Properties of 3.89/3.96-MeV states in ^{11}Be

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I have reanalyzed previous data from the ^{9}Be(t, p) reaction to extract energies and widths for the two states near 3.9 MeV. Results are energies of 3889.27 $\pm$ 1.03 and 3954.53 $\pm$ 1.16 and widths of 3.2(8) and 7.9(7), all in keV, for the $5/2^-$ and $3/2^-$ states, respectively.

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The $3/2^-$ and $5/2^-$ states near 3.9 MeV in ^{11}Be [1] have been of interest recently. Peters *et al.* [2] populated one or both of them in neutron removal from ^{12}Be and observed n decay to the 2^+ state of ^{10}Be. Their peak in the relative ^{10}Be$\,+\,n$ energy spectrum had a full width at half maximum (FWHM) of 150 keV. With no contribution from the $5/2^-$ state, they extracted a relative energy of 80(2) keV, implying $E_x = 3.949(2)$ MeV for the $3/2^-$ state. In a ^{9}Be(t,p) experiment [3], the energy of this state had been reported as 3.955(1) MeV. The compilation lists the width of this state as 15(5) keV and that of the $5/2^-$ as <10 keV. But Pullen *et al.* [4] reported widths of <10 keV for both. We did not extract widths for these states in the (t,p) paper [3], but I have subsequently reanalyzed those data in an effort to do so. That is the subject of the present Brief Report. But first, I will briefly review the history of these two states. (See Tables I and II.)

Both states were first observed in the ^{9}Be(t,p) ^{11}Be reaction, at bombarding energies near 5 and 10 MeV [4]. Excitation energies were reported as 3.890(20) and 3.960(20) MeV, both with widths Γ<10 keV. No angular distributions were presented for either state. Later, both states were observed in the same reaction, but at $E_t = 20$ MeV [5], and the same E_x's were given (but now with $\Delta E = 30$ keV). Widths were listed as $\Gamma < 10$ and $\Gamma = 15(5)$ keV for the 3.89- and 3.96-MeV states, respectively. Again, no angular distributions were presented. In the same reaction at 23 MeV [6], excitation energies were stated as 3.877(30) and 3.943(30) MeV. Angular distributions were presented, but with no distorted-wave curves. Those authors assigned $J \geqslant 7/2$ and $J^\pi = 3/2^-$, on the basis of their L assignments of $L \geqslant 3$ and $L = 0$ for 3.89 and 3.96 MeV, respectively.

At 15 MeV [3], the 3.96-MeV angular distribution appeared to be dominated by $L = 2$, but $J^\pi = 3/2^-$ was taken as established. The state was suggested to have the structure of ^{9}Be(g.s.)$\,\times\,(sd)^2$. Based on its energy and cross section, the 3.89-MeV state was suggested to be a $3/2^+$ state with the configuration ^{10}Be$(2^+) \times 2s_1/_2$. Its angular-distribution shape was nondescript. Energies of the two states were reported [3] as 3.888(1) and 3.955(1) MeV. Now, the J^π values appear to have been firmly established as $5/2^-$ and $3/2^-$, with the $5/2^-$ assignment coming primarily from its observation in β decay of ^{11}Li [7].

I have reanalyzed the 15-MeV data [3], fitting both peaks with convolutions of a Gaussian shape for the resolution (assumed to be the same for these two nearby states) and Breit-Wigner shapes for the natural widths of the states. I have also re-examined the extraction of excitation energies, because of a recent small improvement [8] to the mass excess of ^{11}Be. Figure 1 displays a spectrum of this region of excitation for the ^{9}Be(t,p) reaction at an outgoing angle of 3.75°. The two peaks are seen to be quite narrow and to be approximately well fitted by Gaussian shapes. However, closer inspection of the 3.96-MeV peak reveals that the Gaussian curve is wider than the experimental peak shape near the maximum and below the data in the tails of the peak—both are indications of some natural width.

In the original (t,p) experiment [3], outgoing protons were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsion plates. Data were collected as counts vs distance along the focal plane. Under the conditions of this experiment, a distance of 1/4 mm along the focal plane corresponds to an energy bin of 1.87 keV at the location of the 3.96-MeV peak. At this point on the focal plane, and for this experiment, the total experimental resolution width was about 9.8(8) keV. Throughout, I will use the terms channel and 1/4 mm interchangeably.

