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β-Decay Study of the rp-Process Nucleus ^{96}Cd

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The half-life of the even-even N=Z nucleus ^{96}Cd, one of the last waiting points along the reaction path of the rp-process, has been measured for the first time at the National Superconducting Cyclotron Laboratory, and was found to be $1.03^{+0.24}_{-0.21}$ s. The ^{96}Cd nuclei were produced by fragmentation of a 120 MeV/u ^{112}Sn primary beam on a Be target and selected with the A1900 Fragment Separator. Further purification was achieved using the recently commissioned Radio Frequency Fragment Separator system. The fragments of interest were unambiguously identified and their β decay was measured with the NSCL Beta Counting System (BCS) in conjunction with the Segmented Germanium Array (SeGA). Implantations were correlated with their subsequent decays on an event by event basis, and prompt and β-delayed γ-rays from the decay of implanted nuclei were identified, if present. The implications of the measured half-life of ^{96}Cd on the calculated rp-process final abundances are discussed.

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1. Introduction

Type I X-ray bursts are thermonuclear explosions near the surface of a neutron star that accretes hydrogen and helium rich matter from a low mass companion in a binary system [1, and references therein]. At accretion rates $\leq 10^{-8}$ $M_{\odot}yr^{-1}$, when temperatures in the range of 0.2 to 2.0 GK and densities $\rho \geq 10^{5}$ $g{\cdot}cm^{-3}$ are reached, nuclear burning proceeds through the αp and the rp processes [2]. The rapid proton capture process (rp-process) consists of a series of fast (p,γ) reactions and β decays taking place near the proton-drip line. Depending on system parameters and ignition conditions the rp-process can extend into the A ≈ 92 – 110 mass region [2], [3], where the Sn-Sb-Te cycle represents a natural endpoint [2]. Network calculations indicate that the even-even N=Z nuclei beyond ^{56}Ni represent the major waiting points along the reaction path of the rp-process and their β-decay half-lives, therefore, determine the processing timescale and final composition. Among these waiting points, ^{96}Cd was the only one with experimentally unknown properties, and this work reports on the first measurement of its β-decay half-life. To a first approximation, the final abundances of A=96 nuclei in the burst ashes directly scale with the half-life of ^{96}Cd.

A question that remains unanswered in nuclear astrophysics is that of the origin of the light p-nuclei ^{92}Mo, ^{94}Mo, ^{96}Ru, and ^{98}Ru, which are observed with relatively high abundances in the solar system [1]. The rp-process in X-ray bursts has been proposed as a possible production mechanism of these nuclei [4], [1], provided that the synthesized matter can somehow escape the gravitational potential of the neutron star. In principle, for any rp-process nucleosynthesis scenario for A=92-96 nuclei where the reaction flow proceeds along the proton drip line, the half-life of ^{96}Cd will directly determine the amount of ^{96}Ru produced.

From the point of view of nuclear structure, there also exists a considerable interest in the region around ^{96}Cd, since heavy N=Z nuclei near doubly magic ^{100}Sn are an important testing ground for shell model calculations. The theoretical predictions for the β-decay half-life of ^{96}Cd range from 0.3 s [5] to 2.2 s [6]. In addition, a β-decaying $J=16^{+}$ spin-gap isomer, with a half-life of 0.5s, has been predicted at an excitation energy of about 5.3 MeV in ^{96}Cd [7]. Our measurement, therefore, provides a constraint for nuclear models in this mass region.

2. Experimental Techniques

N ≈ Z nuclei around ^{100}Sn, including ^{96}Cd, were produced at NSCL by fragmentation of a primary beam of ^{112}Sn at 120 MeV/u impinging on a 195 mg/cm^{2} Be target. The secondary beam was first selected with the A1900 Fragment Separator. A 40.6 mg/cm^{2} Kapton wedge was used at the dispersive focal plane of the A1900, and the momentum acceptance of the separator was set to 1%.

