| Title | 94 $\beta$-Decay Half-Lives of Neutron-Rich 55Cs to 67Ho: Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation |
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| Citation | Physical Review Letters, 2017, v. 118 n. 7, p. 072701:1-7 |
| Issued Date | 2017 |
| URL | http://hdl.handle.net/10722/240333 |
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94$\beta$-Decay Half-Lives of Neutron-Rich 55Cs to 67Ho: Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation


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(Received 29 September 2016; revised manuscript received 12 December 2016; published 16 February 2017)

The $\beta$-decay half-lives of 94 neutron-rich nuclei $^{144-153}$Cs, $^{146-154}$Ba, $^{148-156}$La, $^{150-158}$Ce, $^{153-160}$Pr, $^{156-162}$Nd, $^{159-163}$Pm, $^{160-166}$Sm, $^{161-168}$Eu, $^{165-170}$Gd, $^{166-172}$Tb, $^{169-175}$Dy, $^{172-175}$Ho, and two isomeric states $^{174}$Er, $^{176}$Dy were measured at the Radioactive Isotope Beam Factory, providing a new experimental basis to test theoretical models. Strikingly large drops of $\beta$-decay half-lives are observed...
The rapid neutron-capture \( (r-) \) process, a series of neutron captures competing with \( \beta \) decays occurring in extreme neutron-rich stellar environments, is responsible for the origin of about half of the elements heavier than iron in the Universe [1]. The fact that the astrophysical sites of the \( r \) process and its exact mechanism have not been identified yet makes the \( r \) process one of the most exciting subjects in astrophysics [2].

The two most prominent features of the \( r \)-process abundance in the solar system are the large abundance of \( ^{52}\text{Te} \), \( ^{54}\text{Xe} \) (mass number \( A \sim 130 \)) and \( ^{78}\text{Pt} \), \( ^{79}\text{Au} \) (\( A \sim 195 \)), which are understood in terms of the enhanced stability of nuclei with filled major neutron shells (of neutron number \( N = 82 \) and \( N = 126 \)). However, the production mechanism of the smaller and broader peak of rare-earth elements (REE) (\( A \sim 165 \)) is instead still a controversial topic [3–5]. In environments with extremely high neutron-to-seed ratios, such as in merging neutron stars, the \( r \) process may synthesize very heavy nuclei (\( A > 278 \)), which then decay by nuclear fission. The REE peak could receive a major contribution from such a process and its structure could reflect closely the mass distribution of fission fragments [6,7]. Alternatively, the REE peak could be formed in any astrophysical sites where a long duration \( (n, \gamma) \Rightarrow (\gamma, n) \) equilibrium persisted, during the \( r \)-process freeze-out when the temperature or neutron density are too low to sustain the explosive nuclear burning. The signature of this dynamical formation mechanism would be encoded in masses (as well as \( \beta \)-decay and neutron-capture rates) [4]. The currently unknown nuclear structure of exotic nuclei could be embodied in the REE peak. In this region of the nuclear chart, \( K \) mixing, vibration degeneracy, shape coexistence, quadrupole deformation, and the strength of the first-forbidden \( \beta \) decays are highly uncertain. Shell gaps arising from mid-shell deformation are of special interest for the \( r \) process, and, recently, evidence for a deformed shell gap was reported in \( ^{64}\text{Gd} \) and \( ^{62}\text{Sm} \) at \( N = 100 \) [8].

Therefore, the REE peak may contain a unique signature of the unknown astrophysical sites, possibly of the late \( r \)-process conditions to which the main \( r \)-process peaks may be insensitive [9]. However, to interpret such a signature, the various nuclear processes such as fission, neutron capture, and \( \beta \)-decay of exotic nuclei have to be experimentally known or reliably modeled. This Letter reports on the first measurements of a large set of \( \beta \)-decay half-lives and their systematic trends, whose theoretical predictions are difficult because the half-lives depend on a multitude of nuclear properties, for example, deformation, level structure and spin, as well as \( Q_\beta \).

