

MEASURING THE B-DECAY PROPERTIES FOR EXOTIC RARE-EARTH ISOTOPES

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ABSTRACT:

Many questions remain open even after the observation of the GW170817 event regarding the astrophysical environment of the r -process. A key factor in the comparability of observations and theories is the nuclear properties of the isotopes synthesized during the explosion, which are not or only poorly known. Recently, in experiments at the RIKEN Nishina Center, we have significantly extended the existing β -decay half-life ($T_{1/2}$) and delayed neutron emission probability (P_n value) database. It was shown that these data are essential for understanding the formation of the so-called rare-earth r -process abundance peak (REP). Using the ^{162}Pm isotope as an example, the main steps of the analysis are presented.

KEYWORDS: Nuclear astrophysics, r -process, rare-earth abundance peak, half-life, delayed neutron emission probability, experimental results

INTRODUCTION:

The wide range of isotopes observed in the Universe is the result of a few key nucleosynthesis processes. According to our current understanding, only the lightest isotopes (^1H , ^3He , and ^7Li) originated from the Big Bang. The bulk of the elements up to iron (Fe) is synthesized in stars via stellar burning. In AGB stars, in massive stars during the stellar burning phase, and in the explosive end-phases of massive stars, even heavier isotopes are produced mainly by free neutron capture (s -process, r -process) and to a small extent by the p -process (Burbidge *et al.*, 1957).

The slow neutron capture process (so-called s -process) operates close to the valley of stability where the typical time between two consecutive neutron captures is longer than the lifetime of the produced isotope ($\lambda_{n\gamma} \ll \lambda_\beta$). The endpoint of this process is the ^{209}Bi isotope (Käppeler *et al.*, 2011). Therefore, there must be an additional process, creating heavier elements than Bi (U, Th). This, so-called r -process, which takes place on a timescale of seconds, can only occur in an environment with a very high neutron density. A summary of the conditions and corresponding possible astrophysical environments required for the r -process to be successful is given in (Cowan *et al.*, 2021). By the parallel detection of gravitational waves (GW170817 event) and optical counterparts, in 2017 for the first time, it was proved that r -process isotopes can be formed during the merge of neutron stars (Abbott *et al.*, 2017). Furthermore, theoretical modelling suggested that collapsars could also be the site of the r -process which is supported by observing the abundance of old galactic halo stars (Reichert *et al.*, 2020). Abundance calculations using precise nuclear physics inputs may provide additional constraints on the details of the nucleosynthesis processes.

The abundance distribution of the r -process is characterized by two main maximums, located at $A \sim 130$ and $A \sim 195$, the formation of these peaks is associated with a more stable structure of the relevant isotopes due to the closed neutron shell. However, in between the two peaks, there is a third, smaller maximum (at $A \sim 160$), called the rare-earth abundance peak, which forms during the freeze-out period (when the material starts to decay back to stability) of the r -process. Accordingly, understanding the synthesis of the lanthanides may allow the probe of the freeze-out conditions. The formation of the REP is sensitive to variables that control the neutron density and neutron-to-seed ratio in the late stages of the r -process. The detailed modelling of the REP formation (Mumpower *et al.*, 2012b) showed that it is possible to constrain the range of astrophysical conditions of a potential site, but at first, the uncertainty of the nuclear physics inputs must be reduced.

For this reason, the β -decay properties of 28 isotopes of Pm, Sm, Eu, and Gd were measured (Kiss *et al.*, 2022). Most importantly, the β -delayed one-neutron-emission probabilities (P_{1n} values) have been measured for the first time and the β -decay half-life ($T_{1/2}$) database was significantly improved and

extended toward more neutron-rich species. In the following, we will show the main steps of the analysis using the ^{162}Pm isotope as an example.

EXPERIMENTAL APPROACH:

The experiment was performed in RIKEN Nishina Center, located at Wako-shi, Japan. The ^{238}U primary beam is accelerated in several steps up to 345 MeV/nucleon and then bombarded into a 5 mm thick ^9Be target with an intensity of about 60 pA. Identification of isotopes with varying proton/neutron ratios is performed using the BigRIPS separator, where energy loss (ΔE), magnetic rigidity ($B\rho$) and time-of-flight (ToF) measurements are performed at various focal points of the beamline (Fukuda *et al.*, 2013).

