β-decay half-lives of new neutron-rich rare-earth isotopes ^{159}Pm, ^{162}Sm, and ^{166}Gd

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The new neutron-rich rare-earth isotopes ^{159}Pm, ^{162}Sm, and ^{166}Gd produced in the proton-induced fission of ^{238}U were identified using the JAERI on-line isotope separator (JAERI-ISOL) coupled to a gas-jet transport system. The half-lives of ^{159}Pm, ^{162}Sm, and ^{166}Gd were determined to be 1.5 ± 0.2, 2.4 ± 0.5, and 4.8 ± 1.0 s respectively. The partial decay scheme of ^{166}Gd was constructed from $\gamma\gamma$-coincidence data. A more accurate half-life value of 25.6 ± 2.2 s was obtained for the previously identified isotope ^{166}Tb. The half-lives measured in the present study are in good agreement with the theoretical predictions calculated by the second generation of the gross theory with the atomic masses evaluated by Audi and Wapstra.

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The present investigation is a part of our series of decay studies of neutron-rich rare-earth isotopes produced in the proton-induced fission of actinides with the JAERI (Japan Atomic Energy Research Institute)–ISOL (Isotope Separator On-line). In our previous work, the new isotopes ^{161}Sm, ^{165}Gd, and ^{166,167,168}Tb produced in the proton-induced fission of ^{238}U were successfully identified with the JAERI-ISOL coupled to a gas-jet transport system [1–3]. The assignment of the isotopes was unambiguously performed based on the observation of characteristic x rays associated with the β^- decay of the mass-separated nuclei, those isotopes were mass separated as monoxide ions ($^{A}M^{16}O^{+}$ where M represents a rare-earth element). In this paper, we report on the β-decay half-lives of new neutron-rich isotopes ^{159}Pm, ^{162}Sm, and ^{166}Gd, as well as on the remeasured half-life of ^{166}Tb. The measured half-life values are compared with those from theoretical predictions.

The experiments were performed at the JAERI tandem accelerator facility. A stack of eight ^{238}U targets was bombarded with 15.5 MeV proton beams with an intensity of about 3 μA. Each target (4 mg/cm^2 in thickness) was electrodeposited on an aluminum-foil backing and located inside a target chamber. Fission products emitted from the targets were transported into a surface-ionization type thermal ion source of the JAERI-ISOL with the He/PbI$_2$ gas-jet stream [4]. The transported atoms were ionized as monoxide ions $^{A}M^{16}O^{+}$ in the ion source, accelerated with 30 kV, and mass separated with a mass resolution of $A/\Delta A \approx 800$. The mass-separated products were implanted into an aluminized mylar tape in a tape transport system and were periodically transported to the measuring position. The measuring position was equipped with a sandwich-type plastic scintillator for β-ray measurements, and two Ge detectors for x/γ-ray measurements set behind the scintillator; one was a short coaxial n-type Ge detector (ORTEC LOAX), and the other was a coaxial n-type Ge detector (ORTEC GAMMA-X) with 35% relative efficiency. β–γ and γ–γ coincidence events were recorded event by event, together with time information. In order to enhance the chemical reaction of $M + \mathrm{O} \rightarrow M\mathrm{O}$ in the ion source, a small amount of oxygen gas was intermittently injected into the gas-jet stream.

The new isotope ^{159}Pm was produced in the fission of 15.5 MeV $p + {}^{238}$U, and the ions of ^{159}Pm^{16}O^{+} with $A = 175$ were mass separated. The separated products were transported to the measuring position at time intervals of 4.2 s. Figure 1 shows the β-coincident x/γ-ray spectra accumulated during 12 h. The low energy portion measured of the γ-ray spectrum measured with the short coaxial Ge detector and the high energy portion measured with the 35% coaxial Ge detector are depicted in Fig. 1(a) and (b), respectively. Most of the γ lines observed in the spectra are identified as the known γ transitions from the β^- decay of ^{159}Sm, indicated by open circles, while 71.8 and 261.3 keV γ lines with an approximately 1.5 s half-life were clearly observed that were coincident with the Sm x rays. Thus, both the γ lines were assigned to those from the β^- decay of ^{159}Pm. The half-life of ^{159}Pm was determined to be 1.5 ± 0.2 s as a weighted average of the half-life values of 1.6 ± 0.2, 1.5 ± 0.4, and 1.4 ± 0.3 for the Sm K_α x rays, and 71.8 and 261.3 keV γ rays, respectively, as shown in the inset of Fig. 1(a).

