Population of 13Be in a Nucleon Exchange Reaction

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Abstract
The neutron-unbound nucleus Be13 was populated with a nucleon exchange reaction from a 71 MeV/u secondary B13 beam. The decay-energy spectrum was reconstructed using invariant mass spectroscopy based on Be12 fragments in coincidence with neutrons. The data could be described with an s-wave resonance at $E_r=0.73(9)$MeV with a width of $\Gamma_r=1.98(34)$MeV and a d-wave resonance at $E_r=2.56(13)$MeV with a width of $\Gamma_r=2.29(73)$MeV. The observed spectral shape is consistent with previous one-proton removal reaction measurements from B14.

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Population of $^{13}$Be in a nucleon exchange reaction

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The neutron-unbound nucleus $^{13}$Be was populated with a nucleon exchange reaction from a 71 MeV/u secondary $^{13}$B beam. The decay-energy spectrum was reconstructed using invariant mass spectroscopy based on $^{12}$Be fragments in coincidence with neutrons. The data could be described with an $s$-wave resonance at $E_x = 0.73(9)$ MeV with a width of $\Gamma_x = 1.98(34)$ MeV and a $d$-wave resonance at $E_x = 2.56(13)$ MeV with a width of $\Gamma_x = 2.29(73)$ MeV. The observed spectral shape is consistent with previous one-proton removal reaction measurements from $^{14}$B.

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I. INTRODUCTION

Recent experimental investigations of the level structure of the neutron-unbound nucleus $^{13}$Be agree about the overall strength distribution of the excitation energy spectrum [1–6], but there is no consensus on its interpretation. While there seems to be general agreement about the presence of a broad $s$-wave resonance below 1 MeV and a $d$-wave resonance at 2 MeV, the composition of the observed peak around 500 keV, as well as the decay paths of the $d$-wave resonance, are still being discussed. Earlier reports of a narrow low-lying $s$-wave state [7,8] have been attributed to a sequential decay from the first excited $2^+$ state in $^{14}$Be to $^{12}$Be [3,6,9].

In 2010, Kondo et al. [3] reported a low-lying $p$-wave resonance at 510(10) keV populated by a one-neutron removal reaction from $^{14}$Be at 69 MeV/u. However, a recent analysis of these data, as well as a new measurement at a higher beam energy on a hydrogen target (304 MeV/u), preferred an interpretation which fits the $\sim500$ keV peak with only two interfering broad $s$-wave resonances [4,5]. Moreover, the presence of additional $p$- or $d$-wave strength could not be ruled out, indicating that an $\ell \neq 0$ resonance around 1 MeV might exist [5]. The fits in both papers included a significant decay branch of the $d_{5/2}$ state to the first excited $2^+$ state in $^{12}$Be.

While neutron-removal reactions are expected to populate positive-parity states as well as negative-parity states, proton-removal reactions should be more selective and populate only positive-parity states. Randisi et al. [6] measured the decay-energy spectrum of $^{13}$Be following the one-proton removal reaction from $^{14}$B at 35 MeV/u and argued that the $\sim500$ keV peak consists of an $s$-wave resonance as well as a low-lying $d$-wave resonance. In addition, Randisi et al. searched for the decay of the $d_{5/2}$ resonance at 2 MeV to the first excited $2^+$ state in $^{12}$Be by measuring the $\gamma$ rays from this state in coincidence. No significant branch of this decay mode was observed.

In the present work, the nucleon exchange reaction ($-1p + 1n$) from $^{13}$B was used to populate states in $^{13}$Be. Similar to the proton-removal reaction it is expected to only populate positive-parity states. This type of reaction has been shown to have sizable cross sections at intermediate beam energies. For example, the one-proton removal–one-neutron addition ($-1p + 1n$) reaction has been utilized with stable ($^{48}$Ca) as well as radioactive ($^{48}$K, $^{48}$Cl) beams to explore the structures of $^{48}$K, $^{48}$Ar, and $^{48}$S [10]. The inclusive cross sections were 0.13(1) and 0.057(6) mb for the $^9$Be($^{48}$K,$^{48}$Ar) and $^9$Be($^{48}$Cl,$^{48}$S), respectively. This ($-1p + 1n$) reaction was also used for the first time to measure neutron unbound states in the study of $^{26}$F populated from a 86 MeV/u $^{20}$Ne beam [11].

II. EXPERIMENTAL SETUP

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A 120 MeV/u $^{18}$O primary beam from the Coupled Cyclotron Facility bombarded a 2.5 g cm$^{-2}$ $^9$Be production target. The A1900 fragment separator was used to separate and select the $^{13}$B secondary beam. The final energy of the beam was 71 MeV/u, with an intensity of approximately $8 \times 10^5$ particles per second and a purity of 96%. The $^{13}$B beam impinged upon a 51 mg cm$^{-2}$ $^9$Be target where $^{13}$Be was populated with a nucleon exchange reaction from a 71 MeV/u secondary $^{13}$B beam. The decay-energy spectrum was reconstructed using invariant mass spectroscopy based on $^{12}$Be fragments in coincidence with neutrons. The data could be described with an $s$-wave resonance at $E_x = 0.73(9)$ MeV with a width of $\Gamma_x = 1.98(34)$ MeV and a $d$-wave resonance at $E_x = 2.56(13)$ MeV with a width of $\Gamma_x = 2.29(73)$ MeV. The observed spectral shape is consistent with previous one-proton removal reaction measurements from $^{14}$B.

