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Study of decay properties for Ba to Nd nuclei relevant for the formation of the r-process rare-earth peak (A∼160)

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Abstract. At the RIKEN Nishina Center, exotic neutron-rich isotopes of Ba, La, Ce, Pr, and Nd were measured. This work reports their half-lives ($T_{1/2}$) and β-delayed neutron-emission probabilities (P_{xn}). The setup consisted of the BigRIPS in-flight separator for particle identification, the Advanced Implantation Detector Array (AIDA) for ions and β detection, and the BRIKEN neutron counter for neutron detection. Using this arrangement, 4 new $T_{1/2}$ and 14 new P_{1n} were measured. Furthermore, 38 $T_{1/2}$ and 2 P_{1n} values were remeasured, decreasing the uncertainties for some of them. In addition to improving predictions of nucleosynthesis models that describe the production of the rare-earth peak at A$\sim$160 via the r-process, these additional experimental data should help to constrain theoretical models for calculations of $T_{1/2}$ and P_{xn} in this region.

1 Introduction

Nearly half of the nuclei heavier than iron are produced via rapid neutron capture (the r-process) in explosive stellar scenarios. Above the mass number $A = 100$,, there are two main peaks in the r-process solar-system abundances, located at $A \sim 130$ and $A \sim 195$. Located between them, the Rare-Earth Peak (REP) is a tiny but definite peak at mass $A \sim 160$ that results from the freeze-out during the last stages of neutron exposure. Determining the late-time conditions at the r-process site may thus be possible using the formation of the REP as a special probe. According to theoretical models and sensitivity studies, the half-lives ($T_{1/2}$) and β-delayed neutron emission probabilities (P_{xn}) of very neutron-rich nuclei, in the mass region $A \sim 160$ for 55≤Z≤64, are critical for the formation of the REP [1, 2].
From 2016 to 2021, the BRIKEN project operated at the Radioactive Isotope Beam Factory (RIBF) in the RIKEN Nishina Center. This collaboration has carried out a thorough measurement program of the β-decay properties of the most neutron-rich nuclei experimentally available. The BRIKEN REP proposal focused on measurements from Ba to Gd ($Z = 56 - 64$). The entire REP proposal comprised three experimental campaigns. Recently, a first publication containing the experimental findings for Pm to Gd ($Z = 61 - 64$) species has been released [3]. The main goal of this study is the data analysis for Ba to Nd ($Z = 56 - 60$) species. Figure 1 shows the overlap among the targeted area in our study and the high astrophysical impact region proposed by Mumpower et al. [2]. The experimental setup, the status of the data analysis in this region, and future perspectives are discussed in this work.

2 Experimental setup

The exotic neutron-rich isotopes were produced at the RIKEN Nishina Center using a ^{238}U primary beam, bombarding a ^{9}Be target. The products from the fragmentation and fission reaction were selected using the BigRIPS in-flight separator and directed to the F11 focal plane through the Zero-Degree Spectrometer (ZDS) [5]. Each ion reaching the experimental area was identified by measuring its atomic charge (Z), and its mass-to-charge ratio (A/Q). Identified ions were implanted in the Advanced Implatation Detector Array (AIDA) [6]. AIDA comprises a stack of six silicon Double-Sided Strip Detectors (DSSD). Each DSSD has a thickness of 1 mm, and 128 strips per side.

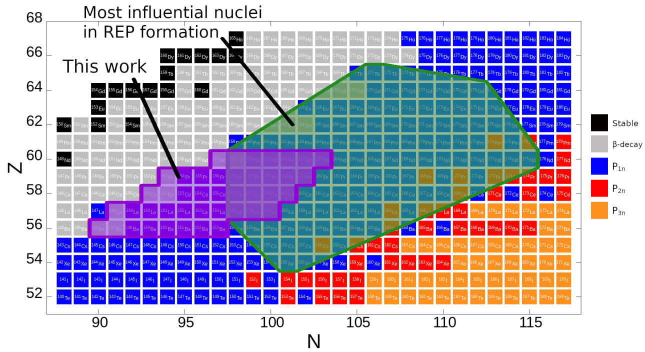

Figure 1. (Color online) This scheme shows a section of the table of isotopes. The green region indicates the most influential nuclei in rare-earth peak formation [2]. The purple area shows the isotopes that were measured in this experiment. The figure also depicts the main decay channel predicted by theoretical models for each isotope [4].