Figure 2 shows the β-coincident x/γ-ray spectrum measured in the $A = 178$ fraction with the 35% coaxial Ge detector during 18 h. The cycle time for sample collection and measurement was 6.2 s. The γ-ray peaks due to the known $A = 162$ isotopes of ^{162}Eu (71.4 and 164.8 keV, indicated by solid circles), ^{162}Gd (403.0 and 442.1 keV, indicated by open circles), and ^{162}Tb (260.0 keV, indicated by an open square) are observed in the spectrum. Also, weak γ-ray peaks arising from the mass-separated molecular ions of ^{143}Ba (assumed to be ^{143}Ba^{35}Cl) and ^{159}Sm (assumed to be ^{159}Sm^{19}F), as well as the ^{160}Sm^{18}O^{+} ions, are observed. In addition to these

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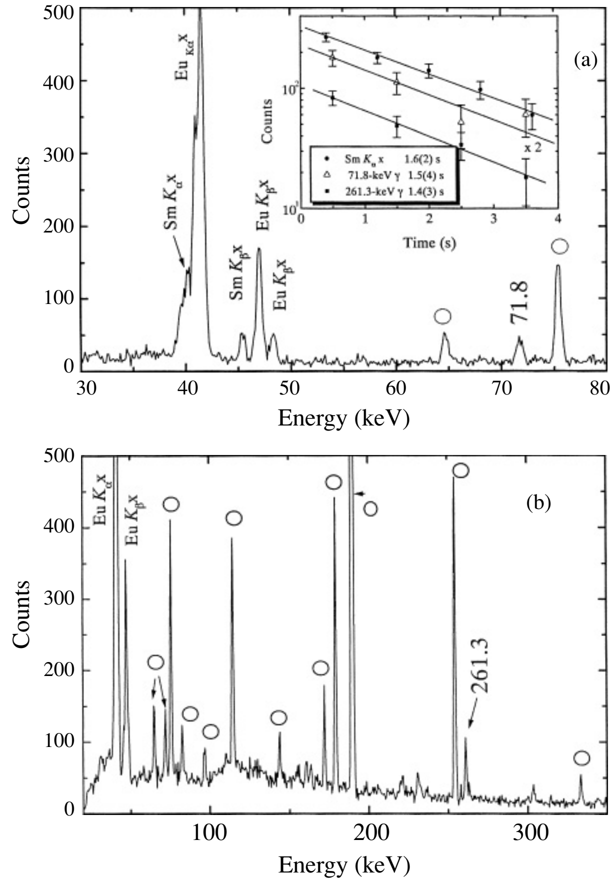

FIG. 1. β-coincident γ-ray spectra measured with (a) a short coaxial Ge detector and with (b) a 35% coaxial Ge detector for $A = 175$. The inset shows the decay curves of the Sm K_α x rays, 71.8 and 261.3 keV γ rays. The open circles indicate the γ rays associated with the decay of ^{159}Sm.

TABLE I. Energies relative intensities, and coincidence relations of γ rays in the β^- decay of ^{166}Gd.

E_γ (keV)	Intensity (%)	Coincident γ rays
Tb *K*X		*K*X, 40.0, 118.8, 536.0
40.0 ± 0.2	23 ± 6	*K*X, 118.8, 975.5
118.8 ± 0.2	22 ± 6	40.0, 536.0
158.8 ± 0.2	22 ± 6	536.0
536.0 ± 0.2	37 ± 12	*K*X, 40.0, 118.8, 158.8
975.5 ± 0.3	84 ± 21	40.0
1015.5 ± 0.3	100	

γ transitions, previously unobserved γ lines having a half-life of ~2.5 s and energies of 36.0, 736.6, and 741.1 keV are also seen in the spectrum. None of these lines are associated with the decay of the contaminant isotopes already identified. Thus, we assign these new transitions to the β^- decay of ^{162}Sm. The decay curve for the 741.1 keV γ ray is shown in the inset of Fig. 2, and the half-life has been determined to be 2.4 ± 0.5 s as a weighted average of the half-life values of 2.6 ± 0.7, 2.0 ± 1.1, and 2.4 ± 0.7 s for 36.0, 736.6, and 741.1 keV γ rays, respectively.

