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


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Abstract. Half-lifes ($T_{1/2}$) of exotic neutron-rich isotopes of Ba, La, Ce, Pr, and Nd were measured at the RIKEN Nishina Center. The experimental setup consisted of the BigRIPS in-flight separator for ion selection identification, the Advance Implantation Detector Array (AIDA) for ions and $\beta$ detection, and the BRIKEN detector for neutron counting. Using this setup, 4 new $T_{1/2}$ have been measured for the first time, and 38 $T_{1/2}$ have been remeasured with improved precision in several cases. These new experimental data should help to constrain theoretical models for calculations of $T_{1/2}$. The status of the experimental analysis and preliminary results are provided in this contribution.

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1 Introduction

Rapid neutron capture in explosive stellar scenarios (the r-process) produces almost half of the nuclei heavier than iron. For nuclear masses $A > 100$, there are two main peaks in the r-process solar system element abundances, located at $A = 130$ and $A = 195$, which are associated with the neutron shell closure at $N = 82$ and $N = 126$ affecting the r-process path during the $(n, \gamma) \leftrightarrow (\gamma, n)$ equilibrium. The Rare-Earth Peak (REP), on the other hand, is a small but distinct peak around mass $A \sim 160$ that results from the freeze-out in the final stages of neutron exhaustion. Thus, the formation of the REP may provide a unique probe for examining the late-time conditions at the r-process site. According to theoretical models and sensitivity studies, the half-lives ($T_{1/2}$) and beta-delayed neutron emission probabilities ($P_{\text{xn}}$) of very neutron-rich nuclei, in the mass region $A \sim 160$ for $55 \leq Z \leq 64$, are critical for the formation of the REP [1, 2].

The BRIKEN project [3, 5] has been in operation from 2016 to 2021 at the Radioactive Isotope Beam Factory (RIBF) in the RIKEN Nishina Center. This collaboration has carried out a thorough measurement program of the $\beta$-decay properties of the most neutron-rich nuclei experimentally available. The BRIKEN REP proposal focused on measurements from Ba to Gd ($A \sim 160$) at the RIKEN Nishina Center. The entire REP proposal comprised three experimental campaigns. Recently, a first publication has been released with the experimental results for Pm to Gd [6]. The data analysis for Ba to Nd species will be presented at later stage. Results on $P_{\text{xn}}$ values will be presented at later stage. The experimental setup and status of the data analysis on this region are also discussed.

2 Experimental setup

The exotic neutron-rich isotopes were produced at RIKEN Nishina Center using a 60 pmA $^{235}$U primary beam, with an energy of 345 MeV/nucleon, bombarding a 5 mm thick $^9$Be target. The fragments from the collision are selected by BigRIPS in-flight separator and guided to the experimental area through the Zero-Degree Spectrometer (ZDS) [7]. 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 Implantation Detector Array (AIDA)) [10]. AIDA consists of a stack of six silicon Double-Sided Strip Detectors (DSSD) separated by 10 mm gaps. Each DSSD has a thickness of 1 mm, and 128 strips per side. The strips on the two sides are perpendicular to each other, forming a 16384-pixel silicon detector. This configuration offers a high spatial resolution, allowing the reconstruction of implant and $\beta$-decay events.

The BRIKEN neutron counter [11] was placed surrounding AIDA in order to detect directly the $\beta$-delayed neutrons. It consisted of 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, thus providing an almost 4$\pi$ neutron detector. Neutron moderation is required in order to achieve high overall detection efficiencies thanks to the large cross section for thermal neutrons in the reaction $n_\text{th} + ^3\text{He} \rightarrow \gamma + ^3\text{H} + p$. The HDPE block has a central hole of 11.6 cm x 11.6 cm where AIDA is inserted. It also has additional holes at both sides, where two CLARION-type clover detectors are placed to offer $\gamma$ detection capabilities [11]. Figure 1 provides a scheme and a picture of the BRIKEN setup. The neutron efficiency of the BRIKEN detector has been calculated by Monte Carlo (MC) simulations, it is independent of the neutron energy up to 1 MeV, it has a nominal value of 68.6% and shows a smooth decrease at higher energies. The MC calculations of the neutron efficiency have been validated experimentally using a $^{252}$Cf neutron source, obtaining good agreement between the measurement and simulations [12]. The rawdata is collected by three independent data acquisition systems (DAQs) from BigRIPS, AIDA, and BRIKEN detectors. For this reason, a synchronization signal has been fed into each DAQ, thus producing a common timestamp reference and allowing the reconstruction offline of the identified implant-decay events.

