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β-decay of neutron-rich nuclei with Z $\approx$ 60 : The origin of rare-earth elements

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A large fraction of the rare-earth elements around $A = 160$ observed in the solar system are produced in the astrophysical rapid (r-) neutron-capture process. However, current stellar models cannot completely explain the relative abundance of these elements partially because of nuclear physics uncertainties. To address this problem, a β-decay spectroscopy experiment was performed at RI Beam Factory (RIKEN), aimed at studying a wide range of very neutron-rich nuclei with Z $\approx$ 60. This experiment provides a test of nuclear models as well as experimental inputs for r-process calculations.

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1. Introduction

Approximately half of the elements heavier than iron are produced in the rapid (r-) neutron-capture process. However, the site of r-process and the physical conditions in which it operates are still unknown. What is known is the elemental and isotopic abundance pattern that it produces. Two distinct peaks around $A = 130$ and $A = 195$ are the most prominent features of such pattern, and they are associated with the neutron-closed shells at $N = 82$ and $N = 126$, respectively [1]. The second most prominent feature is the rare-earth element peak around $A = 160$. The abundance distribution of rare-earth elements observed in r-process enhanced metal-poor stars is consistent with the one observed in the solar system, indicating that the rare-earth elements are produced almost entirely by the r-process [2].

One theoretical model shows that fission recycling plays a crucial role in the formation of the rare-earth elements peak. The rare-earth nuclei between $A = 110$ and $A = 170$ can be produced from the spontaneous and β-delayed fission of nuclei around $A = 278$ [3], while the $A = 130$ peak disappeared due to the high neutron density which is required to make r-process path up to the fission region.

The other theoretical model predicts that the formation of the rare-earth peak is very sensitive to the thermodynamics conduction during freeze out, and therefore, the peak can provide a powerful tool to probe late-time r-process conditions [4]. To understand the formation of the rare-earth peak, neutron-capture cross sections (n,γ), β-decay half-lives and β-delayed neutron emission probability are necessary. Due to the current experimental limitations these are difficult to measure and theoretical models have to be employed to predict them. Since calculated half-lives are less sensitive to small shift in the single particle levels of exotic nuclei than stable nuclei and depend strongly on β-decay Q value [5], β-decay half-lives of exotic nuclei are not only an important r-process input but also provide nuclear structure information in very exotic region by comparing the prediction of the theoretical nuclear models.

2. Experimental setup

Very neutron-rich nuclei around ^{158}Nd were produced using in-flight fission of ^{238}U beam accelerated to 345 MeV/nucleon and colliding with Be target. The secondary beam including a cocktail of very neutron-rich isotopes was purified and identified in the large acceptance BigRIPS separator. Selected and identified neutron-rich nuclei with approximately 200pps rate were implanted in the β-decay counting system WAS3ABi (Wide-range Active Silicon-Strip Stopper Array for Beta and ion detection) that consisted of a stack of five Double-Side Silicon-Strip Detectors (DSSDs) [6]. Each DSSD was 1-mm thick and segmented with 60 strips in the horizontal direction and 40 strips in the vertical direction with 1-mm width for each strip and a distance of 0.5 mm between neighboring DSSDs [7]. The position and time of implantations as well as the following β-decay events were measured. The β-decay curve was constructed by combining the position and time correlation. The high-efficiency EURICA spectrometer that was used to measure isomeric γ rays and the β-delayed γ rays, consisting of twelve germanium cluster detectors with seven crystals for each cluster, was surrounding WAS3ABi. Lifetimes of short-lived excited states down to tens of picoseconds were measured by eighteen LaBr3 (Ce) detectors in conjunction with two plastic scintillators mounted in the upstream and downstream of WAS3ABi.

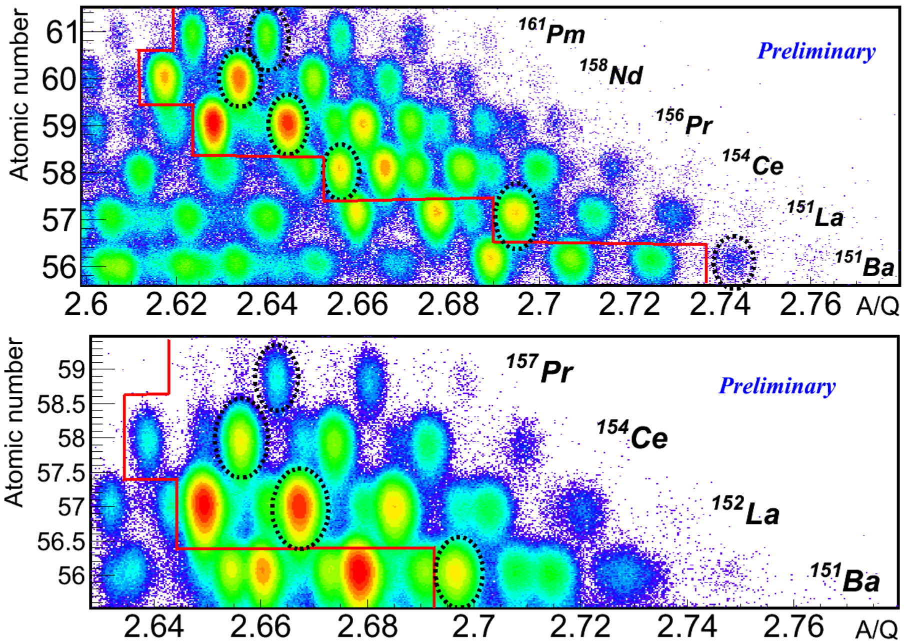

Figure 1: (color online) The figure shows the particle identification in this experiment, and the nuclei with new β-decay half-lives are located in the right side of the red line.

