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Phys. Rev. Lett. **108**, 102501 — Published 9 March 2012

DOI: 10.1103/PhysRevLett.108.102501

First observation of ground state dineutron decay: ^{16}Be

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We report on the first observation of dineutron emission in the decay of ^{16}Be. A single-proton knockout reaction from a 53 MeV/u ^{17}B beam was used to populate the ground state of ^{16}Be. ^{16}Be is bound with respect to the emission of one neutron and unbound to two-neutron emission. The dineutron character of the decay is evidenced by a small emission angle between the two neutrons. The two-neutron separation energy of ^{16}Be was measured to be 1.35(10) MeV in good agreement with shell model calculations using standard interactions for this mass region.

PACS numbers 1.10.-k 7.20.+n 1.10.Dr

Exotic types of radioactivity have been proposed and searched for with great interest for decades. The simultaneous two-proton decay was proposed by Goldansky [1] for nuclei with an even number of protons beyond the dripline. This 2p decay can proceed either through a simultaneous three-body breakup or through the emission of a diproton system which then breaks up into two protons later in the decay. Two-proton radioactivity was observed for the first time in 2002 [2, 3]. Although some evidence for the observation of a diproton has been reported (e.g. [4, 5] and most recently in [6]) no clear cases are presently known [7]. Blank and Ploszajczak state in their review: "All experiments performed up to now seem to indicate that the sequential decay prevails, as long as intermediate states for 1p emission are energetically accessible." In addition, the identification of diproton clusters is difficult since even if they could be present inside the nucleus they may not survive as they penetrate the Coulomb barrier.

In analogy to the proton dripline, dineutron emission could be possible beyond the neutron dripline. The absence of the Coulomb barrier would make the identification easier as the correlation of the dineutron cluster would be better conserved during the decay. Hansen and Jonson first suggested the presence of a dineutron in the two-neutron halo nucleus ^{11}Li [8]. Charge radii measurements in ^{8}He and ^{6}He indicated that the two halo-neutrons in ^{6}He are preferentially located together on one side of the ^{4}He core [9].

Previous measurements of multiple neutron emissions in β-delayed two- and three-neutron radioactivity [10, 11] did not measure any neutron correlations, and the decays most likely proceed sequentially via intermediate states, similar to the proton emitters. An ideal case for searching for dineutron decay is an unbound nucleus for which the single-neutron emission is greatly suppressed. This is the case for nuclei beyond the neutron dripline where a nucleus is bound with respect to single-neutron emission but unbound with respect to two-neutron emission. Two such nuclei, ^{5}H and ^{10}He [12, 13], have been studied, and some evidence for a dineutron component has been observed in ^{10}He [13]. In both cases the intermediate unbound systems (^{4}H and ^{9}He) have broad resonances which can extend below the single-neutron emission threshold, thus favoring the sequential decay.

A nucleus predicted to be bound with respect to one-neutron emission but unbound with respect to two-neutron emission is ^{16}Be. It was shown to be unbound in a recent ^{40}Ar fragmentation experiment [14], however, nothing else is known about ^{16}Be. Shell model calculations [15] predict the one- and two-neutron separation energies to be +1.8 MeV and −0.9 MeV, respectively. Mass extrapolations from the Atomic Mass Evaluation 2003 [16] assign corresponding values of +0.2(7) MeV and −1.6(5) MeV. The intermediate system, ^{15}Be, was found to be unbound by more than 1.54 MeV in our previous work [15], in agreement with shell model calculations. Knowing the location of the intermediate system, even as a lower limit, is important for characterizing the 2n-unbound ^{16}Be. The level and decay schemes for neutron rich beryllium isotopes are shown in Fig. 1. Sequential two-neutron emission from ^{16}Be is expected to be suppressed since the ground state of ^{15}Be is a narrow resonance at a significantly higher energy. This makes ^{16}Be an ideal candidate for the search of dineutron decay. In the present work we report on the first observation of this exotic decay in ^{16}Be.

