Energies and widths in ^{13}Be

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I have calculated spectroscopic factors connecting three d resonances in ^{13}Be to the three lowest states of ^{12}Be. Combined with single-particle widths computed in a potential model, I have estimated the widths expected for the various decays. Comparing measured and calculated widths suggests that the resonance near 1 MeV is not $5/2^+$ and that the one just above 2 MeV is the lowest $5/2^+$ resonance.

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I. INTRODUCTION

Previously [1], I summarized the experimental and theoretical history concerning low-lying resonances in ^{13}Be, which has no bound states. My principal aim was to use a simple model to calculate the absolute energy of the lowest $5/2^+(sd)^3$ state. For ^{19}O and ^{17}C, calculations within this same model missed the absolute energy of the lowest $5/2^+$ state by only 103 keV in ^{19}O and by 56 keV in ^{17}C, thus giving some confidence to the prediction for ^{13}Be. The result was $E_n = 1.79$ MeV [1]. As the first $5/2^+$ resonance was thought to be about 2.0 MeV, that result suggested that the lowest $5/2^+$ state was primarily of $(sd)^3$ structure. Three experiments since that time have served to both clarify and confuse the issue [2–4].

In later calculations by Randisi *et al.* [3], the energies of the lowest $(sd)^3$ states were considerably different from mine. They had a cluster of states at the low end of their spectrum; my energies were more spread out. My predicted energies were absolute, while theirs were adjusted to make the $1/2^+$ energy appear at 0.4 MeV. So, the fact that their energies are lower than mine has little significance. By comparison with those calculations, they associated a resonance at $E_n = 0.85$ MeV with their lowest $5/2^+$ state. None of the two most recent experiments [3,4] had the ability to determine the ℓ value of the decay. The only reason for the $5/2^+$ suggestion was the closeness in energy to that calculated. Another resonance at 2.35 MeV was suggested as the second $5/2^+$ state. Here, I investigate the situation for the first two $5/2^+$ states, by considering both energies and widths expected for them.

As part of their experiment [5] on proton removal from ^{13}B in order to look for neutron decays from unbound states in ^{12}Be, a Michigan State University group also collected data for ^{12}Be$+n$ coincidences, which they interpreted [4] as decays of ^{13}Be resonances, presumably populated in a charge-exchange reaction of proton removal followed (or preceded) by neutron addition. It is difficult to ascertain whether they learned anything new about the states of ^{13}Be, or if their data are consistent with earlier work [2–4,6], even though they state "The observed spectral shape is consistent with previous one-proton removal reaction measurements from ^{14}B." However, they also state, correctly, that their reaction could have populated states that earlier reactions would not have populated. They performed both two-resonance and three-resonance fits. The numerical results for the two-resonance fit are given in their abstract, while those from the three-resonance fit are listed in their table. Both sets are discussed in the text. However, in the three-resonance fit, the energy and width of the lower resonance were held fixed at the values from Randisi *et al.* [3] and the energy and width of the highest resonance were held fixed at the values determined in the two-resonance fit.

I note that in the three-resonance fit [4] the middle resonance at 1.05 MeV is primarily a one-channel phenomenon, whereas, at somewhat higher energy, counts in four consecutive channels are above the fitted curve. So, there could be another resonance around 1.5 MeV. I also note that at the highest energies about 20 of 25 channels have counts that exceed the fitted curve, perhaps indicating the presence of another resonance there.

For clarity, I reproduce in Tables I and II the results of [3,4] for both two- and three-resonance fits. It can be seen that the relative strength for the third resonance in [4] is almost 6 σ larger than that in [3]. It is therefore extremely unlikely that the 2.56-MeV bump in [4] contains only one resonance. If more than one state is present, there is no way to know what the energy would be for possible decays to excited states. Reference [2] had reported evidence for a resonance near 5 MeV decaying to the 2^+ state.

When discussing the $(sd)^3$ calculations of Randisi *et al.*, Marks *et al.* stated "It should be mentioned that the low-lying $3/2^+$ and $5/2^+$ states predicted by the (0–3)$\hbar\omega$ shell-model calculations using the WBP interaction [6] are not present in the simplified scheme by Fortune [29]," where [6,29] refer to [3,1], respectively, in this paper. In fact, as stated above, those states were the primary focus of my calculations. I demonstrated that it was the first $5/2^+$ state of ^{13}Be that was primarily of $(sd)^3$ character. Later calculations agreed.

