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A two-proton knockout reaction from a ^{17}C beam at 55 MeV/u was used to produce the unbound nucleus ^{15}Be. No significant number of events were observed for the decay of ^{15}Be into a neutron and a ^{14}Be fragment. An upper limit for the ^{14}Be production cross section of 0.079±0.038 mb was extracted, which is more than an order of magnitude smaller than the predicted two-proton knockout reaction cross section. Based on these results we conclude that any populated states in ^{15}Be decay through three sequential neutron decays into ^{12}Be, via the unbound first excited state of ^{14}Be. Therefore, these states in ^{15}Be must be neutron unbound by more than 1.54 MeV, which is the location of the first excited 2^+ state in ^{14}Be.

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I. INTRODUCTION

Exotic structures at the neutron drip line have recently been the subject of many experimental and theoretical studies. Neutron-unbound nuclei have become accessible at major radioactive beam facilities around the world via the use of invariant mass analysis. Although not as sensitive as γ spectroscopy, this neutron spectroscopy extends the study of the evolution of the nuclear shells even beyond the neutron drip line (e.g. [1–4]).

A special type of decay of neutron-rich systems is the decay via two-neutron emission. Several 2n-unbound states have been studied using invariant mass analysis such as the recent experiments on ^{11}Li, ^{14}Be, and ^{24}O [1, 5, 6]. Two-neutron radioactivity has been observed in β-delayed neutron emission experiments, e.g. [7], which corresponds to two sequential single neutron decays. In order to study the simultaneous 2n decay mechanism, it is beneficial to look for nuclei which are unbound with respect to two-neutron emission but bound with respect to single neutron emission. The nucleus ^{16}Be is predicted to be such a case. Shell model calculations (see Section III for details) predict that the neutron separation energy for ^{16}Be is $S_{\rm n} = +1.8$ MeV, while the 2n-separation energy is $S_{\rm 2n} = -0.9$ MeV (Fig. 1, black dashed lines). Extrapolations in the latest Atomic Mass Evaluation (AME2003) [8] ssuggest that ^{16}Be is possibly bound for single neutron emission by 0.2 MeV, but unbound with respect to the 2n decay into ^{14}Be by 1.58 MeV (Fig. 1, grey dashed lines). The uncertainties in both values are more than 0.5 MeV and are indicated in the figure by grey boxes. Experimentally, ^{16}Be is known to be unbound since 2005 through the fragmentation of an ^{40}Ar beam on a Be target [9]. ^{15}Be was never specifically shown to be unbound, however, the fact that its heavier isotone ^{16}B is unbound [10, 11] strongly supports the assumption that ^{15}Be is indeed neutron unbound. The first step in identifying whether ^{16}Be decays by simultaneous 2n-emission is to identify the location of the unbound ^{15}Be, which is the goal of the present work.

II. EXPERIMENTAL DETAILS

The experiment was carried out at the National Superconducting Cyclotron Laboratory at Michigan State University. The fragmentation of a stable ^{22}Ne primary beam on a 1810 mg/cm^2 Be target was used to produce a ^{17}C beam

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at 55 MeV/u, which was selected in the A1900 fragment separator. ^{15}Be was populated via the two-proton knockout reaction from the ^{17}C secondary beam on a 470 mg/cm^2 thick Be target. The experimental setup was identical to the one used in [13]. It consisted of the Modular Neutron Array for neutron detection and the Sweeper dipole magnet together with a suite of particle detectors for the detection of the recoiling fragments. More details of the setup can be found in Ref. [13].

The incoming ^{17}C beam was 73% pure. The main contaminants were products of beam interaction with the Al wedge degrader at the intermediate focal plane of the A1900. These contaminants were removed in the offline analysis using the time-of-flight between the A1900 focal plane and a timing scintillator placed in front of the reaction target (Fig. 2a). The ^{17}C-beam gate shown in Fig.2a contained less than 0.5% contamination from lighter elements. The element identification after the reaction is shown in Fig. 2b in a ΔE–E spectrum. The brightest group corresponds to the ^{17}C incoming beam, providing a reliable guide for the element identification shown in the figure. The second group in the carbon region is a small fraction of the incoming beam that missed the target. Gating on the beryllium group from Fig. 2b the different isotopes of beryllium were identified in Fig. 2c (black dots), where the x-axis was calibrated to be the mass/charge (A/Z) ratio. Three prominent peaks in the spectrum correspond to the isotopes ^{10,11,12}Be. The region around $A/Z = 3.5$, where the isotope ^{14}Be was expected, presents no clear peak. The open circles in Fig. 2c correspond to the same isotopes of beryllium, requiring a neutron coincidence, showing even more clearly that the region where ^{14}Be was expected presents no signature of this isotope.