Large amounts of contamination in the secondary beam come from the low momentum tails of higher peaked rigidity fragments that extend into the acceptance of the A1900 Fragment Separator. Therefore, the secondary beam was sent to the Radio Frequency Fragment Separator (RFFS) [8] in order to achieve the beam purity necessary for the proper correlation of implants and decays and to avoid radiation damage in our implantation detector. The RFFS applies a vertical sinusoidal 100 kV peak potential between two parallel plates at the same frequency as that of the coupled cyclotrons. The ions are deflected in such a way that a set of vertical slits placed ~3 m downstream of the cavity blocks unwanted products that lie outside of the time-of-flight range of the isotopes of interest. This effectively results in a velocity dependent selection of fragments. The overall contamination rate was reduced by about a factor of 200, which yielded an average accepted rate of about 50 counts per second. The fragments of interest were then directed to the experimental end station, which was composed of the NSCL β-Counting System (BCS) and 16 detectors from the Segmented Germanium Array (SeGA).

The BCS [9] was composed of three silicon PIN detectors whose thicknesses were chosen to ensure that the nuclei were stopped in a 995 μm Double Sided Si Strip Detector (DSSD). The DSSD is segmented into 40 1-mm strips in both the x and y dimensions creating 1600 individual pixels that register time and position of every implanted ion as well as its subsequent β decays. The β calorimeter, consisting of a stack of six 1 mm Single Sided Si Strip Detectors (SSSD) and a 1 cm thick planar Ge detector, was placed downstream of the DSSD to veto light particles (see also contributions by Lorusso et al., [10] and Stoker et al., [11] to these proceedings). The β-detection efficiency of the DSSD, determined from the fitting of the decay curves of some of the most abundant isotopes, was 37%.

The particle identification (PID) was performed using the energy loss measurement provided by the PIN detectors and two different measurements of the time of flight (TOF) of each ion. One TOF determination was taken between the cyclotron RF and the first PIN detector; the second was measured between a plastic scintillator at the focal plane of the A1900 Fragment Separator and PIN1. The PID was verified by the observation of γ-rays emitted by known microsecond isomers (e.g. ^{90}Mo, ^{93}Ru and ^{96}Pd) that reached the experimental end station when the RFFS slits were open.

3. Results and Discussion

Correlations of implanted ions and their subsequent decays were performed via software by monitoring an implantation pixel and its nearest neighbors for 10 s after an implantation occurred. The time–dependent decay of ^{96}Cd was evaluated with a Maximum Likelihood analysis (MLH) that considered the decay of the parent, growth and decay of the daughter and granddaughter nuclei, as well as β-decay background events (see also the contribution by Montes et al. to these proceedings [12]). The background was calculated as a function of time and pixel position, resulting in an average rate of 0.1 s^{-1} over the 10 s correlation time. The value obtained for the half-life of ^{96}Cd is $1.03^{+0.24}_{-0.21}$ s from a sample of 274 implants. Shown in Fig. 1 is the decay curve obtained for ^{96}Cd with a χ^2 fit that agrees with the result of the MLH analysis.

We did not find evidence of the decay of the predicted spin-gap isomeric state with a half-life of 0.5 seconds. A series of Monte Carlo simulations were done assuming several different proportions of two components present in the secondary beam and the MLH analysis was run to generate the corresponding likelihood curves. The shapes of the obtained likelihood curves were very similar in all cases and therefore they could not be used to identify the two different β-decay components.

In Fig. 2 we show a comparison of our measured ^{96}Cd half-life to the various theoretical predictions. The model that most closely predicts the half-life, within the experimental uncertainties, is the one by Möller et al. [13]. Their model is based on the finite-range droplet model and folded-Yukawa single-particle potential published in [14]. The shell model calculation overpredicts the half-life of ^{96}Cd by about a factor of 2.

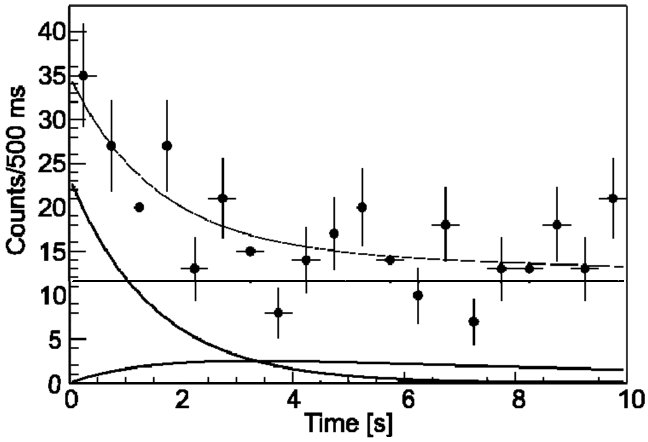

Fig. 1 Decay curve for ^{96}Cd. This fit considers an exponential parent decay, exponential daughter growth and decay and a linear background.