3. Experimental results

In this experiment, 27 new β-decay half-lives were expected with about 75 different nuclei implanted shown in Fig. 1. The particle identification was performed according to the ΔE-TOF-Bρ method and high performance detectors along the beam line were used, including high-efficiency delay-line parallel-plate avalanche counter (PPAC), Ion Chamber and plastic scintillators. Identification of fission fragments around ^{158}Nd was possible, but a significant contamination of hydrogen-like species was present. At such energy, fully-stripped nuclei may pick up electrons when interacting with aluminum wedge degraders or beam-line detectors, changing their charge states. In the particle identification plot, these species will partially overlap with heavier isotopes. This effect is particularly strong in this experiment because of the high atomic number of the nuclei transmitted. By using trajectory reconstruction method [8], the sigma of A/Q value was significantly improved to 0.15 %. The fit of decay curves includes the exponential decay of a parent nucleus and the contribution from the decay of daughter and granddaughter nuclei, as well as a constant background. Five-to-ten times the β-decay half-life was chosen as the time correlation window between implantation and its following β-decay events.

Figure 2 shows the systematic tendency of preliminary β-decay half-lives as a function of neutron number from Cs to Pm in comparison with the predictions of two theoretical models. One is the KTUY mass formula [9] combined with a gross theory of β-decay (GT) [10], and the other one is the FRDM formula [11] combined with the deformed quasi particle random phase approximation (QRPA) [12]. Our results are consistent with the literature values except ^{150}La. The difference between the predictions of two theoretical models are very large, ranging in some case up to one order of magnitude. Compared with experimental results, odd-Z nuclei favor the KTUY+GT2, which predicts longer half-lives and a smoother systematic trend than FRDM+QRPA. However, this is not true for even-Z nuclei and in some cases neither of the two models can reproduce the experimental results. So the experimental results in more exotic regions will be needed to improve the theoretical models.

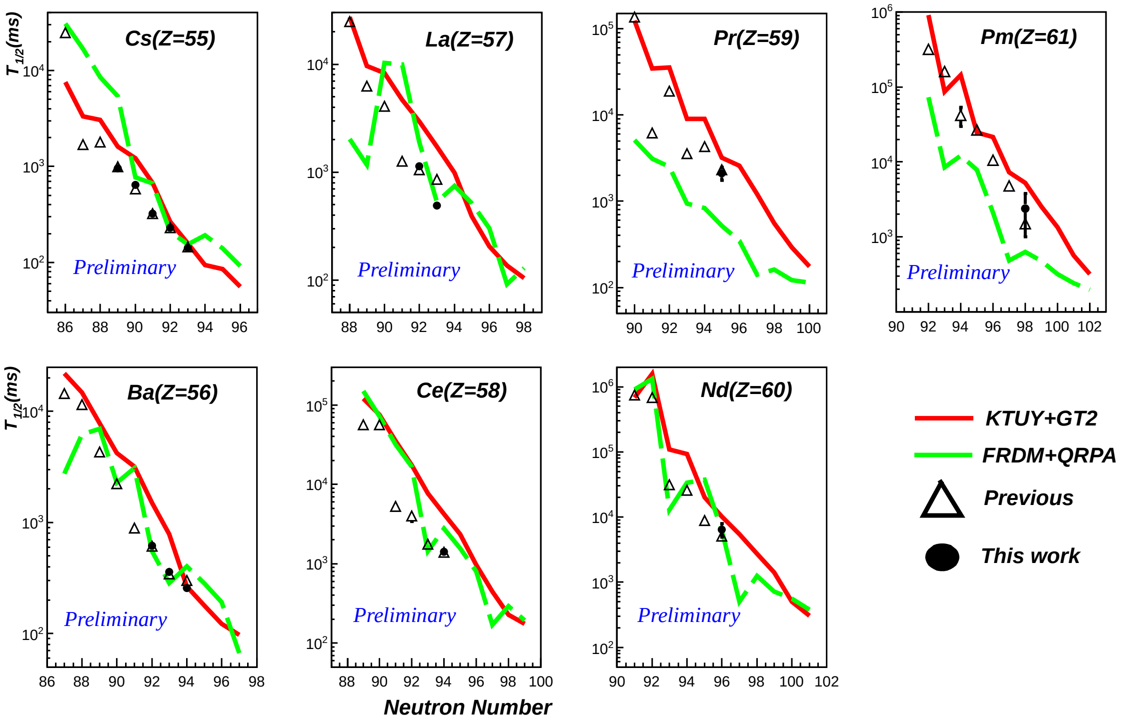

Figure 2: (color online) Systematic tendency of preliminary half-lives for elements(Ba, Ce, Nd, Cs, La, Pr, Pm) (triangles stand for previous measurement and black dots stand for the measurement in this experiment) in comparison with two theoretical models KTUY [9] + GT2 [10] (red line)and FRDM [11] + QRPA [12] (green line).

4. Summary

To understand the mechanism of production of rare-earth elements in the universe, a β-decay spectroscopy experiment was performed at RIBF, RIKEN Nishina Center. 27 new β-decay half-lives of rare-earth nuclei have been measured and r-process simulation will be performed. Theory and experiment provide the prospect for $N = 100$ subshell closure [13]. Such subshell closure could contribute to the formation of the rare-earth elements peak. In future, properties of nuclei in more exotic region will be measured and the mechanism of rare-earth elements peak will be understood more clearly.

5. Acknowledges

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