The rigidity of the Sweeper magnet was set so that ^{14}Be would be within the acceptances of the charged-particle detectors. The other three isotopes had lower rigidities and thus only a fraction of their distribution could be detected. The divergence of each isotope from the central trajectory can be observed through a position spectrum taken with the Cathode-Readout Drift Chamber (CRDC), positioned at the exit of the Sweeper magnet. The position spectrum that corresponds to the beryllium isotopes is shown in Fig. 2d. The isotopes ^{10,11,12}Be are less rigid than the Sweeper magnet setting and are shown in the right hand side of the spectrum, with their distributions limited by acceptance cuts. The events that could correspond to ^{14}Be from Fig. 2c are also shown in the position spectrum (solid black line). ^{14}Be had a higher rigidity compared to the magnet setting and was expected on the left-hand side of the spectrum. Even though no prominent peak was observed in the isotope identification spectrum, the few observed events seem to be located at the expected position. These events were used to estimate an upper limit in the ^{14}Be production cross section. It should be noted that the spectra shown in Fig. 2d do not require a coincidence with events in the neutron detector array, therefore the observed events could come from all possible reaction mechanisms that can produce ^{14}Be from a ^{17}C + ^{9}Be reaction.

The cross section calculation included the absolute detection efficiencies and geometric acceptances of all detectors used for this measurement. Some of the detector efficiencies changed during the measurement period due to detector modifications and drifts, therefore the corrections were done separately for each run. The average charged particle detection efficiency throughout the experiment was 39(12)%. This included all detectors used for the particle identification which were: two CRDCs, the timing scintillator at the target location and the thin scintillator used for energy loss. For the calculation of the geometric acceptances the experimental setup was described in a Monte Carlo simulation which included the characteristics of the detectors as well as the reaction mechanism and energy loss components. The geometric acceptance for ^{14}Be fragments was 65(7)%. Since no prominent peak was observed in the region of interest, the width of the gate was taken based on the neighboring isotopes resulting in an area of 264$\pm$ 89. Assuming that all the observed events belong to the ^{14}Be isotope, the ^{14}Be production cross section was determined to be 0.079$\pm$0.038 mb. For the reasons stated above this can only be taken as an upper limit.

III. DISCUSSION

Shell model calculations were performed using the code NuShellX [14]. The calculations were done in the *s*-*p*-*sd*-*pf* model space using the WBP Hamiltonian [12]. Specific truncations were used which restricted the valence proton excitations within the *p* shell and the valence neutron excitations within the *p* and *sd* shell. No neutron excitations to the *pf* shell were allowed. These calculations predicted a $3/2^+$ ground state for ^{15}Be together with a low lying $5/2^+$ excited state at approximately 300 keV and additional states above 1.2 MeV excitation energy. In a direct two-proton knockout reaction from a ^{17}C beam the only state that is expected to have any significant population in ^{15}Be is the $3/2^+$ ground state. The spectroscopic overlaps for transitions to the excited states are small (< 0.1). Direct two-proton removal cross section calculations were performed using these shell-model spectroscopic overlaps (expressed as two nucleon amplitudes) and using the methodology detailed in Refs. [15, 16]. This model was shown to be in good agreement with two-proton knockout reaction experiments [17, 18]. The predicted 2p-removal reaction cross section to the ^{15}Be ground state is 0.99 mb.

According to this calculated cross section one would expect to observe an order of magnitude more ^{15}Be decays in the experiment. Since this is not the case we can conclude that ^{15}Be is populated, however there might be an alternative path for its decay. One such possible path would be available if the populated state in ^{15}Be was located above the first excited 2^+ state in ^{14}Be, which is unbound. This state was measured to be at an excitation energy of 1.54 MeV [1]. Decays into this state will then proceed through two additional sequential neutron decays (as shown in Fig. 3) resulting in ^{12}Be + 3n. The present experiment did not collect sufficient statistics to attempt the challenging task of a three-neutron analysis. Nevertheless, based on these results one can conclude that the ground state of ^{15}Be is probably unbound by more than 1.54 MeV.

