# Possible $3^+$ state in $^{12}$Be from the $^{11}$Be($d, p$) reaction

H. T. Fortune

*Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*

(Received 25 May 2021; accepted 6 July 2021; published 16 July 2021)

A simple calculation indicates that the observed energy and width of a state at 6.02(15) MeV in $^{12}$Be, populated in the $^{11}$Be($d, p$) reaction, are consistent with expectation for the first $3^+$ state with dominant configuration $^{10}$Be(ground state) $\times(2s_{1/2})(1d_{5/2})$.

DOI: 10.1103/PhysRevC.104.014314

## I. INTRODUCTION

An extension of the investigation of the $^{11}$Be($d, p$) $^{12}$Be reaction [1,2] discovered a $0^-$ state at an excitation energy of $3.21^{+0.12}_{-0.04}$ MeV and a $2^-$ state (or a $2^-/1^-$ doublet) at 4.44(15) MeV [3]. The spectrum also contained a third peak that was strong and reasonably narrow at 6.02(15) MeV. The choice of possible states near this energy that would be expected to be narrow and strong in this reaction is severely limited. Here, I examine the likely nature of this state.

## II. CALCULATIONS AND RESULTS

The most likely candidate for this third peak is the first $3^+$ state in $^{12}$Be whose dominant structure is $^{10}$Be[ground state (g.s.)] $\times\ (2s_{1/2})(1d_{5/2})$. I can use a simple model to estimate its expected energy. In $^{18}$O, the energy of the first $3^+$ state is well described by the expression $E_{2n}(3^+) = E_d + E_s + V_{ds}(3^+)$, where $E_d$ and $E_s$ are the neutron energies of the $5/2^+$ and $1/2^+$ first excited states, respectively, in $^{17}$O, and the value of the two-body matrix element is $V_{ds}(3^+) = 0.607$ MeV [4].

A model that has been quite successful in reproducing energies and other properties of $(sd)^2$ states in many light nuclei is one in which local single-particle energies are used, but the two-body matrix elements are taken to be the same in different nuclei (and taken from $^{18}$O) [5–7]. Applied to $^{12}$Be, this model would predict $E_{2n}[^{12}\text{Be}(3^+)] = E_d + E_s + V_{ds}(3^+)$ where now $E_d$ and $E_s$ are the $5/2^+$ and $1/2^+$ energies in $^{11}$Be, and $V_{ds}$ $(3^+)$ is still 0.607 MeV. This expression provides $E_{2n} = 1.380$ MeV. Details of the calculation are given in Table I. With the $2n$ threshold at 3.673 MeV in $^{12}$Be [8], the resulting excitation energy is 5.053 MeV. But this is not the excitation energy relative to the physical $^{12}$Be(g.s.). Rather, it is the excitation energy relative to the energy of the first $(sd)^2$ $0^+$ state. A g.s. wave function in common use has g.s. $= a(sd)^2 + b(p$ shell) with $a^2 = 0.68$, $b^2 = 0.32$ [9]. The excited $0^+$ state at 2.24 MeV [10] has the orthogonal configuration. With these wave functions, the $(sd)^2$ $0^+$ state is at 0.717 MeV in $^{12}$Be so that $E_x(3^+) = 5.77$ MeV is the expected $3^+$ excitation energy relative to the physical $^{12}$Be g.s. This is quite close to the observed energy of 6.02(15) MeV. Other $0^+$ wave functions [1,2,11] have more $(sd)^2$ in the first excited $0^+$ state. Using them would increase the predicted $3^+$ energy slightly.

