# BETA-DEACY SPECTROSCOPY IN THE $^{100}$Sn REGION: IMPACT ON RP-PROCESS CALCULATIONS

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β-decay in the neighborhood of $^{100}$Sn was studied at the National Superconducting Cyclotron Laboratory (NSCL). The new half-lives of $^{96,97}$Cd, along with several new β-delayed proton emission branching ratio for nuclei in this region have an impact on the composition of type-I X-ray burst ashes predicted by network calculations.

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## 1. Introduction

Type I X-ray bursts are thermonuclear explosions on the surface of neutron stars accreting hydrogen- and helium-rich matter from a low-mass ($M \leq 1M_{\odot}$) main-sequence- or giant-companion star. Under specific conditions, the accreted gas, heated and compressed on the surface of neutron stars undergoes unstable-hydrogen burning. A series of (p,γ) and β-decay reactions (rp-process) drives the energy-generating reaction sequence into the $^{100}$Sn region, with the α-unbound Te isotopes providing a natural end- point [1]. The process lasts up to several minutes depending on the amount of hydrogen present at ignition. The explosive event is detected by space telescopes as a rapid and dramatic increase of X-ray flux (X-ray burst). In this contribution we show that precise information about the spectroscopy of rp-process nuclei and their decay modes are necessary for reliable astrophysics calculations. In particular, we report our recent results in the $^{100}$Sn region, which are important to predict the composition of heavy rp-process ashes, and the abundance of the p-nuclei $^{92,94}$Ru, and $^{96,98}$Ru, whose large abundance in the solar system is still not understood. The region exhibit β-delayed proton (βp-) emission, a decay mode that previous to our experiment was not included in the rp-process calculations for lack of experimental data. Such decay mode was pointed out as a factor in the discussion of the p-nuclei problem [2].

## 2. Experimental technique and setup

The production of $^{100}$Sn and neighboring neutron-deficient isotopes at the NSCL Coupled Cyclotron Facility was described in Ref. [3]. Such nuclei were produced by fragmentation of a 120 MeV/nucleon $^{112}$Sn beam, with an average intensity of 10.7 p-nA, impinging upon a 195 mg/cm$^2$ $^9$Be target. Reaction products were selected with the NSCL A1900 fragment separator [4] operated in achromatic mode and with momentum acceptance limited to 1%. Further purification was necessary and provided by the Radio Frequency Fragment Separator (RFFS), a velocity filter [5]. Fig. 1 shows the particle identification spectrum for the most exotic isotopes. The magnetic- and velocity-purified beam was then implanted in a 985 μm thick double-sided silicon strip detector (DSSD), part of the NSCL Beta Counting System (BCS) [6] shown in the left panel of Fig. 2. The DSSD was segmented into 40 1-mm wide strips horizontally and vertically, resulting in 1600 virtual pixels. The BCS included also three Si PIN detectors for beam diagnostic and particle identification. The DSSD provided the implantation position and implantation time of radioactive nuclei as well as position, detection time, and energy deposited by emitted protons and positrons. Correlation in time and correlation in position between implanted nuclei and subsequent detected positrons allowed to construct decay curves and study β-delayed γ-radiation.

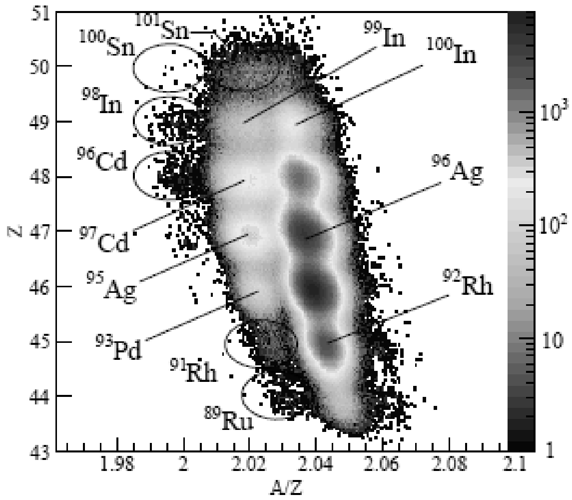


Figure 1. Particle identification spectrum of the nuclei transmitted through the RFFS. The group of low-Z contaminants that passed through the RFFS at a phase difference of around $360^{O}$ is not shown. The species labeled are relevant to the present contribution

The detection efficiency for β-decays correlated correctly to the preceding implantation was determined to be 36(4)%, while an intrinsic βp-detection efficiency of 100% was assumed since the proton energy (>1 MeV) was well above the detection threshold (~200keV).