The result of the present work is also in agreement with the previously known structure of the three nuclei involved in this experiment, namely ^{17}C and ^{14,15}Be. Simple shell model assumptions would place the last 3 neutrons of ^{17}C in the $d_{5/2}$ orbital, suggesting a $5/2^+$ ground state. However, It was shown in many experiments (e.g. [19–21]) that the ground state spin and parity of ^{17}C is $3/2^+$ coming from the coupling of a mixture of a $s-d$ neutron to the first excited state of a ^{16}C core (2^+), with the dominant component being the d. Starting with this ground state configuration in ^{17}C and assuming that the removal of two protons leaves the remaining neutrons undisturbed (e.g. [22–24]), the populated states in ^{15}Be should also have this complex structure. On the other hand, ^{14}Be has been of experimental and theoretical interest due to its 2n-halo structure. Recent theoretical analysis has shown that the ground state configuration of ^{14}Be is most probably also a complex one, having components from the coupling of s, p and d neutrons with a ^{12}Be(0^+) core, but also with an excited ^{12}Be(2^+) core [25, 26]. Sugimoto et al. [1] argue (based on shell model calculations) that ^{14}Be(g.s.) should be a normal (traditional) ^{12}Be core with the two valence neutrons occupying levels in the sd shell and with the first excited 2^+ state being a $0\hbar\omega$ excitation within the neutron sd orbitals. The NuShellX calculations performed in the present work result in similar configurations as the ones described by Sugimoto et al. [1] for both the 0^+ ground state and the 2^+ excited state. Based on these calculations the spectroscopic factor between the $3/2^+$ ground state of ^{15}Be and the 0^+ state in ^{14}Be is 0.043 (ℓ=2). The overlaps with the 2^+ state in ^{14}Be are 1.27 with ℓ=2 and 0.084 with ℓ=0. If energetically possible, the most probable decay from ^{15}Be($3/2^+$) is thus the ℓ=0 decay to the first excited ^{14}Be(2^+). These calculations support our conclusion that the $3/2^+$ state in ^{15}Be is neutron unbound by more than 1.54 MeV and decays through the excited 2^+ state in ^{14}Be. In addition, our results provide an independent consistency check of the configurations of the ground state of ^{17}C and of ^{14}Be, since the previous description of these isotopes is able to reproduce our results. The conclusions of the present work support the arguments that ^{16}Be is expected to be bound with respect to single neutron emission and it therefore remains a good candidate for the study of a simultaneous 2n-decay.

IV. CONCLUSIONS

The present work reports a first attempt to populate and study the neutron-unbound nucleus ^{15}Be. A two-proton knockout reaction from a ^{17}C secondary beam was used, with an expected cross section of the order of 1 mb. Based on the small number of events observed in the ^{14}Be ground state channel we conclude that ^{15}Be is unbound by more than 1.54 MeV. In this case the observed results can be explained by the decay of ^{15}Be through the first excited state in ^{14}Be. The latter is neutron unbound and would not have been observed in the present setup. Shell model calculations support this conclusion although one cannot be certain that the aforementioned $3/2^+$ state in ^{15}Be is indeed the ground state, as predicted by the shell model, or a low lying excited state. In any case its structure cannot be described as a ^{14}Be(0^+) core plus one neutron, but rather as a ^{14}Be(2^+) core + n. If the populated state in ^{15}Be is indeed the ground state as predicted, we can conclude that the neutron separation energy of ^{15}Be is expected to be high (negative), supporting the expectation that ^{16}Be should be unbound only with respect to two neutron emission. In order to gain a better insight into the structure of ^{15}Be, different reactions will need to be used to populate it, such as the ^{14}Be(d,p)^{15}Be, which ensures the strong spectroscopic overlap between the ground state of ^{14}Be and any populated states in ^{15}Be.

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Figures

FIG. 1: Decay and level schemes for neutron rich Be isotopes. The dashed lines correspond to shell model calculations with the WBP interaction [12], while the dotted lines are taken from AME2003 [8]. The grey boxes indicate the uncertainty in the AME2003 values. The solid black lines represent the ground state and first excited state of ^{14}Be from Ref. [1].

FIG. 2: (Color Online) a) Incoming beam identification from time-of-flight between A1900 and target, b) ΔE - E element identification spectrum, c) Beryllium isotopes with (open circles) and without (black dots) neutron coincidences. The dashed lines show the area where ^{14}Be fragments were expected and they denote the gate used for the cross section calculation. d) Position spectrum after the sweeper magnet for beryllium isotopes.

FIG. 3: Proposed decay scheme for the decay of the $3/2^+$ state in ^{15}Be. The decay to the ground state of ^{14}Be (dashed line) is expected to be weak, and the main decay path should be the decay through the first excited 2^+ state.

