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Phys. Rev. C **90**, 027304 — Published 21 August 2014

DOI: 10.1103/PhysRevC.90.027304

Two-proton decay from the Isobaric Analog State in ^{8}B

K. W. Brown, W. W. Buhro, R. J. Charity, J. M. Elson, W. Reviol, and L. G. Sobotka
Departments of Chemistry and Physics, Washington University, St. Louis, Missouri 63130, USA

Z. Chajecki, W. G. Lynch, J. Manfredi, R. Shane, R. H. Showalter, M. B. Tsang, D. Weisshaar, and J. R. Winkelbauer
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

S. Bedoor and A. H. Wuosmaa*
Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008, USA.

The Isobaric Analog State in ^{8}B is confirmed to decay by two-proton emission to the Isobaric Analog State in ^{6}Li, which emits a 3.563 MeV gamma ray. Upper limits on the yield to isospin breaking decay channels are also reported. The three-body correlations from the two-proton decay from $^8\mathrm{B}_{IAS}$ to $^6\mathrm{Li}_{IAS}$ are statistically different than the two-proton decay of its isospin partner, $^8\mathrm{C}_{g.s.}$.

PACS numbers: 21.10.Dr,27.20.+n,23.50.+z

Proton-rich nuclei beyond the proton drip line will decay by the emission of charged particles. In some cases these nuclei will decay by emitting two protons in a single step, i.e. $2p$ decay. In a recent paper we showed that the ground state of ^{8}C, the mirror of the 4-neutron halo system ^{8}He, has a very unusual decay [1]. It decays by $2p$ emission to the ground state of ^{6}Be, the mirror of another neutron halo system ^{6}He. The ^{6}Be nucleus itself undergoes $2p$ decay, and thus ^{8}C undergoes two sequential steps of $2p$ decay. In this work we will examine the decay of the isobaric analog state (IAS) of ^{8}C in ^{8}B. In Ref. [1] we presented evidence that this state also undergoes $2p$ decay to the isobaric analog state of ^{6}Be in ^{6}Li. This would be the first case of $2p$ decay between IAS states and this decay would be the analog of the first $2p$-decay step of $^8\mathrm{C}_{g.s.}$, in both cases the $2p$ decay is between T=2 and T=1 states.

Prompt two-proton emission was originally thought to occur only when one-proton decay was energetically forbidden [2]. However this definition has been extended to democratic $2p$ decay, where $1p$ decay is energetically allowed but where the $1p$ decay energy is of the same magnitude as the width of the $1p$ daughter [3]. The confirmation of the $2p$ decay of the $^8\mathrm{B}_{IAS}$ would further extend this to a third class of $2p$ emitters where $1p$ decay is energetically allowed, but isospin forbidden.

With increasing mass, ^{12}O is the next known $2p$ emitter after ^{8}C. Its isobaric analog state in ^{12}N has also been ascribed to this new third class of $2p$ emitters [4] decaying to the isobaric analog state in ^{10}B. In both $^8\mathrm{B}_{IAS}$ and $^{12}\mathrm{N}_{IAS}$ decay, the daughter isobaric analog states decay by γ emission, but in both studies [1, 4] the γ ray was not detected allowing a small uncertainty to our interpretation of the decay sequence and thus in the existence of this third class of $2p$ decay. This deficiency is remedied in the present work where the $2p$ decay of $^8\mathrm{B}_{IAS}$ is revisited and the γ ray from the decay of the $^6\mathrm{Li}_{IAS}$ daughter is observed. In addition we measure the correlations between the decay products and compare them to those previously determined for the $2p$ decay of $^8\mathrm{C}_{g.s.}$.

A primary beam of ^{16}O (E/A = 150 MeV) was extracted from the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University with an intensity of 175 pnA. This beam impinged on a ^{9}Be production target and a secondary beam of ^{9}C (E/A = 68 MeV) was selected using the A1900 fragment separator. The secondary beam had an intensity of 1.2 x 10^5 pps and a ^{9}C purity of 52% with the main contaminant being ^{6}Li.