The β-coincident x/γ-ray spectrum for the $A = 182$ fraction measured with the 35% coaxial Ge detector is shown in Fig. 3. The data were accumulated during a period of $10\,\text{s} \times \sim 9000$ cycles. Eight γ rays following the β^- decay of ^{166}Tb, indicated by open circles, are clearly seen, and six other previously unknown γ lines with energies of 40.0, 118.8, 158.8, 536.0, 975.5, and 1015.5 keV are observed. The intensities of the 40.0, 118.8, and 158.8 keV γ rays decayed with half-lives of 6.5 ± 2.5, 4.0 ± 1.4, and 4.7 ± 1.8 s, respectively. The decay curve of the 118.8 keV γ ray is depicted in the inset of Fig. 3. The 40.0 and 536.0 keV γ rays were coincident with Tb *K* x rays and coincident with each other. The 118.8, 158.8, and 975.5 keV γ rays were also coincident with the 40 and 536,2 536, and 40.0 keV γ rays, respectively. Thus, it was found that these γ rays were attributed to the β^- decay of ^{166}Gd. The half-life of ^{166}Gd was determined to be 4.8 ± 1.0 s as a weighted average. γ-ray energies, intensities, and coincident relations associated with the β^- decay of ^{166}Gd are summarized in Table I. A partial decay scheme of ^{166}Gd is proposed as shown

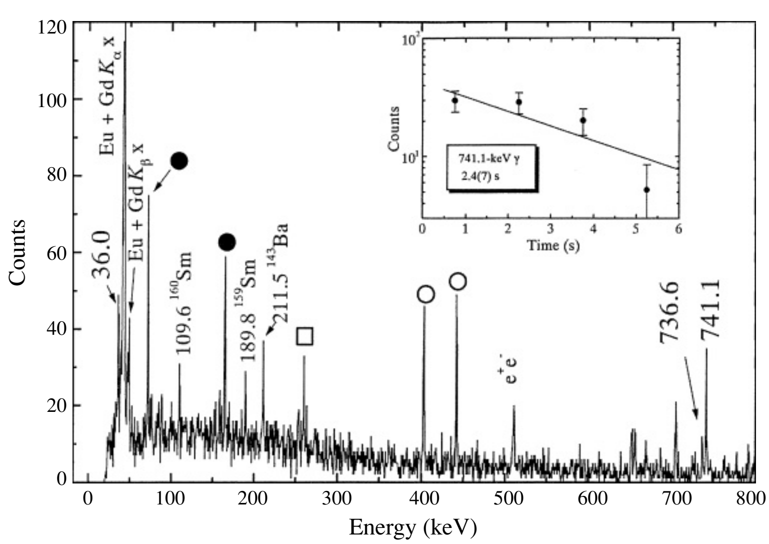

FIG. 2. β-coincident γ-ray spectrum measured with a 35% coaxial Ge detector for $A = 178$. The inset shows the decay curve of the 741.1 keV γ ray. The open and closed circles, and the open square indicate the γ rays associated with the decays of ^{162}Eu, ^{162}Gd, and ^{162}Tb, respectively.

