

Neutron knockout of ^{12}Be populating neutron-unbound states in ^{11}Be

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Neutron-unbound resonant states of ^{11}Be were populated in neutron knockout reactions from ^{12}Be and identified by $^{10}\text{Be}-n$ coincidence measurements. A resonance in the decay-energy spectrum at 80(2) keV was attributed to a highly excited unbound state in ^{11}Be at 3.949(2) MeV decaying to the 2^+ excited state in ^{10}Be . A knockout cross section of 15(3) mb was inferred for this 3.949(2) MeV state, suggesting a spectroscopic factor near unity for this $0p_{3/2}^-$ level, consistent with the detailed shell model calculations.

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Several recent experiments have mapped the level structure of ^{11}Be . Hirayama *et al.* [1] observed the β -delayed neutron decay from polarized ^{11}Li , identifying neutron-unbound levels in ^{11}Be and assigning spin and parity to each. Previous neutron knockout experiments have identified additional levels, and highlighted significant mixing with sd -shell states [2,3]. We also report on neutron-unbound excited states in ^{11}Be populated by neutron knockout from ^{12}Be and investigated by in-beam neutron-decay spectroscopy. These data show a resonance at a decay energy of 80(2) keV indicating population of the known $3/2^-$ state at 3.949(2) MeV in ^{11}Be decaying to the first 2^+ state in ^{10}Be via neutron emission. The uncertainty of the measured energy for this state is significantly improved over the previous accepted value [4]. The measured knockout cross section of 15(3) mb implies a spectroscopic factor near unity for this $3/2^-$ state.

The reports of Hirayama *et al.* [1], Aoi *et al.* [5], and Morrissey *et al.* [6] from β decay of ^{11}Li , noted excited states in ^{11}Be including (1.778 MeV)($J^\pi = 5/2^+$), (2.690 MeV)($J^\pi = 3/2^-$), and (3.949 MeV)($J^\pi = 3/2^-$), which are also observed in this work. Additionally, Navin *et al.* [3] demonstrated the importance of sd intruder states to

understanding the structure of ^{11}Be by using neutron-knockout reactions from ^{12}Be to populate the $1/2^+$ and the $1/2^-$ states in ^{11}Be . These levels from $\nu(1s_{1/2})^2$ and $\nu(0p_{1/2})^2$ valence neutron configurations in ^{12}Be were found to be populated with nearly equal probability. This significant shell-level mixing with the sd shell, the subsequent fragmentation of simple single-particle strengths [7,8], α -particle clustering, and resulting deformation contribute to the disappearance of the eight-neutron magic shell gap in ^{12}Be . Further identified a possible resonance at approximately 3.5 MeV decay energy Pain *et al.* [2]. They also observed a narrow resonance near zero due to a state (or two states) in ^{11}Be at about 4 MeV excitation energy that subsequently decays via neutron emission to the first excited 2^+ state of ^{10}Be at 3.368 MeV, but these paths could not be well defined by their data because of limitations in their experimental setup. We employed the neutron-knockout technique of Refs. [2,3] using the modular neutron array (MoNA) [9,10]. Figure 1 displays the level scheme for the low-lying energy levels in ^{10}Be and ^{11}Be including the neutron decay energies seen in the present experiment.

The experiment consisted of a primary beam of ^{18}O accelerated to 120 MeV/nucleon with the coupled cyclotron facility [12] at the National Superconducting Cyclotron Laboratory; this beam impinged onto a 1080 mg/cm² ^9Be production target. The secondary beam of 90 MeV/nucleon ^{12}Be , produced by fragmentation, was separated with the A1900 fragment separator [13] utilizing a 750 mg/cm² acrylic achromatic wedge degrader installed at the dispersive image. The average intensity of the ^{12}Be beam was about 60 000 particles per second, with a momentum spread of $\pm 0.5\%$ and a purity of over 99%.

