Physics Letters B 699 (2011) 141–144

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Half-lives of ground and isomeric states in ^{97}Cd and the astrophysical origin of ^{96}Ru

G. Lorusso [a,b,c,*], A. Becerril [a,b,c], A. Amthor [a,b,c], T. Baumann [a], D. Bazin [a], J.S. Berryman [a,d], B.A. Brown [a,b,c], R.H. Cyburt [a,b], H.L. Crawford [a,d], A. Estrade [a,b,c], A. Gade [a,c], T. Ginter [a], C.J. Guess [a,b,c], M. Hausmann [a], G.W. Hitt [a,b,c,1], P.F. Mantica [a,d], M. Matos [a,b], R. Meharchand [a,b,c], K. Minamisono [a], F. Montes [a,b], G. Perdikakis [a,b], J. Pereira [a,b], M. Portillo [a], H. Schatz [a,b,c], K. Smith [a,b,c], J. Stoker [a,d], A. Stolz [a], R.G.T. Zegers [a,b,c]

[a] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[b] Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA
[c] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[d] Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA

ARTICLE INFO

Article history:
Received 18 December 2010
Received in revised form 9 March 2011
Accepted 20 March 2011
Available online 1 April 2011
Editor: D.F. Geesaman

Keywords:
^{97}Cd
rp-process
Spin-gap isomer
β-delayed proton decay
X-ray burst
p-nuclei

ABSTRACT

First experimental evidence for a high-spin isomer ($25/2^+$) in ^{97}Cd, a waiting point in the astrophysical rapid proton capture process, is presented. The data were obtained in β-decay studies at NSCL using the new RF Fragment Separator system and detecting β-delayed protons and β-delayed γ rays. Decays from ground and isomeric states were disentangled, and proton emission branches were determined for the first time. We find half-lives of 1.10(8) s and 3.8(2) s, and β-delayed proton emission branches of 12(2)% and 25(4)% were deduced for the ground and isomeric states, respectively. With these results, the nuclear data needed to determine an rp-process contribution to the unknown origin of solar ^{96}Ru are in place. When the new data are included in astrophysical rp-process calculations, one finds that an rp-process origin of ^{96}Ru is unlikely.

The rapid proton capture process (rp-process [1]) is thought to power type I X-ray bursts [2,3], thermonuclear explosions on the surface of neutron stars that accrete hydrogen-rich matter from an orbiting companion star. The explosions typically release 10^{38}–10^{39} ergs of energy producing bursts that last between a few seconds to a few minutes. With a recurrence time of only hours to days, and close to 100 bursting systems observed in the Galaxy, type I X-ray bursts are the most common thermonuclear explosions in the cosmos.

The rp-process is a sequence of rapid proton captures and β decays near the proton drip line predicted to reach the Sn region in some bursts [4,5]. The slow β decays, the so-called waiting points, play a particularly important role in rp-process models — they are by far the slowest reactions, and therefore control the rate of nuclear energy release, the shape of the observed burst light curve, and the composition of the burst ashes. The latter is crucial to understand nuclear processes occurring deeper in the neutron star crust and crust cooling [6]. In addition, a small fraction of the burst ashes may be ejected [7], potentially contributing to the origin of the ^{92,94}Mo and ^{96,98}Ru isotopes. These isotopes are found in surprisingly large amounts in the solar system that cannot be explained by current s- or p-process models [8]. With accurate knowledge of nuclear physics parameters the composition of the ashes can be modeled and compared with solar system abundances to determine whether X-ray bursts (or any rp-process occurring under similar conditions) are a possible source of the neutron deficient Mo and Ru isotopes in the solar system. If so, more detailed studies of the possible ejection mechanism and event frequency are warranted.

The half-lives of all β-decaying isotopes along the path of the rp-process have been determined experimentally and have been

* Corresponding author. Current address: RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan.
E-mail address: lorusso@ribf.riken.jp (G. Lorusso).
[1] Current address: Khalifa University of Science, Technology, and Research, Abu Dhabi Campus, P.O. Box 127788, Abu Dhabi, United Arab Emirates.