The ^{9}C secondary beam bombarded a 1-mm-thick ^{9}Be target. The charged particles produced in this second interaction were detected in the High Resolution Array (HiRA) [5]. For this experiment, the array consisted of 14 ΔE-E [Si-CsI(Tl)] telescopes located 85 cm downstream of the target, subtending polar angles from 2.0° to 13.9° in the lab. The telescopes were arranged in five towers with a 2-3-4-3-2 arrangement. The center tower had a small gap between the two innermost telescopes to allow for the unreacted beam to pass through. Each telescope consisted of a 1.5-mm-thick, double-sided Si strip ΔE detector followed by a 4-cm-thick CsI(Tl) E detector. The ΔE detectors are 6.4 cm x 6.4 cm in area with each of the faces subdivided into 32 strips. Each of the 14 HiRA detector modules has 4 CsI(Tl) E detectors, each spanning a quadrant of the preceding Si ΔE detector. Signals produced in the Si were processed in one of two ways. For the two detectors immediately above and below the beam, the signals were amplified using external charge-sensitive amplifiers (CSAs) and then resistively spilt into low- and high-gain channels before being processed by the HINP16C chip electronics [6]. This provided roughly six times the dynamic range of the other

* Present Address: Department of Physics, University of Connecticut, Storrs, Connecticut 06269, USA

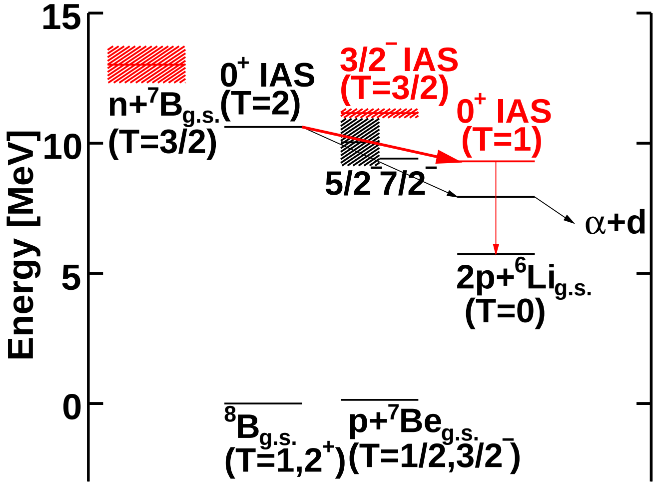

FIG. 1. (Color Online) Set of levels relevant for the decay of the IAS in ^{8}B. The levels are labeled by their spin-parity (J$^{\pi}$ and isospin (T) quantum numbers. Colors indicate isospin allowed transitions. The width of the J$^{\pi}$ = 7/2^{-} state in ^{7}Be is not known, but assumed to be wide as in the mirror.

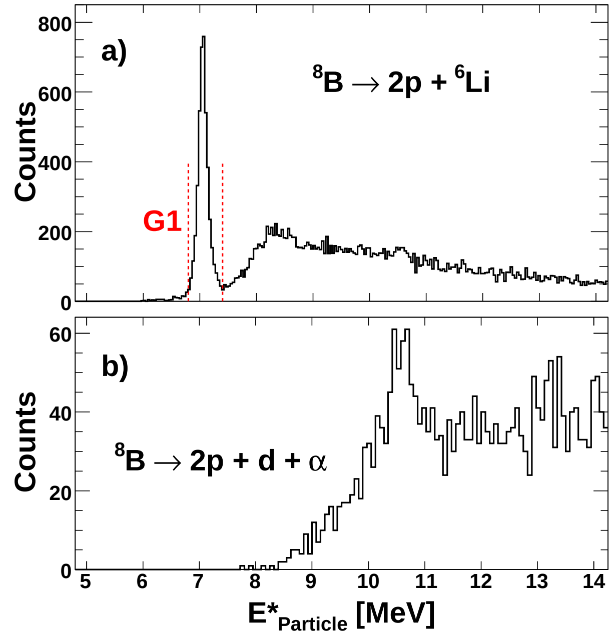

FIG. 2. (Color Online) The excitation-energy spectrum from charged-particle reconstruction determined for ^{8}B from detected a) $2p$-^{6}Li and b) $2p$-α-d events.These energies assume no missing decay energy due to γ-ray emission.