Two \( \beta \)-decay spectroscopy experiments optimized for transmission of \( ^{158}\text{Nd} \) and \( ^{170}\text{Dy} \) were performed at the Radioactive Isotope Beam Factory (RIBF) by using in-flight fission of a 345 MeV/A \( ^{238}\text{U} \) primary beam with an average intensity of 7 and 12 pA, respectively. After selection and identification in the large-acceptance BigRIPS separator, exotic nuclei of interest were transported through the ZeroDegree Spectrometer (ZDS) and implanted in the beta-counting system Wide range Active Silicon-Strip Stopper Array for Beta and ion detection (WAS3ABi) at a rate of about 100 ions/s [10]. High purity germanium cluster detectors of the Euroball RIKen Cluster Array (EURICA) surrounded WAS3ABi to detect any \( \gamma \) rays emitted from the implanted nuclei [11–18]. The particle identification (PID) achieved with the TOF-B\( \rho \)-\( \Delta E \) method is shown in a two-dimensional plot of atomic number (\( Z \)) and the temperature or neutron density are too low to sustain the explosive nuclear burning. The signature of this dynamical formation mechanism would be encoded in masses (as well as \( \beta \)-decay and neutron-capture rates) [4]. The currently unknown nuclear structure of exotic nuclei could be embodied in the REE peak. In this region of the nuclear chart, \( K \) mixing, vibration degeneracy, shape coexistence, quadrupole deformation, and the strength of the first-forbidden \( \beta \) decays are highly uncertain. Shell gaps arising from mid-shell deformation are of special interest for the \( r \) process, and, recently, evidence for a deformed shell gap was reported in \( ^{64}\text{Gd} \) and \( ^{62}\text{Sm} \) at \( N = 100 \) [8].
The nuclei used in the fit were either measured in our experiment to confirm the previous results. The half-lives of daughter $\beta$-rays, as well as a constant background. In some cases, contributions from the decays of parent, daughters, grandmothers, and great-grandmothers were accounted for in the half-life analysis. The analysis allowed control of the purity of the ions, so that it could be accounted for in the half-life analysis. The $\beta$-decay half-life of an isotope of interest was extracted from the fit of the time distribution of electrons detected after the implantation of an ion, and correlated to them in position and time [20–24], employing the least-squared and unbinned maximum likelihood methods in a parallel analysis that included systematic discrepancies with theoretical predictions in some cases.

To some extent, given the sensitivity of the experimental nuclear masses in the region of nuclei measured here, the KTUY + GT2 and FRDM + QRPA models both reproduce the systematic trends of odd-even staggering present in the experimental results, while the RHB + $pn$-RQRPA model does not. Among the three models, the KTUY + GT2 provides the most consistent predictions across all the elements considered. In contrast, FRDM + QRPA underestimates systematically the half-lives of $^{59}_{35}$Pr, $^{61}_{35}$Pm, and $^{67}_{57}$Ho isotopes, and RHB + $pn$-RQRPA shows systematic differences with respect to experiment, which depend on atomic number $Z$. In particular, the underestimate of half-lives seen for $^{55}_{35}$Cs isotopes slowly evolves with $Z$ to a substantial overestimate for $^{65}_{29}$Tb and $^{67}_{57}$Ho isotopes. Finally, we observe that KTUY + GT2 does not seems to be able to predict effects due to the fine nuclear structure and the complex nature of the $\beta$ decay. This is likely a consequence of the phenomenological approach of the GT2 model. For these effects, we find that the FRDM + QRPA model allows a more detailed interpretation of the measured data, as described in the following.