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2011.03.043

included in rp-process model calculations. This advancement is attributed to concentrated experimental efforts at rare isotope beam facilities, which are now reaching full potential. However, if β-decaying isomeric states are present, which are typically populated differently in the laboratory and in the stellar environment, then the half-life measured in the laboratory could be a mixture of half-lives and therefore not necessarily what is needed to characterize the rp-process path. We show here that this is the case for one of the rp-process waiting points, ^{97}Cd.

^{97}Cd plays an important role in rp-process calculations. As we will show, its half-life affects the production of $A = 97$ nuclei, which decay into ^{97}Mo. Unlike ^{92,94}Mo and ^{96,98}Ru, ^{97}Mo is largely produced in the s-process. Therefore, its rp-process production must be low for the rp-process to be a viable contributor to galactic nucleosynthesis. In addition, ^{97}Cd has been shown to be a β-delayed proton emitter [9,10], although the branching was not determined. It has been pointed out [11,12] that β-delayed proton emission may move some fraction of the abundance of mass $A = 97$ into mass $A = 96$ during freeze-out. The half-life and β-delayed proton emission branch $b_{\beta p}$ of ^{97}Cd, therefore, also affect the production of ^{96}Ru.

Shell-model calculations for ^{97}Cd and other neighboring isotopes have predicted the possible existence of spin-gap isomers — specific high-spin states that are lowered in energy such that γ decay requires a high angular momentum transfer, which results in an extended γ-decay lifetime and a possible β-decay branch.

A $21/2^+$ β-decaying spin-gap isomer in ^{95}Pd is known experimentally [13], and similar spin-gap isomers in ^{95}Ag ($23/2^+$), ^{96}Cd (16^+), and ^{97}Cd ($25/2^+$) are expected in the pure $\pi\nu(1p_{1/2}, 0g_{9/2})$ hole space [14]. However, the predicted existence of these isomers and their decay modes depend sensitively on the proton–neutron interaction employed in the shell model calculations. Indeed, the predicted $23/2^+$ isomer in ^{95}Ag has been identified experimentally [15,16], but its main decay is by γ emission. The considerably shorter-than-predicted lifetime makes the existence of a significant β-decay branch in this case unlikely.

Two important open questions for ^{97}Cd are then whether a spin-gap isomer exists and whether it has a substantial β-decay branch. The questions are of high relevance for rp-process calculations. In the rp-process, waiting points such as ^{97}Cd are produced by proton capture with low orbital angular momentum. The ground-state spin of ^{96}Ag is not known with certainty, but is predicted to be 8^+ in line with current experimental constraints. A 2^+ assignment cannot be excluded, but in either case the population of the $25/2^+$ state in ^{97}Cd, predicted at an excitation energy of 2.4 MeV [14], via a low orbital angular momentum proton capture and a subsequent γ-decay cascade is unlikely. Therefore, the ^{97}Cd ground state half-life should be used in astrophysical model calculations. On the other hand, reactions used to produce rare isotopes in the laboratory can populate high-spin states as well. Half-life measurements for neutron-deficient isotopes in the rp-process, such as the previous measurement of ^{97}Cd [10], often have insufficient statistics to distinguish different parent states and the quoted half-life may not represent a pure ground state half-life if a β-decaying isomer is present. It is therefore critical to identify β-decaying isomers in rp-process waiting points so that ground and isomeric state decays can be disentangled to ensure the half-lives extracted from experiments are those needed in the astrophysical model calculations.