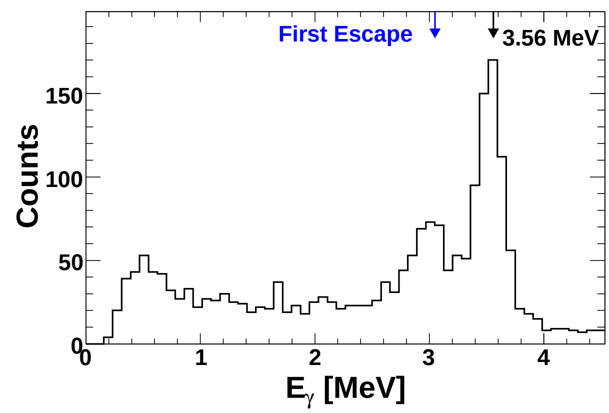

FIG. 3. (Color Online)Gamma-ray energies measured in coincidence with p-p-^{6}Li events. This spectrum includes add-back from nearest neighbors and has been Doppler-corrected eventwise.

telescopes. The other Si detectors were processed with the HINP16C chip electronics and amplified with CSAs internal to the chip. Signals from the CsI(Tl) detectors were processed using conventional electronics. HiRA Si detectors were calibrated using a ^{228}Th alpha source and the CsI(Tl) detectors were calibrated using proton and $N = Z$ cocktail beams each with energies of 55 and 75 MeV/A.

Gamma rays were measured in coincidence with charged particles using the CAESium-iodide scintillator ARray (CAESAR) [7]. In this experiment CAESAR comprised 158 CsI(Na) crystals covering the polar angles between 57.5° and 142.4° in the lab. The first ring(A) and the last two rings (I,J) of CAESAR in its nominal configuration were removed due to space constraints. Calibrations of CAESAR were performed using ^{88}Y, AmBe, ^{60}Co, and ^{22}Na sources.

From the decay scheme shown in Fig. 1 one can see that one-nucleon decay from the IAS in ^{8}B is either energy allowed but isospin forbidden (p), or isospin allowed but energy forbidden (n). Two-proton decays to the ground and first excited states of ^{6}Li are also energy allowed but isospin forbidden. The only energy and isospin allowed decay mode is $2p$ decay to the IAS in ^{6}Li which is known to decay by emitting a 3.563-MeV γ ray [8].

The reconstructed excitation-energy distribution of ^{8}B fragments from detected 2p + ^{6}Li events is shown in Fig. 2(a). The excitation energy was calculated based on the assumption that the detected ^{6}Li fragment was produced in its ground state. The only state in ^{6}Li with any significant gamma-decay branch is the IAS (T=1) state at 3.563-MeV. The narrow peak at 7.06±0.020 MeV from the reconstructed particle energies was observed previously [1] and was assigned as the IAS in ^{8}B at an excitation energy of 10.61 MeV assuming the decay populated the IAS in ^{6}Li. The spectrum of γ rays in coincidence with the reconstructed $2p$+^{6}Li events satisfying gate $G1$ in Fig. 2(a) is shown in Fig. 3. The γ-ray energies are corrected for nearest neighbor scattering and are Doppler-corrected eventwise. The spectrum has two main peaks, one at 3.56 MeV and another 511 keV lower. As a 3.563 MeV γ ray has a high probability for pair-production, the γ-ray spectrum is consistent with a single γ-ray of energy 3.563 MeV, confirming the IAS-to-IAS decay path. Adding the 3.563 MeV γ ray energy to the centroid of