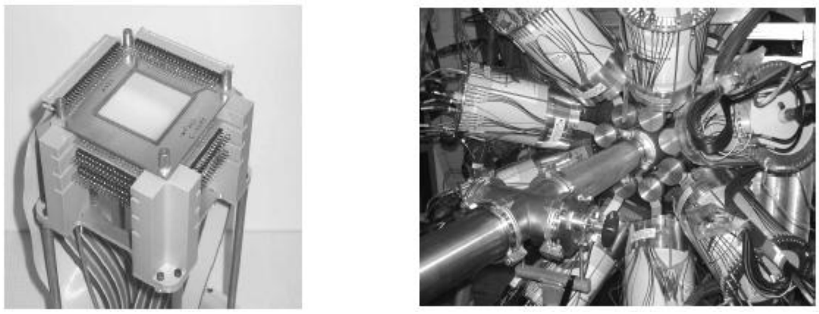

Figure 2. (Left panel) Silicon detector stack of the Beta Counting System.
(Right panel) The SeGA array comprising 16 high purity germanium detectors.

The DSSD was followed by a β-calorimeter consisting of six single-sided silicon strip detectors (SSSD) approximately 1 mm thick, and a planar Ge detector approximately 10 mm thick. The calorimeter was capable of stopping β-particles with energies up to 14 MeV. γ -rays emitted within 20 μs of either an implanted ion, a proton, or a positron were detected with 16 high purity germanium detectors from the NSCL Segmented Germanium Array (SeGA) [7]. The detectors were arranged in two concentric rings, one upstream and one downstream of the DSSD (see right panel of Fig. 2), resulting in an efficiency of about 6% at 1 MeV and an energy resolution ranging from 2.5 to 2.8 keV FWHM.

## 3. Main experimental results with astrophysics implication

### 3.1. *β-decay of 97Cd*

The nucleus $^{97}$Cd is a waiting point of the rp-process since the rp-process matter flow proceeds through β-decay of $^{97}$Cd rather than proton capture [8].

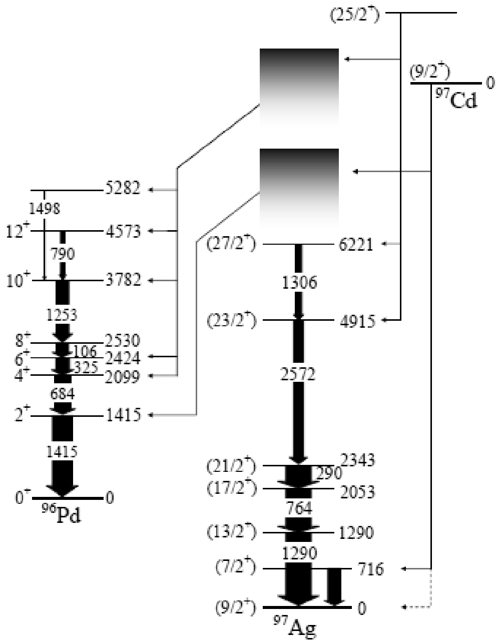


Figure 3. Decay scheme of the ground state and 25/2$^+$ isomeric state in $^{97}$Cd. Figure adapted from Ref. [12].

