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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) mb 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

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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 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.

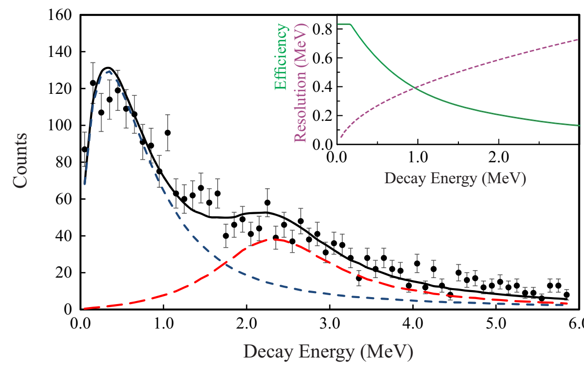

FIG. 1. (color online) Decay-energy spectrum of ^{13}Be fit with two components. The solid black line is the sum of simulated decay-energy spectra from an s-wave resonance (short-dashed blue line) and a d-wave resonance (long-dashed red line) with parameters listed in the text. The insert shows the energy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

III. DATA ANALYSIS

The decay energy spectrum of ^{13}Be was reconstructed by the invariant-mass method and is shown in Figures 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 Figure 1.

In order 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 parameterized 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 $\nu 2s_{1/2}$ 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.* was 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 Figure 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 $(-1\text{p}+1\text{n})$ 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 recation 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 [25]. Transition densities that were input to FOLD were calculated using the shell-model code OXBASH [26]. The CKII interaction [27] was used in the p-shell model space to calculate the transition densities for the ^{9}Be–^{9}B system, and the WBP interaction [28] 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. [29] was double-folded over the transition densities to produce form factors. Optical-model potential parameters were taken from Ref. [30].

Guided by $(0-3)\hbar\omega$ shell model calculations Randisi

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 the 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).

J^π	E_r	Γ_r	$I/I_{1/2^+}$	E_r	Γ_r	$I/I_{1/2^+}$
	Randisi *et al.* [6] (−1p)			present work (−1p+1n)		
$1/2^+$	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

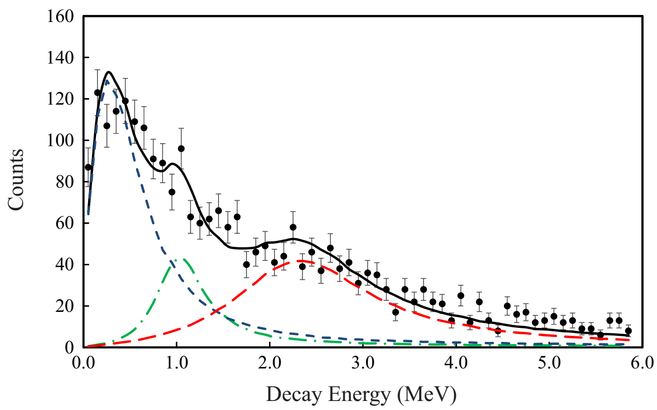

FIG. 2. (color online) Decay-energy spectrum of ^{13}Be fit with three components. The solid black line is the sum of simulated decay-energy spectra from an s-wave resonance (short-dashed red line) and two d-wave resonances (long-dashed red line and dot-dashed green line) with parameters listed in the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

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 Figure 2. A completely unconstrained three-resonance fit resulted in degenerate values for the lower two resonances. Thus the values for the s-wave resonance was 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}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 [23]. This discrepancy has recently been reiterated and is not fully understood [24].

Finally, the present data show no evidence for 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 ^{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 can not 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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