The BRIKEN neutron counter [7] was placed surrounding AIDA in order to detect the β-delayed neutrons. It comprised an array of 140 ^{3}He-filled proportional tubes embedded in a 90 cm x 90 cm x 75 cm High-Density PolyEthylene (HDPE) moderator. Given the large cross section for thermal neutrons in the capture reaction n_{th} + ^{3}He→ ^{3}H+p, neutron moderation is necessary to achieve high overall detection efficiencies. The HDPE block has a central hole where AIDA is inserted. The block also has two additional holes at the lateral sides, where two CLARION-type clover detectors are placed to offer γ detection capabilities [7]. The neutron detection efficiency of the BRIKEN detector has been calculated by Monte Carlo simulations and validated experimentally using a ^{252}Cf neutron source [8]. The BRIKEN counter offers a nominal value for the efficiency of 68.6% up to 1 MeV. At higher energies, the efficiency decreases smoothly. Concerning the data acquisition, the raw data is collected by three independent data acquisition systems (DAQs) from BigRIPS, AIDA, and BRIKEN detectors. To create a common timestamp and enable the reconstruction of the identified events, a synchronization signal has been fed into each DAQ. The primary objective of this experiment was to measure the $T_{1/2}$ and P_{xn} linked to the implanted ions' decay. To achieve this, for each identified isotope, we built correlation histograms between implant, beta, and neutron events. Then, we fitted the histograms using the solution to the Bateman equations [9] for all the decay descendants. The fit procedure was run on all histograms associated with the isotope of interest at the same time to achieve self-consistency in the fit parameters [10].

3 Preliminary results

The top panel of Figure 2 presents the particle identification (PID) of the ions implanted on AIDA. In the lower part, there is the projection of the PID matrix onto the A/Q axis for the Pr isotopes. The A/Q resolution obtained is sufficient to ensure a good separation of fully stripped and H-like ions in the less exotic region ($A < 159$). Figure 3 presents the preliminary findings of the measured $T_{1/2}$ in this work. This study yielded 4 new half-lives: ^{157}La, ^{159}Ce, ^{161}Pr, and ^{163}Nd. For these new half-lives, the determination of the precise values and uncertainties is still ongoing. By improving particle identification, we expect to reduce the charge-state contamination. Additionally, a total of 38 $T_{1/2}$ have been remeasured with an improved accuracy in several cases. The P_{1n} values were measured for the first time for a vast majority of the isotopes. In this work, 14 new P_{1n} values ($^{151-152}$Ba, $^{151-153}$La, $^{154-156}$Ce, $^{155-158}$Pr, and $^{160-160}$Nd) are preliminary reported. Two P_{1n} values (^{149}La and ^{150}La) have also been remeasured with an increased accuracy. The P_{2n} values in this region are 0, because the Q_{b2n} values are less than zero [12]. Figure 3 compares our $T_{1/2}$ preliminary findings with assessed nuclear data from the ENSDF and some theoretical models: Relativistic Hartree-Bogoliubov plus proton-neutron Relativistic Quasi-Particle Random-Phase

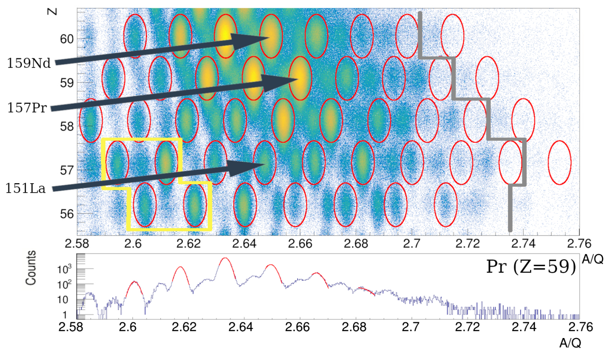

Figure 2. (Color online) Identification plot of the REP-BRIKEN 2018 experiment. Each red circumference corresponds to an identified isotope. The gray line represents the upper bound of the previously measured $T_{1/2}$ [11]. Yellow box highlights previously measured P_{1n} values. The bottom panel depicts the projection of the PID matrix on the A/Q axis for the Pr ($Z = 59$) isotopes.

