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Low-lying levels of ^{9}B

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We present calculations for the energies and widths of the lowest $1/2^+$, $1/2^-$, and $5/2^+$ levels of ^{9}B, taking into account the information known for the mirror levels in ^{9}Be. Comparison is made with the experimental data.

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I. INTRODUCTION

There have been many recent attempts to determine the energies and widths of the low-lying levels of ^{9}B. Our primary concerns are analogs in ^{9}B of the $1/2^+$, $1/2^-$, and $5/2^+$ low-lying levels of ^{9}Be (the $3/2^-$ ground states and the lowest $5/2^-$ excited states are well established). Recent experimental results [1–7] are listed in Table I. These states are all unbound, broad, and overlapping, presenting serious problems for the analysis of experimental spectra. That analysis would have been greatly simplified had the ^{8}Be ground state been stable for transfer reactions. In its absence, we may use the computed ^{9}B analogs as a guide for the analysis of experimental data. None of the papers in Table I made use of this approach. We note the considerable range of energies and widths for the $1/2^+$ state and the almost complete overlap of the $1/2^-$ and $5/2^+$ levels.

Of particular interest are the energy and other properties of the $1/2^+$ level. In the calculation of Sherr and Bertsch [9], the analog of the 1.684 MeV $1/2^+$ level of ^{9}Be was computed to be at 0.94 MeV. They noted that this was a normal Thomas-Ehrman shift despite the fact that the ^{9}Be level was neutron unbound and therefore could not be a ^{8}Be *s*-wave neutron scattering resonance. (A recent calculation by Efros and Bang [10] yielded a similar result.) However, a subsequent calculation by Barker [11] predicted the ^{9}B $1/2^+$ level to be at 1.8 MeV, a negative Thomas-Ehrman shift—again as a consequence of the lack of a neutron resonance. In addition to settling this disagreement, an interesting reason for better knowledge of ^{9}B was suggested (and investigated) by Buchmann *et al.* [7]. The stellar reaction ^{4}He$(\alpha n,\gamma)^9$Be leads to the formation of seed elements essential for the *r* process. The properties of the ^{9}B analogs are of use in determining those of ^{9}Be.

An extensive experiment on the levels of ^{9}B was recently carried out by Gete *et al.* [8] who investigated the β decay of ^{9}C and the β-delayed particle decays of ^{9}B. Data collected included singles, double, and triple coincidence spectra involving the $\alpha\alpha p$ final state reached via decays through ^{5}Li(gs) and ground and first excited states of ^{8}Be. The authors performed a phenomenological analysis, extracting energies and widths of several ^{9}B levels. In a subsequent paper, Buchmann *et al.* [7] gave results of *R*-matrix fits and discussed implications for stellar reaction rates. Of course, the $1/2^+$ and $5/2^+$ states are expected to be weak in β^+ decay, and Ref. [8] saw them but only weakly.

In their fits, Refs. [7,8] took the energies and widths of the ^{5}Li and ^{8}Be states to be those given in the compilation and did not vary them in their fits. They also appear to have used incoherent sums of partial-wave contributions, but they do point out the possibility of interference among amplitudes. They point out the definite presence of decays from below 1.5 MeV in ^{9}B, but mention that derived properties of the $1/2^+$ first-excited state depend sensitively on the energies and widths assumed for the other states. Buchmann *et al.* [7] give $E_x=0.827$ MeV, $\Gamma=0.382$ MeV for the $1/2^+$ state.

They found that the 2.34-MeV $5/2^-$ state decays primarily via the ^{5}Li(gs) channel (as expected), but its nearness to threshold caused a distortion that necessitated unnatural adjustments to the properties of this state and/or of the ^{5}Li(gs) in order to fit the triple coincidence spectrum.

