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Update on energies and widths in ^{13}Be

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I have compared new experimental information on resonances in ^{13}Be with results of theoretical calculations. For the $1/2^+$ resonance at 0.86 MeV, the reported width of 1.70(15) MeV is considerably larger than the single-particle limit of 1.3 MeV. For the first $5/2^+$, the calculated width and 2^+ branching ratio for neutron decay are both in rough agreement with the data. I discuss the possibility that events from decay of the second $5/2^+$ to ^{12}Be(2^+) could contribute to the 0.86-MeV peak. If the 4.0-MeV resonance is indeed $3/2^+$, then its width should be considerably larger than reported.

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I. INTRODUCTION

A recent experiment [1] has greatly improved our understanding of resonances in ^{13}Be, which has no bound states. Three other relatively recent experiments had served to both clarify and confuse the issue [2–4]. Ribeiro *et al.* [1] used proton knockout from a 400 MeV/nucleon ^{14}B beam incident on a CH$_2$ target to produce ^{13}Be, and they detected ^{12}Be $+ n$ in coincidence. The experiment also had the ability to detect coincident ^{12}Be γs. They report a $1/2^+$ resonance at an energy of 0.86(4) MeV with a width of 1.70(15) MeV and a $5/2^+$ resonance at an energy of 2.11(5) MeV. For the latter, they took the width of 0.4 MeV from earlier heavy-ion-induced transfer experiments [5,6]—the reaction ^{13}C(^{14}C, ^{14}O) ^{13}Be at $E_{\rm Lab} = 337$ MeV [5] and the ^{14}C(^{11}B, ^{12}N)^{13}Be reaction at $E_{\rm lab} = 190$ MeV [6]. Ribeiro *et al.* [1] observed low-energy neutrons in coincidence with γs of energy $\sim$2 MeV, which they interpreted as evidence that the $5/2^+$ resonance also decayed to the 2^+ of ^{12}Be, in addition to the ground state (g.s.). Their branching ratio (BR) was $2^+/\text{g.s.} = 0.1/(0.24) = 0.42$ [1,7].

Reference [1] adopted a low-lying $1/2^-$ resonance near 0.5 MeV from Ref. [8]. They argue correctly that a negative-parity state should not be produced in proton removal from ^{14}B, but that it should be populated in neutron removal from ^{14}Be—which was the procedure used in Ref. [2,8]. Ribeiro *et al.* also included in their analysis a second $5/2^+$ and first $3/2^+$ resonances, with both J$^\pi$ assignments tentative. They took both energies (2.92 and 4.0 MeV, respectively) and widths (both 0.4 MeV) from the heavy-ion work [5,6]. Both are weak. The resolution width (FWHM) in Ref. [1] was about 0.7 MeV at $E = 2$ MeV, and it increases as $E^{0.75}$. Thus, all the widths, except for $1/2^+$, are significantly less than the resolution width, and that is the justification for the use of earlier widths.

Here, I examine the new experimental evidence in comparison with model calculations.

II. CALCULATIONS AND RESULTS

I have calculated single-particle (sp) widths in a potential model, using a Woods-Saxon shape with geometrical parameters r_0, $a = 1.26$, 0.60 fm. Well depth was adjusted to reproduce resonance energy, and the width was computed from the phase shift. For $\ell = 2$, the width calculation is straightforward. The absence of a barrier for an s-wave neutron resonance is somewhat of a complication, but I have used the relationship $\Gamma_{\rm sp}(\ell = 0) = (2E)^{1/2}$, where both energy and width are in MeV. From these $\ell = 0$ and 2 sp widths, I have computed expected widths with the expression $\Gamma_{\rm calc} = S\,\Gamma_{\rm sp}$, where S is the relevant ^{12}Be $+ n$ spectroscopic factor, given previously [9]. Relevant information is displayed in Table I.

The $1/2^+$ resonance could have a spectroscopic factor near unity, but even if so, the reported width of 1.70(15) MeV is significantly larger than the sp width of 1.3 MeV. I return to this discrepancy below. Even though the first theoretical $5/2^+$ state has a (sd)^3 component that is larger than the $1d_{5/2}$ component [10], its spectroscopic factor to ^{12}Be (g.s.) is quite large—0.94 in my calculations. This happens because of the large (sd)^3 component in ^{12}Be (g.s.). With my S and $\Gamma_{\rm sp}$, the computed width for decay of the first $5/2^+$ state to the g.s. is 0.63 MeV, slightly larger than the old experimental width of 0.4 MeV. However, it appears that the newer data [1–4] could easily accommodate a larger width. For decay of this state to the 2^+ of ^{12}Be, Ref. [1] quotes a neutron energy of 0.1 MeV. With this energy, my computed width is 0.13 MeV (Table I) for s-wave decay (at this low energy, d-wave decay is weak enough to ignore), giving an expected $\text{BR}(2^+/\text{g.s.}) = 0.13/0.63 = 0.21$—to be compared with the experimental BR quoted above of 0.42. The authors quote a relative yield of 0.1 (no uncertainty given) for decay through the 2^+ and 0.24(4) for g.s. decay. (Just in passing, I note that a neutron energy of 0.4 MeV for decay to the 2^+ would provide exact agreement with the experimental BR.)