Approximation (RHB+pn-RQRPA, 2016) [13], Finite-Range Droplet-Model mass formula (2012) plus Quasiparticle-Random-Phase Approximation (FRDM+QRPA, 2018) [4], and the proton-neutron Finite Amplitude Method (pnFAM, 2020) [14]. Compared with the evaluated nuclear data, our results are consistent within a 3σ error band. Furthermore, in Figure 4, our preliminary results for the P_{1n} values are compared with evaluated nuclear data from the ENSDF and some theoretical predictions: RHB+pn-RQRPA (2016) [13], FRDM+QRPA (2018) [4], and the proton-neutron Relativistic Quasiparticle Random-Phase Approximation plus Hauser-Feshbach statistical model (pn-RQRPA + HFM, 2021) [15]. Regarding the comparison with theoretical models, our data supports the overall trend for all P_{1n} predictions. In particular, the RHB+pn-RQRPA model gives estimates for Ba, Ce, Pr, and Nd ($Z = 56$, 58, 59, and 60) that are in close agreement with the experiment, but it significantly overestimates La ($Z = 57$) nuclei. In a comparison of the three models under consideration, pn-RQRPA + HFM best replicates the experimental data and provides good agreement for most of the isotopes.

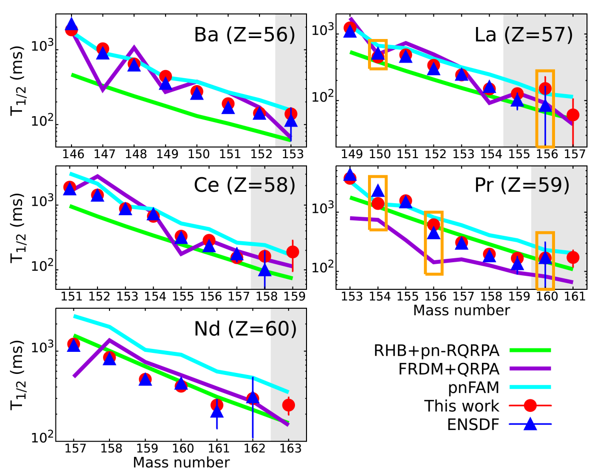

Figure 3. (Color online) Preliminary half-lives derived in this work (red circles) and previous measurements (blue triangles). These results are compared to three theoretical models: RHB+pn-RQRPA [13] (green), FRDM+QRPA [4] (purple), and pnFAM [14] (light-blue). The grey region highlights expected improvements in the determination of $T_{1/2}$ by the end of the data analysis. Potential isomer contributions are indicated by orange boxes [16].

4 Remarks and future work

In this work, preliminary results from measurements of exotic isotopes in the REP region at the RIKEN Nishina Center are presented. Four new $T_{1/2}$ and 14 new P_{1n} values are reported for the first time. 38 $T_{1/2}$ and 2 P_{1n} values were remeasured, improving the data accuracy for many of them. As we covered above, there is still some work ongoing. By reducing

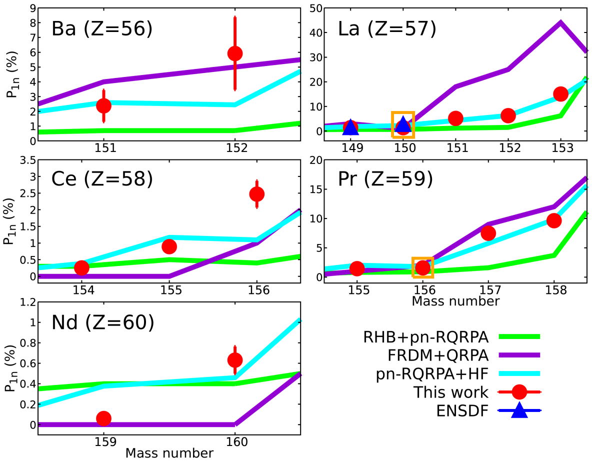

Figure 4. (Color online) Preliminary results for P_{1n} from this work (red circles) and previous measurements (blue triangles). These experimental results are compared to the following theoretical models: RHB+pn-RQRPA [13] (green), FRDM+QRPA [4] (purple), and pn-RQRPA + HFM [15] (light-blue). Orange boxes indicate potential isomer contribution [16].

the contamination from charge states, the data reported for the most exotic region should be improved. Aside from that, the impact of potential isomers on the studied isotopes must be assessed. Lastly, the evaluation of the astrophysical impact of the new nuclear data on the description of the r-process in the REP region will be developed in the following months.

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