For the $1/2^-$ excited state, Gete *et al.* [8] obtained $E_x=2.8$ MeV, $\Gamma=2.5$ MeV (their Table II) in fitting the ^{8}Be(gs)$+p$ spectrum and $E_x=(4.0\text{ MeV})$, $\Gamma=0.57$ MeV (their Table III) from the fit to the ^{5}Li(gs)$+\alpha$ spectrum. In the *R*-matrix fits [7], derived parameters were $E_x=3.1$ MeV, $\Gamma=263$ MeV (presumably an *R*-matrix width). These results (as well as those of other experiments) will be reviewed in Sec. III.

II. COMPUTATIONS

Any state in ^{9}Be can be expanded as a sum of products of states of a mass-8 core (including both $T=0$ and 1) coupled to a nucleon, in all allowed angular momenta of relative motion. For "in-shell" states, this sum will usually include core states at quite high excitation, because of antisymmetry required between the last nucleon and the *p* shell nucleons in the core. However, for "wrong-parity" states, in which the ninth nucleon is in the next major shell, the tendency toward weak coupling will usually require only a few low-lying states in the core.

A sum of direct products of a mass-5 core and a mass-4 particle and their relative motion is also separately complete. Because we wish to address alpha widths here, we will also compute energies for this mass partition. Of course, expan-

TABLE I. Experimental excitation energies and widths (in MeV) of the lowest $1/2^+$, $1/2^-$, and $5/2^+$ levels of ^{9}Be and ^{9}B.

	$1/2^+$		$1/2^-$		$5/2^+$	
J^π	E_x	Γ	E_x	Γ	E_x	Γ
^{9}Be	1.68	0.22	2.78(12)	1.08(11)	3.05	0.282
^{9}B						
Reactions						
$(^3\mathrm{He},\alpha)$ [1]					2.79(3)	0.55(4)
(p,n) [2]			2.75(30)	3.13(20)	2.71(10)	0.71(10)
$(^3\mathrm{He},t)$ [3]	1.16(5)	1.30(5)			2.72(4)	
$(^6\mathrm{Li},{}^6\mathrm{He})$ [4]	1.32(8)	0.86(26)	(2.95)	(1.16)		
$(^3\mathrm{He},\alpha p)$ [5]	1.8 ± 0.2	0.9 ± 0.3				
$(^6\mathrm{Li},t)$ [6]	[a]	[b]	2.91	3.03		
$^9\mathrm{C}(\beta^+)$ [7]	0.83	0.38	2.8[c]	2.5[c]	2.93(20)	0.95(48)

[a] Reference [6] gives 1.6(1) from two-state fit, 0.73(5) from three-state fit.

[b] See the text (Sec. III A).

[c] From Table II of Ref. [7].

sion in a given mass-partition basis is most useful if the majority of the strength involves a few simple (usually low-lying) core states. The Coulomb energies for the two mass partitions should be equal, but as we see below, they are slightly different, leading us to average the two for final ^{9}B energies quoted.

Our computations follow those of Ref. [9]. Resonances in a Woods-Saxon well are determined by $d\delta/dE$, the rate of change of the scattering phase, rather than by the usual cross section vs E. For nucleons interacting with a ^{8}Be core, we use $r_0=1.25$ fm, corresponding to a nuclear radius of 2.50 fm, but for an α particle plus ^{5}He or ^{5}Li cores, we use $R=2.70$ fm. For all cases we use $a=0.65$ fm.

Two changes from Ref. [9] are made. In that paper, nucleons were coupled only to the ground states of the cores for $A=9$ to 17. Differences between experimental and computed values for the known levels of $A=9$, 11, 13, 15, and 17 ranged from 25 to 260 keV. In the present work we include the cores of levels of ^{8}Be, ^{8}Li, and ^{8}B [13] and also ^{5}He and ^{5}Li cores [12] (which Buchmann *et al.* [7] observed in their investigation of ^{9}C β^+ decay—previously only the α decay of the $5/2^-$ level of ^{9}B had been observed).

TABLE II. ^{8}Be ($T=0$), ^{8}Li–^{8}Be–^{8}B ($T=1$), and ^{5}He–^{5}Li core states. All excitation energies are in MeV and are taken from Ref. [12] for $A=5$ and Ref. [13] for $A=8$.