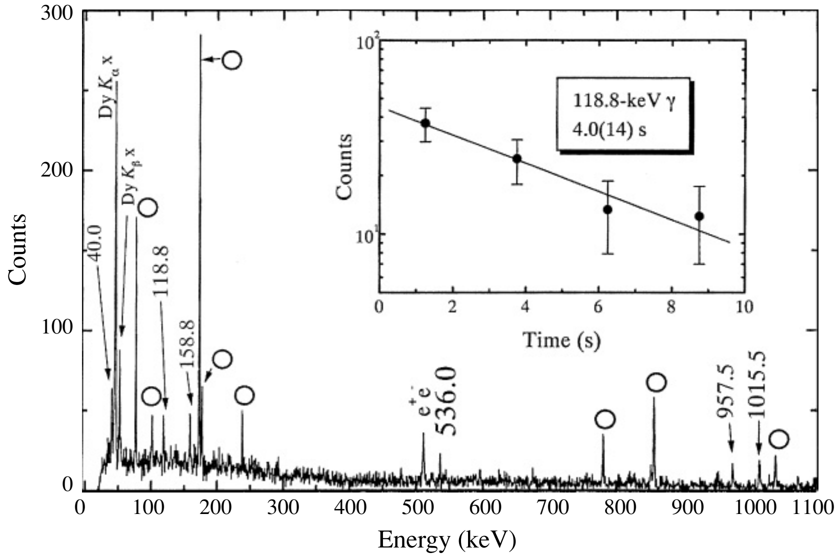

FIG. 3. Same as Fig. 2 but for $A = 182$. The inset shows the decay curve of the 118.8 keV γ ray. The open circles indicate the γ rays associated with the decay of ^{166}Tb.

in Fig. 4. The γ transition of 1015.5 keV is incorporated on the basis of energy level matching.

The half-life of ^{166}Tb, 21 ± 6 s, was previously determined, and its partial decay scheme was proposed [1]. In the present study, the accuracy of the half-life value was improved by measuring the decay of intense γ rays. The data were accumulated during the detection period of $60\,\mathrm{s} \times {\sim}900$ cycles. The β-coincident γ rays of 76.6, 101.3, 172.8, 177.1, 238.1, 780.5, 857.0, and 1039.8 keV following the decay of ^{166}Tb are clearly observed. The intensities of the 76.6, 172.8, and 857.0 keV γ rays decayed with the half-lives of 24 ± 3, 28 ± 3 s, and 23 ± 5 s, respectively. By taking a weighted average of these values, the half-life of ^{166}Tb was newly determined to be 25.6 ± 2.2 s.

In Table II, the half-life values measured present work and previous works [1–3] are compared with those from theoretical predictions. GT2-1996 by Tachibana *et al.* [5] is the second generation of the gross theory with the evaluated Q_β values [6]. The quasiparticle random-phase approximation (QRPA) calculations by Möller *et al.* [7] are based on the quasiparticle random-phase approximation with the finite range droplet model (FRDM) masses [8], while *pn*-QRPA is the earlier microscopic calculation using the proton-neutron quasiparticle random-phase approximation by Staudt *et al.* [9] with the masses calculated by the macroscopic-microscopic model [10]. The calculated half-life value depends on the input Q_β values as well as the β-decay strength function. In the GT2-1996, the one particle strength function D_Ω, which represents the distribution of the β-decay strength of one particle, plays a crucial role in the calculation of the total β-decay strength function. Here, Ω denotes the type of the β-decay operator. The Fermi, Gamow-Teller, and first-forbidden transitions are taken into account in the model. The QRPA used for modeling the astrophysical r process considers only the Gamow-Teller β-decay strength function, although it takes into account the predicted spin and parity for the ground state of a nucleus to calculate the half-life and other quantities.

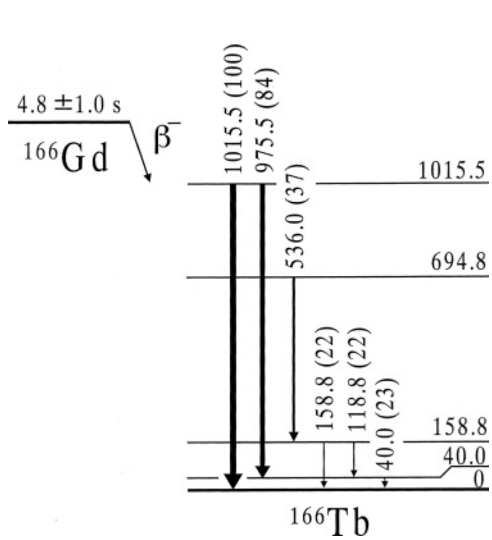

FIG. 4. Proposed decay scheme of ^{166}Gd. Energies are in keV and relative γ-ray intensities are given in parentheses.