The experimental determination of the decay properties of ^{97}Cd was made possible at National Superconducting Cyclotron Laboratory with the implementation of the new Radio Frequency Fragment Separator (RFFS) [17]. Results on the β decay of ^{96}Cd, ^{98}In, and ^{100}Sn have already been reported from the same experiment [18]. The mixed rare isotope beam entering the RFFS was

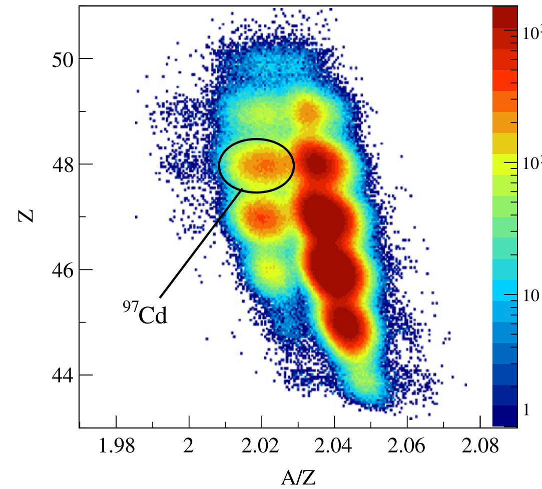

Fig. 1. (Color online.) Particle identification spectrum of the heavy nuclei arriving at the BCS.

produced by fragmentation of a 120 MeV/u ^{112}Sn beam with 10.7 pnA average intensity impinging on a 195 mg/cm^2 ^{9}Be target [18]. The reaction products were selected through the A1900 fragment separator [19] operated in achromatic mode with a 1% momentum acceptance. A 40.6-mg/cm^2 thick Kapton wedge, shaped to preserve the achromatism of the separator, was placed at the intermediate image of the A1900 to provide a selection in nuclear charge Z. Further purification of the ^{97}Cd rare isotope beam by a factor of 200 was achieved with the RFFS, rejecting contaminants with a different time-of-flight to the experimental setup. The RFFS enabled β-decay studies in this mass region that were previously impossible due to rate limitations.

After the two step separation the rare isotope beam was delivered to the Beta Counting System (BCS) [20], which was surrounded by 16 γ-ray detectors from the Segmented Germanium Array (SeGA) [21]. After traversing three Si PIN diodes, the beam particles were implanted into a double-sided Si strip detector (DSSD) with thickness 985 μm, which was electrically segmented into 40 1-mm strips both horizontally and vertically to give 1600 individual detector pixels. The PIN diodes provided an event-by-event identification of the incoming particles via energy loss and time-of-flight relative to a start signal from a plastic scintillator in the A1900 focal plane. The particle identification spectrum of the most exotic isotopes implanted is shown in Fig. 1 [18].

The pixelation of the DSSD and event time stamping provided location and time of each implanted ion. The DSSD was also used to detect emitted protons and β particles, which were then correlated in time and location to a preceding ion implantation. The detection efficiency for correlated β decays was measured to be 37(4)%. An intrinsic βp detection efficiency of 100% was assumed, since the proton signal was well above threshold. The number of correlated βp events was corrected for data-acquisition dead-time with corrections of less than 10%. Because of the high pixelation of the DSSD, events with a β particle alone and events with a proton accompanied by a β particle were fully distinguishable on the basis of the different energy deposited per pixel.

A fit to the time distribution of more than 10^4 correlated βp events was used to extract the half-life of ^{97}Cd (see Fig. 2). Two components are clearly evident in the decay curve, with half-lives of 1.10(8) s and 3.8(2) s. There was no evidence for a third component. The existence of two β-decaying states was confirmed by the analysis of βp-delayed γ rays. The γ spectrum recorded in coincidence with βp activity from ^{97}Cd is presented in Fig. 3. The 6 most intense γ rays are in coincidence and, with the exception

