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Continuum three-body decays of ^{9}Be($5/2^-$)

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We describe and discuss various three-body decay mechanisms for ^{9}Be($5/2^-$). We find that its decay to $n+$ ^{8}Be(2^+) is a small fraction of the total decay.

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I. INTRODUCTION

We are interested here in the decay of the $5/2^-$ state at 2.43 MeV in ^{9}Be [1] to a final state containing a neutron and two α particles. One branch of that decay can be easily isolated because of the relatively long lifetime of the ground state (gs) of ^{8}Be. First, ^{9}Be emits a neutron to ^{8}Be(gs) which then splits into two α's. This process is sufficiently different kinematically that it can be separated from the other decay processes experimentally. However, this branch is only 6–7% [1–3] of the total decays. The question is how do we calculate the decay width (lifetime) for these other decays? Properties of the relevant states are summarized in Table I.

These other decays have been given a variety of labels, including continuum three-body, simultaneous three-body, direct three-body, democratic, quasisequential, virtual sequential, sequential two-body, and perhaps others. Some of these labels are only semantics, but others imply a fundamental difference in the physics. We emphasize at the outset that, however the decay process is calculated, if the decays are indistinguishable and more than one amplitude is involved, the total decay is obtained by summing the amplitudes coherently. It would be incorrect to add the widths for the separate decays. However, if it should turn out that one of the widths is much larger than the others, then that width will dominate—no matter how the arithmetic is done.

Here, we consider three different processes in which

(i) an α particle is emitted first, leaving the gs of ^{5}He [4], which then decays into $\alpha + n$;
(ii) the neutron is emitted first, leaving ^{8}Be in its 2^+ excited state, which then decays into two α's; and
(iii) the neutron and an α particle are emitted at exactly the same instant.

For brevity we refer to these as M_1, M_2, and M_3, respectively. The afore-mentioned decay through ^{8}Be(gs) we call M_0. The process M_3 is the limit of the other two as the ^{8}Be(2^+) and ^{5}He widths become infinite (lifetimes go to zero). Whether it can also exist as a separate process is still an open question.

Several groups [5–7] have correctly stated that the energy and angular correlations for processes M_1–M_3 are identical. It is not possible to separate them experimentally. But, it is possible to think of them differently. Our aim here is to compute the widths for the decays. It should be obvious that a description of the decay process that does not provide a width (or lifetime) is of little use.

As a computational exercise, we can separately calculate the width for M_1 and M_2—in each case ignoring the presence of the other one. This procedure is used all the time when dealing with unbound states with multiple decay channels. One branch is selected and its decay width is calculated assuming it is not affected by the presence of the other branches. Then another branch is selected, the process is repeated, etc. If the branches are independent, the widths are added to get the total width. If quantum mechanics demands it, the decay amplitudes are added, rather than the widths.

In the present case, the ^{9}Be($5/2^-$) state is bound [1] with respect to the central energy of the ^{8}Be(2^+) and ^{5}He states. So, the decay can proceed only through the low-energy tail of the profiles of these intermediate states. The calculations then become an exercise in carefully computing barrier penetration.

The time evolution of the three processes is illustrated schematically in Fig. 1. We let t_1 be the time at which the first particle is emitted and t_2 be the time at which the second particle is emitted. The events are then distributed along the t_1-t_2 axis. For M_1 and M_2, the time structure is determined by the lifetimes of the intermediate states. For M_3, everything happens at exactly $t_1 - t_2 = 0$. Common sense might indicate that this third process is unlikely. The times are so short that this thought experiment can never be actually performed, but we can still think about it. In the present situation, the ^{8}Be(2^+) and ^{5}He lifetimes are so short that the first-emitted particle is still within the range of the nuclear force when the second decay takes place. So, rescattering will be significant and could change the time profile. But, we see no reason to expect a "clumping" at $t_1 - t_2 = 0$.

