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HALF-LIFE MEASUREMENT USING IMPLANT-($\beta - \gamma$) TIME CORRELATIONS IN THE REGION OF NEUTRON-RICH LANTHANIDES*

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Neutron-rich lanthanides were produced via in-flight fission of a ^{238}U primary beam at the RIBF, RIKEN Nishina Center to measure half-lives ($T_{1/2}$) and beta-delayed neutron emission probabilities (P_n) in order to constrain r-process abundance calculations. $^{159-166}$Pm, $^{161-168}$Sm, $^{165-170}$Eu, and $^{167-172}$Gd ions were implanted in the Advanced Implantation Detector Array (AIDA), and β-delayed neutrons and γ-rays were detected by the surrounding detector array (BRIKEN). For the validation of $T_{1/2}$ values derived from implantation–β (i–β) time correlations, γ-spectroscopic methods were used as well. The experimental results of the β-delayed γ-spectroscopy of ^{162}Pm are presented here as an example. A half-life value from γ-decay curves was derived with a comparable uncertainty to the result from the i–β method, and a mean value well within the 1σ range.

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1. Introduction

About half of the stable isotopes heavier than iron are the result of the rapid neutron capture process (r-process). The main signature of the solar r-process abundance distribution are two large abundance peaks, located at $A \approx 130$ and $A \approx 195$, which originate from the increased stability at the neutron shell closures $N = 82$ and $N = 126$. A smaller abundance peak exists in between these two peaks at $A \approx 160$, which is known as the "rare-earth peak" (REP) formed during the freeze-out stage of the r-process [1]. Recently, an experiment was carried out in order to measure half-lives ($T_{1/2}$) and β-delayed neutron emission probabilities (P_n) of isotopes most likely playing a role in the formation of REP [2].

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2. Experimental method and data analysis

The experiment was performed at the RIBF facility at RIKEN Nishina Center. A radioactive ^{238}U primary beam with a 345 MeV/nucleon kinetic energy and intensity of about 60 pnA was impinged on a 5 mm thick ^{9}Be target. The secondary beam was separated and identified using the standard ΔE–$B\rho$–ToF method in the BigRIPS separator [3]. Neutron-rich $^{159–166}$Pm, $^{161–168}$Sm, $^{165–170}$Eu, and $^{167–172}$Gd isotopes were implanted in the Advanced Implantation Detection Array (AIDA) consisting of a stack of six double-sided silicon strip detectors (DSSSDs) [4]. AIDA was centered inside the BRIKEN neutron detector, which consisted of 140 ^{3}He-filled proportional counters embedded in a large polyethylene moderator matrix. For the details of the detector design, see [5], and as for the commissioning, see [6]. Two CLARION-type high-purity germanium (HPGe) detectors [7] were inserted horizontally from the left and right sides into holes in the matrix facing the center of the silicon detector array at a distance of only 6 cm. These detectors were used to determine $T_{1/2}$ values and study the de-excitation of the daughter isotopes. For example, the energy spectrum of γ-rays emitted in the β decay of ^{162}Pm and a deduced partial decay-scheme is shown in Fig. 1.

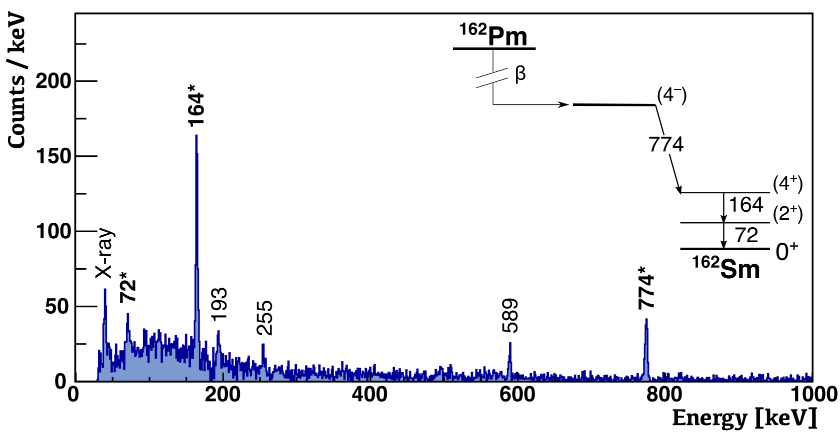

Fig. 1. Energy spectrum of γ-rays emitted in the β-decay of ^{162}Pm. The peaks marked with an asterisk are delayed by an isomeric state, and confirmed by earlier experimental data of [8] and [9]. The inset shows the partial decay-scheme of ^{162}Pm.

