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Resonances in ^{16}B

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Using information from nearby nuclei and a simple model, I estimate that the lowest resonance in ^{16}B should have $J^\pi = 2^-$ and the structure ^{17}C$(1/2^+) \times (p_{3/2})^{-1}$, and not 0^-, as previously supposed. If the 2^- is not the ground state, it should be very close in energy.

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I. INTRODUCTION AND HISTORY

Ten states should exist at relatively low excitation energy in ^{16}B. These arise from couplings of a $1p_{3/2}$ proton hole to the $3/2^+$ ground state (g.s.) and $1/2^+$, $5/2^+$ excited states of ^{17}C at 0.22 and 0.33 MeV, respectively. These are indicated in Table I. A longstanding puzzle is why only one or two of them have been observed.

Very little information is available concerning ^{16}B. Kryger *et al.* [1] confirmed earlier suggestions [2,3] that it has no bound states. Using the ^{14}C(^{14}C, ^{12}N)^{16}B reaction, Kalpachieva *et al.* [4] reported two resonances in ^{16}B: a narrow one at threshold [$E = 40(40)$ keV] and one at $E = 2.40$ MeV with a width of 0.15 MeV. The peak near threshold in this reaction is in a region of the spectrum that contains two unidentified peaks in the same reaction with a ^{12}C target. Reference [4] states "Between the two ^{14}B states at 8.03 MeV and 10.15 MeV the lowest-lying ^{16}B peak can be identified [see Fig. 10(b)]." My point is that in just this region in the spectrum with a ^{12}C target, there are two unidentified peaks. I know from personal experience that impurities in a ^{12}C target are not usually a problem, but to what do these counts belong? With the ^{12}C target, these two unidentified peaks (or count-rate fluctuations?) are considerably weaker than the three strong ^{14}B peaks. With the ^{14}C target, the supposed ^{16}B(g.s.) is only slightly weaker than the ^{14}B peaks. A suggestion worth pursuing might be the possibility that the two unidentified peaks with the ^{12}C target and the supposed ^{16}B(g.s.) seen with the ^{14}C target might be due to an impurity that is present in both targets, but to a much lesser extent in the ^{12}C target than in the ^{14}C one. Slightly different locations might be explained by the slight difference in angular range in the two spectra. So, it is possible that this peak does not correspond to a state in ^{16}B. If the g.s. is indeed 0^-, as mentioned below, I think it is extremely unlikely that it would have been selectively populated in this heavy-ion reaction.

This reaction on a ^{12}C target did not populate the 2^- ground state (g.s.) of ^{14}B, but did populate a $4^-/2^-$ doublet near 2.1 MeV in ^{14}B. The authors explained that the weak population of the ^{14}B ground state is understood from a consideration of the reaction mechanism, which favors large angular momentum transfers. The 4^- and second 2^- states have a predominant structure of a neutron in the $1d_{5/2}$ orbital, whereas the 2^- g.s. primarily contains a $2s_{1/2}$ neutron. Based on this argument, Kalpachieva *et al.* suggested 4^- for the state near threshold. They did not rule out the possibility of a 2^- state nearby. They pointed out the obvious discrepancy between the experimental level energies and the theoretical predictions—most of the theoretical levels were not observed.

Lecouey *et al.* [5] used proton removal from a secondary beam of ^{17}C to investigate ^{16}B. They reported a narrow resonant structure at $E = 85 \pm 15$ keV above the ^{15}B + n threshold, with a width of $\Gamma \ll 100$ keV. They interpreted the small width as indicating $\ell = 2$ decay. They suggested a dominant structure of ^{17}C$(3/2^+) \times (1p_{3/2})^{-1}$, with $J^\pi = 0^-$ to 3^- for the structure they observed. They stated that "…the relatively high energies of the bound excited states in ^{15}B suggest that the feature observed here does not arise from the decay of a high-lying level in ^{16}B to a bound excited state in ^{15}B." Shell-model calculations carried out within the s-p-sd-fp model space predicted 0^- for the g.s. of ^{16}B. Given the kinematics of the heavy-ion reaction discussed above, I think it is very unlikely that a 0^- state would have been selectively populated in that reaction [4].

Spyrou *et al.* [6] performed an experiment with a secondary ^{19}C beam to investigate ^{18}B. With the same experimental setup and procedure, they repeated the ^{16}B experiment with a ^{17}C beam and reported a narrow ^{16}B resonance at $E = 60(20)$ keV. The supposed 2.4-MeV resonance has never been confirmed, and no other resonances in ^{16}B have been suggested.