A schematic sketch of the AIDA-BRIKEN detector setup is in Figure 1 of (Tolosa-Delgado *et al.*, 2019), whose main components summarize below. After the aluminum degrader (to adjust the kinetic energy) at focal point F11, the radioactive isotopes were implanted in the Advanced Implantation Detector Array (AIDA) which consists of six double-sided silicon strip detectors (DSSSD). In addition, the setup contained a 10 mm thick plastic scintillation detector behind the DSSSD stack to veto passing low-mass particles (Griffin *et al.*, 2015). To detect the neutron and gamma events from decay, AIDA is placed in the center of the BRIKEN neutron counter containing 140 ^3He -filled proportional counters embedded in a polyethylene matrix that acts as a neutron energy moderator. The slowed neutrons are detected by the $^3\text{He}(n,p)^3\text{H}$ reaction. The neutron detection efficiency of the system was determined by simulation and by experimental measurements with a ^{252}Cf neutron source (Pallas *et al.*, 2022). Since the β -delayed neutron emitters have moderate $Q_{\beta n}$ -values (< 6 MeV) in our experiments, in the analysis the nominal average neutron detection efficiency ($\bar{\epsilon}_n = 66.8 \pm 2.0\%$) determined in (Tolosa-Delgado *et al.*, 2019) was used. Furthermore, two CLOVER-type HPGe detectors were inserted into the polyethylene matrix horizontally from opposite sides for γ spectroscopy.

After the identification of the fragments with the BigRIPS separator, the AIDA-BRIKEN detector system is used to detect implantation events, subsequent decays, and associated neutrons as well as γ -photons.

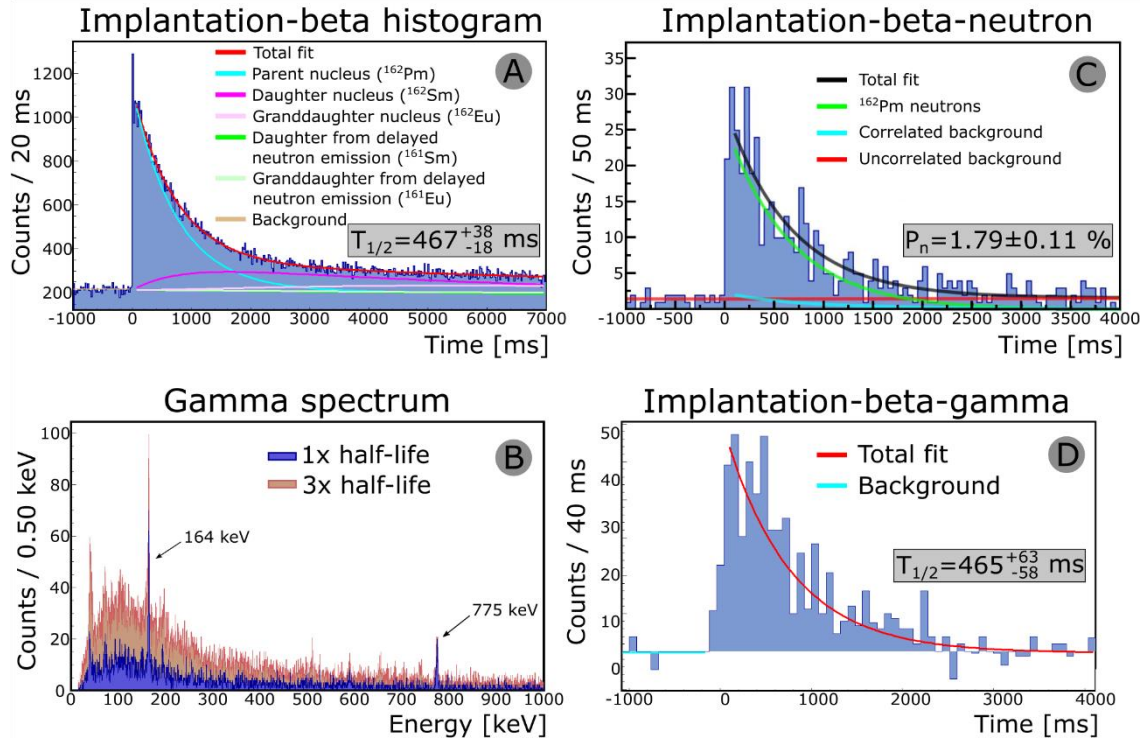


Figure 1.: The β -decay of ^{162}Pm . Panel A shows the Bateman fit of the i- β histogram with contributions from later members of the decay series. Panel B shows the fit of the i- β -n histogram with an exponential function. Panel C shows the low energy part of the γ -spectrum measured by the HPGe detectors. Blue indicates the spectrum detected during one half-life and brown indicates the spectrum detected during three half-lives so that gamma events

associated with the parent nucleus can be identified. The i - β - γ histogram for the 162 keV γ -peak, shown in panel D, was fitted by an exponential function to derive the half-life. See the text for details.