II. CALCULATIONS AND RESULTS

I have computed spectroscopic factors connecting both $5/2^+$ states and a $3/2^+$ state to the ground state (g.s.), first 2^+

TABLE I. Results of two recent experiments on ^{13}Be resonances, from two-resonance fits (energies and widths in MeV).

	Randisi *et al.* [3] $(-1p)$		Marks *et al.* [4] $(-1p+1n)$	
J^π	E_r	Γ_r	E_r	Γ_r
$1/2^+$	0.70(11)	1.70(22)	0.73(9)	1.98(34)
$5/2^+$	2.40(14)	0.70(32)	2.56(13)	2.29(73)

TABLE II. Results of two recent experiments on ^{13}Be resonances, from three-resonance fits (energies and widths in MeV).

J^π_n	Randisi *et al.* [3] ($-1p$)			Marks *et al.* [4] ($-1p+1n$)		
	E_r	Γ_r	Rel. Str.	E_r	Γ_r	Rel. Str.
$1/2^+$	0.40(3)	$0.80^{+0.18}_{-.12}$	1.00	0.40[a]	0.80[a]	1.00
$5/2^+{}_1$	$0.85^{+0.15}_{-0.11}$	$0.30^{+0.34}_{-0.15}$	0.40(7)	1.05(10)	0.50(20)	0.63(15)
$5/2^+{}_2$	2.35(14)	1.50(40)	0.80(9)	2.56(13)[b]	2.29(73)[b]	3.88(50)

[a]Fixed at values from Ref. [3].
[b]From two-resonance fit.

and excited 0^+ state of ^{12}Be, as did Randisi *et al.* [3]. Results are compared in Table III. Perhaps surprisingly, there are no major differences in the two sets of spectroscopic factors. We suggested previously [7] that the second $5/2^+$ state should preferentially decay to the excited 0^+ state, rather than to the g.s. We see from the spectroscopic factors that this expectation holds in both calculations. The second $5/2^+$ and first $3/2^+$ resonances have very small S's to the g.s. in both calculations.

I have also used a potential model to compute single-particle widths for the decays, and then the expected widths for various decay channels, using the expression $\Gamma_{\rm calc} = S\Gamma_{\rm sp}$. For both sets of spectroscopic factors, the reported experimental widths are significantly larger than the calculated ones. Details follow.

A. If the first $5/2^+$ state is at 0.85 or 1.05 MeV

If the first $5/2^+$ state is this low, its only allowed decay is to the g.s. Single-particle widths for $E_n = 0.85$ and 1.05 MeV are, respectively, 68 and 100 keV. With these *sp* widths and the S's from Table III, the expected widths are 41 or 57 keV if the resonance energy is 0.85 MeV, and 67 or 94 keV if the energy is 1.05 MeV. (Throughout, I give results for both sets of spectroscopic factors.) In Table IV, these expected widths are compared with the experimental widths of 300 [3] or 500 keV [4] (with large uncertainties). If an apparent enhancement factor of 1.6 [8] is removed, the experimental widths are both still more than three times the expected ones, though the differences are then less than 2 σ.

B. If the second $5/2^+$ state is at 2.35 or 2.56 MeV

With the given S's for the second $5/2^+$ resonance, the expected widths depend on the resonance energy as depicted in Table V. Recall that this state was associated with the resonance at 2.35 MeV [3] or 2.56 MeV [4]. For either energy, the reported widths are larger than those expected by more than a factor of 10, as demonstrated in Table V. The differences between experimental and calculated values are about 3 σ.

Given the large discrepancy between observed and expected widths for both $5/2^+$ states, it thus appears very likely that the suggested assignment [3,4] of $5/2^+{}_1$ and $5/2^+{}_2$ to these two resonances is incorrect. I explore another possibility in the next subsection.

TABLE III. Spectroscopic factors for $^{13}\text{Be} \rightarrow {}^{12}\text{Be} + n$ for lowest d-wave resonances.