The secondary beam was directed onto a 102 mg/cm² ^9Be reaction target. Charged particles were deflected by the large gap sweeper magnet [14,15], and the neutrons were detected by the MoNA [9,10]. The setup and the charged-particle

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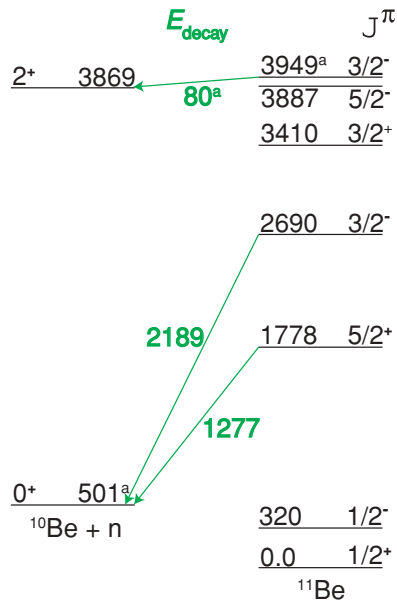


FIG. 1. (Color online) ^{11}Be level scheme up to 4 MeV including the first two states in ^{10}Be . Only the neutron decay energies observed in this experiment are shown. Energies are given in keV along with known spin and parity assignments. (^a denotes values derived in the current work incorporating the recently remeasured separation energy from Ref. [11].)

detectors after the sweeper magnet are described in Fig. 4 of Ref. [9]. Additionally, a steel blocker was installed in front of the first cathode readout drift chamber (CRDC) to protect it from the low-momentum tail of the unreacted ^{12}Be beam.

The energies of the neutrons were calculated from the flight time between a timing detector in front of the reaction target and MoNA, located at zero degrees and positioned 8.2 m from the reaction target. Their angles relative to the beam axis were assigned by the first interaction point in MoNA. Timing the arrival of the light at each end of the neutron detector bars yields a horizontal position with a standard deviation of 3 cm. The vertical and longitudinal position resolution is 5 cm (one-half the bar width and height of 10 cm) [9,16].

The directions of the charged particles behind the sweeper magnet were measured by two CRDCs. The position resolution of the CRDCs was 1.5 mm in the horizontal dispersive plane. The energy and emission angle of each fragment at the reaction target was calculated using a transformation matrix constructed from the measured magnetic field maps of the sweeper [17] using the beam physics code package COSY INFINITY [18,19]. The elemental identification of the charged fragments was based on energy loss in a plastic scintillator downstream of the two CRDCs. Isotopic separation of the beryllium nuclei was based on the measured horizontal angle determined by the two CRDCs and the fragment flight time between the timing detector at the target to the thin scintillator detector labeled dE in Ref. [20]. The results presented below are based on events with a neutron in coincidence with a ^{10}Be fragment. This coincidence gate yields a clean neutron spectrum with little background. The decay energy can be determined by subtracting the mass of the decay products from the invariant mass of the neutron-fragment system as described in Ref. [21]. The neu-

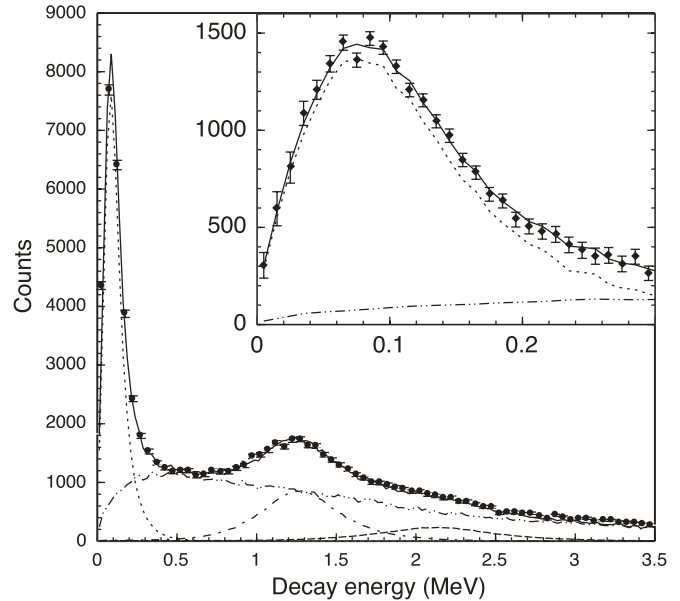


FIG. 2. Decay energy spectrum from ^{10}Be -neutron coincidence data. The simulation (solid line) is the sum of three resonances with decay energies of 80 keV (dotted line), 1.28 MeV (dot-dashed line), and 2.19 MeV (dashed line). In addition, a nonresonant background component (double-dot dashed line) was included. The insert shows a separate fit to the low energy range with higher fidelity, confirming only one low-energy peak at 80 keV.