A single-proton knockout reaction from a ^{17}B beam was used to populate ^{16}Be. Knockout reactions have been shown to be a powerful tool for studying the structure of

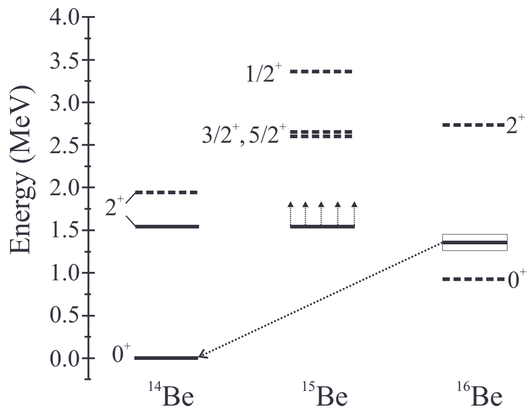

FIG. 1: Level and decay scheme for neutron rich isotopes of beryllium. The solid lines correspond to experimental data from [17], [15] and the present work, while the dashed lines represent shell model calculations in the *s*-*p*-*sd*-*pf* model space using the WBP interaction [18]

exotic nuclei at these energies [19]. Knowing the configuration of the initial beam-nucleus ground state, as well as that of the final state, can help with understanding the observed decay. In the case of a two-neutron decay, the energy and structure of the intermediate system is also important. In this case the beam nucleus ^{17}B is known to have a significant mixing of the $\nu(2s_{1/2})$ and $\nu(1d_{5/2})$ configurations [20–22], which provides evidence for a two-neutron halo structure. ^{16}Be is therefore expected to be populated with a similar neutron configuration. The picture is similar for the final nucleus ^{14}Be, with a known two-neutron halo structure; however, it is more complicated due to the fact that its ground state probably has components from the coupling of s, p and d neutrons with not only a ^{12}Be(0^+) core, but also with an excited ^{12}Be(2^+) core [23, 24]. ^{14}Be has no bound excited states and therefore any ^{14}Be events observed in our experiment correspond to its ground state. The goal of the experiment was to populate the 0^+ ground state of ^{16}Be and reconstruct its decay into ^{14}Be and two neutrons.

The experiment was performed at the National Superconducting Cyclotron Laboratory, at Michigan State University. A 120 MeV/u ^{22}Ne primary beam impinged on a 2938 mg/cm^2 Be target to produce the secondary ^{17}B beam at 53 MeV/u. The ^{17}B beam was selected through the A1900 fragment separator [25] with the use of a 1050 mg/cm^2 Al achromatic degrader at its intermediate focal plane. The average total secondary beam intensity was 250 pps, of which 75% corresponded to the isotope of interest, ^{17}B. The other main beam component was ^{19}C together with some additional light fragments that were produced in the Al degrader. The different components of the beam were separated by time-of-flight. Less than 0.1% contamination from the ^{19}C beam component was present in the ^{17}B beam gate.

The ^{16}Be nucleus of interest, was populated via a one-proton knockout reaction from the ^{17}B beam interacting with a 470 mg/cm^2 beryllium target. The unbound ^{16}Be was reconstructed from the products of its decay, ^{14}Be and two neutrons. The charged fragment was bent 43° by the Sweeper dipole magnet [26] and was detected in a suite of position and energy sensitive detectors. The neutrons were detected by the Modular Neutron Array (MoNA) [14], located 7.9 m downstream from the target location, centered on the beam axis.

