Identification of ^{161}Sm and ^{165}Gd

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(Received 17 March 1998)

Two new neutron-rich rare-earth isotopes ^{161}Sm and ^{165}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 were determined to be 4.8 ± 0.8 s for ^{161}Sm and 10.3 ± 1.6 s for ^{165}Gd. The assignment of these isotopes was based upon the observation of Eu and Tb K x rays in the β-gated x/γ-ray spectra measured for the separated mass fraction 177 and 181 as monoxide ions $^{161}Sm^{16}O^{+}$ and $^{165}Gd^{16}O^{+}$, respectively. [S0556-2813(98)06308-0]

PACS number(s): 27.70.+q, 21.10.Tg, 23.20.Lv, 25.85.Ge

Nuclear properties such as half-lives and neutron binding energies of neutron-rich rare earth isotopes are particularly important in astrophysical calculations involving the rapid neutron capture process [1] as well as in the field of nuclear structure and reactor technology [2]. These isotopes have mainly been produced in the thermal neutron-induced fission of ^{235}U [3,4], the spontaneous fission of ^{252}Cf [5,6], and the multinucleon transfer reactions with heavy ions [7,8]. On the other hand, relatively high fission yields in the fragment mass region around $A\sim165$ where it is predicted that there would be strongly deformed nuclei with $Z\approx65$ and $N\sim100$ are expected via the proton-induced fission of actinides.

To study decay properties of neutron-rich rare earth isotopes with mass number beyond $A=160$ using proton-induced fission of actinides, we have developed the gas-jet coupled thermal ion source system in the JAERI (Japan Atomic Energy Research Institute)-ISOL (Isotope Separator On-Line) [9]. In the previous work, the new isotope ^{166}Tb produced in the proton-induced fission of ^{238}U was successfully identified with this unique system, where ^{166}Tb was mass separated as a monoxide ion $^{166}Tb^{16}O^{+}$ [10]. In this paper, we report on the identification of the further two isotopes ^{161}Sm and ^{165}Gd with this system, and the measured half-life values are compared with those from the predictions.

A stack of eight ^{238}U targets was bombarded with 20 MeV proton beams with the intensity of about 1 μA at the JAERI tandem accelerator facility. Each target (4 mg/cm^2 thick) was electrodeposited on an aluminum-foil backing and located inside the target chamber. Fission products emitted isotropically from the targets were thermalized in argon gas loaded with NaCl aerosols, then transported into the ISOL through a capillary. The transported nuclides were ionized in the thermal ion source, and mass separated electromagnetically. A mass resolution of about 900 ($M/\Delta M$) around $A\approx100$ was achieved in the present system. The separation efficiency of the whole system was a few percent for the isotopes of La, Pr, Pm, and Eu, and the total transit time between production and detection was evaluated to be about 3 s. The detailed performance of the ISOL and the gas-jet coupled thermal ion source is described elsewhere [9].

The mass-separated products were collected on an aluminized Mylar tape and transported to the detection port at prescribed time intervals. The detection port was equipped with two plastic scintillators, 30 mm$\times$30 mm$\times$1 mm, for the measurement of β rays through the Mylar window and two Ge detectors set behind the scintillators; one was a planar detector with 5 cm in diameter and 1 cm thick having an energy resolution of 0.61 keV full width at half maximum (FWHM) at 122 keV and the other was a coaxial detector with 28% in relative efficiency and 1.8 keV FWHM at 1.33 MeV. β-γ and γ-γ coincidence data were taken with these four detectors and recorded event by event together with time information.

