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Energy and width of ^{11}B($1/2^+$, $T = 3/2$)

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I find that data for the reaction ^{10}Be(p,γ) can be reasonably well described with a $1/2^+$ resonance whose width is 640 keV, rather than the accepted 210 keV.

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The energy and width of the lowest $T = 3/2$ state in ^{11}B [1] is a matter of some debate [2,3]. This state should be the analog of the $1/2^+$ ground state (g.s.) of ^{11}Be, and should have the isospin structure (1/3) $^{10}\mathrm{Be} \times p + (2/3)^{10}\mathrm{B}(0+, T = 1) \times n$. The proton width of the analog in ^{11}B can be computed from $\Gamma_p = \mathrm{C}^2\mathrm{S}\Gamma_{\mathrm{sp}}$, where $\mathrm{C}^2 = 1/3$, S should be the same as in ^{11}Be; and Γ_{sp}, as computed in a potential model, is about 2.4 MeV [2] for a state at the supposed position of ^{11}B($1/2^+$, $T = 3/2$). If the (d,p) spectroscopic factor of ^{11}Be(g.s.) is anywhere near the value 0.7–0.8 commonly found [4], this state should, therefore, have a width of about 600 keV, whereas the value in the compilation [1] is barely 1/3 of that. Listed in Table I are the compiled values of energy and width of the supposed analogs of the first two states of ^{11}Be, together with results from two experiments [5,6]. At least two other experiments [7,8] provide similar data for the $1/2^-$ state, but not for the $1/2^+$. The $1/2^-$, $T = 3/2$ assignment [7] is from the reaction ^{13}C(p,^{3}He) in comparison with ^{13}C(p,t). The $1/2^+$ state was not observed in that reaction, and should not have been, because it contains a $2s1/2$ nucleon that is absent in the ^{13}C target.

Primary evidence for the J^π, T assignment for the lower level comes from the reaction ^{10}Be(p,γ), which yielded the assignment [6] $J^\pi = 1/2^+(3/2^+)$, $T = 3/2$, with the energy and width as given in Table I. The authors of Ref. [6] also observed a higher resonance that they took to be the $1/2^-$, and a structure near $E_x = 12.17$ MeV that they were unable to distinguish as an actual state or a $^{10}\mathrm{B}^* + n$ threshold-opening feature. I set out to determine whether those data could accommodate a $1/2^+$ state of much larger width.

In the calculations, the $1/2^-$ width was held fixed at the compiled value of 200 keV, and the position was allowed to vary only slightly from the compiled energy. For the $1/2^+$ state, the energy was allowed to vary slightly, but whatever the energy, the energy-dependent width was constrained at the values $\Gamma_p(\mathrm{E}) = \mathrm{C}^2\mathrm{S}\Gamma_{\mathrm{sp}}(\mathrm{E})$, where $\mathrm{S} = 0.75$, and $\Gamma_{\mathrm{sp}}(\mathrm{E})$ came from a potential-model calculation. For each state, the resonance cross section was computed as

$$\sigma(E) = \frac{N}{k^2}\left(\frac{E + 11.228\ \mathrm{MeV}}{E_0 + 11.228\ \mathrm{MeV}}\right)^3 \left(\frac{\Gamma_p}{(E - E_0)^2 + \Gamma_p^2/4}\right), \quad (1)$$

where hk is the momentum of the proton, and all quantities are in the center-of-mass system. As stated above, $\Gamma_p(1/2^-)$ was held fixed at 200 keV, but $\Gamma_p(1/2^+)$ had the energy dependence given by the potential model. The results are in arbitrary units, but the normalization contains (among other factors) the gamma width. The cubic factor in the numerator is from the energy dependence of the gamma width for a dipole transition. Thus, four parameters are allowed to vary—two resonance energies (but over a very narrow range) and their two normalizations. Again the widths contained no free parameters. I added a small nonresonant cross section that varied slowly with energy, decreasing linearly from 1.4 μb/sr at $E_{\mathrm{c.m.}} = 0.6$ MeV to zero at 2.0 MeV. The final results are relatively insensitive to this nonresonant term and to the presence or absence of the cubic factor in the numerator.