The decay schemes, including the spin and parity of the ground states, of the nuclei under consideration and their daughter nuclei are not available. It is not meaningless, however, to compare the experimental half-life values with those of the theoretical predictions. The present data and those in Refs. [1–3] are in good agreement with the calculations with the GT2-1996. The half-lives calculated by the QRPA for ^{159}Pm, ^{161}Sm, ^{162}Sm, ^{166}Gd, and ^{168}Tb slightly over- and underestimate the experimental ones, while those for ^{165}Gd, ^{166}Tb, and ^{167}Tb significantly differ from the experimental results. For the evaluation of the theoretical predictions, we calculate the average deviation $\bar{x}$ for ratios of calculated to experimental half-lives, discussed in Ref. [11], as

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i,$$

where

$$x_i = \begin{cases} y_i, & \text{if} \quad y_i \geqslant 1 \\ 1/y_i, & \text{if} \quad y_i < 1 \end{cases},$$

TABLE II. Experimental and predicted half-lives of the eight neutron-rich rare-earth isotopes.

Isotope	Experiment		Calculation		
	Present work $T_{1/2}$ (s)	Previous work $T_{1/2}$ (s)	GT2-1996 [5] $T_{1/2}$, Q_β [6] (s), (MeV)	QRPA [7] $T_{1/2}$, Q_β [8] (s), (MeV)	*pn*-QRPA [9] $T_{1/2}$, Q_β [10] (s), (MeV)
^{159}Pm	1.5 ± 0.2		3.08, 5.52	0.642, 5.59	2.80, 5.29
^{161}Sm		4.8 ± 0.8 [2]	6.72, 4.80	13.434, 4.57	12.6, 4.98
^{162}Sm	2.4 ± 0.5		2.69, 3.90	6.650, 3.51	4.79, 3.97
^{165}Gd		10.3 ± 1.6 [2]	16.0, 4.19	>100, 3.76	18.4, 4.14
^{166}Gd	4.8 ± 1.0		5.58, 3.31	36.023, 2.79	4.21, 3.20
^{166}Tb	25.6 ± 2.2	21 ± 6 [1]	33.6, 4.89	>100, 4.96	82.8, 4.81
^{167}Tb		19.4 ± 2.7 [3]	18.2, 4.10	>100, 3.93	63.0, 3.86
^{168}Tb		8.2 ± 1.3 [3]	7.25, 5.97	11.733, 6.06	28.6, 5.78

and

$$y_i = T_{1/2}^{\mathrm{cal}} / T_{1/2}^{\mathrm{exp}}.$$

The calculated average deviation for the eight isotopes is given by $\bar{x} = 1.36$ (GT2-1996) and $\bar{x} = 2.43$ (*pn*-QRPA), while $\bar{x} = 3.36$ for the isotopes except for ^{165}Gd, ^{166}Gd, and ^{167}Tb is obtained in the case of QRPA (it calculates the half-lives of those isotopes with a lower limit of 100 s). To examine the predictive power of the three calculations in the region around $A = 60$, we calculated the average deviation $\bar{x}$ using the measured half-lives of very neutron-rich isotopes for the elements from Ti to Ni [12]. The average deviation for 24 isotopes is $\bar{x} = 1.90$ (GT2-1996), $\bar{x} = 3.24$ (*pn*-QRPA) (except for ^{66}Mn), and $\bar{x} = 3.18$ (QRPA) (except for ^{60}V). The GT2-1996 used with evaluated Q_β values has the best predictive power in both regions of the neutron-rich isotopes.

In conclusion, the new isotopes ^{159}Pm, ^{162}Sm, and ^{166}Gd produced in the 15.5 MeV proton-induced fission of ^{238}U were identified using the gas-jet coupled JAERI-ISOL system. The half-lives of the β decays were determined and compared with those from the theoretical predictions based on the second generation of the gross theory, the QRPA, and the *pn*-QRPA calculations. The measured half-life values were in good agreement with the predictions calculated with the gross theory.

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