Final state	$5/2^+{}_1$		$5/2^+{}_2$		$3/2^+$	
	Randisi	Present	Randisi	Present	Randisi	Present
g.s.	0.67	0.94	0.01	0.0004	0.04	0
2^+s	0.08	0.29	0.23	0.15		0.19
2^+d	0.05	0.02	0.01	0.005	1.13	1.32
Exc. 0^+	<0.01	$\sim$0	0.65	0.85	0.01	0

C. If the first $5/2^+$ state is at 2.35 or 2.56 MeV

If the resonance above 2 MeV is the first $5/2^+$ state in ^{13}Be, the situation is much more favorable. In that case, with the spectroscopic factors from Table III, only two decays are significant—to the g.s. and by s decay to the 2^+ state. Decays by d-wave emission to the 2^+ and excited 0^+ states are calculated to be completely negligible. Computed and measured widths are listed in Table VI. Now, the measured and expected widths are of a similar magnitude. In fact, if the suggested enhancement factor of 1.6 in experimental widths is removed (last row of Table VI), the differences are only about 1 σ.

From this analysis, it seems likely that the first $5/2^+$ state in ^{13}Be is above 2 MeV (with some uncertainty). The second one would then be somewhat higher—perhaps close to 3 MeV.

It could then be that the resonance at 0.85 or 1.05 MeV, if it exists, is due to decay of the second $5/2^+$ state to the excited 0^+, or to s-wave decay of the second $5/2^+$ state (or first $3/2^+$) to the 2^+. An experiment designed to explicitly look for these decays would be very valuable.

III. SUMMARY

I have calculated spectroscopic factors connecting three d resonances in ^{13}Be to the g.s. and two excited states of ^{12}Be. Perhaps surprisingly, the results are in good agreement with those from a more sophisticated approach [3]. Combining these S's with single-particle widths computed in a potential model, I calculated widths expected for all of the allowed

TABLE IV. Calculated and experimental widths (keV) for decay of first $5/2^+$ (at the energies indicated) to g.s. of ^{12}Be.

	$E_r = 0.85$ MeV	$E_r = 1.05$ MeV
Calculated	41, 57	67, 94
Experimental	300^{+340}_{-150}	500(200)
Exp./1.6	188^{+212}_{-94}	312(125)

TABLE V. Calculated and experimental widths (keV) for decay of proposed [3,4] second $5/2^+$ to states in ^{12}Be.

Final State	$E_r = 2.35$ MeV		$E_r = 2.56$ MeV	
	Γ_{sp}	Γ_{calc}	Γ_{sp}	Γ_{calc}
g.s.	638	0.26, 6	769	0.32, 8
2^+s	500	74, 115	671	99, 154
2^+d	3.2	0.016, 0.032	13.5	0.07, 0.14
Exc. 0^+	0.34	0.22, 0.29	5.1	3.3, 4.3
Sum		75, 121		102, 166
		Γ_{exp}		Γ_{exp}
Exp.		1500(400)		2290(730)
Exp./1.6		940(250)		1430(460)

TABLE VI. Calculated and experimental widths (MeV) for decay of first $5/2^+$ (at the energies indicated) to states in ^{12}Be.

Final State	Γ_{calc}	
	$E_r = 2.35$ MeV	$E_r = 2.56$ MeV
g.s.	0.427, 0.599	0.515, 0.722
2^+s	0.04, 0.14	0.05, 0.19
Sum	0.47, 0.74	0.56, 0.91
	Γ_{exp}	
Exp.	1.5(4)	2.29(73)
Exp./1.6	0.94(25)	1.43(46)

decays. The conclusion is that the differences in measured and expected widths are in serious conflict with the hypothesis of a $5/2^+$ resonance near (or just below) 1 MeV and a second one above 2 MeV. However, identifying the resonance just above 2 MeV with the *first* $5/2^+$ resonance gives good agreement between experimental and calculated widths. I also suggest that the resonance near 1 MeV, if it exists, might correspond to decay of a second $5/2^+$ resonance to the excited 0^+ state of ^{12}Be (and/or first $3/2^+$ or second $5/2^+$ decaying by s wave to the 2^+). I strongly urge an experiment designed to look specifically for such decays.

Note added. I have just learned of unpublished data [9,10] for the reaction ^{14}B$(p,2p)$ (in reverse kinematics) in which $^{13}\text{Be} \rightarrow {}^{12}\text{Be} + n$ decays were detected in coincidence with prompt 2.1-MeV gamma rays. Those data provide convincing evidence that a peak near 0.95 MeV corresponds to decay of a ^{13}Be resonance to the first 2^+ state of ^{12}Be.

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