For the reconstruction of the ^{16}Be decay we identified events where ^{14}Be was in coincidence with two neutrons in MoNA. In order to remove cross talk events (events where a single neutron interacts twice in MoNA) and enhance the two-neutron signature, the 144 plastic scintillator bars were arranged in four separate walls, all centered along the beam axis. Each wall was 160 cm in height (16 detector bars). Three walls were 20 cm thick (2 layers of detectors, with 100 cm space between walls), while the last wall was 30 cm thick (3 layers of detectors, placed with 80 cm space to the previous wall). This geometry allowed for larger distances between the neutron interactions and improved the resolution for measuring the velocity between interaction points. The selection of two-neutron events was done by including the following conditions in the analysis [27]: A cut was applied for selecting events where the distance between the first and second hit had to be larger than 50 cm. A second cut required the time difference between the first and second hits in the detector to be shorter than the time it would take a beam-velocity neutron to travel between their respective interaction points.

The effectiveness of the cuts was tested using reactions where only one neutron was expected in the data. This was done with events from the single-proton knockout reaction from the ^{19}C component of the secondary beam. This reaction populates ^{18}B which decays by single-neutron emission to ^{17}B [28]. The number of single-neutron events from the ^{18}B decay that survived the 2n-conditions was 3.2(2)% of the total events. Based on this calculation and assuming a similar cross section for the population of ^{15}Be and ^{16}Be from ^{17}B [29, 30], we estimate that there is less than 10% contribution of single-neutron events from ^{15}Be→^{14}Be+n in our 2n-selection. It should also be noted that the contribution of 1n events from the ^{15}Be breakup counted as 2n events will add to the decay energy spectrum in the region above

3 MeV because the single-neutron that is being counted twice corresponds to a decay above 1.5 MeV.

Fig. 2 shows the experimental results (black triangles) compared to three different decay models produced in Monte Carlo simulations. The simulation package included the geometry and resolution of all detectors involved in the experiment, the map of the magnetic field, as well as the reaction and decay mechanisms. The neutron interactions in MoNA were simulated in GEANT4 [31] using the physics class MENATE_R [32] which was found to provide excellent agreement with the experimental observables. The three decay models used in the simulations which are presented in Fig. 2 were: 1) (dotted lines) A sequential emission of the two neutrons assuming that the decay proceeds through a broad state in the intermediate system ^{15}Be [33]. A decay through the $3/2^+$ and $5/2^+$ states has to be a d-wave, and because they are much higher in energy than the ^{16}Be ground state this type of sequential decay is not possible. The only possible contribution from a sequential decay is through the high lying $1/2^+$ state in ^{15}Be. This state could correspond to a broad s-wave which can extend lower in energy than ^{16}Be and allow for a sequential decay; 2) (dashed lines) A simultaneous emission of the two neutrons via a three-body breakup where the initial state breaks up into a ^{14}Be and two neutrons [34]. This breakup model represents the extreme limit of a three-body decay and includes no interactions between the three particles; 3) (solid lines) A dineutron decay. In this case the two neutrons are emitted together and the dineutron breaks up immediately after its emission. The dineutron breakup is modeled using an s-wave line shape [35] based on its known scattering length of -18.7 ± 0.7 fm [36] and pairing energy of 0.87 MeV [37]. In all three cases the initial state was simulated as a Breit-Wigner line shape.

As shown in Fig. 2, the three-body (a) and individual two-body (b, c) decay energy spectra are not sensitive to the decay mode. All three decay modes could fit the experimental data satisfactorily. However, the sequential and three-body breakup modes of decay deviate significantly from the data for the two-neutron correlation parameters. This can be seen in Fig. 2d which shows the relative energy of the two neutrons as well as in Fig. 2e which presents the opening angle between the two neutrons in the ^{16}Be center-of-mass frame. In particular, in the latter figure, the up-bend of the data at small opening angles ($\cos\theta_{\mathrm{n-n}} \sim 1$) can only be reproduced by the dineutron decay mode. We also looked for correlations between the two neutrons and the ^{14}Be fragment. Fig. 2f shows the angle between ^{14}Be and the first of the two neutrons ($\cos(\theta_{^{14}\mathrm{Be-n1}})$. Once again, the dineutron decay fits the experimental data much better than the other decay modes. These comparisons show clearly that the dominant contribution in the decay of ^{16}Be is through the emission of a dineutron. Apart from the decay mechanism, the only free parameters in our simulation were the location and width of the initial state. We performed a χ^2 minimization analysis, and the best fit to the experimental data corresponded to a two-neutron separation energy for ^{16}Be of 1.35(10) MeV with a width of $0.8^{+0.1}_{-0.2}$ MeV.