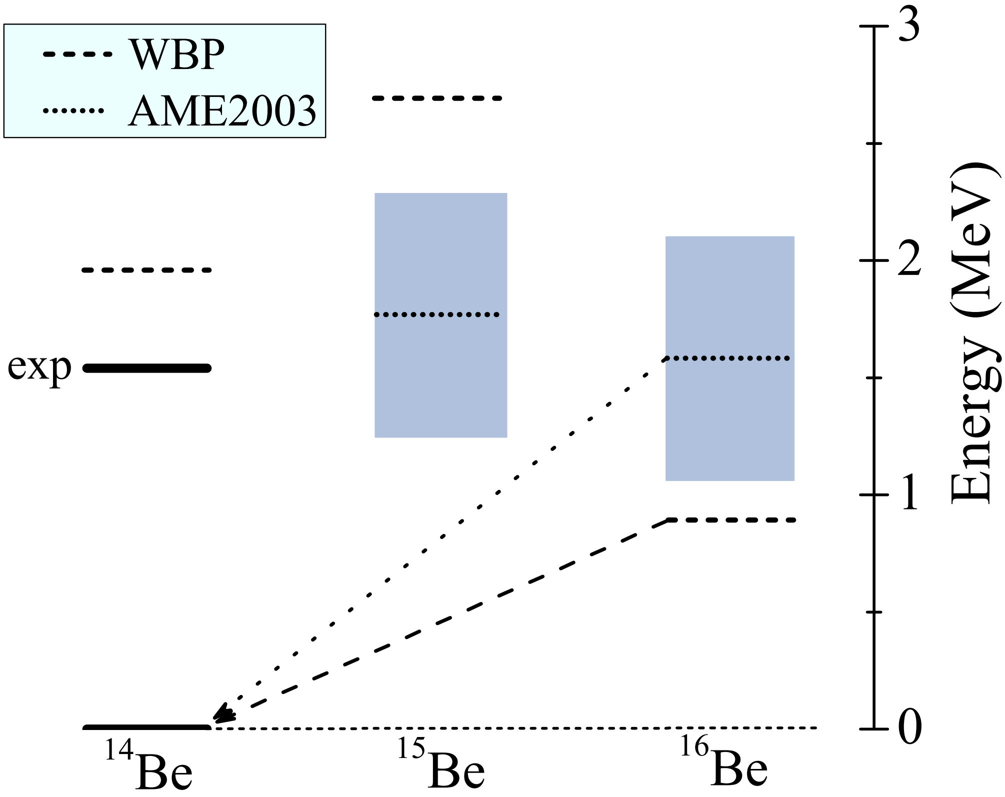
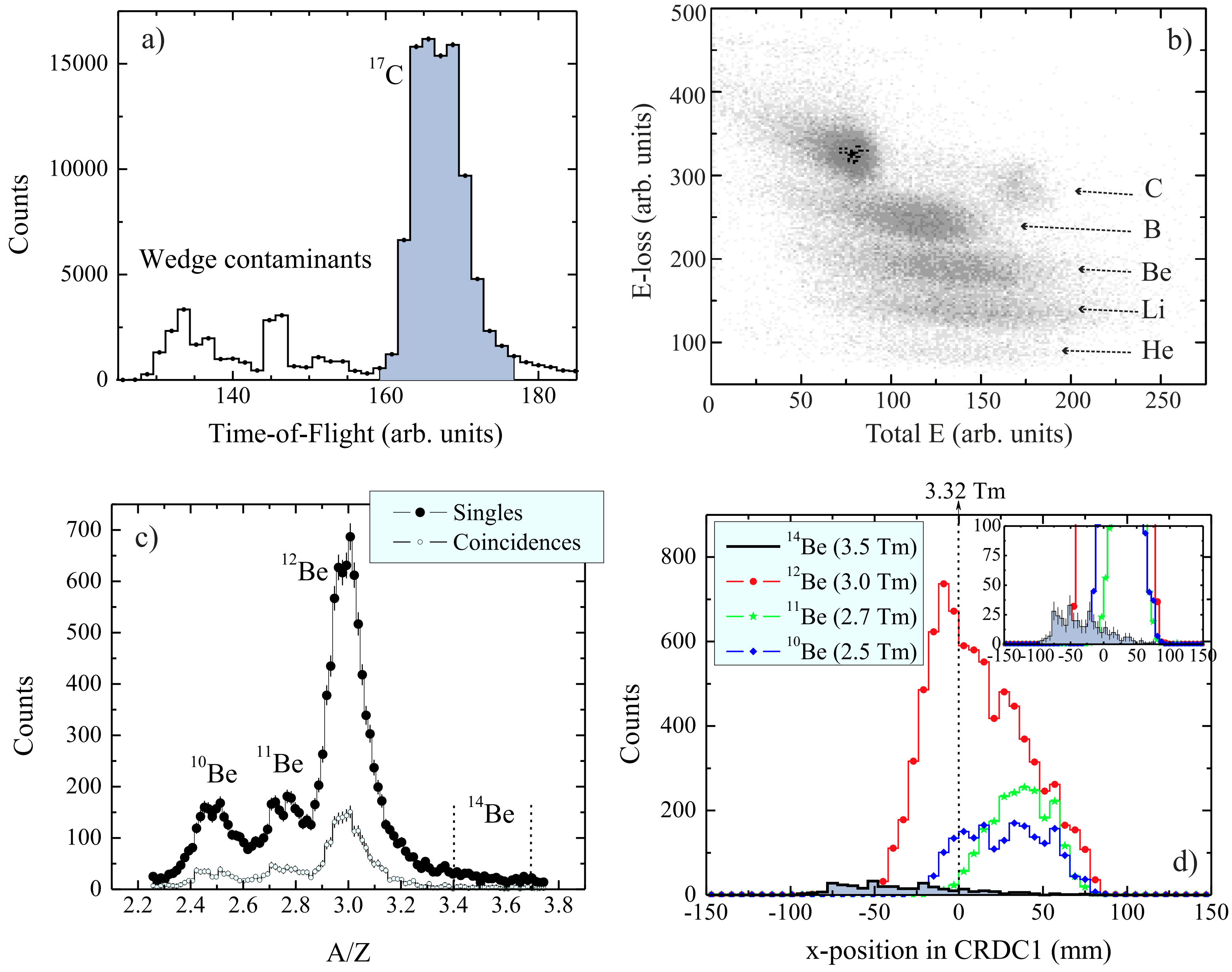