Several shell-model calculations have been performed for ^{16}B. The first was by Poppelier *et al.* [7]. Their four lowest states were 0^- g.s., followed by 2^-, 3^-, and 4^- at 0.95, 1.10, and 1.55 MeV, respectively. Lecouey *et al.* [5], in a full *s*-*p*-*sd*-*fp* space, found a 0^- g.s., followed by 3^-, 2^-, and 4^- states at 0.649, 0.943, and 1.389 MeV, respectively. Dufour and Descouvemont [8] computed levels of ^{16}B in a ^{15}B + n model, in which they coupled a single neutron to various states of ^{15}B. This is not a natural basis, because all the low-lying states of ^{15}B contain at least two neutrons in the sd shell, and coupling an sd-shell neutron to them could run afoul of the Pauli Principle. Nevertheless, they found a slightly bound ($E =$ –0.012 MeV) 1^- g.s., followed by 0^-, 2^-, and 3^- states at 0, 0.24, and 1.03 MeV, respectively. Their 0^- state had the structure ^{15}B$(5/2^-) \times d$, and hence a very small spectroscopic factor for decay to ^{15}B(g.s.). Because the $5/2^-$ state of ^{15}B is primarily ^{16}C$(2^+) \times (1p_{3/2})^{-1}$, and the 0^- of ^{16}B is mostly

TABLE I. Low-lying states in ^{17}C and corresponding $1p_{3/2}$ hole states in ^{16}B.

^{17}C core		$^{16}\mathrm{B} = {}^{17}\mathrm{C} \times \pi(1p_{3/2})^{-1}$
J^π	E_x (MeV)	J^π
$3/2^+$	0.0	0^-–3^-
$1/2^+$	0.22	1^-, 2^-
$5/2^+$	0.33	1^-–4^-

$^{17}\mathrm{C}(3/2^+) \times (1p_{3/2})^{-1}$, except for the problem with the Pauli Principle, the dominant structure of the 0^- state of Ref. [8] is realistic.

Despite the preference in previous calculations for the 0^- resonance to be the g.s. or very low lying, I expect the g.s. of ^{16}B will turn out to be 2^-, or the 2^- will be very close to the g.s. In what follows, I make use of the systematic behavior in nearby nuclei in order to make predictions about ^{16}B.

II. CALCULATIONS AND RESULTS

A well-known phenomenon in light nuclei is the decrease of the $2s_{1/2}$ single-particle energy (spe), relative to that for $1d_{5/2}$, as one moves from ^{17}O toward smaller A nuclei. In a potential model with a finite diffuse well, the effect is attributed to the difference in radial wave functions for $\ell = 0$ and 2. In a shell-model description in which the spe's are independent of A, the behavior results from changes in particle-hole matrix elements as the number of $1p$-shell holes is changing. In any case, the phenomenon is well understood. The aim here is to use this behavior to make predictions for ^{16}B, about which very little is known.

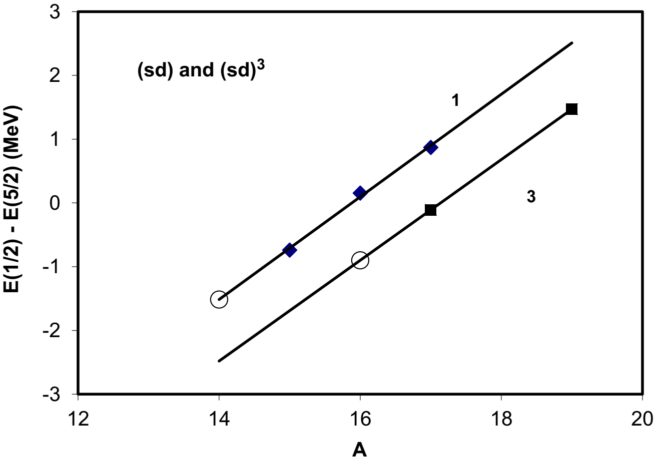

FIG. 1. Excitation energy differences $E(1/2^+)$–$E(5/2^+)$ vs A for sd (upper) and $(sd)^3$ (lower) nuclei, with linear trend lines. Open circles are resulting predictions for ^{14,16}B.

TABLE II. Excitation energies (MeV) of $1/2^+$ and $5/2^+$ states in relevant nuclei.