trons are moving near beam velocity (90 MeV in the current experiment) and are forward focused. This results in a neutron acceptance of 60% for decay energies less than 2.5 MeV. The resolutions described above propagate through the invariant-mass equation and broaden the resolution of the decay energy as the square root of the energy; from a standard deviation of 75 keV at 300 keV, to 200 keV for a decay energy of 1500 keV [16].

The decay energy spectrum is shown in Fig. 2 and two prominent peaks are indicated, one produced by a low-energy decay (less than 100 keV), and the other with an energy of 1.28 MeV. The overall shape of the spectrum is similar to the decay energy spectrum presented in Ref. [2]. A detailed simulation of the data, as described below, further indicates the presence of a broad resonance with decay energy of 2.19 MeV.

Monte Carlo simulations were performed which incorporated the geometric acceptances and measured resolutions of the neutron and charged particle detectors. The resonances were modeled by Breit-Wigner distributions. For the simulation shown in Fig. 2, the resonant energies of $^{11}\text{Be}^*(1.778\text{ MeV})$ (dot-dashed line) and $^{11}\text{Be}^*(2.690\text{ MeV})$ (dashed line) and their widths (100 and 200 keV) were kept constant at the values reported in Ref. [4] along with the proportional intensities of the two as reported by Pain *et al.* [2]. For the third low-decay-energy peak (dotted line), the energy, width, and relative population with respect to the other two resonant level were free parameters. A background distribution due to nonresonant neutrons and neutrons from the direct diffractive breakup channel of ^{12}Be was included with a Maxwellian distribution, $\sqrt{E} \exp(-E/E_0)$, where E_0 was a free parameter (see Ref. [22] concerning modeling of the nonresonant background). The magnitude and E_0 parameter

of the background (double-dot dashed line) were also treated as free parameters, the final best-fit curve with $E_0 = 5.0$ MeV was nearly identical to the background curve of Ref. [2]. The angle and position distributions of the incoming ^{12}Be beam used in the simulation were adjusted to reproduce the angle and position distributions of the fragments in the charged particle detectors.

Due to a technical failure of the beam counting monitor, it was not possible to extract the cross section directly from the experiment. The overall normalization to extract the cross section of populating the low-energy peak was done by scaling relative to the cross sections reported by Pain *et al.* [2]. Since the beam energy (39 MeV/nucleon) was much lower than the present experiment (90 MeV/nucleon), the reported cross sections of Pain *et al.* were scaled to account for the reduction of knockout cross sections with faster beams. This was done by calculating the single-particle cross sections for each state at both energies using the same eikonal reaction model [23] used in Ref. [2]. The single-particle cross section ratio for the former to current beam energies is 0.62 for all three states observed: $^{11}\text{Be}^*(1.778 \text{ \& } 2.690 \text{ \& } 3.949 \text{ MeV})$. The reported cross sections for the 1.778 and 2.690 MeV states were then scaled by this factor of 0.62 (keeping the relative magnitudes constant) and the cross section of the low-energy peak was determined.