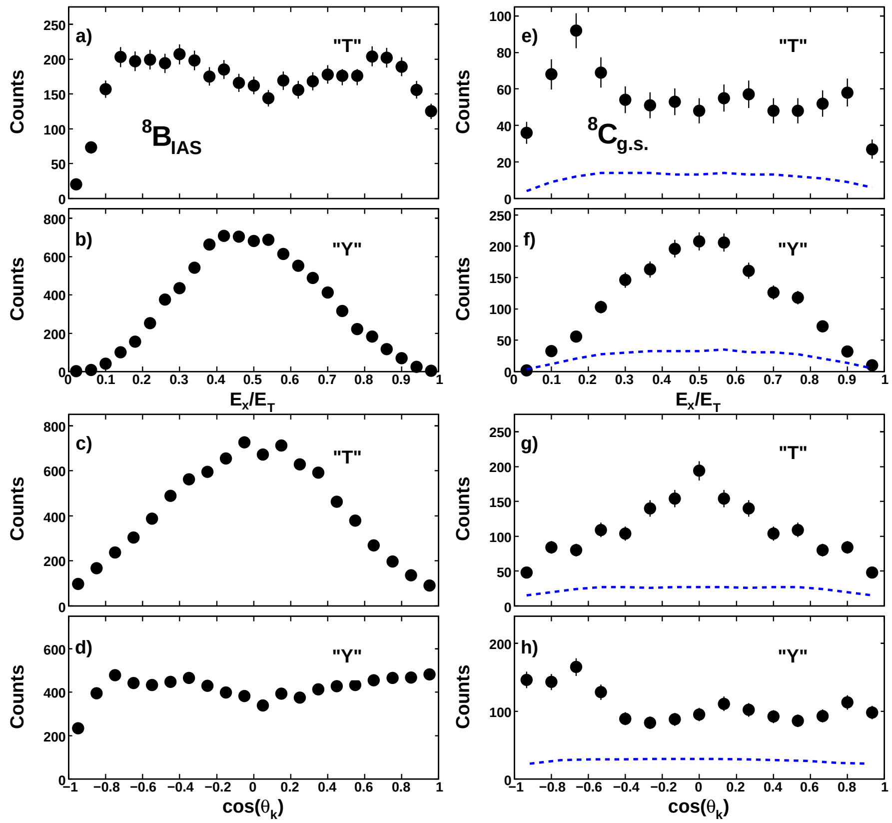

FIG. 4. (Color Online)Projected three-body correlations from the decay of $^8B_{IAS}$ to the $2p$+$^6Li_{IAS}$ exit channel in the (a)(c) T and (b)(d) Y Jacobi systems. Energy correlations are shown in (a) and (b), angular correlations in (c) and (d). The right panel shows the same as the left, but now the correlations are associated with the first step of $^8C_{g.s}$ decay to $2p$+^{6}Be.

the peak in Fig. 2(a), gives us a total excitation energy of 10.614±0.020MeV which is consistent with the tabulated value of 10.619±0.009 MeV[8].

While the γ ray following the $2p$ decay of $^{12}N_{IAS}$ was not measured in Ref. [4], the decay scheme is logically the same as for $^8B_{IAS}$. The present measurement for $^8B_{IAS}$ therefore provides support for the assigned decay path for $^{12}N_{IAS}$ [4].

In light nuclei, isospin violation at the few percent level is not uncommon. Therefore it is not surprising that we also see weak decay branches from $^8B_{IAS}$ to the low lying T=0 levels in ^{6}Li. From the correlations between the decay products, the $2p$+d+α exit channel is studied as well, Fig 2(b). The channel is populated mostly by an isospin-forbidden $2p$ decay to the J^π=3$^+$, excited state of ^{6}Li which subsequently decays to a d+α pair. There is also a hint of $2p$ decay directly to $^6Li_{g.s.}$, Fig. 2(a). After correction for detector efficiences, the decays through these channels have yields no more than: 10% ($2p$+d+α) and 11% ($2p$+$^6Li_{g.s.}$) relative to the isospin-conserving decay. No evidence was observed for isospin-forbidden decay to the p+^{7}Be channel. At the 3σ level, we deduce an upper limit of 7.5% for this decay.

We now turn to the three-body correlations in the $2p$ decays of $^8B_{IAS}$ and its isospin partner $^8C_{g.s.}$. In principle nine momentum variables are needed to describe a three-body decay. Of these, three describe the center-of-mass motion, three describe the Euler rotation of the decay plane (for $J=0$ systems all orientations are quantum-mechanically identical), and the three-body decay energy is fixed. Thus we are left with two remaining variables to describe the correlations. Convenient choices for these variables are the fractional part of the total kinetic energy associated with the relative motion of two of the fragments (E_x/E_T) and the angle between the relative momentum vector of those two fragments and the momentum of the third (θ_k). The Jacobi Y system uses the relative momentum vector between the core and one of the protons, and the Jacobi T system has the relative momentum between the two protons. Further description of the two systems can be found in Refs. [9, 10].