Shell model calculations were performed in the s-p-sd-pf model space with the WBP Hamiltonian [18] using the code NuShell [38]. The results of the calculations are shown in Fig. 1. The calculated two-neutron separation energy for ^{16}Be is 0.9 MeV, in reasonable agreement with the experimental result at 1.35(10) MeV and within the uncertainty of the calculations (330 keV). The ground state of ^{16}Be is expected to be populated from a ^{17}B beam via the removal of a $p_{3/2}$ proton with a spectroscopic factor, C^{2}S=0.4. The two-nucleon transfer amplitudes (TNA) for ^{16}Be to ^{14}Be obtained with WBP are 0.90, 0.33 and 0.34 for $(d_{5/2})^2$, $(d_{3/2})^2$ and $(s_{1/2})^2$, respectively. Following the formalism used for diproton decay [39], the dineutron spectroscopic factor is $S=(16/14)^4$ $(0.461)^2 = 0.36$, where all three of the TNA contribute. The full three-body phase space for two-proton decay has been calculated by Grigorenko et al. [40, 41] for pure shell-model configurations. When rates from these full three-body calculations are combined with the shell-model TNA values, good agreement for the experimental decay width of ^{54}Zn was obtained [42], but the observed angular correlations are not yet fully understood. Three-body calculations for two-neutron decay with constraints to the expected shell-model wavefunctions remain to be carried out.

Due to the absence of an angular momentum barrier, the dominant component is expected to be the s-wave. However, a three-body virtual state can be presented as a relatively sharp resonance in contrast to the two-body virtual state [43]. In this case the initial state can have a measurable width, despite its s-wave character. The shape of the initial state is most probably not the same as a standard resonance. Because of the experimental resolutions, our results are not sensitive to small changes in the shape of the decay, and for this reason, a Breit-Wigner line shape was used in our analysis.

In summary, we report on the first observation of the dineutron decay in the unbound nucleus ^{16}Be. ^{16}Be was populated via a single-proton knockout reaction from ^{17}B. The ^{16}Be decay was reconstructed event by event from the decay products $^{14}\mathrm{Be} + \mathrm{n} + \mathrm{n}$. The present observation of a dineutron decay confirms the models that predict dineutron clusters inside neutron rich nuclei. The dineutron decay observed in the present work is indicative of such a structure in the original nucleus ^{17}B, a known two-neutron halo.

The authors gratefully acknowledge the support of NSCL operations staff for providing a high quality beam during the experiment. They would also like to acknowledge the support of the MoNA Collaboration during the reconfiguration of MoNA. This work was supported by the National Science Foundation under Grants No.

PHY-08-55456, PHY-06-06007, PHY-10-68217, PHY-07-57678, and by DOE Grant No. DE-FG02-92ER40750.