The decay energy of the low-energy peak was found to be $S_n = 80(2)$ keV as shown in the inset of Fig. 2 with a cross section of 15(3) mb. Systematic uncertainties, due to various beam parameters that fit the measured distributions recorded in the charged-particle detectors, account for the limited resolution of fitting the decay width leading to an upper limit of 40 keV, which is consistent with the accepted value of 15 keV [4]. The uncertainty of the centroid of the peak is much less affected, and a χ^2 analysis yields a 2 keV standard deviation for the uncertainty of the 80 keV value. By adding the measured value of the first excited 2^+ state in ^{10}Be at 3.368 03(3) MeV [24] and the recently improved neutron separation energy of 501.3(6) keV [11], this neutron decay energy corresponds to an excitation energy of 3.949(2) MeV in ^{11}Be , and improves the uncertainty of the currently adopted energy of this state [the second $3/2^-$ state at 3.956(15) MeV in Ref. [4]]. The present value is below the value measured by Hirayama *et al.* for this state, $3.969_{-0.009}^{+0.020}$ MeV, from ^{11}Li β decay [1]. The lack of evidence for a resonance below 80 keV shows that the $^{11}\text{Be}^*(3.887)$ state, decaying to the 2^+ in ^{10}Be , is not measurably populated in the present knockout reaction.

The large measured cross section of 15(3) mb for the neutron decay of $^{11}\text{Be}^*(3.949)$ is similar in magnitude to the cross sections for populating $^{11}\text{Be}^*(1.778 \text{ and } 2.69)$, as reported in Ref. [2]. The reported cross sections for populating these two states, after scaling by the single-particle cross section ratio (0.62) for the different beam energies, are 19(3) and 14(3) mb, respectively. The knockout reaction model calculation [23] yields a single-particle cross section of 31.4 mb to populate the second $3/2^-$ state in ^{11}Be . Haigh *et al.* [25] measured the decay branching from this 3.949 MeV state to both the ground state (with a decay energy of 3.45 MeV that is outside the geometric acceptance of our setup) and to the 2^+ excited state (the 80 keV channel we measured) of ^{10}Be with a two-neutron pickup reaction ($^{16}\text{O}, ^{14}\text{O}$) on ^9Be . Their results

show that the branching to these two channels is equal. Earlier work by Hirayama *et al.* [1] also measured the branching ratio (with large uncertainties) from $^{11}\text{Be}^*(3.949)$ following the β decay of ^{11}Li . Therefore, our measured cross section to the first excited state in ^{10}Be is doubled to get the total single-neutron knockout cross section from ^{12}Be to the $^{11}\text{Be}^*(3.949)$ state. This total production cross section of 30(6) mb leads to a spectroscopic factor of 1.0(2) when compared to the reaction model calculation [23]. This value is about twice the observed spectroscopic factor of the lower-lying states in ^{11}Be measured in Refs. [2,3], supporting the interpretation for the character of this $3/2^-$ state as predominantly single-particle, likely due to hole correlations in the $0p_{3/2}$ orbital.

The experimental results can be compared to calculations in the p shell with the WBP Hamiltonian [26] that include up to two particles excited into the sd shell [27]. The wave function for the $^{12}\text{Be } 0^+$ ground state is calculated to comprise 31% $0\hbar\omega$ with p -shell configurations and 69% $2\hbar\omega$ with two nucleons excited into the sd shell. The calculated energies of the first two $3/2^-$ states are about 1 MeV too low compared to their measured values; and the experimental energy of a third $3/2^-$ state is not known, but calculated to be 4.24 MeV. The first $3/2^-$ state in ^{11}Be is produced by one-nucleon removal from the $0\hbar\omega$ component of the ^{12}Be ground state with an observed spectroscopic factor of 0.40(6) [2], which is significantly smaller than the calculated value of 1.576. The second $3/2^-$ state in ^{11}Be (81% $2\hbar\omega$) is produced by one-nucleon removal from the $2\hbar\omega$ component of the ^{12}Be ground state. The experimental spectroscopic factor reported herein of 1.0(2) is in reasonable agreement with the calculated value of 0.69. See Table I for more details.