3 Data analysis methodology

The main goal of this experiment is to measure half-lives ($T_{1/2}$) and $\beta$-delayed neutron branchings ($P_{\text{xn}}$) associated with the decay of the implanted ions. To this end, we took advantage of the good spatial and time resolution of our setup in order to build spatial and temporal correlations. Thus, for each identified implanted isotope, we build a correlation between implants and beta events ($H_{\beta}$ histogram). This histogram stores the time difference between an implant and all the $\beta$ events that took place in the same position within a defined time window. Using this procedure, the truly correlated decays will form a decay curve clearly distinguishable from the background produced by uncorrelated events. In the case of the $\beta$-delayed neutrons, we built the implant-$\beta$-neutron correlation ($H_{\beta\text{xn}}$ histograms). These histograms are constructed in a similar way as the $H_{\beta}$, but they require the detection of $x$ neutrons ($x=1, 2, \ldots$) in the BRIKEN counter within a fixed time window with respect to the $\beta$ detection. The last step to obtain the physical magnitudes of interest, namely $T_{1/2}$ and $P_{\text{xn}}$, is to fit all histograms using the solution of the Bateman equations ([4]), for all the decay descendants [5]. We used the
The initial number of implanted parent nuclei is \( N_1 = N_1(t=0) \), the decay constant is \( \lambda = \ln(2)/T_{1/2} \), and the number of k-type nuclei in a given decay path at time \( t \) is \( N_k(t) \). The branching ratio \( b_{i,i+1} \) in the decay chain from nucleus \( i \) to nucleus \( i+1 \) defines the decay path. The backward-time distribution was used to calculate the correlated accidental background. The fit procedure is performed simultaneously on all histograms in order to get self-consistency on the fit parameters [5]. As an example of the data analysis, the decay path and the fit are shown in Figures 2 and 3, respectively, for the decay of \(^{153}\text{La}\).

![Figure 2](image1.png)  
**Figure 2.** Diagram depicting the various decay paths for \(^{153}\text{La}\) disintegration. Each number below a nucleus is the \( T_{1/2} \) used as input.

![Figure 3](image2.png)  
**Figure 3.** Fit to implant-\( \beta \) time correlation histograms (top) and implant-\( \beta \)-\( \text{In} \) time correlation histograms (bottom) for \(^{153}\text{La}\). All the decay chain from Figure 2 was used to run the fit, but in this figure only the isotopes with a significant contribution are included.

![Figure 4](image3.png)  
**Figure 4.** Identification plot of the REP-BRIKEN 2018 experiment. Each red circumference corresponds to an identified isotope. The grey line indicates the limit of previously measured \( T_{1/2} \) [9]. Yellow box highlights previously measured \( P_{1\alpha} \) values. The bottom panel depicts the projection of the PID matrix on the \( A/Q \) axis for the Pr isotopes.

\[^{153}\text{Nd} \] The determination of the final values and uncertainties for these new half-lives is still in progress. We expect to achieve a further reduction of the charge-state contamination in the most exotic region by improving the particle identification. This is being implemented based on the correlation between \( A/Q \) and the total ion energy...
Figure 5. Preliminary results for $T_{1/2}$ from this work (in red), previous measurements (in blue). These results are compared to three theoretical models: RHB+pn-RQRPA [13] (in green), FRDM+QRPA [14] (in purple), and pnFAM [15] (in light-blue). The grey region highlights expected improvements on the determination of half-lives by the end of the data analysis. Orange boxes indicate potential isomer contribution [16].

Acknowledgment

This work has been supported by the Spanish Ministerio de Economía y Competitividad under Grants. FPA2014-52823-C2-1-P, FPA2014-52823-C2-2-P, FPA2017-83946-C2-1-P, FPA2017-83946-C2-2-P and grants from Ministerio de Ciencia y Innovacion PID2019-104714GB-C21, PID2019-104714GB-C22. Supported by Generalitat Valenciana regional grant PROMETEO/2019/007. Supported by European Union FEDER funds. It also has been supported by NKFIH (NN128072).

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