The energy and angular correlations in both the Jacobi T and Y coordinates are shown in Fig. 4 for $^8B_{IAS}$ decay (left) and the first step of $^8C_{g.s.}$ decay (right). In order to determine the three-body correlations in the first step of $^8C_{g.s.}$ decay, we required that one and only one of the six possible pairs of protons, together with the α particle, reconstructed to the correct invariant mass of the ^{6}Be intermediate [1]. This event selection places some uncertainty on the extracted correlations due to a background of misassigned pairs of protons from the first and second $2p$-decay steps. This background is expected to be smooth, and one estimation of this background, described in Ref.[1, 11] is shown by the dashed curves in Fig. 4(e-h). In the Jacobi T energy distribution for ^{8}C$_{g.s.}$ decay, Fig. 4(e), an enhancement at low relative proton energies, a region often called the "diproton" region, is observed. The Jacobi T energy distributions for the decay of the isospin partner ^{8}B$_{IAS}$ are shown in Fig. 4(a). Distortions due to the detector acceptance and resolution are expected to be small and of similar magnitude for $2p$ decay of ^{6}Be and ^{8}C [1, 12]. One observes two broad features at low and high relative energies, corresponding to so called "diproton" and "cigar" configurations. However, the enhancement of the diproton region seen for ^{8}C decay, is not observed for ^{8}B$_{IAS}$ decay.

The Jacobi Y energy distributions for ^{8}B$_{IAS}$ decay and ^{8}C$_{g.s.}$ decay are shown in Fig. 4(b) and (f) respectively. In a three-body decay, the two protons should have approximately equal energies as this maximizes the product of their barrier penetration factors [2]. This is evidenced by the observation of a single peak at E_x/E_T=0.5 in the proton-core relative-energy spectrum (Jacobi Y system) and suggests that these are prompt $2p$ decays. As was seen for ^{6}Be$_{g.s}$, the Jacobi Y E_x/E_T and Jacobi T θ_k distributions contain the same information, complementary to the Jacobi Y θ_k and Jacobi T E_x/E_T plots.

We have confirmed that IAS-to-IAS $2p$ decay can become the dominate decay mode when all one-nucleon emission channels are either energy or isospin forbidden. The three-body correlations from the two-proton decay of ^{8}B$_{IAS}$ to ^{6}Li$_{IAS}$ were measured and found to be statistically different from its isospin partner ^{8}C$_{g.s.}$. This difference is of uncertain origin. While it may reflect an initial-state difference, it could also result from distorting effects of the long-range Coulomb interaction which must be followed out to tens of thousands of fm in $2p$ decay theory [13]. While both decay initially to three charged particles, the ^{6}Be from the decay of ^{8}C$_{g.s.}$ will further decay to $2p$+α within a few hundred fm of the initial decay, well within the range of the distorting final-state Coulomb interaction. Thus it is possible that the ultimate five-body final state distorts the measured correlations between the reconstructed fragments of the first three-body decay of ^{8}C$_{g.s.}$, a distortion that would not be present for ^{8}B$_{IAS}$. An additional difference is that the lifetime of ^{8}C$_{g.s.}$ is shorter than that of ^{8}B$_{IAS}$ creating the potential that the former is more sensitive to the nucleon knock-out reaction mechanism creating it [14].

This work was supported by the U.S. Department of Energy, Division of Nuclear Physics under grants NO. DE-FG02-87ER-40316 and No. DE-FG02-04ER-41320 and the National Science Foundation under grant No. PHY-0606007. K.W.B. is supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1143954.

[1] R. J. Charity, J. M. Elson, J. Manfredi, R. Shane, L. G. Sobotka, Z. Chajecki, D. Coupland, H. Iwasaki, M. Kilburn, J. Lee, W. G. Lynch, A. Sanetullaev, M. B. Tsang, J. Winkelbauer, M. Youngs, S. T. Marley, D. V. Shetty, A. H. Wuosmaa, T. K. Ghosh, and M. E. Howard, Phys. Rev. C **82**, 041304 (2010).