Singlet		Triplet				Doublet		
J_n^π	^{8}Be	J_n^π	^{8}Li	^{8}Be	^{8}B	J^π	^{5}He	^{5}Li
0_1^+	0	2_1^+	0	16.77	0	$3/2^-$	0	0
2_1^+	3.04	2_2^+		(20.85)[a]		$1/2^-$	1.27	1.49
4_1^+	11.4	2_3^+		(22.26)[a]				
2_2^+	16.77	1_1^+	0.98	17.64	0.77			
1_1^+	18.15	3_1^+	2.26	19.07	2.32			
3_1^+	19.24	1_2^+		19.87				
		4_1^+	6.53	23.2	(6.5)[b]			

[a] Theory.

[b] Assumed.

The energies of the various sets of cores are listed in Table II. Except for the 0_1^+, 2_1^+, and 4_1^+ core states of ^{8}Be, the remaining ^{8}Be cores lie between 16.8 and 23.32 MeV, a region in which the Coulomb shift becomes essentially constant, as will be noted in the following tables. For ^{5}He and ^{5}Li energies, we use the results from an extended *R*-matrix analysis [12]. In that analysis the boundary condition was taken to be equal to the logarithmic derivative of an outgoing wave function. Thus, the energies and widths from such a fit should be close to the observable ones. “This prescription has been found to give resonance parameters that are free, both formally and practically, of all dependence on the ”geometric“ parameters of *R*-matrix theory, such as boundary conditions and channel radii.” (p. 12 of Ref. [12]).

Table III lists the computations for odd-parity levels $3/2^-$, $1/2^-$, and $5/2^-$ and Table IV shows our results for the $1/2^+$ and $5/2^+$ levels of ^{9}B. The $3/2^-$ ground state and the $5/2^-$ level have precise experimental values with which our results can be compared. For each state in Tables III and IV the first column lists a specific core state, the second column lists the excitation energy E_i computed from the Coulomb energy calculated for this core state, and the third column lists the spectroscopic factors [14] from the structure calculations described in Ref. [15].

The spectroscopic factors given for negative-parity states to a subset of core states in Table IV of Ref. [16] show little sensitivity to the choice of *p*-shell interaction. The alpha spectroscopic factors are for p^4 or $p^3(sd)$ configurations projected onto the internal 0*s* state of the cluster and transformed to the cluster-core relative coordinate. In addition to the specific core levels, e.g. $(0_1^+,0)$, we list $(J^+,0)$ and $(J^+,1)$ to account for higher levels (unlisted in Table II) which have

TABLE III. Calculated negative-parity levels $(3/2^-,\ 1/2^-,\ 5/2^-)$ of ^{9}B corresponding to cores of ^{8}Be, the triplet ^{8}Li, ^{8}Be, and ^{8}B for $T=1$ cores, and the ^{5}He, ^{5}Li pair. The rows labeled $(J^+,0)$ and $(J^+,1)$ represent cores not previously given, which contain the missing S factors. Averaged calculated excitation energies and experimental energies are given in the last two lines (all energies in MeV).