A very interesting feature of the half-lives systematics seen in Fig. 3 is the sudden drops at $N = 97$ for the elements $^{58}_{35}$Ce, $^{59}_{35}$Pr, $^{60}_{35}$Nd, and $^{62}_{35}$Sm, and at $N = 105$ for $^{63}_{35}$Eu, $^{64}_{35}$Gd, $^{65}_{29}$Tb, and $^{66}_{29}$Dy, but with only small drops from $N = 98$ to $N = 99$ and from $N = 106$ to $N = 107$. It is well known that the nucleon-nucleon pairing interaction causes large fluctuations in $Q_\beta$ along even- $A$ $\beta$-decay chains but has no net effect in odd- $A$ $\beta$-decay chains. For the $^{60}_{35}$Nd isotope chain, the effect leads to a $Q_\beta$ increase by about 2 MeV from $^{156}_{60}$Nd to $^{157}_{60}$Nd, then drops by about 1 MeV in $^{158}_{60}$Nd, with corresponding large fluctuations in the half-lives (see Fig. 3). The calculated $\beta$-decay strength function of $^{157}_{60}$Nd$_{97}$ shows a stronger low-lying strength than $^{156}_{60}$Nd$_{96}$, which makes the decrease of half-life of $^{157}_{60}$Nd$_{97}$ relative to $^{156}_{60}$Nd$_{96}$ larger than what could be expected from $Q_\beta$ systematics alone [see Figs. 4(a), 4(b)]. Alternatively, from $^{158}_{60}$Nd$_{98}$ and $^{159}_{60}$Nd$_{99}$ the calculated and measured drops are much smaller than the expectation that is simply predicted from $Q_\beta$ changes. The reason is that the strength in the $^{159}_{60}$Nd$_{99}$ decay is shifted upward by about 2 MeV relative to $^{158}_{60}$Nd$_{98}$, which makes the almost identical

**Figure 2.** Time distribution of $^{157}_{60}$Pr $\beta$-decay events fitted to the sum of activities of several components: parent nuclei (solid green line), daughter nuclei (solid black line), granddaughter nuclei (dashed black line), as well as a constant background (solid blue line). The other components, including $\beta$-delayed daughter nuclei and $\beta$-delayed granddaughter nuclei, are not shown in this figure.
The situation in nuclei near $N = 105$, where evidence for a deformed subshell gap was discussed [8], we could not find a convincing signature in the half-life trend. The half-life of $^{161}\text{Pm}_{100}$ is longer than that of $^{160}\text{Pm}_{99}$, which is somewhat intriguing (see Fig. 3), but similar features were not found in other elements.

To evaluate the impact of the newly measured half-lives on the $\beta$-process modeling, fully dynamic $\beta$-process network calculations [33] were performed. As to the role of half-lives in the dynamical REE peak formation we intend to study,
where the higher impact from our data is expected, we choose conditions that are typical of the hot r-process not leading to fission recycling. We assumed an initial electron fraction $Y_e = 0.3$ and the entropy $S = 220$ kb/baryon. The time evolution of the temperature after explosion followed an exponential decay with the time constant $\tau = 80$ ms. The matter density followed the same exponential decay but convoluted with a hyperbolic function gradually approaching free expansion [33]. The fine tuning of these conditions was determined by the best reproduction of the REE peak, and does not affect our conclusions as explained in the following. The mass models used in our study were FRDM, KTUY05 [34], HFB-14 (Hartree-Fock-Bogolyubov-14) [35], and all reaction rates for our baseline calculations were taken from the JINA ReaclibV1.0 database [36]. For each mass model we study the effect of our new data to calculations that use half-lives predictions from the three models discussed above (see Fig. 3). The impact of half-lives for each mass model is comparable; therefore in the following we show the result only using KTUY05.

To illustrate the dynamics of the formation of the REE peak in our model, we compare in Fig. 5(a) the time evolution of abundances summed over isobaric chains in the three mass regions $A = 154–160$, $A = 161–167$, and $A = 168–174$. These regions contain the progenitors of the rising, central, and falling wing of the REE peak. As shown in Fig. 5(a), the three summed abundances rise sharply when free neutrons are numerous ($R = Y_n/Y_{\text{total}} > 1$), and change slowly later during freeze-out. A large decrease of the abundance in the mass region $A = 154–160$ occurs around $t \approx 0.8$ s that corresponds to a similar increase of mass region $A = 161–167$, and a smaller increase of mass region $A = 168–174$, which results in a peak around $A \approx 165$. The nuclei populated at $t \approx 0.8$ s are important and shown as empty squares with a size proportional to their abundance. Part of these nuclei are included our measurements [see Fig. 5(c)]. The sensitivity study indicates that the half-lives of the nuclei far away from stability line with even neutron number are important in the beginning of the $(n, \gamma) \rightarrow (\gamma, n)$ equilibrium, as they determine the initial abundance of progenitors. However, the nuclei in the measured region, which is closer to the stability line, provide a closer impact between odd and even neutron numbers [see Fig. 5(c)]. This is important to shape the final abundance of the REE peak through the competition between $\beta$ decays and neutron captures.