Figure 2 displays the two states, with the $5/2^-$ peak shifted to approximately align the two centroids, and renormalized to have about the same peak height. As expected, it is easy to see that the $3/2^-$ state is slightly wider. Figure 3 displays the 3.96-MeV state with two curves. The two curves are identical convolutions of Gaussian and Breit-Wigner shapes, except for a one-channel shift in the centroid. Clearly the peak centroid is between the peak channels of the two curves, closer to the left-hand one. (Excitation energy increases to the right.) With the new small correction to the ^{11}Be mass excess, this analysis produces for the two states excitation energies of 3889.27 $\pm$ 1.03 and 3954.53 $\pm$ 1.16 keV, which are within the uncertainties of the original analysis [3]. These are averages at seven forward angles. The extracted total observed widths for the two peaks are 14.6(4) and 11.6(4) keV. With a resolution width of 9.8(8) keV, these correspond to natural widths of 7.9(7) and 3.2(8) keV. Note that subtracting the widths in quadrature, as is frequently erroneously done, would have led to large mistakes in the two widths.

With the present excitation energies for the two states, the neutron energies for decay to the 2^+ of ^{10}Be are 20 and 86 keV, and single-particle (sp) widths for $\ell = 1$ are 3.4 and 30 keV (see Table III.). These differ slightly from the values of 2.9 and 36 keV in Ref. [9] because of slightly different neutron energies. Branching ratios (BRs) for these two states have been reported in two different experiments—one of which (β decay

TABLE I. Properties of ^{11}Be(3.89, $5/2^-$) (Energies and widths in keV).

Quantity	Value	Reference
E_x	3890(20)	[4]
	3890(30)	[5]
	3877(30)	[6]
	3888(1)	[3]
	3890(1)	[7]
	3889.27 ± 1.03	Present
Γ_{tot} (expt.)	<10	[4]
S_{th} to 2^+	0.66, 0.57	[11,12]
Γ_{sp} to 2^+	2.9, 3.4	[9], Present
Γ_{th} to 2^+[a]	~1.9	[9]
	1.7–2.2	Present
BR to 2^+ (expt.)	$0.62^{+0.14}_{-0.21}$	[7]
Γ_{tot} (calc.)[b]	$3.1^{+1.5}_{-0.6}$	[9]
	$3.6^{+1.8}_{-0.7}$	Present
Γ_{tot} (expt.)	3.2(8)	Present
S_{2+}(expt.)[c]	$0.58^{+0.20}_{-0.26}$	Present

[a] $\Gamma_{th} = S_{th}\Gamma_{sp}$.
[b] $\Gamma_{tot}(\text{calc.}) = (\Gamma_{th}\text{ to }2^+)/\text{BR}$.
[c] $S_{2+}(\text{expt.}) = \Gamma_{tot}(\text{expt.})\text{BR}/\Gamma_{sp}$.

[7]) resolved the two states and one [^{9}Be(^{16}O,^{14}O) [10] that didn't. I use the BR from the former. In Ref. [7], the BR of the $3/2^-$ state is 78% to the 2^+ state, implying $\Gamma_{2+} = 0.78\Gamma_{tot.} = 6.2(6)$ keV, leading to a spectroscopic factor for that decay of $S = \Gamma_{exp}/\Gamma_{sp} = 0.20(10)$. These results are summarized in Table II.

Reference [9] used the theoretical S [11,12] for the $5/2^-$ state decay to the 2^+, together with the measured BR [7] to predict the width of this state to be $3.1^{+1.5}_{-0.6}$ keV. The result is reasonably consistent with the value of 3.2(8) keV found

TABLE II. Properties of ^{11}Be(3.96, $3/2^-$) (Energies and widths in keV).

Quantity	Value	Reference
E_x	3960(20)	[4]
	3960(30)	[5]
	3943(30)	[6]
	3955(1)	[3]
	$3969^{+0.20}_{-0.09}$	[7]
	3949(2)	[2]
	3954.53 ± 1.16	Present
Γ_{tot} (expt.)	<10	[4]
	15(5)	[5]
	7.9(7)	Present
Γ_{sp} to 2^+	36, 30	[9], Present
BR to 2^+ (expt.)	0.78(4)	[7]
$\Gamma_{expt.}$ to 2^+[a]	6.2(6)	Present
S to 2^+ (expt.)[b]	0.32(17)	[9]
	0.20(10)	Present

[a] $\Gamma_{2+} = \text{BR}\Gamma_{tot}$.
[b] $S_{2+} = \Gamma_{2+}/\Gamma_{sp}$.