^{9}B$(3/2^-)$			^{9}B$(1/2^-)$			^{9}B$(5/2^-)$		
Core$(A=8)$	E_i	S	Core	E_i	S	Core	E_i	S
$(0_1^+,0)$	−0.22	0.57	$(0_1^+,0)$	2.61	0.74	$(2_1^+,0)$	2.49	1.16
$(2_1^+,0)$	0.25	0.74	$(2_1^+,0)$	2.80	0.43	$(4_1^+,0)$	2.91	0.16
$(2_2^+,0)$	0.60	0.36	$(1_1^+,0)$	3.37	0.19	$(2_2^+,0)$	3.02	0.28
$(3_1^+,0)$	0.64	0.17	$(J^+,0)$	3.42(5)	0.64	$(1_1^+,0)$	3.03	0.06
$(J^+,0)$	0.61(1)	0.16				$(3_1^+,0)$	3.05	0.16
						$(J^+,0)$	3.07(4)	0.19
$(2_1^+,1)$	0.12	1.44	$(2^+,1)$[a]	2.9(1)	1.29	$(2^+,1)$[a]	2.6(1)	1.16
$(1_1^+,1)$	0.09	0.73	$(1^+,1)$[a]	2.9(1)	1.45	$(1^+,1)$[a]	2.6(1)	0.71
$(3_1^+,1)$	0.12	0.52	$(J^+,1)$	3.1(2)	0.26	$(3_1^+,1)$	2.58	0.52
$(J^+,1)$	0.15(3)	0.31				$(4_1^+,1)$	2.47	0.43
						$(J^+,1)$	2.7(1)	0.18
$\langle E\rangle$	0.17			2.94			2.64	
Core$(l)(A=5)$								
$(3/2^-)(0)$	−0.10	0.56	$(3/2^-)(2)$	2.61	0.57	$(3/2^-)(2)$	2.21	0.99
$(3/2^-)(2)$	−0.03	0.55	$(1/2^-)(0)$	2.84	0.65			
$\langle E\rangle$	−0.07			2.74			2.19	
E_{calc}	0.05			2.84			2.42	
E_{expt}	0.00						2.361(5)	

[a] Summed over 3 levels.

the missing strength to make the total S sum to 2.0 for $T=0$ and 3.0 for $T=1$.

The E_i for ^{9}B is computed using the well depth V_0 which binds the neutron or α particle in each ^{9}Be level by its experimental value. The final computed excitation energy is given by

$$\langle E\rangle=\sum_i S_iE_i \Big/ \sum_i S_i \tag{1}$$

for each mass partition. The values for $^8\mathrm{Be}+p$ and $^5\mathrm{Li}+\alpha$ are then averaged to get the final numbers we quote for ^{9}B. Below these values are listed the experimental energies. Our values are only higher than these by 0.05, 0.06, and 0.05(3) MeV for the $3/2^-$ ground state, $5/2^-$, and $5/2^+$ levels.

The $1/2^+$ state presents a special problem. Not only is the state unbound in ^{9}Be (and hence, not a true neutron resonance), but its mirror in ^{9}B is above the Coulomb barrier for $^8\mathrm{Be(gs)}+p$, ($\sim$0.8 MeV). We have investigated various methods of estimating the $^9\mathrm{B}(1/2^+)$ energy that arises from the $^8\mathrm{Be(gs)}+p$ $(l=0)$ component. Three standard definitions of the energy of a resonance are widely used—(1) the energy at which the energy derivative of the phase shift, $d\delta/dE$, peaks; (2) the energy at which the nuclear phase shift δ is $\pi/2$; and (3) the energy corresponding to a peak in the appropriate cross section. For narrow resonances, the three definitions give the same results. But for states with $\Gamma_{sp}\approx E$, the three methods diverge, and there is no universally accepted preference. In the present case, the three methods have already diverged at an energy significantly below where the $1/2^+$ is expected. Various approximations and extrapolations give results as low as 0.82 MeV and as high as 1.4 MeV for the c.m. proton energy of the $^8\mathrm{Be}+p$ s-wave "resonance." These correspond to excitation energies of 0.63 and 1.21 MeV, respectively. The approximation used in Ref. [9] (a fourth definition of a resonance) gave $E_x=0.94$ MeV. In the present paper, we find $E_x=1.02\pm0.20$ MeV, by extrapolating the $\delta=\pi/2$ results. The sp width is equally difficult to evaluate, and the uncertainty in energy adds to the uncertainty in sp width. Our value of 1.8 MeV could be uncertain by as much as 25%.