The β-decay half-life of $^{97}$Cd is, therefore, an important input for rp-process calculations. Previous to our experiment, this nucleus was studied in Refs. [9,10]. In particular, Ref. [10] assigned a half-life of 2.8(6) s to the decay of the ground state of $^{97}$Cd. However, shell-model calculations predict two isomeric states, a 1/2− state below 1 MeV, and a 25/2+ state at about 2.4 MeV in $^{97}$Cd [10,11]. Therefore, a possible contribution of isomeric states to the 2.8 sec activity could not be ruled out. The results for the decay of $^{97}$Cd in our experiment were detailed in Ref. [12,13]. Our study showed that the β-delayed proton activity stemming from the implantation of 97Cd had at least two components with half-lives 1.10(8) and 3.8(2) s, respectively. From the balance of the contribution of the two components to the βp- and β-activity, the $b_{\beta p}$ values of 12(2)% and 25(4)% were deduced for the 1.1 s and 3.8 s activity, respectively. β-delayed and βp-delayed radiation allowed to attribute the longer half-life to the decay of a high spin β-decaying state, identified as the 25/2+ isomer predicted by shell model calculations [11].

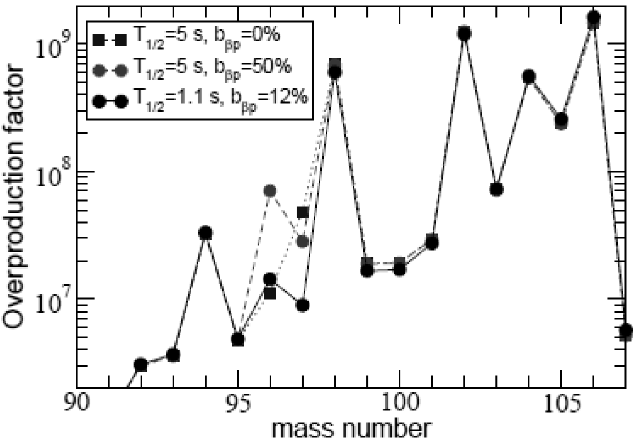


Figure 4. Ratio of produced abundance to solar system abundance for X-ray burst ashes obtained with data on $^{97}$Cd from this work (black circles, solid line) and with a larger half-life of 5 s and bp = 0% (blue squares, dotted line) or bp = 50% (red circles, dashed line).

A detected γ ray of 717 keV determined the assignment of the half-life 1.1 s to the ground state of $^{97}$Cd. For a more detailed discussion on these assignments see Ref. [12]. 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 [1] with ReaclibV1 nuclear reaction rates [14]. 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 (ratio between abundance produced and abundance detected in the solar system), calculated assuming all unstable isotopes have completed their decay chains into the first stable isobar, is shown in Fig. 4. 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. 4). Varying the $^{97}$Cd half-life and $b_{\beta p}$ within the error bars had a negligible effect on the final abundances. The new data exclude, therefore, 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.

### 3.2. *β decay of $^{96}$Cd*

$^{96}$Cd is a possible waiting point in the astrophysical rp-process and a progenitor of the p-nucleus $^{96}$Ru [3]. Our half-life measurement of $1.03^{+0.24}_{-0.21}$ s, reported in Ref. [3], ruled out the possibility that the unknown decay properties of $^{96}$Cd (e.g., and unexpected long half-life) could be at the origin of the p-nuclei problem [3]. The $^{96}$Cd half-life was later revised to 0.67(15) s in Ref. [15] but leaving our conclusions substantially unchanged. From the analysis of the βp-decay data of $^{96}$Cd we also extracted another information. The analysis of the βp activity indicates that the dominant β-decay branching of $^{96}$Cd feeds the lowest 2+ isomeric state in $^{96}$Ag, [13] an information that will be useful whenever the mass measurement of $^{96}$Ag isomeric states will be available. No evidence for the presence $J = 16^+$ isomeric state [11] could be found, which is not surprising given the limited data collected for the $^{96}$Cd decay. The existence of such decay was recently reported in Ref. [15]. This isomer is likely to have MeVs of energy and would therefore not play a role in the rp-process.

