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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 Er=0.73(9)MeV with a width of Γr=1.98(34)MeVand a d-wave resonance at Er=2.56(13)MeV with a width of Γr=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 $E_r = 0.73(9)$ 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 ^{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 ∼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 ∼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 $d_{5/2}$ resonance at 2 MeV to the first excited 2^+ state in ^{12}Be by measuring the γ 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 ^{46}Cl) beams to explore the structures of ^{48}K, ^{48}Ar, and ^{46}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(^{46}Cl,^{46}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 8×10^5 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

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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].

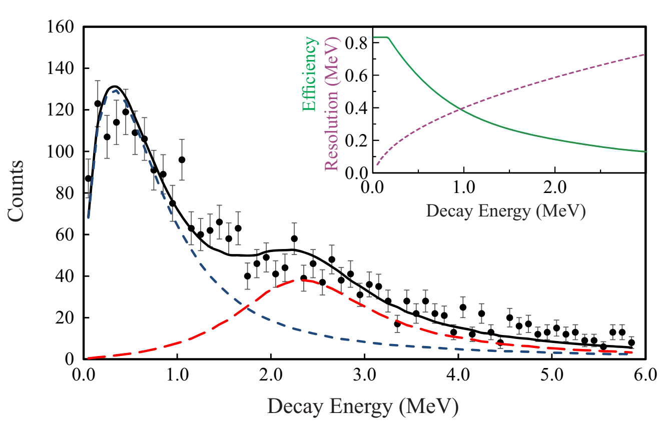

FIG. 1. (Color online) Decay-energy spectrum of ^{13}Be fit with two components. The solid black line is the sum of simulated decay-energy spectra from an s-wave resonance (short-dashed blue line) and a d-wave resonance (long-dashed red line) with parameters listed in the text. The insert shows the energy-dependent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

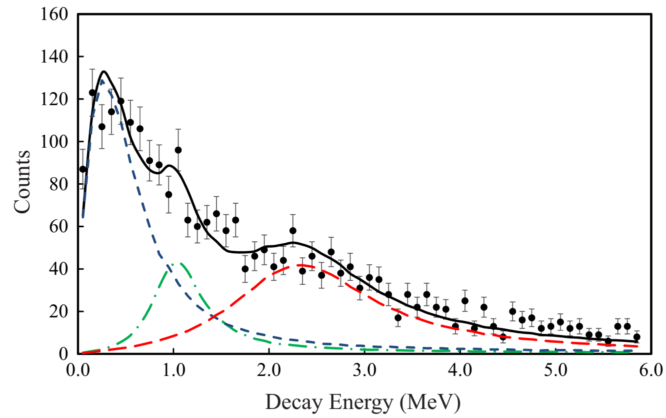

FIG. 2. (Color online) Decay-energy spectrum of ^{13}Be fit with three components. The solid black line is the sum of simulated decay-energy spectra from an s-wave resonance (short-dashed blue line) and two d-wave resonances (long-dashed red line and dot-dashed green line) with parameters listed in the text.

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 $\nu 2s_{1/2}$ and $\nu 1d_{5/2}$ components, and states with the same configurations are expected to be populated in ^{13}Be by proton removal [6]. The ground state of ^{13}B has spin and parity of $3/2^-$ 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

TABLE I. Resonance parameters for the three-component fits. For each state with the proposed spin and parity (J^{π}) shown, the resonance energy (E_r), resonance width (Γ_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 ($-1p+1n$).

	Randisi *et al.* [6] ($-1p$)			Present work ($-1p+1n$)		
J^{π}	E_r	Γ_r	$I/I_{1/2^+}$	E_r	Γ_r	$I/I_{1/2^+}$
$1/2^+$	0.40 ± 0.03	$0.80^{+0.18}_{-0.12}$	1.00	0.40[a]	0.80[a]	1.00
$5/2^+_1$	$0.85^{+0.15}_{-0.11}$	$0.30^{+0.34}_{-0.15}$	0.40 ± 0.07	1.05 ± 0.10	0.50 ± 0.20	0.63 ± 0.15
$5/2^+_2$	2.35 ± 0.14	1.50 ± 0.40	0.80 ± 0.09	2.56 ± 0.13[b]	2.29 ± 0.73[b]	3.88 ± 0.50

[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 $^{13}\mathrm{B} - ^{13}\mathrm{Be}$ 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)$\hbar\omega$ 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 MeV, $\Gamma_r = 0.80$ MeV) and the parameters for the second d-wave resonance were kept at the value extracted from the two-parameter fit ($E_r = 2.56$ MeV, $\Gamma_r = 2.29$ 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 $2\hbar\omega$ $^{10}\mathrm{Be} \otimes (\nu 2s1d)^3$ 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)$\hbar\omega$ 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)$\hbar\omega$ 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 $^{13}\mathrm{B}(-1p+1n)$ 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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