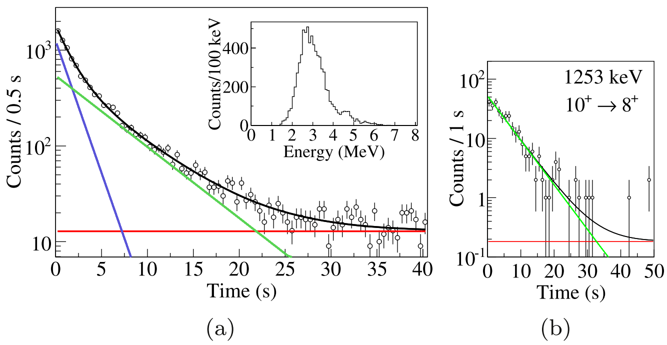

Fig. 2. (a) Decay curve of the ^{97}Cd β-delayed proton activity, along with the best fit (black), which includes two decay time components (blue and green) and a constant background (red). The inset shows the energy deposited in the DSSD by the β-delayed proton emission events. (b) Decay curve of the ^{97}Cd β-delayed proton activity gated on the 1253 keV γ ray corresponding to the $10^+ \to 8^+$ transition in ^{96}Pd. The best fit (black) includes one decay time component (green) and a constant background (red). (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

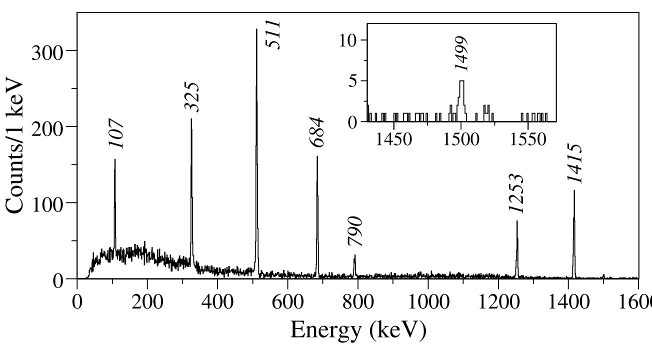

Fig. 3. γ spectrum recorded in coincidence with β-delayed protons from the decay of ^{97}Cd.

of the 511 keV line, result from the deexcitation of the known $12^+ \to 10^+ \to 8^+ \to 6^+ \to 4^+ \to 2^+ \to 0^+$ cascade in the daughter ^{96}Pd [22] (see Fig. 5). The half-lives derived from the decay curves gated on each of the $12^+ \to 10^+ \to 8^+ \to 6^+ \to 4^+ \to 2^+$ γ-ray transitions were 3.4(3) s, 4.2(3) s, 3.8(2) s, 3.60(15) s, and 3.62(15) s (see also Fig. 2). These half-lives are consistent with the 3.8(2) s component and inconsistent with the 1.10(8) s component, indicating that these transitions are primarily fed by the long-lived component of the ^{97}Cd βp decay. Feeding states with such a high spin is mainly expected from parent states with spin 17/2 or higher, because of selection rules and the substantial angular momentum barrier for protons emitted with high-orbital angular momentum. We therefore assign our measured half-life of 3.8(2) s to the decay of the predicted $25/2^+$ high-spin isomer [14, 10]. The predicted half-life of the $25/2^+$ state is 0.6 s [10], somewhat shorted than observed.

The 1415 keV, $2^+ \to 0^+$ transition has a shorter half-life of 2.92(15) s, indicating direct feeding of the 2^+ state in ^{96}Pd by the short-lived component, as expected from β-delayed proton emission from a lower-spin state. Indeed, a two component fit does improve the quality of the decay curve fit for the $2^+ \to 0^+$ transition. The spin assignment of $25/2^+$ for the 3.8(2) s decay component is reinforced by the observation of β-delayed γ rays (see Fig. 4) resulting from the deexcitation of the known cascade $27/2^+ \to 23/2^+ \to 21/2^+ \to 17/2^+ \to 13/2^+ \to 9/2^+$ in the daughter nucleus ^{97}Ag [23] (see Fig. 5). From the transitions $21/2^+ \to 17/2^+ \to 13/2^+ \to 9/2^+$ the β-decay half-lives 3.8(6), 3.8(6) and 3.9(7) s were extracted respectively.

