.03	0.009	0
0_3^+	Second ^{10}Be(g.s.)$\otimes(sd)^2 0^+$	4.35	0.31	$1.8\varepsilon^2$[a]
2_3^+	Second ^{10}Be(g.s.)$\otimes(sd)^2 2^+$	4.68	0.09	0.020
0_4^+	^{10}Be$(2^+)\otimes(sd)^2 2^+$	5.48	0.24	0.02
2_4^+	^{12}Be p-shell 2^+	5.46	0.12	0.05 or 0.14[b]

[a] ε^2 is the intensity of p-shell 0^+ in this state, assumed to be 0.02 here.
[b] See the text.

unobserved states are predicted below 4 MeV, but in the region of 4 to 5.5 MeV, several states are expected—including the third (and perhaps fourth) 0^+, the second (and perhaps third) 2^+, the first 2^-, and perhaps a second 1^- state. These possibilities are listed in Table II. States above this region, such as the 2^- with configuration ^{11}Be$(3/2^-)\otimes s$ are not included. I have estimated the expected excitation energies of these states in a model that includes shell-model and weak-coupling considerations. These are also listed in Table II.

The aim now is to evaluate spectroscopic factors connecting these states to the first two states of ^{11}Be. The 2^- state has $S = 1$ to $1/2^-$, whereas 1_2^- has $S = 0$. Of course, both have $S = 0$ to the g.s. The lowest undiscovered positive-parity state is 2_2^+ with an unperturbed energy of 4.03 MeV. Its structure is two sd-shell neutrons with $J = 0$, coupled to the 2^+ state of ^{10}Be. It can decay to the g.s. via the small component of $2^+\otimes d$ in the g.s. The spectroscopic factor for $2^+ \to$ g.s. is then 0.009. It has no strength to the $1/2^-$. Consideration of $B(E2)$'s in ^{12}Be concluded [13] that the first 2^+ contained about 19% of this configuration so that mixing would put the 2_2^+ state somewhat higher. The third 0^+ state is primarily the second $(sd)^2$ 0^+ state and is predicted at 4.35 MeV. It has $S = 0.31$ to the g.s. This 0^+ state could contain a small component ε of the p-shell 0^+, although the first two 0^+ states exhaust most of this strength. But, because the p-shell S for $0^+ \to 1/2^-$ is so large, S for 0_3^+ to $1/2^-$ is $1.8\varepsilon^2$. For present purposes, I take ε^2 to be about 0.02. The third 2^+ state is predominantly the second $(sd)^2$ 2^+ state and is expected near 4.68 MeV. It has $S = 0.09$ for the g.s. and $S = 0.02$ for $1/2^-$.

The fourth 0^+ and 2^+ states are both expected near 5.5 MeV. This 0^+ configuration is an $(sd)^2$ 2^+ state coupled to the 2^+ of ^{10}Be. It has $S = 0.24$ to $1/2^+$ and $S = 0.02$ to $1/2^-$. The 2^+ state has about 80% of the p-shell 2^+ state and about 20% of the lowest $(sd)^2$ 2^+ state. It has $S = 0.12$ to the g.s. [from the $(sd)^2$ component]. In a pure p-shell calculation, S is about 0.05 for decay to the $1/2^-$. However, in the ^{9}Be(t,p) reaction [14], the $1/2^-$ state was populated with a cross section that was about twice that expected for the pure p-shell state. The conclusion there was that it contained about 9% of the configuration ^{9}Be(g.s.)$\otimes[(sd)^2 2^+]$. That impurity component would increase S from 0.05 to 0.14 for $2_4^+ \to 1/2^-$. In what follows, I give results for both possibilities. Both of these latter states may be too high in energy to be candidates for the state(s) observed in proton removal, but I include them for completeness.

The energies of the other states in Table II are all close enough that they could be considered as candidates for the state(s) observed by Ref. [6]. I have computed single-particle widths for all these states to decay by $\ell = 1$ to one of the first two states of ^{11}Be and by $\ell = 0$ and/or 2 to the other one. These are listed in Table III. As pointed out in Ref. [6], if the decaying state has negative parity, the observed $\ell = 1$ decay must be to the g.s. so that the other allowed decay (with $\ell = 0$ and/or 2) would be to the first-excited state—thus having a smaller decay energy. However, if the decaying state has positive parity, its observed decay is to the first-excited state, and the other allowed decay has higher energy. These are all listed in Table III.