One recent paper [8] considered the competition between two-body and three-body decays for this state. They varied their two-body interactions to fit the low-energy α-α and n-α scattering data and adjusted a three-body interaction to reproduce the energy and width of the $5/2^-$ state. They found that a small fraction of the decays proceed via ^{8}Be(0^+), but "no decays proceed via ^{8}Be(2^+) or ^{5}He structures".

Grigorenko and Zhukov [9] quote an old compilation [10] as stating that three-body decays are ~0.93–0.95 and two-body decays are 0.07–0.05. But, it is clear from the context that by "three-body" the compiler meant all non-gs decays. Reference [9] also states that "separation of these decay

TABLE I. Properties of relevant states.

Nucleus	J^π	E_x (MeV)	E_{unb} (MeV)	Γ
^{9}Be	$5/2^-$	2.43	0.764[a]	0.78(13) keV
^{8}Be	0^+	0.00	0.092	5.57(25) eV
	2^+	3.03	3.12	1.51 MeV
^{5}He	$3/2^-$	0.00	0.985	0.963 MeV

[a]Relative to ^{8}Be(g.s.) + n.

branches is reliably experimentally observed." For the latter, they cite Ref. [11]. However, that paper states that "we have found that the beta-delayed spectra can be fitted with sequential decays, only, when the decays through ^{5}He are included."

II. CALCULATION

Again, we emphasize that we have computed the width for M_1 by turning off M_2, and vice versa. This is easily done in the calculation just by temporarily setting the relevant spectroscopic factor to zero. The experimental width [1] of ^{9}Be($5/2^-$) is 0.78(13) keV. Using 7% for the branching ratio [1–3] through ^{8}Be(gs), that width (M_0) would be 0.055 keV (see Table II). In Ref. [12], the width for M_1 was calculated to be 0.92 keV (also in Table II), very close to the experimental value. Our estimate for the n decay width (M_2) was so small we did not list it. Then, along came an experimental paper [5] that claimed M_2 dominated—thereby encouraging us to revisit the calculation of its width. (We now know [8] that the experimental conclusion was in error because it relied on a method of separating M_1 and M_2 that does not exist.)

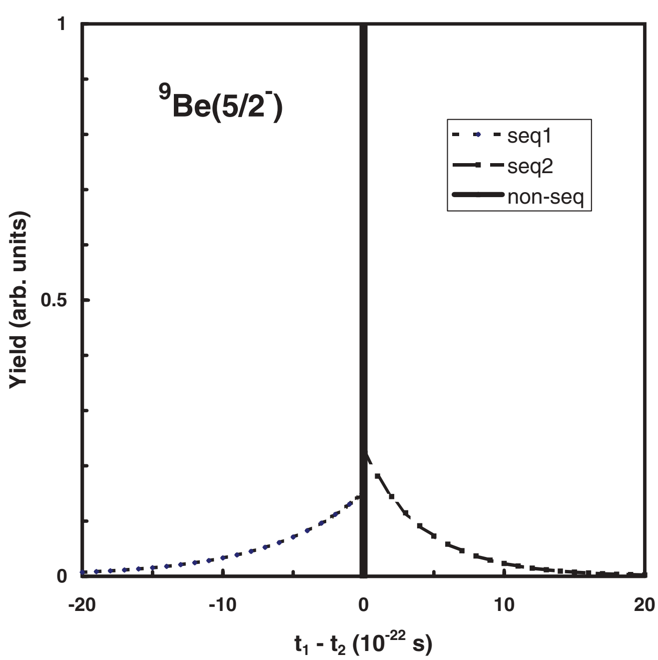

FIG. 1. (Color online) Schematic representation of the time structure (see text) of the three-body decays: M_1 (short dashes), M_2 (long dashes), and M_3 (solid). The first two are governed by the lifetimes of ^{5}He and ^{8}Be(2^+), while for the latter all the events are at $t_1 - t_2 = 0$.