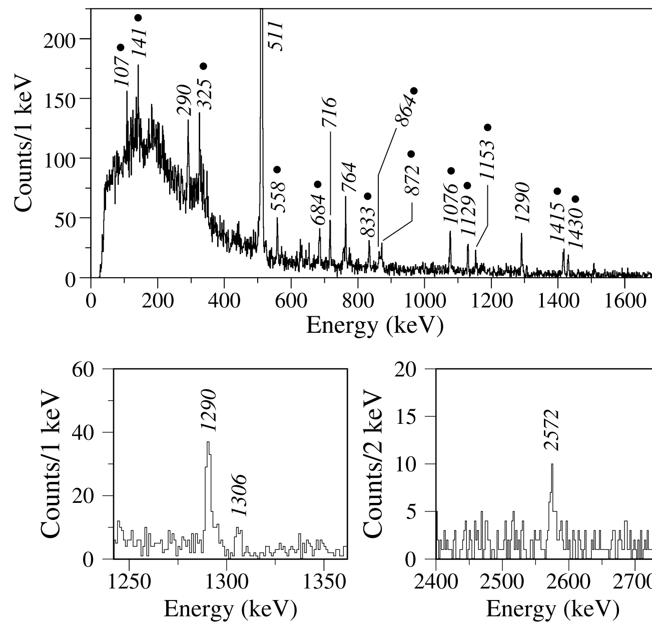

Fig. 4. Sections of the γ spectrum recorded in coincidence with β-decay events without proton emission within 3 s of a ^{97}Cd implantation. Filled circles indicate background lines originating from the known decays of other isotopes implanted into the detector.

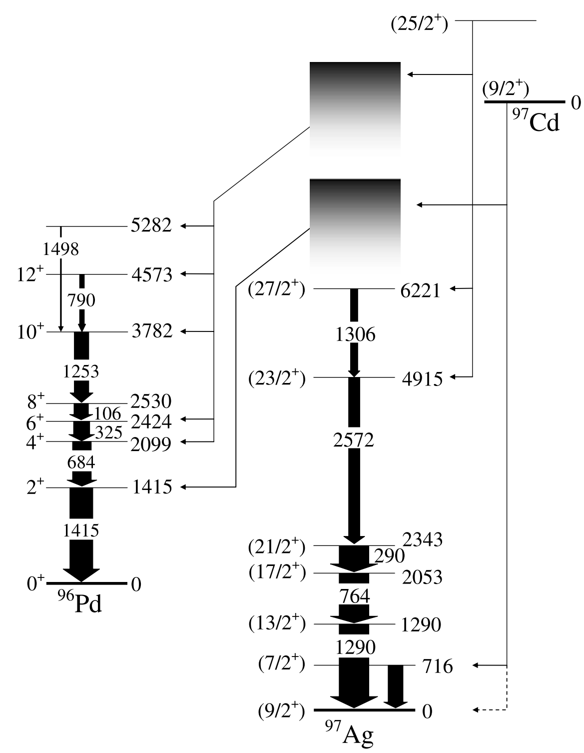

Fig. 5. Levels of ^{97}Ag and ^{96}Pd populated respectively in the β and βp decay of ^{97}Cd. Intermediate unresolved states in ^{97}Ag are indicated by grey boxes, and the width of the arrows representing γ rays are proportional to the γ-ray intensity observed in the experiment. Feeding of the ^{97}Ag ground state is assumed.

In principle, the shorter-lived component could originate from the ^{97}Cd ground state, or a $1/2^-$ isomeric state, which has also been predicted in ^{97}Cd [14]. To resolve between these possibilities we examined the γ-ray spectrum recorded in coincidence with β particles, shown in Fig. 4. A transition with an energy of 716.2(4) keV, which does not occur in coincidence with any other transition,