ANALYSIS AND RESULTS:

The implantation- β histograms (i - β) show the number of correlated β -events as a function of the detection time from implantation (panel A of Fig. 1). The half-lives of the daughter and even granddaughter nuclei in this nuclear range are so short that the β -decay events from them are not negligible. Thus, the i - β histograms include not only the events from the β -decay of the implanted parent isotope but also the events from the decay of subsequent members of the decay chain. Hence the half-lives were obtained by binned maximum likelihood fitting of the time distributions of the i - β correlations using the sum of Bateman's equations, taking into account the activity of the mother, daughter, granddaughter, and great-granddaughter (where applicable) nuclei and the β -delayed neutron branch of the decay chain. In our case the Bateman equation can be written as:

$$N_k(t) = N_{10} \prod_{i=1}^{k-1} (\lambda_i b_{i,i+1}) \times \left(\sum_{i=1}^k \frac{e^{-\lambda_i t}}{\prod_{j=1 \neq i}^k (\lambda_j - \lambda_i)} \right)$$

where $N_k(t)$ is the number of k -type nuclei at any given t time, N_{10} is the initial ($t = 0$) number of implanted parent nuclei, $\lambda = \ln 2/T_{1/2}$ is the decay constant, and $b_{i,i+1}$ is the branching ratio from nucleus i to $i + 1$ nucleus. The branching ratios determine the decay path, so to account for the delayed neutron emission branch, the branching ratio is set to be the delayed neutron emission probability (P_n). With the branching ratios isomer states can also be considered. Thus, knowing the half-lives of the subsequent decay series members, the number of implantations, and the P_n values, the decay constant of the parent nucleus can be determined. Random β -decay events were derived from the backward time distributions. For more details on the analysis method see (Tolosa-Delgado *et al.*, 2019).

β -delayed neutron emission occurs when the decay of a neutron-rich isotope leads to a level in the daughter above the neutron separation energy (S_n) and thus the decay can be followed by the emission of neutron(s). The phenomenon is characterized by the emission probability, known as the P_n value.

To derive the P_n values, the number of the neutron-gated β -decay events was derived by fitting an exponential function to the background subtracted time distribution of implant- β -neutron (i - β -n) correlations. The studied isotopes can be divided into three groups from the evaluation point of view. In the case of the lightest isotopes where $Q_{\beta n}$ -values are small or even negative (so this decay channel is closed) the number of implantation-beta-neutron (i - β -n) events were derived by numerical integration and the P_n values were found to be consistent with zero. Similarly, only a conservative upper limit for the P_{1n} value was determined, and numerical integration was applied for the most neutron-rich isotopes with less than 50 neutron events. Furthermore, in numerous cases there were sufficient statistics to fit the i - β -n histogram with exponential functions to determine the number of i - β -n correlation events (panel B of Fig. 1). Since the half-life determination is influenced by the P_n value (it is the branching ratio in the Bateman equation) and vice versa, the fitting procedure described above was performed using an iterative approach.

An independent method to derive the half-life values and to validate the results based on the Bateman fits is to measure the time evolution of yield of the γ -ray transitions emitted during the decay of the implanted isotope. However, to use this approach at first the γ -transitions associated with the decay must be identified. This was done by examining the time evolution of the gamma spectrum (1 half-life and 3 half-lives shown in panel C) and the time distribution of the implantation-beta-gamma (i - β - γ) correlation events was fitted by the combination of an exponential function and a linear background (panel D).

Using the above methods, the following results were obtained for the ^{162}Pm isotope: $T_{1/2} = 467_{-18}^{+38}$ ms from i - β fitting (Kiss *et al.*, 2022), which is in good agreement with the $T_{1/2} = 465_{-58}^{+63}$ ms preliminary result found from the i - β - γ method. The half-life of this isotope has been measured previously: $T_{1/2} = 630 \pm 180$ ms (Wu *et al.*, 2017). Our result agrees with the literature data, but its uncertainty is significantly lower and thus already suitable for use in astrophysical calculations. The P_{1n} -value was

determined experimentally for the first time for this isotope and was found to be 1.79 ± 0.11 % by exponential fitting (Kiss *et al.*, 2022).