BigRIPS, AIDA, and BRIKEN were run with independent data acquisition systems (DAQs). To combine the information from the three DAQs, the absolute time stamps were synchronized regularly throughout the experiment, using common signals distributed to all three systems.

Implantations were distinguished from β-decay events based on their larger deposited energy. Correlations between implantation and β-decay events were performed if they were detected in the same or neighboring pixels of one DSSSD within a time window of 20 seconds. The prompt γ-rays were measured using a 10 μs time window from β-events, while a 100 μs time window was used for isomeric states. The add-back algorithm was used to improve the detection efficiency, with a time window of 40 ns between γ-rays in the same CLARION-type detectors.

The half-life values and the number of detected β-decays of the parent isotope were derived from the Bateman fits of the implant-β time correlations [2].

However, the Bateman fits are inherently susceptible to systematic uncertainties, originating from the fact that an entire decay chain contributes to the implant-β time correlations, not only the isotope of interest.

3. γ-spectroscopy of the β-decay of ^{162}Pm

As an example, the γ-spectroscopy study of the β-decay of ^{162}Pm will be presented. For this isotope, we have counted approximately 100 000 implantation events, resulting in about 1 000 β-delayed γ-events. The energy spectrum of β-delayed γ-rays was derived using a gate on the implantation identification plot to filter ^{162}Pm-related implantations and the β-events were selected as earlier specified. The background contribution was sampled using β-events with negative time correlations with respect to the implantation, while the contribution of the daughter isotope was estimated using two energy spectra sampled on different positive time windows, and from the integration of the Bateman functions. The resulting energy spectrum is shown in Fig. 1.

The three most intense γ-rays at $E_\gamma = 72$ keV, $E_\gamma = 164$ keV, and $E_\gamma = 774$ keV were seen in the earlier work of Yokoyama *et al.* [8] and Patel *et al.* [9] who were looking for γ-rays delayed by K-isomers. The level ordering is confirmed in our work by $\gamma\gamma$-coincidences and γ-intensities. The matching energy of γ-peaks confirms our implant identification. On the other hand, it proves that the $K^\pi = 4^-$ band-head state is populated through the β-decay.

The implantation-$\beta - \gamma$ time correlations were fitted by the exponential functions for the two most intense γ-rays at $E_\gamma = 164$ keV and 774 keV resulting in half-lives of 500$\pm$76 ms and 468$\pm$81 ms, respectively. Including the asymmetrical systematic uncertainties, a total half-life value of $T_{1/2}(\mathrm{i}\beta\gamma) = 487^{+46}_{-43}$ ms was deduced from the summed decay curves, as shown in Fig. 2, well within 1σ compared to earlier results of $T_{1/2}(\mathrm{i}\beta) = 467^{+38}_{-18}$ ms [2] and $T_{1/2}(\mathrm{W.u.}) = 630 \pm 180$ ms [10].

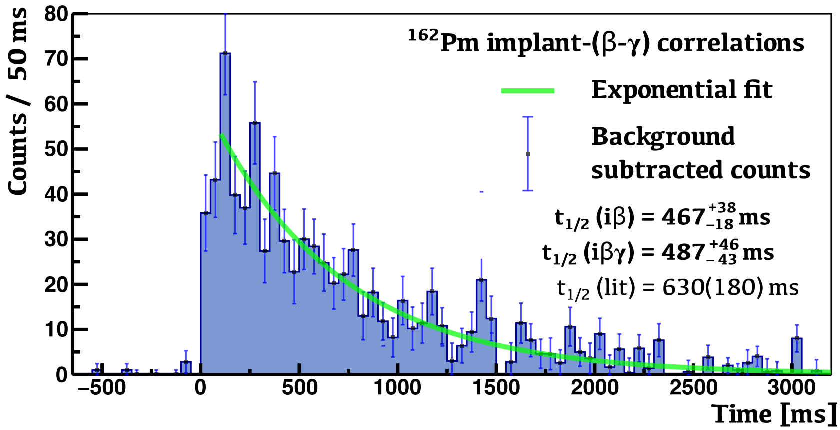

Fig. 2. Time correlations of ^{162}Pm implantations and confirmed β-delayed γ-rays after the Compton-related background subtraction. The correlations were fitted using an exponential function plus a constant background.

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