Table V summarizes predictions of $^9\mathrm{B}(1/2^+)$ excitation energy and width from various calculations. Reference [9] computed the profile function for a dipole transition from ^{9}B(gs). Barker [11] used R-matrix to fit the $^9\mathrm{B}(1/2^+)$ energy and added a calculated Coulomb energy to obtain the $^9\mathrm{B}(1/2^+)$ energy. Descouvemont [17] used a microscopic

TABLE IV. Calculated $1/2^+$ and $5/2^+$ excitation energies of ^{9}B corresponding to ^{8}Be ($T=0$) and ^{5}He, ^{5}Li cores (energies in MeV).

^{9}B($1/2^+$)			^{9}B($5/2^+$)		
Core(l)($A=8$)	E_i	S	Core(l)	E_i	S
0^+(0)	1.07	0.69	0^+(2)	2.95	0.50
2^+(2)	1.86	0.27	2^+(0)	2.68	0.28
			2^+(2)	3.09	0.19
$\langle E\rangle$	1.29			2.90	
Core(l)($A=5$)					
$3/2^-$(1)	1.50	0.72	$3/2^-$(1)	2.71	0.77
$1/2^-$(1)	1.78	0.23	$3/2^-$(3)	2.94	0.12
			$1/2^-$(3)	3.15	0.11
$\langle E\rangle$	1.57			2.79	
E_{calc}	1.43			2.85	
E_{expt}				2.79(3)	

three-cluster model $\alpha+\alpha+$nucleon. Tanaka *et al.* [18] did an analytic continuation of bound-state energies for ^{8}Be, ^{9}Be, and ^{9}B. Efros and Bang [10] used a potential model to obtain a pole in ^{9}B at 0.6 MeV and a peak at $E_p=1.13$ MeV ($E_x=0.94$ MeV). Our calculations suggest $E_x=1.0$ MeV. In Tables IV and VII we have used the average of the values from Table V excluding that of Ref. [11]. The width has been scaled to correspond to the final average excitation energy of 1.43 MeV, assuming $\Gamma\propto\sqrt{E}$ above the barrier.

In addition to the excitation energies we have computed the nucleon and α-particle single particle widths. Table VI lists these for the known ^{9}Be and ^{9}B $3/2^-$ and $5/2^-$ levels, and Table VII for the $1/2^+$, $1/2^-$, and $5/2^+$ levels. E is the excitation energy and $\Gamma_{calc}=\Sigma_i S_i\Gamma^i_{sp}$ where the S_i are listed in Tables III and IV.

In these calculations we had to average over the large widths of the ^{5}He(gs), ^{5}Li(gs), and ^{8}Be(2^+) cores. These widths had negligible effects on the values of E_i, but large effects on particle widths—especially on the proton decay of the ^{9}B($5/2^-$) level at 2.36 MeV, nominally bound with respect to the ^{8}Be(2^+) level. For α decay of a state at E_x in ^{9}B, we must evaluate the decay width by convoluting over the profile of the appropriate ^{5}Li state:

$$\Gamma_\alpha(E_x)=\frac{\int \Pr(E_{\alpha p})\Gamma_\alpha(E_T-E_{\alpha p})dE_{\alpha p}}{\int \Pr(E_{\alpha p})dE_{\alpha p}}, \qquad (2)$$

where for decay to ^{5}Li(gs), we have $E_T=E_x+0.277$ MeV. Similar procedures were used for α decay of ^{9}Be states to ^{5}He, and for decays to ^{8}Be(2^+)+nucleon. We integrated from 0 to 7 MeV.

TABLE V. Predictions of ^{9}B($1/2^+$) excitation energy and width (both in MeV).

E_x	Γ	Ref.
0.94	1.40	[9]
1.84, 1.79[a]	3.33, 3.79[a]	[11]
1.15	1.3	[17]
1.3	2.0	[18]
0.94	1.64	[10]
1.0	1.8	present

[a] Values from Table III of Ref. [11] correspond to a spectroscopic factor, S_1 of 0.6 or 0.248. Converting to $S=1.0$ gives E_x, Γ values listed here. (We took values for $a_c=6$ fm in Ref. [11].)

TABLE VI. Widths (in keV) for ^{9}B(gs) and lowest $5/2^-$ level in ^{9}Be and ^{9}B.