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TABLE I. Energies, decay modes, and widths in ^{13}Be (energies and widths in MeV).

^{13}Be state	Decay	E_n	S[c]	Γ_{sp}	Γ_{calc}[d]	Γ_{exp}
$1/2^+$	to g.s.	0.86[a]	$\sim$1	1.3	1.3	1.70(15)[a]
$5/2_1^+$	to g.s.	2.11[a]	0.94	0.67	0.63	0.4[b]
	to $2^+ + \mathrm{s}$	(0.1)[a]	0.29	(0.45)	(0.13)	
$5/2_2^+$	to g.s.	2.92[b]	0.0004	1.4	0.0006	0.4[b]
	to $2^+ + \mathrm{s}$	0.8	0.15	1.25	0.19	
	to $2^+ + \mathrm{d}$	0.8	0.005	0.082	0.0004	
	To exc. 0+	0.68	0.85	0.066	0.056	
$3/2^+$	to g.s.	4.0[b]	$\sim$0	2.82	small	0.4[b]
	to $2^+ + \mathrm{s}$	1.9	0.19	1.9	0.37	
	to $2^+ + \mathrm{d}$	1.9	1.32	0.52	0.69	

[a] Reference [1].
[b] References [5,6].
[c] Reference [9].
[d] $\Gamma_{\mathrm{calc}} = S\,\Gamma_{\mathrm{sp}}$.

The second $5/2^+$ state is predicted to have an extremely small decay branch to ^{12}Be(g.s.), with the largest decay to the first excited 0^+ state of ^{12}Be [11]. The experiment of Ref. [1] was not sensitive to this excited 0^+ decay, but they appear to have observed some g.s. decays. Other than the excited 0^+ decay, the other important branch should be s-wave decay to the 2^+, for which the computed width is 0.19 MeV, considerably smaller than the supposed experimental width of 0.4 MeV. Reference [1] did not report observation of this decay, but I note that such a decay would have a neutron energy near 0.8 MeV. The presence of such decays might account for the fact that the reported width for the 0.86-MeV resonance is significantly larger than the sp limit. If this second $5/2^+$ state does indeed also decay to the excited 0^+, that would add about 0.06 MeV to the computed width.

A decrease in S for the first $5/2^+$ would require an increase in S for the second $5/2^+$. Such changes would move both calculated widths closer to the experimental values.

The $3/2^+$ resonance is predicted to have a very small g.s. branch, but reasonably strong decays to the 2^+, with both s and d. Reference [1] observed 2-MeV γs in coincidence with 2-MeV neutrons, indicating decay of the 4-MeV resonance to ^{12}Be(2^+). With my predictions, the width of this resonance should be considerably larger than 0.4 MeV.

III. SUMMARY

I have compared new experimental results for resonances in ^{13}Be to previous and new model calculations. The reported width of 1.70(15) MeV for the $1/2^+$ resonance is considerably larger than the sp limit of 1.3 MeV, perhaps implying another contribution to that peak in the energy spectrum—for which one possibility is decay of the second $5/2^+$ state to the 2^+ of ^{12}Be. The calculated width for the first $5/2^+$ resonance is in reasonable agreement with (but slightly larger than) the experimental value. Reference [1] was the first to positively identify decays of this state to ^{12}Be(2^+). Their 2^+/g.s. branching ratio is in rough agreement with my calculations. If the 4.0-MeV resonance is indeed $3/2^+$, it should be considerably wider than currently thought.

A recent review [12] identified a few unanswered questions in ^{13}Be. One of them was: Is the lowest resonance near 0.5 MeV $1/2^+$ or $1/2^-$, or are the two unresolved? Reference [1] was unable to answer this question. They state, “To promote one of them as the ground state ^{13}Be is not within the scope of the present paper but certainly a challenge for theory.”

Another unanswered question [12] was: Can better evidence be found for decays of ^{13}Be resonances to excited states of ^{12}Be? Reference [1] has provided convincing evidence for this question as it relates to the first $5/2^+$ state. Another question dealt with events near 1 MeV, and the extent to which they correspond to g.s. decays versus decays of an excited state to an excited state. I referred to this question above, in relation to the width of the $1/2^+$ resonance and the question of decays of the second $5/2^+$ resonance to ^{12}Be(2^+).

Perhaps the most important unanswered question concerns the possibility of decays of the second $5/2^+$ state to the excited 0^+ state. Reference [1] states that this “is indeed an experimental challenge.”

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