The 90° data points were read by hand from an enlarged copy of Fig. 5 of Ref. [6]. Those data display error bars for three energies, at or near relative maxima in the cross section. At lab energies of 1.05, 1.45, and 1.85 MeV, the percentage cross-section uncertainties are approximately 2.9%, 2.9%, and 3.1%, respectively. It is likely that the percentage uncertainties are somewhat larger at energies for which the cross section is smaller. There is an additional (small) uncertainty in reading of the data points. Thus, in the plot of the data in Fig. 1, the uncertainties are a constant percentage of ±4%. The true uncertainty may be slightly larger.

I did not attempt a best fit, but simply tried to ascertain whether the data would allow a broad $1/2^+$ state. Results of one of the calculations are displayed in Fig. 1, along with the data. The data are displayed with the absolute scale of Ref. [6], even though it was later changed [9]. The scale is of no consequence here because the computed yield is in arbitrary units, and the total width is essentially the proton width, which is the present concern. Knowledge of the absolute scale is needed if values of gamma width are to be extracted. Comparison is made only with the 90° data, because the authors of Ref. [6] state that at that angle there is no interference, and no interference is included.

The curves were calculated in the c.m. system and converted to the lab system for plotting, using $E_{\mathrm{lab}} = 1.1\ E_{\mathrm{c.m.}}$. This conversion assumes the lab energies in Ref. [6] have already been corrected for energy loss in the target. If not, that correction should be made to the energies quoted below. Except for the structure near $E_{\mathrm{lab}} = 1$ MeV, the calculated curve is in better agreement with the data than would have been expected. The curves displayed have the $1/2^-$ resonance at a c.m. energy of 1.70 MeV, and the $1/2^+$ at 1.38 MeV. I repeat, these are not best-fit values, but rather arose from visual inspection. These energies are the values of E_0 that were used in Eq. (1) to compute the curves in Fig. 1. The individual computed cross sections peak at 1.30 and 1.69 MeV. The $1/2^-$

TABLE I. Excitation energies (MeV) and widths (keV) of two lowest $T = 3/2$ states in ^{11}B.

Source	$1/2^+$		$1/2^-$	
	E_x	Γ	E_x	Γ
Compilation[a]	12.557(16)[d]	210(20)	12.916(12)	200(25)
^{9}Be(^{3}He,p)[b]	12.563(20)[e]	202(25)	12.920(20)[g]	155(25)
^{10}Be(p,γ)[c]	12.55(3)[f]	230(65)	12.91(2)[h,i]	235(27)
Present	12.61(5)	640(33)	12.93(5)	200(fixed)

[a]Reference [1].
[b]Reference [5].
[c]Reference [6].
[d]$J^\pi = 1/2^+(3/2+)$.
[e]$L = 1$.
[f]$J^\pi = 1/2^+(3/2+)$.
[g]$L = 2$.
[h]In Ref. [6], the $1/2^-$ assignment was taken from ^{13}C(p,^{3}He), [7] who gave $E_x = 12.94(5)$ MeV, $\Gamma = 350(50)$ keV.
[i]Also seen in ^{14}C(p,α) (Ref. [8]) with $E_x = 12.92(2)$ MeV, $\Gamma = 238(15)$ keV.

width was held fixed at 200 keV, and an energy-dependent width was used for the $1/2^+$ state. At $E = 1.38$ MeV, this width is $\Gamma(E_0) = 640$ keV. The full width at half maximum of the calculated curve is 580 keV. Thus, the data do support the interpretation of a wide $1/2^+$ resonance. An uncertainty of 50 keV in the $1/2^+$ resonance position would correspond to an uncertainty in the width of 33 keV. Any uncertainty in the ^{11}Be spectroscopic factor would add to this value. Numerical results are listed in Table I. In Ref. [2], the $1/2^+$ excitation energy was predicted at 12.444 MeV, but the definition of resonance energy there was the peak of the derivative of the phase shift