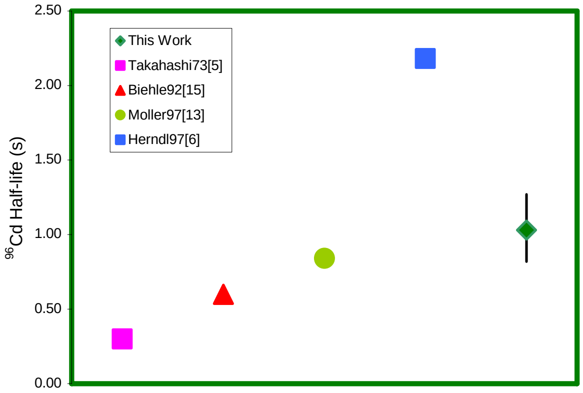

Fig. 2 Comparison of our measured ^{96}Cd half-life to various theretical predictions.

The consequences of the measured ^{96}Cd half-life on the rp-process are explored through a calculation of the final composition of the ashes of an X-ray burst. Fig. 3 shows the result of such calculation using a one zone 1D model that considers instantaneous freezeout, which would favor the production of A=96 material. The overproduction factors –defined as the ratio of produced abundance to solar abundance– calculated for different values of the half-life of ^{96}Cd, including the result of our measurement are shown.

An abundance as high as that produced for A=98 and A=102 would be necessary at A=96 to explain the production of ^{96}Ru by the rp-process. Our measured half-life does not lead to an overproduction factor high enough to support this possibility, thus suggesting that the X-ray bursts may not be the main source of the ^{96}Ru observed in the solar system (see also [16]).

4. Conclusion

Several exotic nuclei in the region around doubly magic ^{100}Sn were produced at NSCL and their β decays are being studied. The high isotope selectivity provided by the newly commisioned RFFS has proven to be critical in these measurements. In this work, we report on the first measurement of the β-decay half-life of ^{96}Cd, which constrains the large range of theoretical half-life calculations for the ground state. Although our experiment was sensitive to both isomeric and β-delayed γ-rays in ^{96}Cd, our statistics for βγ coincidences did not yield conclusive evidence of any γ transitions associated with its decay. We did not find evidence of the existence of the predicted second β-decaying component with a half-life of 0.5s of this isotope, but its existence cannot be ruled out.

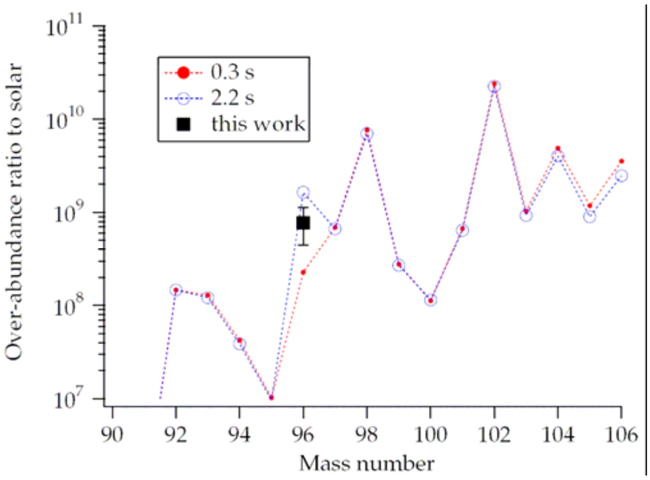

Fig. 3 Predicted overproduction factors relative to solar as a function of mass number for various ^{96}Cd half-lives. Our measured half-life leads to an overproduction factor indicated by the solid square. This X-ray burst calculation considers a rapid rp-process freezout, which favours the production of A=96 species.

With our measured ^{96}Cd half-life, it seems unlikely that an rp-process nucleosynthesis scenario for A=92–96 nuclei, where the reaction flow proceeds along the proton drip line, could be the main responsible for the origin of ^{96}Ru. It should be pointed out, however, that the uncertainties in masses and reaction rates still prevent us from completely excluding this possibility. Also, additional effects, such as reshuffling of the abundances during freezeout, might play a role. Evidently, more experimental data and detailed rp-process calculations that include the updated data are needed.

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