The decay widths are calculated by $\Gamma = C^2S\Gamma_{\text{sp}}$ where the spectroscopic factors C^2S and the single-particle decay widths Γ_{sp} are calculated by Eq. (3F-51) in Ref. [28] using the experimental Q values. The single-particle $l = 1$ decay width for the decay of the first $3/2^-$ to the $^{10}\text{Be } 0^+$ ground state ($Q = 2.19$ MeV) is 1.5 MeV. Combined with the spectroscopic factor of 0.155, the resulting decay width of 0.23 MeV is in good agreement with the experimental value of 0.20(2) MeV [4]. The single-particle $l = 1$ decay width for the decay of the second $3/2^-$ $^{11}\text{Be}^*(3.949)$ state to the two decay channels, $^{10}\text{Be } 2^+$ ($Q = 0.080$ MeV) and 0^+ ($Q = 3.448$ MeV), are 0.020 and 4.0 MeV, respectively. Combined with the calculated spectroscopic factors, 0.22 for the 2^+ channel and 0.0012 for the 0^+ channel, the decay widths are 4.4 and 4.8 keV, respectively. The large variation in spectroscopic factors is due to interference between the various $0\hbar\omega$ and $2\hbar\omega$ wavefunction components of the decaying $3/2^-$ state and the 0^+ or 2^+ states in ^{10}Be . The total experimental width is 15(5) keV [4] and, for equal branching ratios [25], the experimental partial widths would each be half that, around 7(3) keV. The agreement between experiment and theory is surprisingly good, given the small spectroscopic factors involved.

We note that a general feature of analyses of nucleon knockout reactions is that measured cross sections are smaller than those calculated using the eikonal model with shell-model spectroscopic factors. This empirical behavior is shown, for example, in Fig. 6 of Ref. [29]. The observed reduction factors, R_s , show a systematic dependence on the asymmetry of the

TABLE I. WBP Hamiltonian [26] theoretical calculations for the first three $3/2^-$ states in ^{11}Be . Energies, spectroscopic factors, and their wave functions are calculated for the p -shell including up to two particles excited into the sd shell [27].

E^* (MeV)		Spec. factors			Wave-function components (%)	
Theor.	Expt.	From ^{12}Be g.s.	To ^{10}Be 0^+	To ^{10}Be 2^+	$0\hbar\omega$	$2\hbar\omega$
1.76	2.69	1.576	0.155	0.461	73	27
2.80	3.949	0.693	0.0012	0.215	19	81
4.24	?	0.033	0.0053	0.221	70	30

neutron and proton separation energies from the projectile ground state, ΔS . In the present case of weakly bound neutron removal from ^{12}Be , the neutron separation energies to the ^{11}Be ground state and 3.949 MeV excited state correspond to ΔS of -20 MeV and -16 MeV, respectively. These ΔS , and the measured reaction systematics, suggest R_s values of close to unity in the present work.

The nonobservation of the 3.887 MeV state, decaying preferentially to the 2^+ state in ^{10}Be by 14 keV, indicates that this state is not strongly populated by single-neutron removal from ^{12}Be or two-neutron transfer [25]. This interpretation is also consistent with the results of the three-proton stripping reaction from ^{14}N [22] that populated $^{11}\text{Be}^*(3.887)$ but not $^{11}\text{Be}^*(3.949)$, where the likelihood of exciting neutrons to higher subshells exists. This 14 keV decay channel was also observed in Ref. [30], which selectively populated the 3.887 and 3.949 MeV states by two-proton and two-neutron transfer reactions, respectively. Finally, in another MoNA experiment populating unbound states in ^{11}Be by the nonselective reaction of direct fragmentation from ^{48}Ca , neutrons decaying from both excited states near 4 MeV to the 2^+ state in ^{10}Be were observed [20]. The similarities between the setups for that experiment and the present supports our interpretation of the selectivity of the single-neutron knockout from ^{12}Be to $^{11}\text{Be}^*(3.949)$. However, as noted earlier, we cannot rule out the possibility that the $^{11}\text{Be}^*(3.887)$ state is populated and

subsequently directly decays predominantly to the ground state of ^{10}Be by 3.38 MeV neutron decay.

In summary, the resonance observed through neutron-decay spectroscopy measurements of the neutron-unbound excited states in ^{11}Be at a decay energy of 80(2) keV indicates the population of the known second $3/2^-$ state at 3.949(2) MeV in ^{11}Be decaying to the 2^+ state in ^{10}Be via neutron emission. The inferred cross section for this decay branch of 15(3) mb implies a spectroscopic factor near unity for this $3/2^-$ state, consistent with shell-model calculations.

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