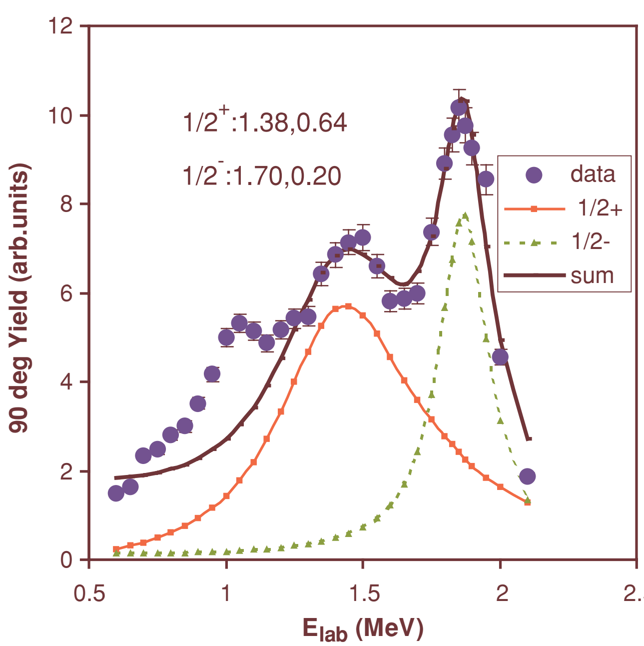

FIG. 1. (Color online) Cross section for ^{10}Be(p,γ_0) at 90° from Ref. [6]. Curves are individual $1/2^+$ and $1/2^-$ resonances, and their sum plus a small nonresonant term (see text).

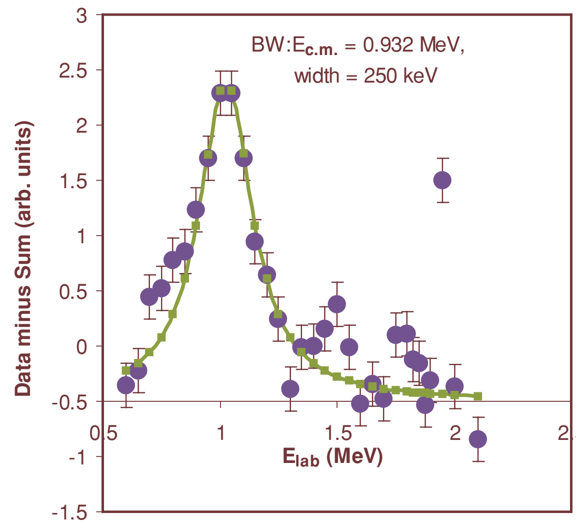

FIG. 2. (Color online) The data of Ref. [6] minus the "sum" curve of Fig. 1. The curve here is –0.5 arb. unit plus a Breit-Wigner shape with the energy and width shown.

dδ/dE. In the present case, with the peak E_0 in the Breit-Wigner expression corresponding to $E_x = 12.61(5)$ MeV, the phase shift derivative peaks at 12.48(5) MeV, reasonably close to the prediction of Ref. [2]. A best fit to the (p,γ) data would perhaps refine this energy further.

A brief mention of the structure below these two resonances seems in order. In Fig. 2 is plotted the difference between the data and the calculated "sum" curve of Fig. 1. For this plot, the uncertainty is a fixed 0.2 μb/sr This value is about 1.4 times the diameter of the points in Fig. 5 of Ref. [6]. The curve in Fig. 2 is -0.5 μb/sr plus a Breit-Wigner shape with c.m. energy 0.932 MeV and width 250 keV. (The negative constant would have been un-necessary if the calculated curve in Fig. 1 had not had a small smoothly-varying non-resonant component.) Reference [6] had $E = 0.94(4)$ MeV and $\Gamma = 230(90)$ keV for this structure Whether this structure corresponds to an actual state remains to be determined. I would have thought that a "threshold cusp" would not have resembled a Breit-Wigner shape.