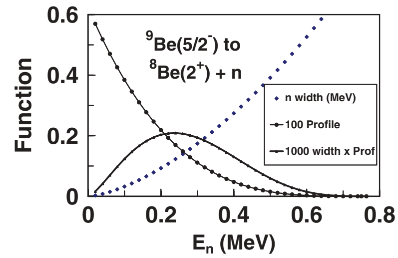

FIG. 2. (Color online) Plot, vs neutron energy, of neutron width, profile function, and their product, appropriate for the decay ^{9}Be($5/2^-$) to ^{8}Be(2^+) + n. The numbers 100 and 1000 are multiplicative factors.

We have computed the width for n decay to ^{8}Be(2^+). We calculated the $\ell = 1$ n single-particle (sp) width as a function of energy from 0.01 to 0.856 MeV using a potential model. The potential was of Woods-Saxon shape with geometrical parameters $r_0, a = 1.25$, and 0.65 fm. These energy-dependent widths must be convoluted with a profile function representing the energy dependence of the ^{8}Be(2^+) state. For this profile we used a resonance shape with an energy-dependent α-α width, computed with a Woods-Saxon plus Coulomb potential for $L = 2$, with one radial node. Parameters here were $r_0 = 1.40$ and $a = 0.60$ fm, where $R = r_0(4)^{1/3}$. At high energies (above the barrier), we used the asymptotic form of the width, $\Gamma \sim E^{1/2}$, matched smoothly to the low-energy dependence.

The low-energy tail of this profile is plotted in Fig. 2. Also plotted in Fig. 2 are the energy-dependent n widths and the product of the width and the profile function. Our product curve is similar to the $\ell = 1$ curve in Fig. 6 of Ref. [5] (but see Fig. 3 and discussion below). The convolution proceeded as described in Ref. [12]. The result is $\Gamma_{\text{nsp}} = 0.046$ keV for decay to ^{8}Be(2^+). Combining with the spectroscopic factor of

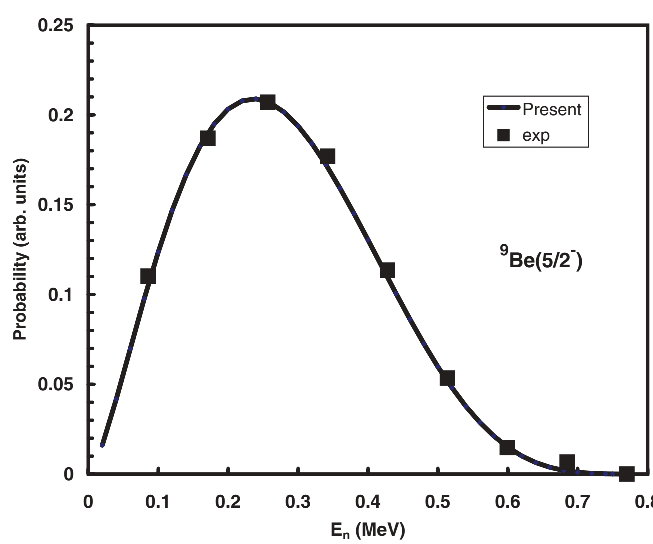

FIG. 3. (Color online) Our distribution of events vs E_n from Fig. 2 compared with the data of Ref. [5], normalized at the peak. Our curve has an absolute scale (Fig. 2), but the data are in arbitrary units.

TABLE II. Calculated widths for various decays of ^{9}Be(5/2$^-$).

Label	Process	Width (keV)	Reference
M_0	$^9\text{Be} \rightarrow {}^8\text{Be(gs)} + n;\ {}^8\text{Be} \rightarrow 2\,\alpha$	0.052[a] or 0.055[b]	[1], Present
M_1	$^9\text{Be} \rightarrow \alpha + {}^5\text{He};\ {}^5\text{He} \rightarrow \alpha + n$	0.92	[12]
M_2	$^9\text{Be} \rightarrow {}^8\text{Be}(2+) + n;\ {}^8\text{Be}(2+) \rightarrow 2\alpha$	0.053	Present
Experimental		0.78(13)	[1]

[a]Computed from $\Gamma_n = S\Gamma_{\text{nsp}}$, using our sp width of 1.1 keV, and $S = 0.047$ (Ref. [1]).
[b]Computed from the branching ratio of 7% [1–3] and the total width (last line).