Nucl.	J^π	E_x
^{19}O	$5/2^+$	0
	$1/2^+$	1.471
^{17}O	$5/2^+$	0
	$1/2^+$	0.871
^{17}C	$1/2^+$	0.220
	$5/2^+$	0.331
^{16}N	2^-	0
	3^-	0.298
	d centroid	0.174
	0^-	0.120
	1^-	0.397
	s centroid	0.328
^{15}C	$1/2^+$	0
	$5/2^+$	0.740
^{14}B	2^-	0
	1^-	0.654(9)
	s centroid	0.245
	3^-	1.38(3)
	2^-	1.86(6)
	4^-	2.04(5)
	1^-	unknown
	d centroid	~1.78

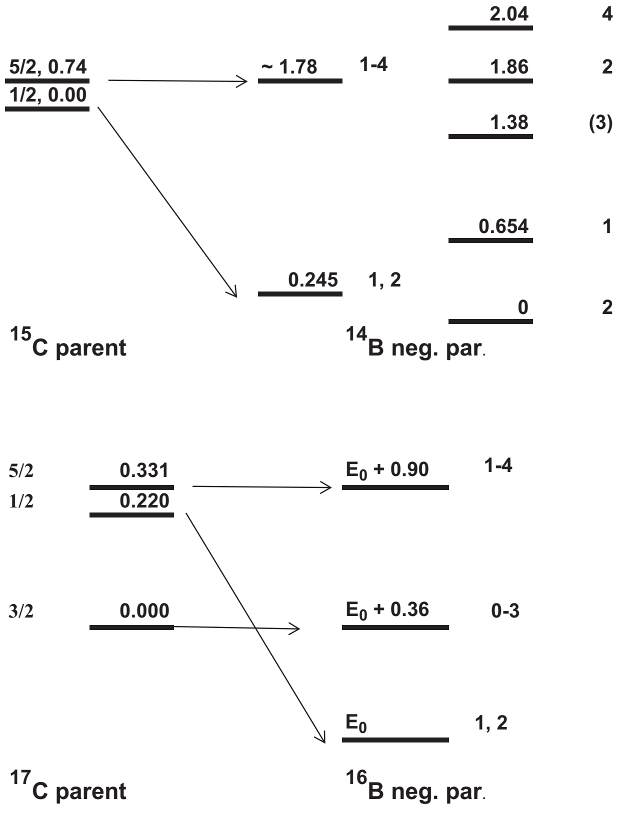

FIG. 2. (Top) Parent states in ^{15}C and $^{15}\mathrm{C} \times p^{-1}$ multiplets in ^{14}B. (Bottom) Parent states in ^{17}C and $^{17}\mathrm{C} \times p^{-1}$ multiplets in ^{16}B.

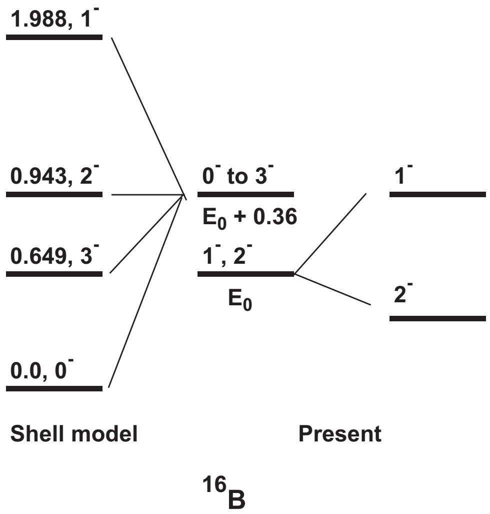

FIG. 3. Combination of shell-model [5] and present predictions.

Energies of relevant $1/2^+$ and $5/2^+$ states in nearby nuclei are listed in Table II. Whenever the core has odd A, the sp, s, and d states will be multiplets, and I have used the $(2J+1)$-weighted excitation energies for them. Resulting energy differences between $2s_{1/2}$ and $1d_{5/2}$ sp states are plotted vs A in Fig. 1. A linear dependence is apparent. I can then use this fit to predict the difference for ^{14}B. The prediction is –1.52 MeV. The centroid of the 2^-, 1^- doublet in ^{14}B is 0.245 MeV. For the d multiplet of levels, the energy of the 1^- state is not known. The centroid of the other three states is 1.78 MeV. Because of its low J, the 1^- energy will not change this number very much. Thus the experimental centroid energy difference in ^{14}B is about –1.5 MeV, to be compared with the linear-fit prediction of –1.52 MeV. The energies of the parent states in ^{15}C and the $^{15}\mathrm{C} \times p^{-1}$ states in ^{14}B are depicted in the top portion of Fig. 2.

I have performed the same analysis for the $1/2^+$ and $5/2^+$ states in $(sd)^3$ nuclei, and those differences are also plotted in Fig. 1. The lines are observed to be virtually parallel, so that the prediction for ^{16}B is –0.90 MeV. Thus, in ^{16}B, the expectation from the present analysis is that the s doublet in ^{16}B will be below the d multiplet by about 0.9 MeV.

