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

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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.

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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

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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 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.

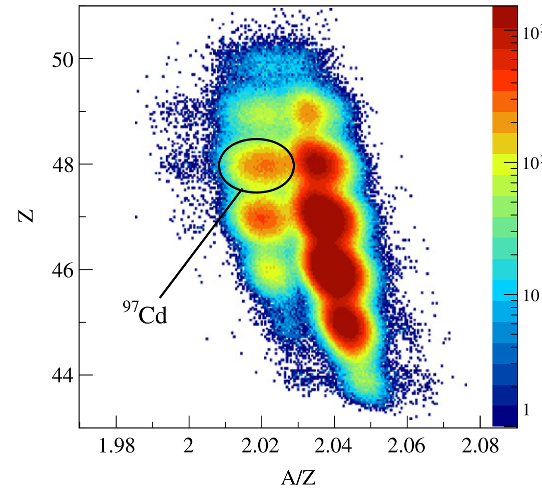

Fig. 1. (Color online.) Particle identification spectrum of the heavy nuclei arriving at the BCS.

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

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