^{161}Sm. As regards the $A=161$ isobaric fraction, the decay properties of ^{161}Eu ($T_{1/2}=27$ s) [3] and ^{161}Gd ($T_{1/2}=3.6$ min) [11] had been studied prior to this work. The fission yield for ^{161}Sm was estimated to be much less than those for ^{161}Eu and ^{161}Gd by extrapolating the mass yield curve [9] and the charge distribution [12] for the fission of 15 MeV $p+^{238}$U: σ_f (^{161}Sm)$\sim$15 μb, σ_f (^{161}Eu)$\sim$80 μb and σ_f (^{161}Gd)$\sim$60 μb. Thus, intense x and γ rays resulting from the β^- decay of ^{161}Eu in the $A=161$ fraction would prevent observation of those from ^{161}Sm. In the previous study, it was indicated that the monoxide-to-elemental ion beam intensity ratio (MO^+/M^+) of europium was several orders of magnitude lower than that of samarium and gadolinium in the present thermal ion source [13]. The $A=177$ fraction containing $^{161}Sm^{16}O^{+}$ was mass separated to iden-

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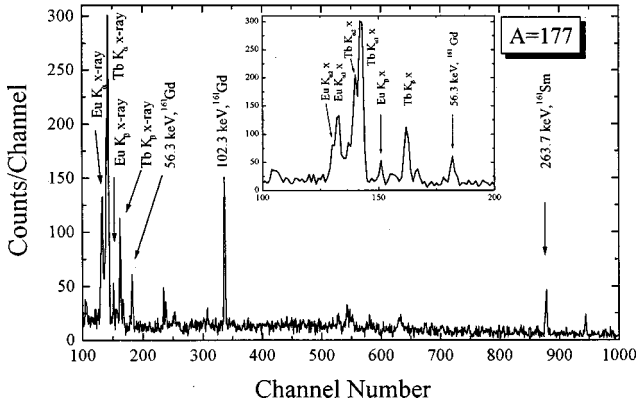

FIG. 1. β-coincident x/γ-ray spectrum measured with a 28% coaxial Ge detector for the $A=177$ fraction. The inset shows the low-energy portion of the x/γ-ray spectrum.

tify the new isotope ^{161}Sm. To enhance the chemical reaction of Sm+O→SmO in the ion source, a small amount of oxygen gas was injected into the argon gas-jet stream. Each collection and counting period was 16 s.

Figure 1 shows a β-coincident x/γ-ray spectrum together with the low-energy portion of the spectrum for the $A=177$ fraction. No clear Gd K x rays from the β^- decay of ^{161}Eu are observed, while the Tb K x rays and the γ rays with energies of 56.3 and 102.3 keV associated with the β^- decay of ^{161}Gd are seen. The new isotope ^{161}Sm was identified by observing the K x rays of Eu in the $A=177$ fraction, as shown in the inset of Fig. 1. The γ ray of 263.7 keV coincident with the Eu K x rays is associated with the β^- decay of ^{161}Sm. The intensities of the Eu K_α x and 263.7 keV γ rays decayed with half-lives of 5.0±0.6 s, 4.8±1.0 s, and 4.4±0.8 s, respectively as shown in Fig. 2. The half-life of ^{161}Sm is determined to be 4.8±0.8 s as an average of each value with systematic errors.

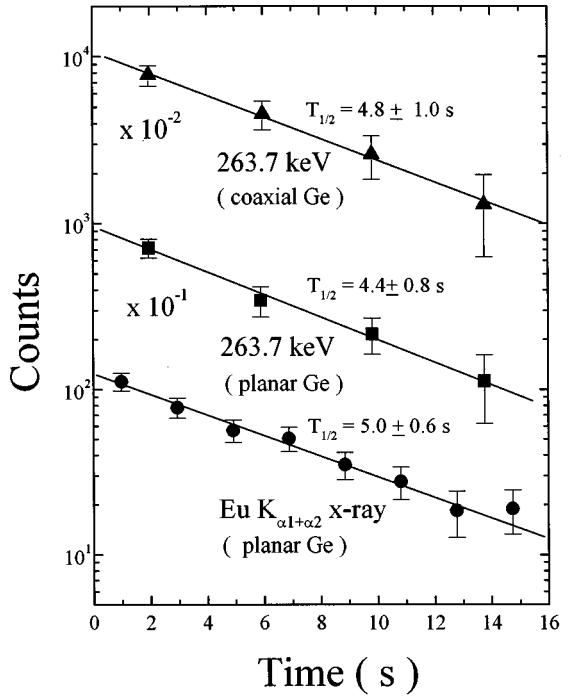

FIG. 2. Decay curves of the Eu K_α x-ray and the 263.7 keV γ-ray peaks obtained at $A=177$ fraction. These x and γ rays were measured with two Ge detectors, planar and 28% coaxial.