### 3.3. *β-delayed proton emission*

β-delayed proton emission of nuclei along the rp-process path alters the composition of the burst ashes depending on the value of their branching ratio $b_{\beta p}$. However, the $b_{\beta p}$ values along the rp-process path are still largely unknown, and theory cannot predict them with sufficient accuracy given the large uncertainties of unknown parameters such as proton separation energies, Q-values, and β-decay strength functions. In the $^{100}$Sn region the $b_{\beta p}$ of $^{93}$Pd and $^{97}$Cd are of particular interest, since via βp emission these nuclei are progenitors of $^{92}$Mo and $^{96}$Ru, respectively.

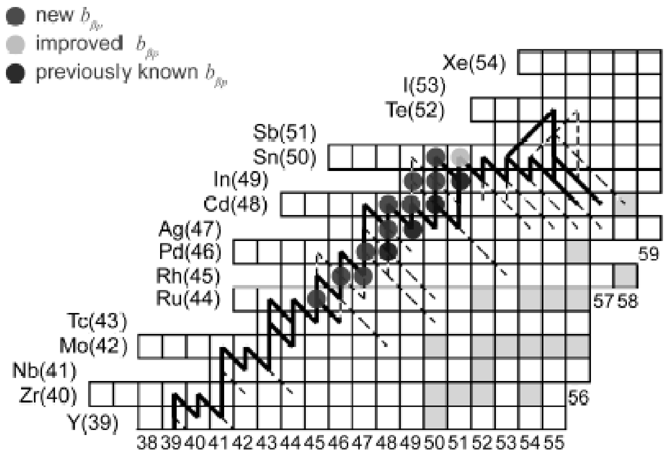


Figure 5. Progenitors for β-delayed proton emission discussed in this paper. The solid and dashed lines denote the path of the rp process with reaction flows of more than 10% and more than 1% of the maximum flow, respectively.

The study of $^{93}$Pd and $^{97}$Cd is therefore relevant for the understanding of an rp-process contribution to the origin of these isotopes, provided an rp-process site that ejects sufficient amounts of the isotopes is found. The radial expansion bursts, powerful bursts that eject part of the neutron star photosphere could be such site [16]. Fig. 5 shows the nuclei for which we have measured $b_{\beta p}$ in relation with the rp-process path. The new $b_{\beta p}$ values are summarized in Table 1, while an extensive discussion on the βp -properties including βp-delayed γ-radiation was reported in Ref. [13]. To study the impact of the new $b_{\beta p}$ on the rp-process, the composition of the burst ashes obtained without any βp emission (this corresponds to previous calculations where this decay mode was neglected) was compared with calculations that took into account the experimentally-determined βp branches, including the ones indicated in Fig. 5.

Fig. 6(a) shows that noticeable effects occur for mass A = 83, 87, 93, 97, and in particular for mass A = 101, because of the sizable $b_{\beta p}$ values of $^{83}$Zr, $^{87}$Mo, $^{93}$Pd, $^{97}$Cd, and $^{101}$Sn.