The $(sd)^3$ space also contains a $3/2^+$ state, whose structure is a combination of d^3 and $d_2^2\,s$. In ^{19}O, its excitation energy is 0.096 MeV, and it is the g.s. of ^{17}C. Thus, the $1/2^+$ state is 1.376 MeV above $3/2^+$ in ^{19}O. With the $1/2^+$ state 0.22 MeV above $3/2^+$ in ^{17}C, the energy difference goes from 1.376 to 0.22 from $A = 19$ to $A = 17$. A linear behavior from ^{19}O to ^{17}C to ^{16}B thus indicates that the $1/2^+$ doublet centroid in ^{16}B will be about 0.36 MeV below the centroid of the $3/2^+$ multiplet. The energies of the parent states in ^{17}C and the $^{17}\mathrm{C} \times p^{-1}$ states in ^{16}B are depicted in the bottom portion of Fig. 2.

Of course, all three multiplets contain 1^- and 2^- states, so that some configuration mixing might be expected to occur. Nevertheless, some of the lowest resonances in ^{16}B should have the dominant configuration of three sd-shell neutrons coupled to $1/2^+$. The structure of this s doublet is $^{17}\mathrm{C}(1/2^+) \times (p_{3/2})^{-1}$, and these states would not have been likely to have been formed in a reaction starting with ^{17}C in its ground state.

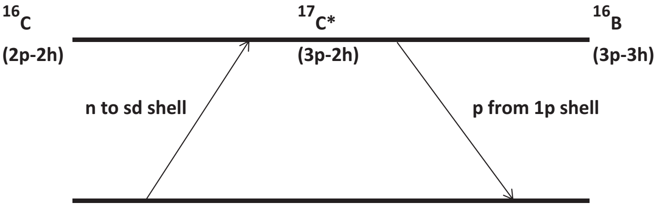

FIG. 4. Possible reaction mechanism for populating states in ^{16}B based on $1/2^+$ and $5/2^+$ states of ^{17}C.

Support for the present suggestion can be found in ^{18}B, where the g.s. has been reported to be 2^- (or 1^-) and to have an s-wave decay to ^{17}B(g.s.) [6]. This state was formed in proton removal from a secondary beam of ^{19}C, whose g.s. is $1/2^+$, with the dominant structure d^4s. The 2^- (1^-) g.s. of ^{18}B would then be $^{19}\mathrm{C}(1/2^+) \times (p_{3/2})^{-1}$. The 2^- g.s. of ^{14}B is primarily of the structure $^{15}\mathrm{C}(1/2^+) \times (p_{3/2})^{-1}$. These comparisons reinforce the expectation that the g.s of ^{16}B will be 2^- and have the dominant structure of $^{17}\mathrm{C}(1/2^+) \times (p_{3/2})^{-1}$.

I now address the question of the absolute energy of this 2^- state. In Fig. 3, I have plotted the energies of the lowest states of each $J^\pi = 0^-$–3^- from the shell-model calculation [5]. The centroid of these four states is 0.95 MeV above the predicted 0^- energy. I have aligned this centroid with my 0^-–3^- centroid. The 1^-, 2^- centroid should be 0.36 MeV below this, as depicted in Fig. 2. If the 1^-, 2^- energy difference in ^{16}B is the same as in ^{14}B (0.654 MeV), then the 2^- state would be 0.245 MeV below this centroid. This analysis puts this 2^- state 0.35 MeV above the shell-model 0^- state. Because each multiplet contains a 2^- state, mixing among them will lower the energy of the lowest one. The simple model contains only one 0^- state, so this effect will not be present there. Thus, if the 2^- state is not the g.s., it should be very close.

One possibility for making this state might be to start with ^{16}C and make use of the reaction pictured in Fig. 4, in which n addition to the sd shell is followed (or preceded) by p removal from the $1p$ shell. As depicted, the first step will primarily populate the $1/2^+$ and $5/2^+$ states of ^{17}C, because the $3/2^+$ state has nearly a vanishing spectroscopic factor to ^{16}C(g.s.). Such a reaction would be expected to populate both the 1^-, 2^- doublet and the 1^- to 4^- multiplet of states. One candidate for a target to be used in such an experiment is ^{13}C.

III. SUMMARY

To conclude, I suggest that the g.s. of ^{16}B should have $J^\pi = 2^-$ and the dominant structure $^{17}\mathrm{C}(1/2^+) \times (1p_{3/2})^{-1}$. If it is not the g.s., it should be very close in energy. Such a state would not have been expected to be populated in proton removal from the $3/2^+$ gs. of ^{17}C, or in the reaction $^{14}\mathrm{C}(^{14}\mathrm{C}, ^{12}\mathrm{N})^{16}\mathrm{B}$.

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