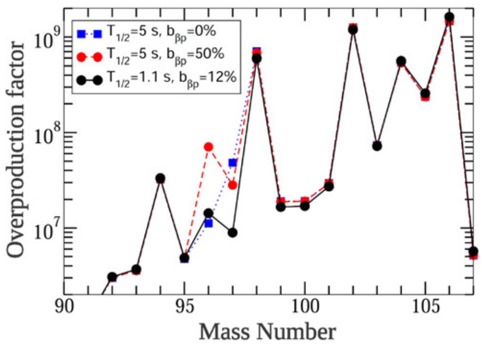

Fig. 6. Overproduction factors (ratio of produced abundance to solar system abundance) for X-ray burst ashes obtained with data on ^{97}Cd from this work (black circles, solid line) and with a larger half-life of 5 s and $b_{\beta p} = 0\%$ (blue squares, dotted line) or $b_{\beta p} = 50\%$ (red circles, dashed line). (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

was found to have a decay half-life of 1.1(2) s, compatible with the short-lived ^{97}Cd decay component, and is likely associated with the β decay of the shorter-lived ground state of ^{97}Cd (presumably $9/2^+$) feeding the first excited $7/2^+$ state in ^{97}Ag. The $7/2^+_1$ state is predicted at an excitation energy of about 700 keV [10]. It is unlikely that the 716 keV transition is associated with the β decay of the $1/2^-$ isomeric state in ^{97}Cd, as this decay would be expected to feed the predicted low-lying $1/2^-$ state in ^{97}Ag [10]. Two hypothetical scenarios have to be considered based on different shell model calculations [10]: (1) The $1/2^-$ state resides above the $7/2^+$ state and γ decays with a predicted half-life of 16 ms to the $7/2^+$ state and then to the ground state. In this case, the 716 keV γ-ray from the deexcitation of the $7/2^+$ ^{97}Ag state should be accompanied by a ≈ 300 keV line from the $1/2^- \to 7/2^+$ transition in ^{97}Ag, and a weaker ≈ 1 MeV line from the deexcitation of the $1/2^-$ state to the ground state. There is no evidence for such transitions. (2) The $1/2^-$ state in ^{97}Ag lies below the $7/2^+$ first-excited state. In this case, the $1/2^-$ state can only decay via a slow M4 transition to the ^{97}Ag ground state, extending the decay time by several seconds. Assignment of the 716 keV γ-ray transition to the decay of the $1/2^-$ state in ^{97}Ag in this scenario is inconsistent with the measured half-life. Therefore we assign the shorter 1.10(8) s half-life to the ground state decay of ^{97}Cd. This half life is consistent with shell model predictions of 0.9–1.1 s [10].

Analyzing the βp and β-only decay curves for ^{97}Cd, $b_{\beta p}$ values of 12(2)% and 25(4)% for the ground state and isomeric state, respectively, were deduced, with a relative production of the isomeric state of 47(10)%.

The implications of the newly measured half-life and $b_{\beta p}$ of the ^{97}Cd ground state on rp-process calculations were explored using a single zone X-ray burst model [4] with ReaclibV1 nuclear reaction rates [24]. The model predicts a rather extended rp-process into the Sn region and is therefore suitable to explore the general features of an rp-process flow in the Cd–Sn region. The overproduction pattern of the ashes, calculated assuming all unstable isotopes have completed their decay chains into the first stable isobar, is shown in Fig. 6. A viable production site for the p-nuclei ^{92,94}Mo and ^{96,98}Ru should show peaks in the overproduction factors at the respective mass numbers. A pattern with pronounced peaks for $A = 94, 96, 98$ is obtained with a relatively long ^{97}Cd half-life of 5 s and a large branching for β-delayed proton emission of 50%. These values reflect the theoretical uncertainties and were chosen to demonstrate the sensitivity of the composition of the burst ashes to the nuclear data. However, with our measurements this scenario can now be excluded. With the new experimental data, the pattern of overproduction factors does not exhibit a significant peak at $A = 96$ (see Fig. 6). Varying the ^{97}Cd half-life and $b_{\beta p}$ within the error bars had a negligible effect on the final abundances. Together with the half-life measurement of ^{96}Cd [18], the new data exclude the significant production of ^{96}Ru in the rp-process. The remaining nuclear physics uncertainty regarding the $A = 96$ production in the rp-process is the Q value for proton capture on ^{97}Cd. If this Q value is larger than predicted, the effective lifetime of ^{97}Cd may be reduced. However, such a discrepancy with theory would only further reduce $A = 96, 97$ production, and not change our conclusion. The unobserved $1/2^-$ predicted state in ^{97}Cd is not likely to play an important role in the rp-process. For the predicted 8^+ ground state spin of ^{96}Ag population by proton capture is unlikely, and most shell model calculations predict the state to be too high in excitation energy to be populated by thermal excitation. Only one model predicts a low-lying $1/2^-$ state (model-2 in [10]) but in that case the predicted half-life of 1.1 s is identical to our measured ground state half-life. However, experimental verification would be desirable.