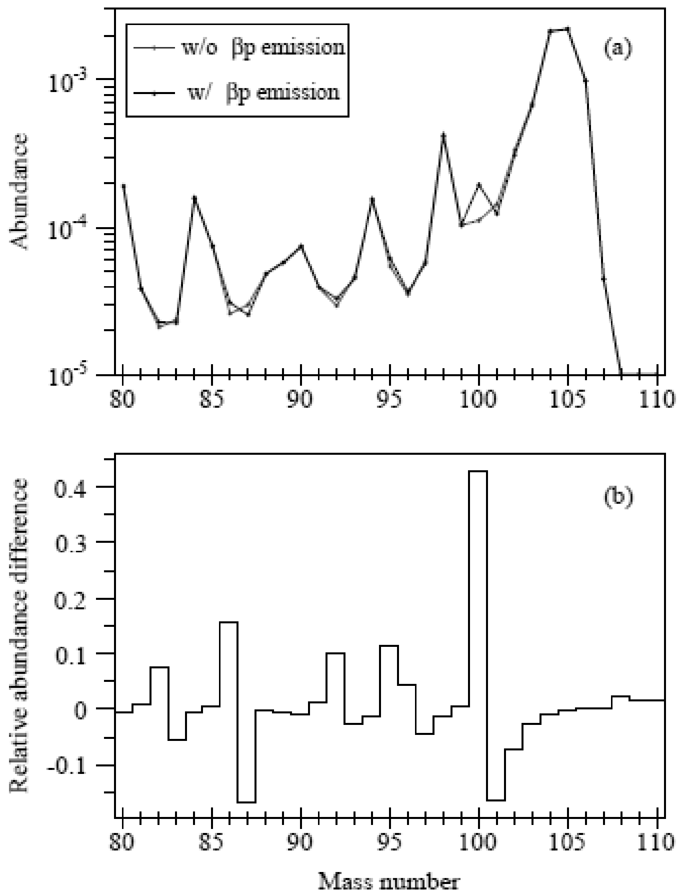


Figure 6. Abundance as a function of the mass number of the composition of X-ray burst ashes calculated with an X-ray burst model with and without βp emission.
(b) Relative abundance difference between the two calculations as a function of mass number.

However, these effects are not dramatic due to the small $b_{\beta p}$ values involved. In the simplest picture, βp emission should only play a role late in the freezeout, when proton capture rates are slow owing to lower temperature or hydrogen exhaustion, as otherwise an emitted proton would tend to be recaptured. As shown in Fig. 6(b), the increase in A = 100 yield was about four times larger than what one would expect from a simple transfer of A = 101 nuclei to A = 100 after freezeout due to the βp branching. This indicates that βp emission also plays a role during the rp process because of inefficient recapturing of emitted protons. This leads to an increase of A = 100 abundance and a decrease in abundance of A = 101–104 because of the reduced reaction flow towards heavier nuclei.

## 4. Conclusion

β-decay spectroscopy of a range of neutron-deficient nuclei near $^{100}$Sn was studied at NSCL. The study of light Cd isotopes and β-delayed proton emission have provided a precise set of new nuclear data that are direct inputs of the rp-process. In particular, we have measured for the first time the half-lives and $b_{\beta p}$ of $^{96}$Cd and of the ground state of $^{97}$Cd. Both of these nuclei are rp-process waiting points and progenitors of the p-nucleus $^{96}$Ru. In addition, our measurements have provided a complete set of $b_{\beta p}$ data for the rp process between A = 92–101. Along with recent mass measurements, [21–23] the results presented here are important steps towards more reliable rp-process calculations in this mass region.

Table 1. $b_{\beta p}$ measured in this work, compared to literature values when available.

| Nucleus | $J^+$ | $b_{\beta p}$ (%) This work | $b_{\beta p}$ (%) Literature |
|---|---|---|---|
| $^{89}$Ru | | $3^{+1.9}_{-1.7}$ | |
| $^{91}$Rh | | 1.3(5) | |
| $^{92}$Rh$^{(g)}$ | $6^+$ | 1.9(1) | |
| $^{93}$Pd | | 7.4(4) | $<5$[17] |
| $^{95}$Ag | | 2.5(3) | |
| $^{96}$Ag | $(8^+)$ | 6.5(8) | 8.5(15)[18] |
| | $(2^+)$ | 14(3) | 18(5)[18] |
| $^{96}$Cd | | 5.5(40) | |
| $^{97}$Cd | $(9/2^+)$ | 11.8(20) | |
| | $(25/2^+)$ | 25(4) | |
| $^{98}$In$^{(g)}$ | | $5.5^{+3}_{-2}$ | |
| $^{98}$In$^{(m)}$ | | 19.5(13) | |
| $^{99}$In | | 0.9(4) | |
| $^{100}$In | | 1.7(4) | 1.6(3)[19] |
| $^{100}$Sn | | $<35$ | |
| $^{101}$Sn | | 22(2) | $14^{+10}_{-6}$[20] |

The impact of the measurements on the production of $^{92}Mo$ and $^{96}Ru$ in the rp process was also addressed. The new half-lives and the new $b_{\beta p}$ values point out to a reduced production of p-nuclei by the rp-process. An earlier speculation [2] that βp emission may significantly alter the composition of heavy rp-process ashes is in fact not supported by these new results.

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