Population of 13Be in a Nucleon Exchange Reaction

B. R. Marks
Hope College

P. A. DeYoung
Hope College

J. K. Smith
Michigan State University

See next page for additional authors

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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


1 Department of Physics, Hope College, Holland, Michigan 49442, USA
2 National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
3 Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
4 Department of Physics, Wabash College, Crawfordsville, Indiana 47933, USA
5 Department of Physics and Astronomy, Augustana College, Rock Island, Illinois 61201, USA
6 Department of Physics and Astronomy, Indiana University at South Bend, South Bend, Indiana 46634, USA
7 Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA
8 Department of Physics, Concordia College, Moorhead, Minnesota 56562, USA
9 Department of Physics, Gettysburg College, Gettysburg, Pennsylvania 17325, USA

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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 $E_\gamma = 0.73(9)$ MeV with a width of $\Gamma_\gamma = 1.98(34)$ MeV and a d-wave resonance at $E_\gamma = 2.56(13)$ MeV with a width of $\Gamma_\gamma = 2.29(73)$ 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), preferred an interpretation which fits the $\sim$500 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- 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 $\sim$500 keV peak consists of an s-wave resonance as well as a low-lying d-wave resonance. In addition, Randisi et al. searched for the decay of the d$_{3/2}$ 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 and $^{48}$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 $^{26}$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...
produced in a nucleon exchange reaction and immediately decayed into $^{12}$Be + n.

The $^{12}$Be reaction products were deflected by a large-gap sweeper magnet [12] and identified from energy-loss and time-of-flight measurements. The $^{12}$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 $^{12}$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 $^{13}$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 $^{14}$B projectile is dominated by a $\pi 1p_{3/2}$ $^3$ proton configuration and a closed $sp$ shell neutron configuration. Removing the odd proton from $^{13}$B is similar to the proton removal from $^{14}$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 $^{13}$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 $^{16}$C to $^{15}$B [21] and Lecouey et al. measured 6.5(15) mb for the proton-removal reaction from $^{17}$C to $^{16}$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 $^{13}$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).

FIG. 2. (Color online) Decay-energy spectrum of $^{13}$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.
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. \((-1p)\) [6] as well as the present nucleon exchange reaction \((-1p+1n)\).

<table>
<thead>
<tr>
<th>(J^p)</th>
<th>(E_r ) (MeV)</th>
<th>(\Gamma_r ) (MeV)</th>
<th>(I/I_{1/2^+})</th>
<th>(E_r ) (MeV)</th>
<th>(\Gamma_r ) (MeV)</th>
<th>(I/I_{1/2^+})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1/2^+)</td>
<td>0.40 ± 0.03</td>
<td>0.80 ± 0.18</td>
<td>1.00</td>
<td>0.40 (^a)</td>
<td>0.80 (^b)</td>
<td>1.00</td>
</tr>
<tr>
<td>(5/2^+)</td>
<td>0.85 ± 0.15</td>
<td>0.30 ± 0.14</td>
<td>0.40 ± 0.07</td>
<td>1.05 ± 0.10</td>
<td>0.50 ± 0.20</td>
<td>0.63 ± 0.15</td>
</tr>
<tr>
<td>(5/2^+)</td>
<td>2.35 ± 0.14</td>
<td>1.50 ± 0.40</td>
<td>0.80 ± 0.09</td>
<td>2.56 ± 0.13 (^b)</td>
<td>2.29 ± 0.73 (^b)</td>
<td>3.88 ± 0.50</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 \(5/2^+_2\) 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 \(2hao \ ^{10}\)Be \(\otimes (\nu 2s 1d)^3\) 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 \(d\) 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 \(^{13}\)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., \(^{15}\)Be, \(^{20}\)B, or \(^{24}\)N) or even two-proton (\(^{23}\)C) removal reactions.

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