The comparison between experimental data and calculated curves displayed above (Figs. 1, 2) do not require the presence of a narrow resonance near 12.5 MeV, even though such a state has been observed in other reactions: In ^{9}Be(^{3}He,p) (Table I) it was at 12.563(10) MeV, with a width of 202(25) keV; in ^{11}B(^{3}He,^{3}He) inelastic scattering [10] it was at 12.51(5) MeV, with $\Gamma = 260(50)$ keV; and in ^{7}Li$(\alpha,\alpha'\gamma)$ [11] a resonance was observed at 12.55(3) MeV, with a width of 150(50) keV. It is very likely that this is the same state in all three reactions. Of course, there is no requirement that this state should be seen in ^{10}Be(p,γ). The ^{7}Li$(\alpha,\alpha'\gamma)$ reaction very strongly favors $T = 1/2$ states, while the other two reactions will populate both $T = 1/2$ and $T = 3/2$. If the present identification of the $1/2^+$ state is correct, the narrow 12.5-MeV state must have $T = 1/2$. It is easy to propose a $T = 1/2$ state that could be strong in the three reactions above, but weak (or absent) in ^{10}Be(p,γ). Some possibilities are states with $J^\pi = 3/2^+, 5/2^+, 5/2^-$, or $7/2^-$, that could

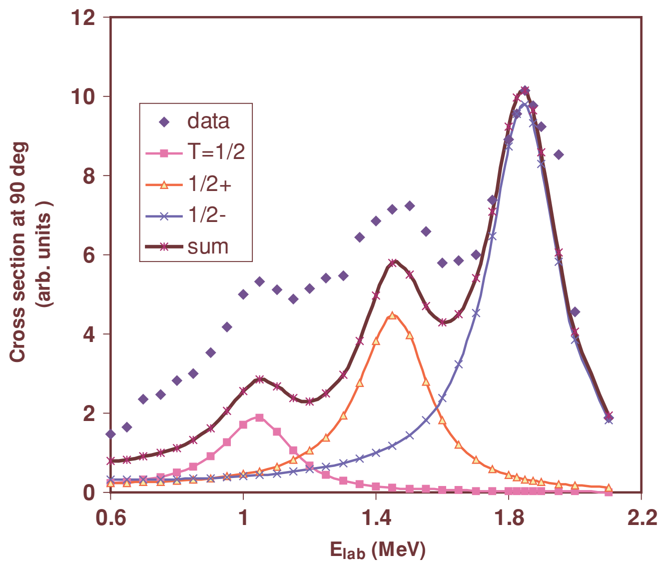

FIG. 3. (Color online) The 90° data of Ref. [6] and three resonance curves computed with the resonance parameters from Ref. [6]. The heavy dark curve is the sum of the three resonance curves. The absolute normalization is the same as in Ref. [6], with 1 arb. unit = 1 μb/sr.

be reached via $L=1$ or 2 in the other reactions, but would require $\ell_p = 2$ or 3 in (p,γ). And, at the low proton energies involved, an $\ell_p = 2$ or 3 resonance would be very weak. It certainly could not have a proton width anywhere near 200 keV, so Γ_p/Γ would be small.

Figure 3 displays again the data of Ref. [6], now compared with three curves (and their sum) calculated with the resonance parameters of Ref. [6]. Here, as elsewhere, 1 arb. unit = 1μb/sr of Ref. [6], even though that scale was modified later [9]. Note that their three resonances do not account for all the cross section. Figure 4 is a plot of the experimental data minus the summed curves resulting from the three resonances of Ref. [6].

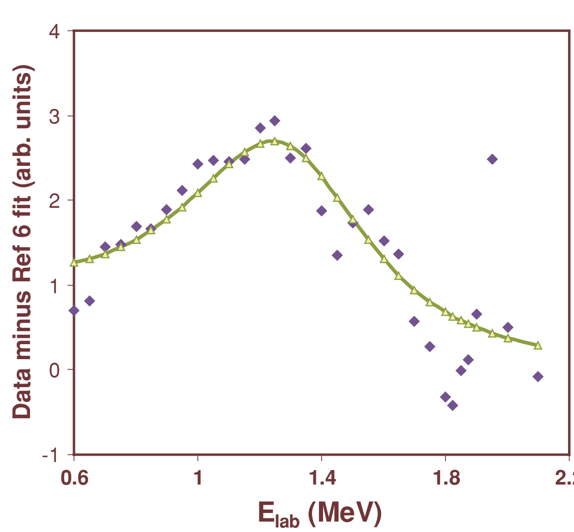

FIG. 4. (Color online) Difference between data and sum curve of Fig. 3. The curve here is a Breit-Wigner shape centered at 1.3 MeV (lab) with width 800 keV (lab).