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produced in a nucleon exchange reaction and immediately decayed into \(^{12}\text{Be} + n\).

The \(^{12}\text{Be}\) reaction products were deflected by a large-gap sweeper magnet [12] and identified from energy-loss and time-of-flight measurements. The \(^{12}\text{Be}\) energy and momentum vectors were reconstructed from position information and a transformation matrix based on the magnetic-field map using the program COSY INFINITY [13]. Coincident neutrons were measured with the Modular Neutron Array (MoNA) [14,15] and the Large-Area Multi-Institutional Scintillator Array (LISA). The energy and momentum vectors of the neutrons were determined from the positions of the neutron interactions in the arrays and the time-of-flight between the arrays and a scintillator located upstream near the target. The nucleon exchange data were recorded simultaneously with the data for the one-proton-removal reaction populating unbound states in \(^{12}\text{Be}\). These results have been published recently in Ref. [16] where further details of the experimental setup and analysis can be found.

III. DATA ANALYSIS

The decay-energy spectrum of \(^{13}\text{Be}\) was reconstructed by the invariant-mass method and is shown in Figs. 1 and 2. The spectrum shows the same general features as the previous measurements with a strong peak around 500 keV and an additional structure at about 2 MeV. The energy-dependent resolution (blue-dotted line) and the overall efficiency (red solid line) are shown in the insert of Fig. 1.

To interpret the measured decay-energy spectrum, Monte Carlo simulations were performed with the incoming beam characteristics, reaction mechanism, and detector resolutions taken into account. The neutron interactions within MoNA-LISA were simulated with GEANT4 [17,18] using the MENATE_R package [19] as described in Ref. [20]. Resonances were parametrized using energy-dependent Breit-Wigner line shapes [16].

The present nucleon exchange reaction is expected to populate the same positive-parity states that were populated in the one-proton-removal reaction. In that case, the valence neutron configuration of the \(^{14}\text{B}\) projectile is dominated by a \((\pi l_\text{p}_{3/2})^3\) proton configuration and a closed \(sp\) shell neutron configuration. Removing the odd proton from \(^{13}\text{B}\) is similar to the proton removal from \(^{14}\text{B}\) while the added extra odd neutron will populate states in the open \(sd\) shell.

Randisi et al. were able to fit their data from the proton-removal reaction based on selectivity arguments with only two components, an \(s\)-wave resonance at \(E_r = 0.70(11)\) MeV with a width of \(\Gamma_r = 1.70(22)\) MeV and a \(d\)-wave resonance at \(E_r = 2.40(14)\) MeV with a width of \(\Gamma_r = 0.70(32)\) MeV [6]. The best fit to the decay-energy spectrum from the present nucleon exchange reactions is shown in Fig. 1 with an \(s\)-wave resonance at \(E_r = 0.73(9)\) MeV with a width of \(\Gamma_r = 1.98(34)\) MeV and a \(d\)-wave resonance at \(E_r = 2.56(13)\) MeV with a width of \(\Gamma_r = 2.29(73)\) MeV. Overall these parameters agree with the results from Randisi et al. with only the width of the \(d\)-wave resonance being somewhat larger.

The overall cross section for populating \(^{13}\text{Be}\) with the \((-1p + 1n)\) reaction was extracted to be 0.30(15) mb which is about an order of magnitude smaller than one-proton-removal reactions on neutron-rich \(p\)-shell nuclei. Kryger et al. reported a cross section of 2.46(3) mb for the proton removal from \(^{16}\text{C}\) to \(^{15}\text{B}\) [21] and Lecouey et al. measured 6.5(15) mb for the proton-removal reaction from \(^{17}\text{C}\) to \(^{16}\text{B}\) [22].

The cross section is somewhat larger than the cross section of 0.1 mb estimated for the charge-exchange reaction based on distorted-wave Born approximation (DWBA) calculations using the code FOLD [23]. Transition densities that were input to FOLD were calculated using the shell-model code OXBASH [24]. The CKII interaction [25] was used in the \(p\)-shell-model space to calculate the transition densities for the

![FIG. 1. (Color online) Decay-energy spectrum of \(^{13}\text{Be}\) fit with two components. The solid black line is the sum of simulated decay-energy spectra from an \(s\)-wave resonance (short-dashed blue line) and a \(d\)-wave resonance (long-dashed red line) with parameters listed in the text. The insert shows the energy-dependent resolution (dotted purple line) and the overall efficiency (solid green line).](image)

![FIG. 2. (Color online) Decay-energy spectrum of \(^{13}\text{Be}\) fit with three components. The solid black line is the sum of simulated decay-energy spectra from an \(s\)-wave resonance (short-dashed blue line) and two \(d\)-wave resonances (long-dashed red line and dot-dashed green line) with parameters listed in the text.](image)
TABLE I. Resonance parameters for the three-component fits. For each state with the proposed spin and parity ($J^p$) shown, the resonance energy ($E_r$), resonance width ($\Gamma_r$), and population relative to the $1/2^+$ state ($I/I_{1/2+}$) are listed for the proton-removal reaction of Randisi et al. [6] as well as the present nucleon exchange reaction ($-1p+1n$).