This $3^+$ state would have two main modes of decay: emission of a $d_{5/2}$ neutron to the $1/2^+$ g.s. of $^{11}$Be and emission of a $s_{1/2}$ neutron to the $5/2^+$ state. Because the $5/2^+$ state is unbound, the latter would appear as a $2n$ decay, the former as $1n$ decay, of course. Because of its unnatural parity, simultaneous $2n$ decay to $^{10}$Be(g.s.) is forbidden. A reasonable spectroscopic factor for this $3^+$ state is in the range of $S = 0.5$–$0.7$. I can use the decay energies and a potential model to estimate the $sp$ widths for the two decays. The $sp$ width for decay to the g.s. is about 1.1 MeV. Widths for $s$-wave neutron decays are notoriously difficult to calculate, but they vary as $E_n^{1/2}$. In the absence of a barrier, the $sp$ width can be approximated as

$$\Gamma_{sp} \approx \hbar/(\text{fly-by time}) = \hbar v/D = \hbar(2E_n/m_n)^{1/2}/D$$
$$= 2[(\hbar^2/2m_n)]^{1/2}E_n^{1/2}/D.$$

Here, $v$ is the magnitude of the velocity, and $D$ is a measure of the nuclear diameter. In the MeV-amu-fm system of units, $\hbar^2/2m_n$ is 20.7, and I use $D \approx 4A^{1/3}$ [$D$ is approximately twice $(R_0 + 2a)$, where $a$ is the diffusivity], resulting in $\Gamma_{\text{sp}} \approx 1E_n^{1/2}$ with both $\Gamma_{sp}$ and $E_n$ in MeV.

Thus, the $s$-wave $sp$ width of the $5/2^+$ state is about 1.03 MeV—very close to the g.s. $sp$ decay width. Thus, one prediction of the present estimate is that the $1n$ and $2n$ decays of the $3^+$ state should be about equal. With $S = 0.5$–$0.7$, the expected total width is about 1.1–1.5 MeV, consistent with the observed width of 1.3(3) MeV. The width of the 6.02-MeV peak is clearly larger than that of the other two peaks. The experimental resolution width is about 1.0–1.2 MeV [3].

Another pair of states that should be strong in the $(d, p)$ reaction is the $1^+$, $2^+$ states with configuration $(2s_{1/2})(1d_{3/2})$, but the $2^+$ state of that configuration should be above 8.5 MeV with $1^+$ even higher.

 

TABLE I. Energies (MeV) relevant to the first $3^+$ state in $^{12}$Be.

| Quantity | Value |
|---|---|
| $E_s$ | −0.503 |
| $E_d$ | 1.276 |
| $V_{ds}$ ($3^+$) | 0.607 |
| $E_{2n}$ ($3^+$) | 1.380 |
| $E_x$ ($3^+$) | 5.053[a] |
| $E_x$ ($3^+$) | 5.77[b] |

[a]Calculated energy relative to the first $(sd)^2$ $0^+$.
[b]Calculated energy relative to the physical $^{12}$Be(g.s.).

## III. SUMMARY

Using a simple model, I have calculated the expected energy and width for the first $3^+$ state of $^{12}$Be with dominant configuration $^{10}$Be(g.s.) $\times$ $(2s_{1/2})(1d_{5/2})$. Both energy and width are consistent with observation for a peak at 6.02(15) MeV in the $^{11}$Be$(d, p)$ reaction.


## ACKNOWLEDGMENT

I am grateful to J. L. Lou and J. Chen for informative correspondence.



[1] J. Chen *et al.*, Phys. Rev. C **98**, 014616 (2018).
[2] J. Chen *et al.*, Phys. Lett. B **781**, 412 (2018).
[3] J. Chen *et al.*, Phys. Rev. C **103**, L031302 (2021).
[4] R. D. Lawson, F. J. D. Serduke, and H. T. Fortune, Phys. Rev. C **14**, 1245 (1976).
[5] H. T. Fortune, M. E. Cobern, S. Mordechai, G. E. Moore, S. Lafrance, and R. Middleton, Phys. Rev. Lett. **40**, 1236 (1978).
[6] H. T. Fortune, Phys. Rev. C **89**, 067302 (2014).
[7] H. T. Fortune, Phys. Rev. C **91**, 044321 (2015).
[8] F. Ajzenberg-Selove, Nucl. Phys. **A506**, 1 (2004).
[9] R. Sherr and H. T. Fortune, Phys. Rev. C **60**, 064323 (1999).
[10] S. Shimoura *et al.*, Phys. Lett. B **560**, 31 (2003).
[11] Le Xuan Chung *et al.*, Phys. Lett. B **774**, 559 (2018).