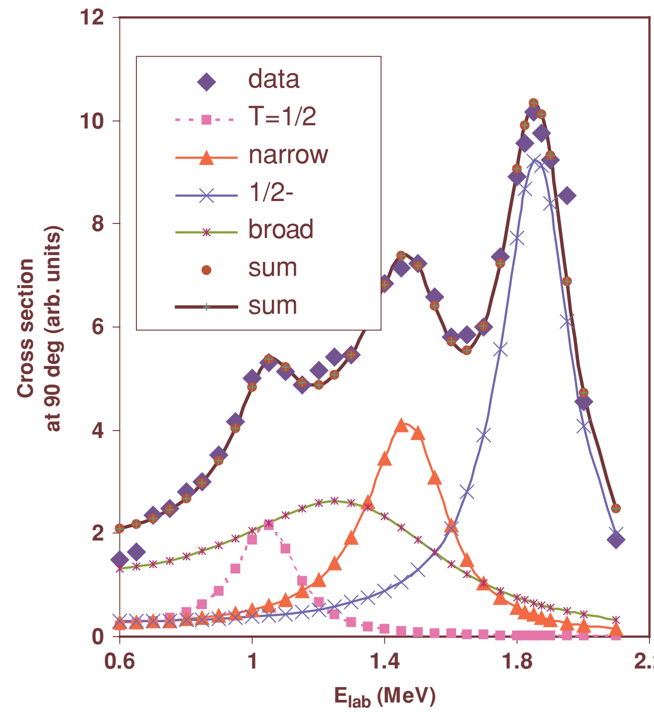

FIG. 5. (Color online) The data of Ref. [6] fitted with four resonances—three narrow, one broad. The solid dark curve is the sum of the four resonance curves.

The curve in Fig. 4 is a Breit-Wigner shape centered at 1.3 MeV (lab), with a width of 800 keV (lab). If three narrow states are indeed present in (p,γ) this broad state remains the best candidate to be the $1/2^+$ state, though it is shifted slightly from the position of the broad peak in Fig. 1. In obtaining an overall fit to the data with four resonances (three narrow, one broad), I discovered that only two narrow resonances were required by the data. A total of three resonances provide an adequate fit if one is broad (Figs. 1 and 2). However, a fit can certainly be obtained with four resonances, as displayed in Fig. 5. With four resonances (when only three are required), the parameters are less well determined. The shape of the broad curve is different in Figs. 1 and 5 because in Fig. 1, the width varies with energy in the manner given by a potential-model calculation, whereas in Fig. 5 the widths of all the resonances have constant values. The parameters of the $1/2^+$ state in Fig. 5 are (in c.m. system) $E = 1.2(1)$ MeV and $\Gamma = 700(100)$ keV, to be compared with 1.38(5) MeV and 640(33) keV, respectively, in Fig. 1. The parameters of the other three resonances have been only very slightly modified from those of Ref. [6]—as can be verified by comparing the three narrow resonances in Figs. 3 and 5. We thus have two possibilities: 1) three resonances—two narrow, one broad, or 2) four resonances—three narrow, one broad. In both cases the $1/2^+$ state is the only one that could be broad. The data cannot be adequately fitted without the presence of this broad resonance. If only two narrow resonances are present, the narrow state observed near 12.5 MeV in three other reactions is absent (or weak) in (p,γ). Whether present in (p,γ) or not, it would necessarily have $T=1/2$. As the strength of the narrow 12.5-MeV resonance is decreased, the energy of the broad resonance moves up.

But, it is confined to a relatively narrow range. If we treat the strength of the narrow 12.5-MeV state as a variable whose value cannot be determined from the (p, γ) data, we can generously assign the parameters of the $1/2^+$ resonance as $E_{\mathrm{c.m.}} = 1.30(12)$ MeV, $\Gamma = 800(150)$ keV if Γ fixed, $\Gamma = 580(100)$ keV at the resonance energy if Γ varies with energy.

The conclusion is that the $^{10}\mathrm{Be}(p, \gamma)$ data of Ref. [6] can be reasonably well described with a $1/2^-$ resonance of width 200 keV plus a $1/2^+$ resonance of width 640 keV, rather than the accepted value of 210 keV. An extra structure near $E_x = 12.17$ MeV has an energy dependence that is consistent with a Breit-Wigner shape.

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