1.16 [12,13] gives a width of 0.053 keV, to be compared with our calculated width for α decay of 0.92 keV [12]. These are also listed in Table II. Of course, in the actual situation, these will not be separate decays—the decay amplitudes will add, not the intensities.

We repeat that the energy distributions for the various three-body mechanisms M_1–M_3 are all identical. From the careful experiment of Ref. [5], we have enlarged their Fig. 6 and read off the data at every tenth point in E_n. These data are plotted in Fig. 3 where they are compared with our curve from Fig. 2, after normalizing at the maximum. Of course, our distribution has an absolute scale, but the data are in arbitrary units. Agreement with the data seems to be much better than in the left-hand side of Fig. 3 in Ref. [8].

A factor of about 18 in the ratio of the calculated widths for M_1 and M_2 may not be sufficient to ignore M_2, so that the amplitudes should be added coherently. We do not know how to calculate the width for M_3. A recent paper [8] espousing M_3 as the only mechanism did not provide a width for M_3 alone. Reference [14] reports a calculated total width of 0.7 keV, obtained from the imaginary part of the complex energy eigenvalue. In their Table IV, they give a calculated branch to ^{8}Be(g.s.) + n of 3%, to be compared with the experimental values of 6(1)% [15] and 7(1)% [16] and our calculated value of 5.5%. Their calculation leaves 0.97 Γ_{tot} for the combination of the decay paths we call M_1, M_2, and M_3. They do not give a value for M_3 alone.

Our result for ^{9}Be is consistent with the situation regarding the mirror 5/2$^-$ state in ^{9}B. Charity *et al.* [17] recently confirmed an earlier report [18] that the decay of the ^{9}B state has a dominant branch to α + ^{5}Li, implying that "the corresponding mirror state in ^{9}Be would be expected to decay through the mirror channel α + ^{5}He, instead of through the n + ^{8}Be(2$^+$) channel…" [17]. We note that R-matrix calculations underestimate the total width for the 5/2$^-$ state of ^{9}B by a factor of 4 [17,19], but a potential-model calculation gets it about right [12].

III. SUMMARY

Reference [12] calculated the width for ^{9}Be(5/2$^-$) $\rightarrow$ α + ^{5}He (called M_1 here) to be 0.92 keV. Here, we have computed the width for ^{9}Be(5/2$^-$) $\rightarrow$ ^{8}Be(2+) + n (M_2) to be 0.053 keV. We have not calculated the width for "true" three-body decay (M_3), but it appears to us that this third process is not needed because the widths of the other two are sufficient to explain the experimental width. Reference [8] does not provide a width for this mechanism, which they claim is the only one participating [apart from the one through ^{8}Be(gs)]. It appears that Ref. [8] has rediscovered the poorly known fact [5–7] that the three processes, M_1, M_2, and M_3, all lead to the same final state, with identical kinematics and identical energy and angular distributions. No measurement can determine the relative contributions of the three. Only a calculation can do that. A correct description involves the coherent sum of the three amplitudes, each with its own normalization, or absolute scale, determined by the relevant spectroscopic factors and barrier penetrations. The total width of the state can be measured and has been. We know of no calculation of the width for just M_3. We have computed the widths for M_1 (Ref. [12]) and M_2 (here), in each case by turning off the others. It is unlikely that M_3 makes a major contribution because the width for M_1 is already comparable to the experimental width. We wonder if it is possible that the process that some label three-body and others label α + ^{5}He may actually be the same.

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