In summary, the long-standing open question of the existence of β-decaying high-spin isomers in the path of the rp-process in the Cd region has been addressed at NSCL using the new RFFS to enable proper correlation of β decays in a multistrip detector on an event-by-event basis. We present unambiguous experimental evidence for the existence of a β-decaying high-spin isomer in the waiting point ^{97}Cd. In addition, the relative strengths of β and β-delayed proton decay from ground and isomeric states of ^{97}Cd were deduced for the first time. The ^{96}Ru production in the rp-process was shown to be sensitive to these nuclear physics properties. The inclusion of the new data in a single zone X-ray burst model allowed a much improved calculation of the amount of $A = 96, 97$ nuclei in the burst ashes. In particular, the new data exclude significant production of ^{96}Ru in rp-process scenarios. The unexplained large abundance of this isotope in the solar system must therefore have a different origin.

Acknowledgements

We thank the NSCL operations department for providing the high intensity ^{112}Sn primary beam and ^{97}Cd secondary beam. This work is supported in part by NSF grants PHY02-16783, PHY-06-06007, PHY08-22648, and PHY-0758099.

References

[1] R. Wallace, et al., Astrophys. J. Suppl. 45 (1981) 389.
[2] T. Strohmayer, et al., New Views of Thermonuclear Bursts (2006) 113.
[3] H. Schatz, et al., Nuclear Physics A 777 (2006) 601.
[4] H. Schatz, et al., Phys. Rev. Lett. 86 (2001) 3471.
[5] J. José, et al., Astrophys. J. Suppl. 189 (2010) 204.
[6] S. Gupta, et al., Astrophys. J. 662 (2007) 1188.
[7] N. Weinberg, et al., Astrophys. J. 639 (2006) 1018.
[8] M. Arnould, et al., Phys. Rep. 384 (2003) 1.
[9] T. Elmroth, et al., Nucl. Phys. A 304 (1978) 493.
[10] K. Schmidt, et al., Nucl. Phys. A 624 (1997) 185.
[11] W. Kurcewicz, et al., Z. Phys. A 308 (1982) 21.
[12] R. Boyd, in: AIP Conference Proceedings, vol. 576, 2001, pp. 358–361.
[13] E. Nolte, et al., Z. Phys. A 305 (1982) 289.
[14] K. Ogawa, Phys. Rev. C 28 (1983) 958.
[15] J. Döring, et al., Phys. Rev. C 68 (2003) 034306.
[16] N. Mărginean, et al., Phys. Rev. C 67 (2003) 061301.
[17] D. Bazin, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 606 (2009) 314.
[18] D. Bazin, et al., Phys. Rev. Lett. 101 (2008) 252501.
[19] D. Morrissey, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 204 (2003) 90.
[20] J. Prisciandaro, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 505 (2003) 140.
[21] W. Mueller, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 466 (2001) 492.
[22] D. Alber, et al., Z. Phys. A 332 (1989) 129.
[23] M. Lipoglavšek, et al., Phys. Rev. C 72 (2005) 061304.
[24] R. Cyburt, et al., Astrophys. J. Suppl. 189 (2010) 240.