[2] V. I. Goldansky, Nucl. Phys. **27**, 648 (1961).

[3] O. V. Bochkarev, L. V. Chulkov, A. A. Korsheninniicov, E. A. Kuz'min, I. G. Mukha, and G. B. Yankov, Nucl. Phys. A **505**, 215 (1989).

[4] M. F. Jager, R. J. Charity, J. M. Elson, J. Manfredi, M. H. Mahzoon, L. G. Sobotka, M. McCleskey, R. G. Pizzone, B. T. Roeder, A. Spiridon, E. Simmons, L. Trache, and M. Kurokawa, Phys. Rev. C **86**, 011304 (2012).

[5] M. Wallace, M. Famiano, M.-J. van Goethem, A. Rogers, W. Lynch, J. Clifford, F. Delaunay, J. Lee, S. Labostov, M. Mocko, L. Morris, A. Moroni, B. Nett, D. Oostdyk, R. Krishnasamy, M. Tsang, R. de Souza, S. Hudan, L. Sobotka, R. Charity, J. Elson, and G. Engel, Nucl. Instrum. Methods Phys. Res. A **583**, 302 (2007).

[6] G. L. Engel, M. Sadasivam, M. Nethi, J. M. Elson, L. G. Sobotka, and R. J. Charity, Nucl. Instrum. Methods Phys. Res. A **573**, 418 (2007).

[7] D. Weisshaar, A. Gade, T. Glasmacher, G. Grinyer, D. Bazin, P. Adrich, T. Baugher, J. Cook, C. Diget, S. McDaniel, A. Ratkiewicz, K. Siwek, and K. Walsh, Nucl. Instrum. Methods Phys. Res. A **624**, 615 (2010).

[8] Evaluated Nuclear Structure Data File (ENSDF), http://www.nndc.bnl.gov/ensdf/.

[9] L. Grigorenko, T. Wiser, K. Miernik, R. Charity, M. Pfützner, A. Banu, C. Bingham, M. Cwiok, I. Darby, W. Dominik, J. Elson, T. Ginter, R. Grzywacz, Z. Janas, M. Karny, A. Korgul, S. Liddick, K. Mercurio, M. Rajabali, K. Rykaczewski, R. Shane, L. Sobotka, A. Stolz, L. Trache, R. Tribble, A. Wuosmaa, and M. Zhukov, Physics Letters B **677**, 30 (2009).

[10] L. V. Grigorenko, T. D. Wiser, K. Mercurio, R. J. Charity, R. Shane, L. G. Sobotka, J. M. Elson, A. H. Wuosmaa, A. Banu, M. McCleskey, L. Trache, R. E. Tribble, and M. V. Zhukov, Phys. Rev. C **80**, 034602 (2009).

[11] R. J. Charity, J. M. Elson, J. Manfredi, R. Shane, L. G. Sobotka, B. A. Brown, Z. Chajecki, D. Coupland, H. Iwasaki, M. Kilburn, J. Lee, W. G. Lynch, A. Sanetullaev, M. B. Tsang, J. Winkelbauer, M. Youngs, S. T. Marley, D. V. Shetty, A. H. Wuosmaa, T. K. Ghosh, and M. E. Howard, Phys. Rev. C **84**, 014320 (2011).

[12] I. A. Egorova, R. J. Charity, L. V. Grigorenko, Z. Chajecki, D. Coupland, J. M. Elson, T. K. Ghosh, M. E. Howard, H. Iwasaki, M. Kilburn, J. Lee, W. G. Lynch, J. Manfredi, S. T. Marley, A. Sanetullaev, R. Shane, D. V. Shetty, L. G. Sobotka, M. B. Tsang, J. Winkelbauer, A. H. Wuosmaa, M. Youngs, and M. V. Zhukov, Phys. Rev. Lett. **109**, 202502 (2012).

[13] L. V. Grigorenko, I. A. Egorova, M. V. Zhukov, R. J. Charity, and K. Miernik, Phys. Rev. C **82**, 014615 (2010).

[14] L. V. Grigorenko, I. A. Egorova, R. J. Charity, and M. V. Zhukov, Phys. Rev. C **86**, 061602 (2012).