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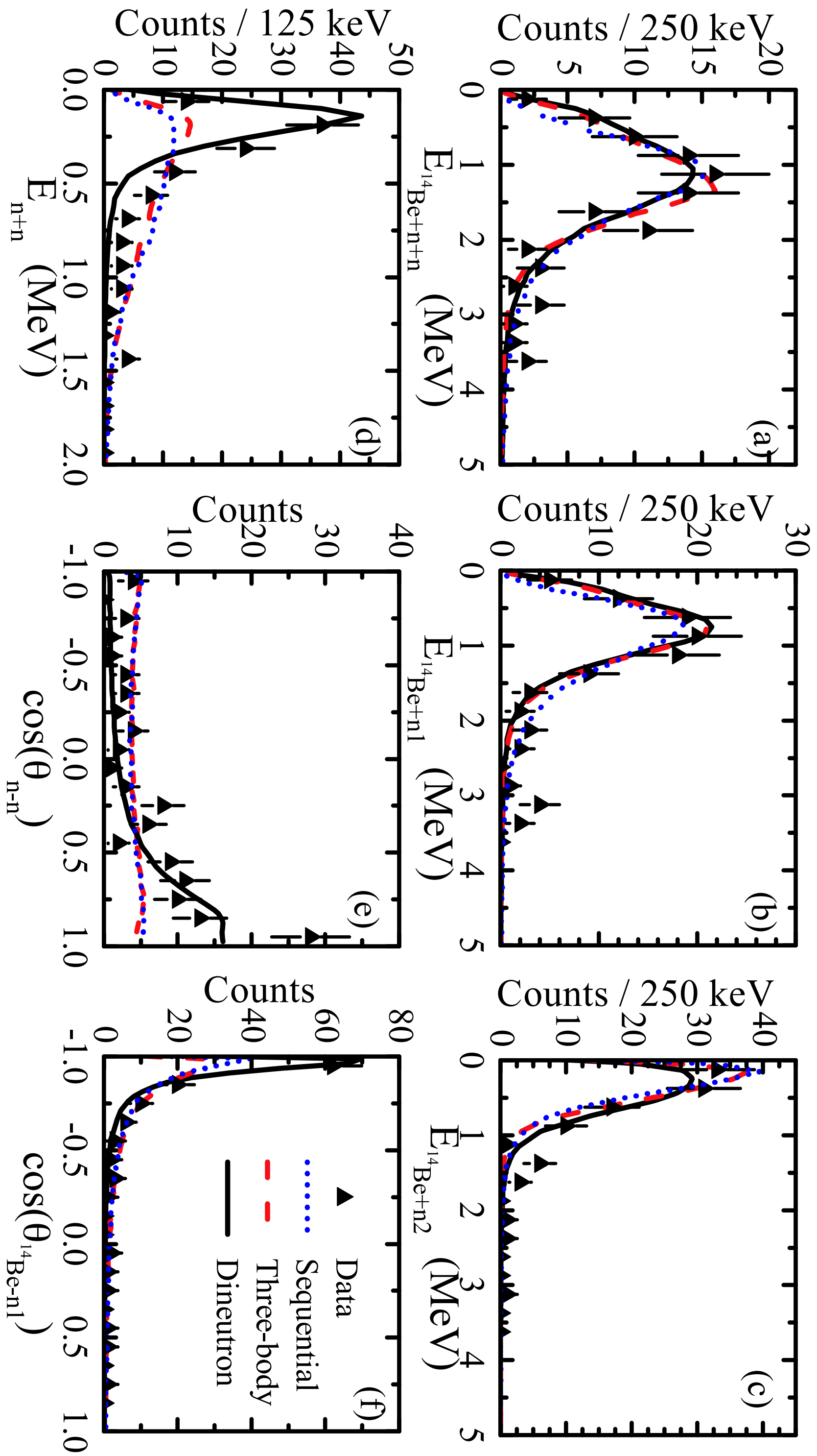

FIG. 2: (Color Online) a) Three-body decay energy from the reconstruction of ^{14}Be+n+n. b, c) Two-body decay energy of ^{14}Be+n, where b) corresponds to the highest decay energy and c) to the lowest. d) Two-body relative energy of the two neutrons. e) Opening angle $\theta_{\text{n-n}}$ between the two neutrons in the center-of-mass frame of ^{16}Be. f) Opening angle ($\theta_{^{14}\text{Be}-\text{n1}}$) between the ^{14}Be fragment and the first neutron in the center-of-mass frame of ^{16}Be. In all figures, the experimental data are shown in black triangles, the sequential emission in dotted lines, the three-body decay in dashed lines and the dineutron decay in solid lines.