A more quantitative estimate of the impact of newly measured $\beta$-decay half-lives on the shape of the REE peak is illustrated in Fig. 6, where the calculated r-process abundances using the new measurements are compared to calculations using theoretical half-lives from different models, respectively. The figure also shows the theoretical uncertainty estimated for each model, determined by varying theoretical half-lives within a factor of 2, which is an estimate of the uncertainty associated with theoretical models based on the comparison with experimental data for less exotic nuclei. From the figure it is clear that the new half-lives have a direct impact on the detailed shape of the REE peak. Changing the astrophysical conditions within reasonable ranges results in a different shape of the REE peak, but does not change the impact of half-lives on the calculated abundance. Above all, the new measurements remove a significant uncertainty in the calculations associated with theoretical half-lives. Alternatively, the sensitivities of rare-earth elemental abundance to our data as well as to the three theoretical models are much smaller, which could help to study the well-known characteristic referred to as r-process universality [38].

In summary, our experiment extends the limit of the known half-lives reaching for the first time into the region
FIG. 6. (a) The $r$-process abundance pattern observed in the solar system (open circles) [39], and calculated using the experimental half-lives from this work (black line). The stable nuclei of each mass number are located on the top. The colored areas represent the uncertainty of calculated abundances, associated with half-life predictions of the models FRDM + QRPA (green), KTUY + GT2 (red), RHB + pn-QRPA (blue). KTUY05 mass and ReactlibV1.0 database of nuclear reaction rates were employed for the baseline calculation. Experimental data and three theoretical predictions replaced the half-lives of nuclei whose values were measured for the first time. (b) Same as above but for the elemental abundance pattern compared with one metal-poor star HD108317 [40].

where the REE peak is expected to form based on some of the most promising $r$-process models [4,41]. Our data have a direct impact in $r$-process abundance calculations affecting almost all mass numbers between $A = 150–170$. This is an important step in the long-term goal of removing nuclear-physics uncertainties so that the REE peak can be used as a unique probe of the $r$-process freeze-out conditions and eventually reveal the currently unknown $r$-process site. Our data also allow the quantification of systematic problems of theoretical global models, and highlight the role of fine details of the $\beta$-decay strength functions in this exotic region of the nuclear chart. The comparison to theoretical models, however, does not show evidence of drastic changes of nuclear structure in the region of these measurements. This provides increased confidence in current mass models and, therefore, in the reliability of $r$-process calculations.

This work was carried out at the RIBF operated by RIKEN Nishina Center, RIKEN and RCNP, Osaka University. The authors acknowledge discussion with Dr. Furong Xu, Dr. Haozhao Liang, and Dr. Kenichi Yoshida. We also acknowledge the EUROBALL Owners Committee for the loan of germanium detectors and the PreSpec Collaboration for the readout electronics of the cluster detectors. Part of the WAS3ABi was supported by the Rare Isotope Science Project which is funded by the Ministry of Education, Science, and Technology (MEST) and National Research Foundation (NRF) of Korea (2013M7A1A1075764). This work was partially supported by KAKENHI (Grants No. 25247045), the RIKEN Foreign Research Program, the Spanish Ministerio de Ciencia e Innovacion (Contracts No. FPA 2009-13377-C02 and No. FPA2011-29854-C04), the UK Science and Technology Facilities Council, the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, Contract No. DE-AC02-06CH11357, under the auspices of the NNSA of the U.S. DOE at Los Alamos National Laboratory under Contract No. DE-AC52-06NA25396, the NASA Grant No. NNX10AH78G, the National Research Foundation Grant funded by the Korean Government (Grants No. NRF-2009-0093817, No. NRF-2015R1D1A1A01056918, No. NRF-2016 R1A5A1013277, and No. NRF-2013R1A1A2063017), and the Hungarian Scientific Research Fund OTKA Contract No. K100835.