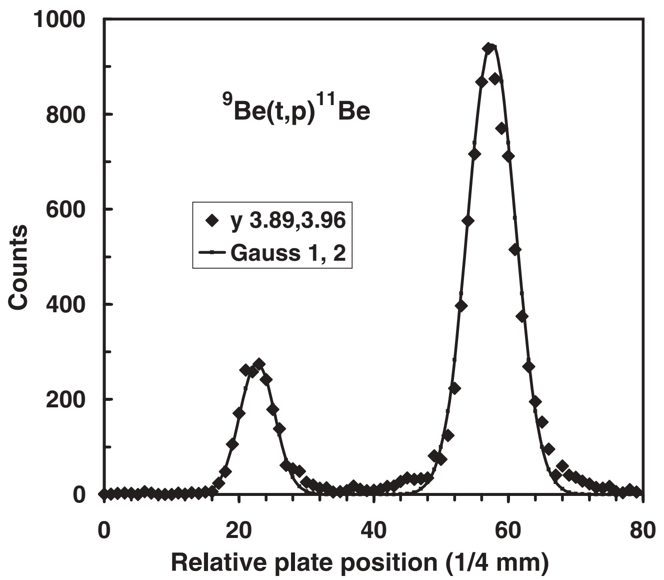

FIG. 1. A portion of the 3.75° spectrum from the reaction ^{9}Be(t,p)^{11}Be [3], showing the 3.89- and 3.96-MeV states, together with Gaussian curves.

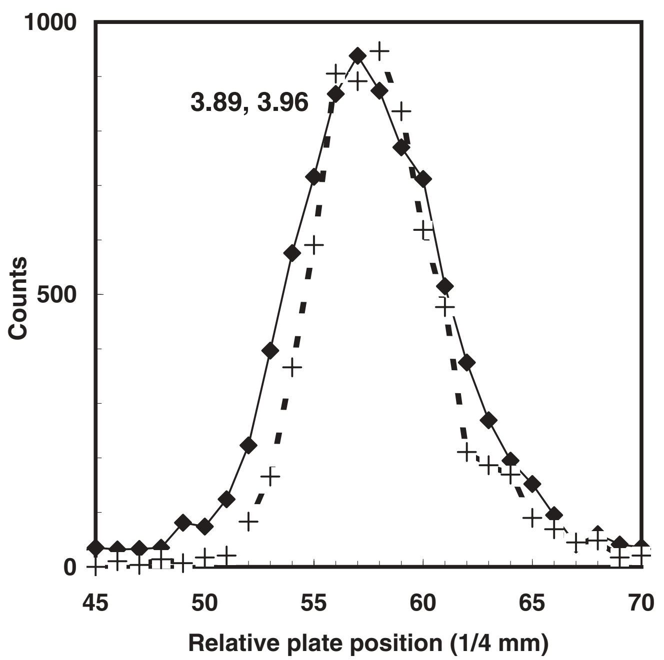

FIG. 2. Data for the 3.96-MeV state (diamonds) and 3.89-MeV state (+'s) (shifted and re-normalized) superimposed.

TABLE III. Energies and single-particle widths (all in keV) for $^{11}\text{Be}* \rightarrow {}^{10}\text{Be}(2^+) + n$.