Single-particle widths for s-wave neutron resonances are difficult to calculate, but they should vary as $\sqrt{E_n}$. For the present purposes, a rough estimate suffices as we will see. The sp width for p-wave decay in this case is also very large and thus difficult to compute. Again, a rough estimate turns out to be sufficient. The expected spectroscopic factors vary over quite a wide range from 0 to 1. However, they are small for all but one of the expected $\ell = 1$ decays, namely, the decay from the fourth 2^+ state, whose configuration is dominated

TABLE III. Estimated widths for various assumptions about the identity of the ^{12}Be state(s) [6] decaying via $\ell = 1$ and $E_n = 1.24$ MeV (energies in MeV and widths in keV).

J^π	Decay to $1/2^+$					Decay to $1/2^-$					Γ_{tot} (calc)
	E_n	ℓ	S	Γ_{sp}	Γ_{calc}	E_n	ℓ	S	Γ_{sp}	Γ_{calc}	
2^-	1.24	1	0	$\sim$1600	0	0.92	2	$\sim$1.0	93	93	93
1_2^-	1.24	1	0	$\sim$1600	0	0.92	2	$\sim$0	93	$\sim$0	Small
						0.92	0	$\sim$0	950	$\sim$0	Small
0_3^+	1.56	0	0.31	(1230)	(381)	1.24	1	0.04	$\sim$1600	$\sim$64	445?
0_4^+	1.56	0	0.24	(1230)	(295)	1.24	1	0.02	$\sim$1600	$\sim$32	327?
2_2^+	1.56	2	0.009	290	3	1.24	1	0	$\sim$1600	0	3
2_3^+	1.56	2	0.09	290	26	1.24	1	0.020	$\sim$1600	32	58
2_4^+	1.56	2	0.12	290	35	1.24	1	0.05;0.14	$\sim$1600	80;224	115;260

TABLE IV. Energies (MeV) and widths (keV) if primary decay is $\ell = 0$, rather than $\ell = 1$.

J^π	Decay to $1/2^+$					Decay to $1/2^-$					Γ_{tot} (calc)
	E_n	ℓ	S	Γ_{sp}	Γ_{calc}	E_n	ℓ	S	Γ_{sp}	Γ_{calc}	
0_3^+	1.24	0	0.31	(1100)	(341)	0.92	1	0.04	950	38	379?
0_4^+	1.24	0	0.24	(1100)	(264)	0.92	1	0.02	950	19	283?

by the p-shell component. For a pure p-shell $1/2^-$ state, S is only 0.05, but results of the ^{9}Be(t,p) ^{11}Be reaction [14] suggested an $(sd)^2$ component in this state. The addition of that component (only about 9% in intensity) increases S to about 0.14. Results are given for both values.

For each decay, I have computed the expected width as $\Gamma_{calc} = S\Gamma_{sp}$. The last column in Table III lists the sum of these expected widths for the two decays. Note that these are small for both negative-parity states and for two of the three 2^+ states. Only the 0^+ states and the fourth 2^+ have expected total widths consistent with the reported width of 634(60) keV. If an apparent enhancement factor of about 1.6 [15] is removed, the experimental result is reduced to about 400(40) keV. Even so, the present calculations require the decaying state(s) to have $J^\pi = 0^+$ and/or 2^+. Note that for the 2^+ state, most of the expected width is to the $1/2^-$ state, whereas for both 0^+ states, most of the predicted width is to the g.s. Thus, if the final state in the decay could be identified in a future experiment, the $0^+/2^+$ ambiguity could be removed.

For completeness, I have also computed the expected widths if the observed primary decay actually has $\ell = 0$, rather than $\ell = 1$. The results are listed in Table IV.

III. SUMMARY

I have computed single-particle widths for probable 3^- and 4^+ states in ^{12}Be. With theoretical spectroscopic factors from a simple shell model, the expected widths $\Gamma_{calc} = S\Gamma_{sp}$ are in good agreement with the experimental results for these two states. For several other expected but unknown states in the region of 4.0 to 5.5 MeV, I have estimated the energies, spectroscopic factors, and sp widths. I then compared the expected widths with the reported width [6] for states(s) decaying by $\ell = 1$ to one or both of the first two states of ^{11}Be with a centroid decay energy of 1.24 MeV. The results eliminate negative parity as the source of the decay and rule out two 2^+ states as the decaying state—leaving one or both 0^+ states and one 2^+ as candidates.

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