<table>
<thead>
<tr>
<th>$J^p$</th>
<th>Randisi et al. [6] ($-1p$)</th>
<th>Present work ($-1p+1n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_r$ ($\text{MeV}$)</td>
<td>$\Gamma_r$ ($\text{MeV}$)</td>
</tr>
<tr>
<td>$1/2^+$</td>
<td>0.40 ± 0.03</td>
<td>0.80 ± 0.18</td>
</tr>
<tr>
<td>5/2$^+$</td>
<td>0.85 ± 0.15</td>
<td>0.30 ± 0.15</td>
</tr>
<tr>
<td>5/2$^+_2$</td>
<td>2.35 ± 0.14</td>
<td>1.50 ± 0.40</td>
</tr>
</tbody>
</table>

$^a$Fixed value from Randisi et al. [6].

$^b$Value taken from two-parameter fit.

$^9$Be-$^9$B system, and the WBP interaction [26] was used in the $spsdpf$-shell-model space to calculate the transition densities for the $^{13}$B $-^{13}$Be system. The effective nucleon-nucleon interaction of Ref. [27] was double folded over the transition densities to produce form factors. Optical-model potential parameters were taken from Ref. [28].

Guided by (0–3)$hao$ shell-model calculations Randisi et al. analyzed their data by introducing a second lower-lying $d$-wave resonance [6]. The resonance energies and widths for this analysis are listed in Table I together with the parameters used to fit the present data as shown in Fig. 2. A completely unconstrained three-resonance fit resulted in degenerate values for the lower two resonances. Thus the values for the $s$-wave resonance were constrained to the value of Randisi et al. ($E_r = 0.40 \text{ MeV}$, $\Gamma_r = 0.80 \text{ MeV}$) and the parameters for the second $d$-wave resonance were kept at the value extracted from the two-parameter fit ($E_r = 2.56 \text{ MeV}$, $\Gamma_r = 2.29 \text{ MeV}$). The resonance energy and width of the first $d$-wave resonance as well as strength of all three components were varied. Figure 2 shows that the nucleon exchange data can be well described with parameters similar to the one-proton-removal reaction.

Table I also includes the ratios of the $d$-wave resonances relative to the $s$-wave resonance for the two reactions. The relative intensities in the proton-removal reaction are governed by the ground-state configuration of $^{14}$B where the spectroscopic factors for populating the 1/2$^+$, 5/2$^+_1$, and 5/2$^+_2$ states were calculated within the WBP shell model to be 0.41, 0.13, and 0.43, respectively, in good agreement with the data [6]. The 1/2$^+$ and 5/2$^+_2$ states are dominated by single-particle configurations, whereas the 5/2$^+_1$ has 2$hao^{10}$Be $\otimes (v2s1d)^3$ parentage.

The intensity of the low-lying $d$-wave resonance in the nucleon exchange reaction is slightly larger than the intensity extracted from the proton-removal reaction, while the intensity of the second $d$-wave resonance is significantly larger. These ratios do not have to be the same for the two different reactions. For example, in addition to the two 5/2$^+$ states, the (0–3)$hao$ shell-model calculations also predict a low-lying 3/2$^+$ state. The spectroscopic factor of this state for proton removal from $^{14}$B is zero, so it is not expected to be observed in the data of Randisi et al. [6]. It could, however, be populated in the present reaction which would reduce the strengths of the two $d$-wave resonances relative to the low-lying $s$-wave resonance. It should be mentioned that the low-lying 3/2$^+$ and 5/2$^+$ states predicted by the (0–3)$hao$ shell-model calculations using the WBP interaction [6] are not present in the simplified scheme by Fortune [29]. This discrepancy has recently been reiterated and is not fully understood [30].

Finally, the present data show no evidence of any low-energy decay from the second $d_{5/2}$ to the first excited 2$^+$ state in $^{12}$Be as was suggested by Aksyutina et al. [5]. Simulations including such a decay branch resulted in an upper limit of less than 10%. This finding is consistent with results by Randisi et al. who extracted a branching ratio of 5(2)% [6].

IV. SUMMARY AND CONCLUSION

In conclusion, the $^{13}$B($-1p+1n$) nucleon exchange reaction was used to populate the neutron-unbound nucleus $^{15}$Be. The decay-energy spectrum can be described with resonance parameters similar to previously reported values for the proton-removal reaction from $^{14}$B. In general nucleon exchange reactions offer an alternative reaction mechanism to selectively populate states in neutron-rich nuclei when the nucleus of interest cannot be populated by single-proton (i.e., $^{13}$Be, $^{20}$B, or $^{24}$N) or even two-proton ($^{23}$C) removal reactions.

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