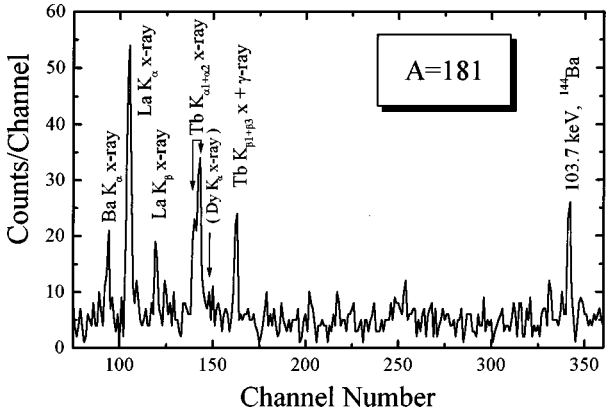

FIG. 3. β-coincident x/γ-ray spectrum measured with a planar type Ge detector for the $A=181$ fraction.

^{165}Gd. For the $A=165$ isobaric chain the known neutron-rich isotopes are ^{165}Td ($T_{1/2}=2.1$ min) [14] and ^{165m,g}Dy ($T_{1/2}=1.3$ min, 2.4 h) [15]. The fission yields are estimated to be: σ_f (^{165}Gd)~7 μb, σ_f (^{165}Tb)~15 μb and σ_f (^{165m}Dy)~4 μb. The new isotope ^{165}Gd was identified at the $A=181$ fraction corresponding to its monoxide. The cycle time for sample collection and measurement were 32 s.

Figure 3 shows a β-coincident x/γ-ray spectrum for the $A=181$ (^{165}Gd^{16}O$^+$) fraction. The Tb K x rays associated with the β^- decay of ^{165}Gd are clearly observed. The x ray peaks arisen from the mass-separated ^{144}Ba^{37}Cl$^+$ ions are also seen. The ingredient Cl ions would come from NaCl contained in the aerosol of the gas-jet system. The La K x rays and the γ rays with energies of 103.7, 156.1, and 172.8 keV (not shown) were assigned to those from the β^- decay of ^{144}Ba ($T_{1/2}=11.5$ s).

The intensity of the Tb $K_{\beta1+\beta3}$ x ray peak is about two times larger than that of the expected x-ray peak. It is re-

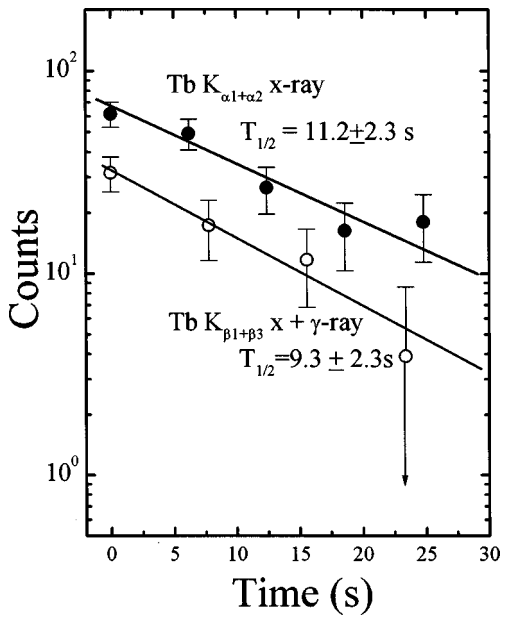

FIG. 4. Decay curves of the Tb $K_{\alpha,\beta}$ x-ray peaks from the β^- decay of ^{165}Gd.

TABLE I. Half-lives of β decay of ^{161}Sm and ^{165}Gd.