E_x	E_n to 2^+	Γ_{sp}
3889	20	3.4
3955	86	30

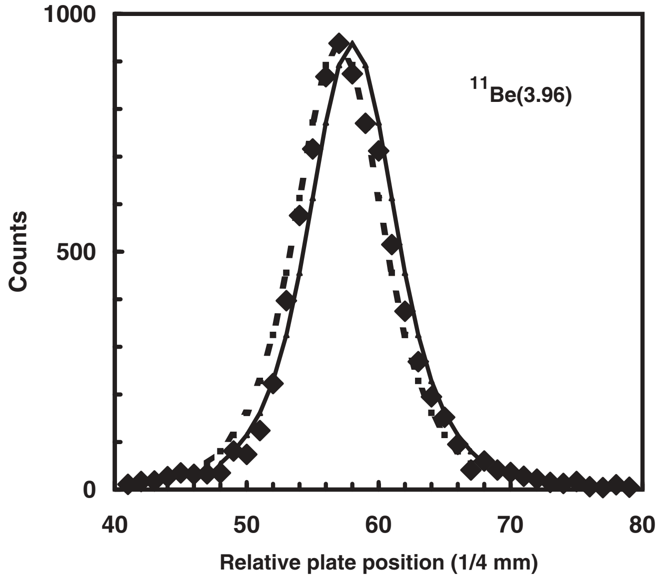

FIG. 3. Data for the 3.96-MeV state, compared with two identical curves differing by one channel (1.87 keV) in the centroid.

here. Repeating that analysis with the new sp width leads to a calculated total natural width of $3.6^{+1.8}_{-0.7}$ keV—not very different from the value in Ref. [9]. Alternatively, I can use the measured natural width and the measured 2^+ BR to compute the partial width for decay to the 2^+, then divide by the sp width to get an experimental spectroscopic factor for the $5/2^-$ to 2^+ decay. The result of $S = 0.58^{+0.20}_{-0.26}$ is consistent with the two theoretical values of 0.66 [11] or 0.57 [12]. All these results are listed in Table I.

Concerning the energy of the $3/2^-$ state, quoted as 3.949(2) MeV in Ref. [2] and as 3.954.5(1.2) here, the difference is 5.5(2.3), about a 2.3σ effect. Data for the two states from Fig. 1 have been replotted in Fig. 4, but now as a function of E_n, the neutron energy relative to ^{10}Be(2^+). Also plotted there is the n decay spectrum from Peters *et al.* [2], multiplied by a factor of 2/3 (just for scaling purposes). These latter points were obtained by enlarging their figure and directly reading off every second data point. The authors state that their resolution

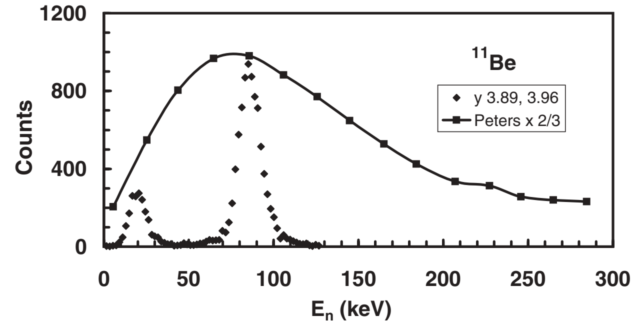

FIG. 4. Data from Fig. 1 (diamonds) replotted vs E_n, compared with the n decay spectrum (renormalized) of Ref. [2] (squares).

varies as the square root of the energy, and give examples at two energies, implying that at 80 keV it should be 36 to 40 keV. And yet, their peak is 150 keV wide—full width at half maximum. Presumably the extra width they observe comes from the "systematic uncertainties" they mention. They state that their quoted resolutions are "a standard deviation." If the FWHM of what they call their resolution is twice the standard deviation, that would be about 80 keV at $E_n = 80$ keV. If these widths add in quadrature, then the FWHM of the systematic uncertainties would need to be about 127 keV, in order to have a total FWHM of 150 keV. If this extra width is independent of neutron energy, then, even for a $5/2^-$ state with no natural width, the FWHM of its peak would be about 133 keV. A small contribution from it could slightly change the extracted centroid of their peak. Perhaps some other way can be found to populate the $3/2^-$ state and measure its energy.

In summary, further analysis of results [3] of the ^{9}Be(t,p)^{11}Be reaction at 15 MeV has provided energies of 3889.27 $\pm$ 1.03 and 3954.53 $\pm$ 1.16 and widths of 3.2(8) and 7.9(7), all in keV, for the $5/2^-$ and $3/2^-$ states, respectively. Widths are consistent with all earlier work, but more definitive. Energies agree with previous results from the same (t,p) data, and with energies from n decay following β decay, but the $3/2^-$ energy differs by 5.5(2.3) keV from the energy found by Peters *et al.* [2].

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