J^π	Nucleus	E (MeV)	Γ^{nuc}_{sp}	Γ^{α}_{sp}	Γ_{calc}	Γ_{expt}
$3/2^-$	^{9}B	0.0	0.93		0.53	0.54(21)
$5/2^-$	^{9}Be	2.43		0.93	0.92	0.77(15)
	^{9}B	2.36	18	55	75	81(5)

For the profile function, $\Pr(E_{\alpha p})$, we have used the distribution of $d\delta/dE$, where δ is the phase shift, calculated with a potential that puts the peak of $d\delta/dE$ at the energies given in Table 5.1 and 5.3 of Ref. [12]. For example, for ^{5}Li(gs) we use $E_p=1.69$ MeV. It turns out that our profile function has a width of 1.20 MeV, to be compared with the value of 1.06 MeV in Ref. [12]. For ^{5}He, the $d\delta/dE$ distribution becomes negative within the integration interval—unphysical behavior for a profile function. Hence, in this case, we matched to a smoothly decreasing (positive) function. This approximation had no effect on the numerator of Eq. (2), but increased the denominator by 6% over the value it would have had if we had intergrated only over the positive portion of $d\delta/dE$. We estimate that the use of different profile functions and/or a different range of integration could change our widths by as much as 20%–30%.

The agreement between our calculated widths and the experimental widths (except for the $5/2^+$ level) is very good.

TABLE VII. Widths (in MeV) for the lowest $1/2^+$, $1/2^-$, and $5/2^+$ levels in ^{9}Be and ^{9}B. For experimental widths in ^{9}B, see Table I. The energies of states in ^{9}B are estimated from our calculated Coulomb energy differences.

J^π	Nucleus	E (MeV)	Γ^{nuc}_{sp}	Γ^{α}_{sp}	Γ_{calc}	Γ_{expt}
$1/2^+$	^{9}Be	1.684(7)				0.217(10)
	^{9}B	1.43(10)	1.89(27)	0.05	1.34(19)	[a]
$1/2^-$	^{9}Be	2.78(12)	1.22(20)	0.01	0.90(15)	1.08(11)
	^{9}B	2.84(12)[b]	3.30(30)	0.14	2.52(22)	[a]
$5/2^+$	^{9}Be	3.05	0.187	0.189	0.239	0.282(11)
	^{9}B	2.79	0.56	0.62	0.76	[a]

[a] See Table I.

[b] E uncertainty from ^{9}Be.

The sizable difference for the $5/2^+$ level might also be due to the assumption of a linear background in Ref. [1], at the time of which the broad underlying $1/2^-$ level was unknown. More impressive spectra of this level were obtained in the ^{10}B(^{3}He$,\alpha p$)^{8}Be experiment of Wilkinson *et al.* [19], who found $\Gamma = 0.71(6)$ MeV. However, they concluded that the decay is "almost completely via ^{8}Be$(0)+p$," in contradiction of our own and Buchmann *et al.*'s [7] finding of 62% α decay.

III. DISCUSSION

A. ^{9}B analog of the ^{9}Be $1/2^+$ level at 1.68 MeV

The computed energy (Table IV) and width (Table VII) are 1.4(1) and 1.3(2) MeV, respectively. The experimental energies and widths are listed in Table I.

The only experimental results which are comparable to ours in both energy and width are those of Burlein *et al.* [4] in their ^{9}Be(^{6}Li$,^6$He) charge exchange reaction. However, Catford *et al.* [20] have repeated the ^{9}Be(^{6}Li$,^6$He) experiment and report nonobservation of the $1/2^+$ state, even though the 20 deg spectrum in their Fig. 5 (the only one with a normalized background drawn in) exhibits significant excess counts above background in the appropriate energy region. We note that neither paper include the broad $1/2^-$ level in their analysis.