		Calculations			
		Gross theory (Refs. [25] and [18])		pn-QRPA (Ref. [24])	
Isotope	Experimental Half-life(s)	Half-life(s)	Q_β (MeV)	Half-lives(s)	Q_β(MeV)
^{161}Sm	4.8 ± 0.8	9.35	4.572 (Ref. [19])	12.6	4.98 (Ref. [22])
		6.72	4.80 (Ref. [23])		
		5.821	4.90 (Ref. [20])		
		4.156	5.15 (Ref. [21])		
^{165}Gd	10.3 ± 1.6	34.3	3.76 (Ref. [19])	18.4	4.14 (Ref. [22])
		27.97	3.83 (Ref. [21])		
		16.0	4.19 (Ref. [23])		
		12.33	4.35 (Ref. [20])		

ported that there is the γ ray resulting from the β^- decay of ^{165}Tb (2.1 min) with the energy of 50.4 keV [14] which is close to that of the Tb $K_{\beta1+\beta3}$ x ray (50.384 and 50.228 keV). As shown in Fig. 3, however, no clear Dy K x rays associated with the β^- decay of ^{165}Tb are observed, and it was found that the intensity ratio of the Dy $K_{\alpha1+\alpha2}$ x ray and 50.4 keV γ ray with the decay of ^{165}Tb was about 2 from the present β-coincident x/γ-ray spectrum observed at the $A=165$ fraction with the collection-counting cycle time of 200 s. And the x/γ-ray peak (Tb $K_{\beta1+\beta3}$ x+γ ray in Fig. 3) of 50.3 keV decays with the half-life of 9.3 ± 2.3 s as depicted in Fig. 4. From these results, we interpret that the contribution from the 50.4 keV γ-ray with the β^- decay of ^{165}Tb would be negligible amounts in the 50.3 keV x/γ-ray peak. Furthermore, in the energy region around 50 keV, no γ ray in the β^- decay of ^{144}Ba was reported [16]. Thus, it is concluded that the 50.3 keV x/γ-ray peak consists of those from the Tb $K_{\beta1+\beta3}$ x ray and the γ ray with the β^- decay of ^{165}Gd. From the expected x-ray intensity ratios for Tb [17], the relative intensities of the Tb $K_{\alpha1+\alpha2}$, $K_{\beta1+\beta3}$ x-rays and a related γ ray are estimated to be 1.56, 0.30, and 0.26(5), respectively.

Figure 4 shows the decay curves of the β-coincident Tb $K_{\alpha1+\alpha2}$ x rays and Tb $K_{\beta1+\beta3}+50.3$ keV γ ray counts. The respective half-lives were measured to be 11.2 ± 2.3 s and 9.3 ± 2.3 s. The average of these two gives the half-life of the β decay of ^{165}Gd, 10.3 ± 1.6 s.

In Table I, the present half-life values are compared with the theoretical predictions calculated by Tachibana *et al.* [18,25] using the gross theory with the selected Q_β values [19,23] and by Staudt *et al.* [24] with the proton-neutron quasiparticle random-phase approximation (pn-QRPA). It is found that the calculation with the gross theory predicts the reasonable half-life values within a factor of 1.2 when the Q_β values by Jänecke and Masson [20] are used, while the pn-QRPA reproduces the experimental values within a factor of 1.8–2.6 with the Q_β values of Möller and Nix [22]. Although the calculated half-life value depends considerably on the input data of the Q_β values as shown in Table I and as discussed in our previous study on the half-life of ^{166}Tb [10], it should be noted that there are a number of factors associated with the β-decay strength function that can affect the accuracy of these calculations. To further the understanding of the β decay half-life systematics of nuclides far from the β stability line, experimental determination of Q_β values is needed.

We would like to express gratitude to Dr. T. Tachibana for calculations of the half-life of β decay. We also thank the JAERI tandem crew for supplying intense and stable beams for the experiments. This work was carried out along a line of the JAERI-University Collaboration Research Project.

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