Figure 1 CG10264 07Sep2011

Figure 2 CG10264 07Sep2011



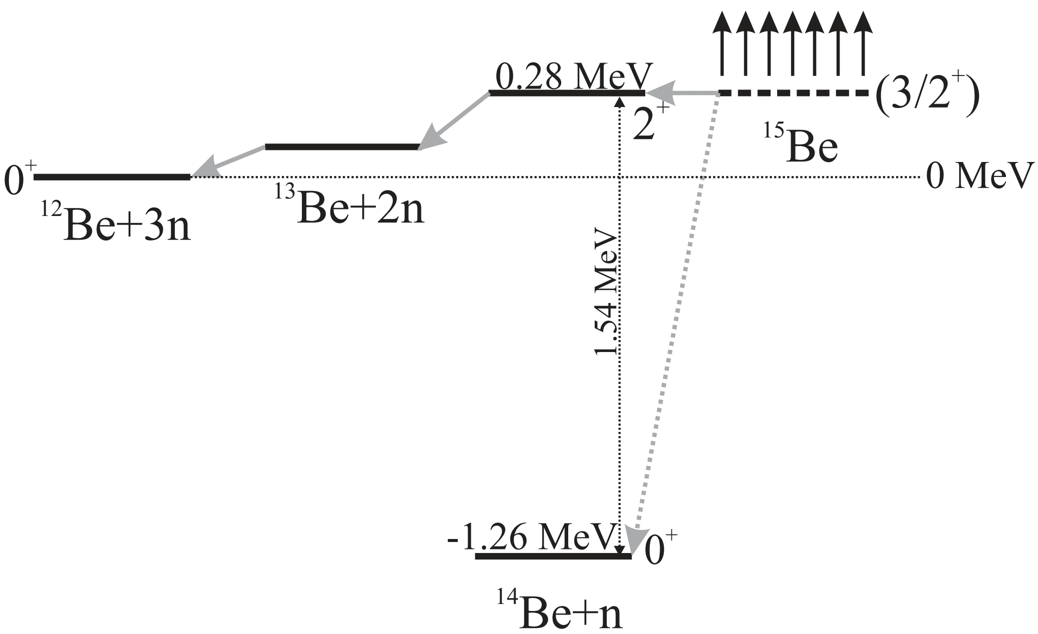


Figure 3 CG10264 07Sep2011