In the ^{6}Li(^{6}Li$,t$) reactions [6], three fits were performed—one including $1/2^-$ and $5/2^+$ states and their interference, another including $1/2^+$ and $5/2^+$ and their interference, and a third including $1/2^+$, $1/2^-$, and $5/2^+$, but no interference. The authors state that their results indicate that all three states must be present to adequately describe the data. With all three states present, Ref. [6] obtained 0.73(5) for the $1/2^+$ excitation energy, while the fit that included only $1/2^+$ and $5/2^+$ states (plus interference) gave 1.6(1) MeV. (Barker [23] has criticized the small uncertainty claimed for the latter by Ref. [6].) Unfortunately they do not make use of their analog ^{6}Li(^{6}Li$,^3$He) ^{9}Be spectrum (their Fig. 2) which, they note, should have similar cross sections to the (^{6}Li$,t$) reaction. The ^{9}Be spectrum shows little if any $1/2^-$ yield, lending weight to their two-level energy which agrees with ours. They did not vary the width in their fitting procedure, but rather assumed the ^{9}Be$(1/2^+)$ width was an *R*-matrix neutron decay width, calculated the reduced width, assumed it to be equal in ^{9}B and computed the corresponding proton *R*-matrix width and kept it fixed. The width in the (^{3}He$,t$) experiment is in good agreement, but the energy is slightly low. The ^{9}C(β^+) results are clearly much too low. Perhaps re-analysis using our results for the $1/2^-$, $5/2^-$, and $5/2^+$ states may yield more consistent $1/2^+$ values. Buchmann *et al.* [7] use their ^{9}C(β^+) energy and width (0.83 and 0.38 MeV) of ^{9}B$(1/2^+)$ to compute the stellar rate for ^{4}He$(\alpha n,\gamma)^9$Be. The $(1/2^+)$ is dominant at low stellar temperatures. Our higher energy and larger width could change the rate. Because of the large variation in experimental and theoretical values, the precise nature of the $1/2^+$ level in this $A=9$ pair remains an open question, despite our initial hope that we could resolve it.

B. ^{9}B analog of the ^{9}Be $1/2^-$ level at 2.78(12) MeV

The calculated excitation energy is 2.84(6) MeV. This has an additional uncertainty of 0.11 MeV, reflecting the energy uncertainty in ^{9}Be, which also carries over to the Γ_{sp} widths. The final calculated width is 2.52(22) MeV. The four $1/2^-$ experimental energies in Table I are consistent with our calculated excitation energy. The widths from the (p,n) and (^{6}Li$,t$) experiments are not inconsistent with our computations; the overlap of the neighboring $5/2^+$ level makes the experimental decomposition difficult.

Our calculations can be used to compute the ratio of α decays to p decays: $S_\alpha\Gamma_{sp}^\alpha/S_p\Gamma_{sp}^p$. Buchmann *et al.* [7] report the ratio of α's to protons for ^{9}B to be 0.006, while our computed result is $(0.57\times0.14)/(0.74\times3.30)=0.033$, a somewhat larger value. Our result for the ratio of α to neutron decay for the ^{9}Be$(1/2^-)$ level is 0.005.

C. ^{9}B analog of the ^{9}Be $5/2^+$ level at 3.05 MeV

For the α/p ratio in ^{9}B we have $(0.77\times0.62)/(0.5\times0.56)=1.71$ in good agreement with Buchmann *et al.* [7] who find the ratio to be 1.6(3). We predict a ratio of 1.56 for ^{9}Be.

All of the experimental energies for the $5/2^+$ in Table I agree with each other and are in good agreement with our prediction. Considering the difficulty of determining large widths, the agreement here is also satisfactory.

IV. CONCLUSIONS

Our calculations indicate a near degeneracy of the $1/2^-$ and $5/2^+$ levels of ^{9}B, supported by the experimental results. The $5/2^+$ and $1/2^-$ agreement between our calculation and results of the (p,n) experiment is again remarkable in view of the complete overlap of the experimental spectra. The most complete experiment is that of Buchmann *et al.* [7] as they measured β^+, proton and α intensities. They report a $1/2^-$ level at ~5 MeV, for which there is no clear ^{9}Be parent. The 7.94-MeV level in ^{9}Be, tentatively assigned $1/2^-$, is too high to be its analog.