OUTLOOK

The high-precision experimental data was used in nuclear reaction network calculations for the *r*-process employing a neutron-star merger and a hot wind scenario. To identify the nuclear physics inputs of importance within the current experimental uncertainties, a new variance-based sensitivity analysis method was used (Kiss *et al.*, 2022). The results of the analysis indicate that only a handful of variables account for nearly all the uncertainty (variance) of the abundance pattern. To better constrain these uncertainties further measurements are needed and thus experimental proposals were submitted to the Program Advisory Committee at RIKEN.

ACKNOWLEDGMENTS

This work was supported by NKFIH (NN128072) and by the ÚNKP-22-2 and ÚNKP-22-3 New National Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund (Project numbers: ÚNKP-22-2-I-DE-75; ÚNKP-22-3-II-DE-132).

REFERENCES

Abbott, B.P. *et al.* (2017) ‘Multi-messenger Observations of a Binary Neutron Star Merger’, *The Astrophysical Journal*, 848(2), p. L12. Available at: <https://doi.org/10.3847/2041-8213/aa91c9>.

Burbidge, E.M. *et al.* (1957) ‘Synthesis of the Elements in Stars’, *Reviews of Modern Physics*, 29(4), pp. 547–650. Available at: <https://doi.org/10.1103/RevModPhys.29.547>.

Cowan, J.J. *et al.* (2021) ‘Origin of the heaviest elements: The rapid neutron-capture process’, *Reviews of Modern Physics*, 93(1), p. 015002. Available at: <https://doi.org/10.1103/RevModPhys.93.015002>.

Fukuda, N. *et al.* (2013) ‘Identification and separation of radioactive isotope beams by the BigRIPS separator at the RIKEN RI Beam Factory’, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 317, pp. 323–332. Available at: <https://doi.org/10.1016/j.nimb.2013.08.048>.

Griffin, C. *et al.* (2015) ‘BETA-DECAY STUDIES OF R-PROCESS NUCLEI USING THE ADVANCED IMPLANTATION DETECTOR ARRAY’, in *Proceedings of XIII Nuclei in the Cosmos — PoS(NIC XIII). XIII Nuclei in the Cosmos*, Debrecen, Hungary: Sissa Medialab, p. 097. Available at: <https://doi.org/10.22323/1.204.0097>.

Käppeler, F. *et al.* (2011) ‘The s process: Nuclear physics, stellar models, and observations’, *Reviews of Modern Physics*, 83(1), pp. 157–193. Available at: <https://doi.org/10.1103/RevModPhys.83.157>.

Kiss, G.G. *et al.* (2022) ‘Measuring the β -decay Properties of Neutron-rich Exotic Pm, Sm, Eu, and Gd Isotopes to Constrain the Nucleosynthesis Yields in the Rare-earth Region’, *The Astrophysical Journal*, 936(2), p. 107. Available at: <https://doi.org/10.3847/1538-4357/ac80fc>.

Mumpower, M.R., McLaughlin, G.C. and Surman, R. (2012) ‘THE RARE EARTH PEAK: AN OVERLOOKED *r* -PROCESS DIAGNOSTIC’, *The Astrophysical Journal*, 752(2), p. 117. Available at: <https://doi.org/10.1088/0004-637X/752/2/117>.

Pallas, M. *et al.* (2022) ‘Efficiency calibration of the BRIKEN detector: the world largest counter for beta-delayed neutrons’. Available at: <https://doi.org/10.48550/ARXIV.2204.13379>.

Reichert, M. *et al.* (2020) ‘Neutron-capture elements in dwarf galaxies: III. A homogenized analysis of 13 dwarf spheroidal and ultra-faint galaxies’, *Astronomy & Astrophysics*, 641, p. A127. Available at: <https://doi.org/10.1051/0004-6361/201936930>.

Tolosa-Delgado, A. *et al.* (2019) 'Commissioning of the BRIKEN detector for the measurement of very exotic β -delayed neutron emitters', *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 925, pp. 133–147. Available at: <https://doi.org/10.1016/j.nima.2019.02.004>.

Wu, J. *et al.* (2017) ' $^{94}\beta$ -Decay Half-Lives of Neutron-Rich Cs 55 to Ho 67 : Experimental Feedback and Evaluation of the r -Process Rare-Earth Peak Formation', *Physical Review Letters*, 118(7), p. 072701. Available at: <https://doi.org/10.1103/PhysRevLett.118.072701>.