A recent paper [21] on the ^{9}Be(^{3}He$,t$)^{9}B reaction presented evidence for a 3.8 MeV state in ^{9}B. However they did not include in their decomposition the probable 2.6 MeV broad $1/2^-$ level at 2.90 MeV. There is also no parent in ^{9}Be for such a level.

For the $1/2^+$ level, the experimental result closest to our prediction is the $E_x=1.32$, $\Gamma=0.9(3)$ MeV of Ref. [4]. It would be interesting to see if re-analysis of the data of Ref. [8], taking our widths into account, might establish the important $1/2^+$ level more precisely.

A major discrepancy between our results and those of experiments is in the ratio of α/n decays for the ^{9}Be $5/2^+$ level and α/p for the ^{9}B $5/2^+$ level. We conclude that it is about 1.6 for both, but while Buchmann *et al.* [7] find this for ^{9}B, the searches with particle-coincidence reactions report no evidence for α decay (Rendic *et al.* [22] for ^{9}Be and Wilkinson *et al.* [19] for ^{9}B).

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[1] J. J. Kroepfl and C. P. Browne, Nucl. Phys. A **108**, 289 (1968).
[2] B. Pugh, Ph.D. dissertation, MIT (1985) quoted by Mikolas *et al.*, in Ref. [16].
[3] K. Kadiza, G. Paić, and B. Antolković, Phys. Rev. C **36**, 1269 (1987).
[4] M. Burlein, H. T. Fortune, P. H. Kutt, R. Gilman, R. Sherr, and J. D. Brown, Phys. Rev. C **38**, 2078 (1988).
[5] N. Arena, Seb. Cavallaro, G. Fazio, G. Giordina, A. Italiano, and F. Mezzanares, Europhys. Lett. **5**, 517 (1988).
[6] M. A. Tiede *et al.*, Phys. Rev. C **52**, 1315 (1995).
[7] L. Buchmann, E. Gete, J. C. Chow, J. D. King, and D. F. Measday, Phys. Rev. C **63**, 034303 (2001).
[8] E. Gete *et al.*, Phys. Rev. C **61**, 064310 (2000).
[9] R. Sherr and G. Bertsch, Phys. Rev. C **32**, 1809 (1985).
[10] V. D. Efros and J. M. Bang, Eur. Phys. J. A **4**, 33 (1999).
[11] F. C. Barker, Aust. J. Phys. **40**, 307 (1987).
[12] D. R. Tilley, C. M. Cheves, J. L. Goodwin, G. M. Hale, H. M. Hoffmann, J. H. Kelley, C. G. Sher, and H. R. Weller, Nucl. Phys. A **708**, 3 (2002).
[13] Preliminary versions of *Energy Levels of Light Nuclei* $A=8$ *and* 9, http://www.tunl.duke.edu/nucldata/.
[14] D. J. Millener, private communication.
[15] J. P. Glickman *et al.*, Phys. Rev. C **43**, 1740 (1991).
[16] D. Mikolas *et al.*, Phys. Rev. C **37**, 766 (1988).
[17] P. Descourvemont, Phys. Rev. C **39**, 1557 (1989).
[18] N. Tanaka, Y. Suzuki, K. Varga, and R. G. Lovas, Phys. Rev. C **59**, 1391 (1999).
[19] D. H. Wilkinson, J. T. Sample, and D. E. Alburger, Phys. Rev. **146**, 662 (1966).
[20] W. N. Catford, L. K. Fifield, E. L. Reber, K. W. Kemper, and J. D. Brown, Nucl. Phys. A **550**, 517 (1992).
[21] H. Akimune *et al.*, Phys. Rev. C **64**, 041305(R) (2001).
[22] D. Rendic *et al.*, Nucl. Phys. A **178**, 49 (1971).
[23] F. C. Barker, Phys. Rev. C **53**, 2539 (1996).