β-decay half-lives of new neutron-rich isotopes ^{167,168}Tb and levels in ^{167,168}Dy

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β-decay half-lives of new neutron-rich isotopes ^{167}Tb and ^{168}Tb produced in the 20 MeV proton-induced fission of ^{238}U have been determined to be 19.4(27) s and 8.2(13) s, respectively, using a gas-jet coupled on-line isotope separator. The present half-lives and those of the recently identified nuclei ^{159}Pm, ^{161}Sm, ^{165}Gd, ^{166}Tb were compared with theoretical predictions. The recent calculation by the gross theory with the new one-particle strength functions shows quite good agreement with the experimental half-lives. Excited states of the daughter nuclides ^{167}Dy and ^{168}Dy have been established for the first time. Level energies of the first 2^+ states in even-even Dy isotopes were found to show an irregular behavior at ^{164}Dy and increasing deformation toward the neutron midshell around $N \approx 104$. [S0556-2813(99)00106-5]

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I. INTRODUCTION

Experimental studies on nuclear properties of neutron-rich nuclei in the mass $A>160$ region are limited to the vicinity of stable nuclei because of difficulties in their productions and observations. So far those nuclei have been produced through the spontaneous fission of ^{252}Cf and heavy-ion multinucleon transfer reactions. Ground-state properties as well as excited states of them and their daughters have been studied through the β^- decay using an on-line isotope separator [1–3] and recently through the prompt γ-ray spectroscopy using a large array of Ge detectors [4,5]. Despite the recent progress in experimental techniques, the most neutron-rich nuclei whose excited states have been established in the $A>160$ region are the ones with only two neutrons in excess over the most neutron-rich even-even stable nuclei with only a few exceptions [2]. In the present work, we have studied the β^- decay of new neutron-rich isotopes ^{167}Tb and ^{168}Tb produced in the 20 MeV proton-induced fission of ^{238}U. This reaction has high relative fission yields for $A>160$ nuclei as well as the spontaneous fission of ^{252}Cf. β-decay half-lives of ^{167}Tb and ^{168}Tb have been determined for the first time, and excited states of their daughters ^{167}Dy and ^{168}Dy which are the nuclei with three and four neutrons in excess over the most neutron-rich stable nucleus, respectively, have also been established.

β-decay half-lives are one of important quantities related to the stability of neutron-rich nuclei. In particular, they play an important role in astrophysical calculations for nucleosyntheses through the rapid neutron capture process (r process) (e.g., see Ref. [6]). Since the r process passes through the very neutron-rich region mostly beyond the limit that experimental data are available, theoretical half-lives also greatly contribute to the calculations. Although the nuclei studied in the present work do not directly influence the r process, their experimental half-lives give a good opportunity to test the validity of various theoretical predictions of β-decay half-lives. In previous work [7–9], we determined β-decay half-lives of new neutron-rich isotopes ^{159}Pm, ^{161}Sm, ^{165}Gd, and ^{166}Tb, and found that the experimental half-lives were systematically shorter than those of theoretical calculations. In particular, the calculated half-lives for ^{166}Tb were 4–8 times as long as the experimental one. To examine further systematically this deviation, β-decay half-lives of more neutron-rich nuclei ^{167}Tb and ^{168}Tb are measured, and are compared with theoretical calculations.

^{167}Dy and ^{168}Dy, the daughter nuclides of ^{167}Tb and ^{168}Tb, lie in the well deformed region near the midshell of both wide proton and neutron open shells. The neutron midshell defined between the $N=82$ and 126 shell closures is located at $N=104$ around which it is expected that the maximum deformation occurs. For Dy isotopes, the midshell nucleus is ^{170}Dy$_{104}$, while the most neutron-rich nucleus whose excited states have been established was ^{166}Dy. Experimental information for the nuclei far from the stable nuclei is highly desired to understand nuclear structure around the midshell region.

II. EXPERIMENTS

The nuclei ^{167}Tb and ^{168}Tb were produced through the proton-induced fission of ^{238}U and mass-separated using the gas-jet coupled on-line isotope separator at Japan Atomic Energy Research Institute (JAERI-ISOL) [10]. A stack of eight ^{238}U targets was bombarded with a 20 MeV proton beam of about 1 μA intensity from the JAERI tandem accelerator. Each target was electrodeposited with a thickness of about 4 mg/cm^2 on an aluminum foil backing. Fission products emitted from the targets were thermalized in argon gas loaded with PbI_2 aerosols, then transported into an ion

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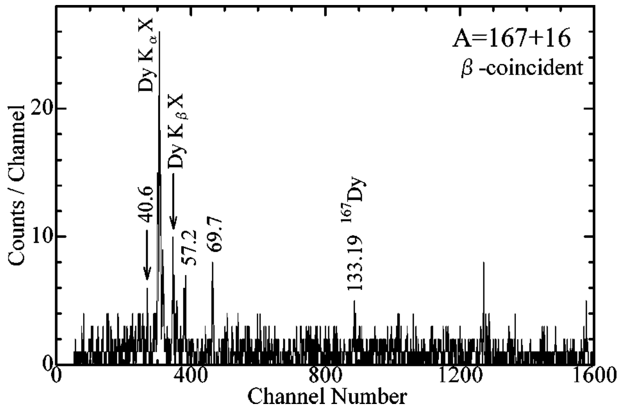

FIG. 1. β-coincident γ-ray spectrum for the mass 167+16 fraction.

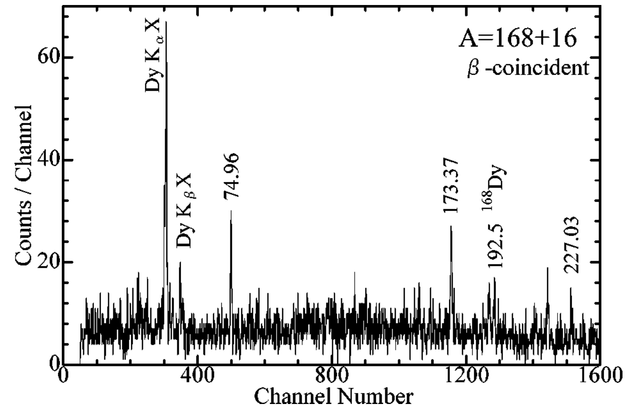

FIG. 3. β-coincident γ-ray spectrum for the mass 168+16 fraction.

source of the ISOL by the gas-jet stream through an 8 m capillary. The ^{167}Tb and ^{168}Tb were ionized in the surface ionization-type thermal ion source and then mass-separated as monoxide ions. The present ion source efficiently ionizes rare-earth elements as both elemental and monoxide ions [7]. If the ^{167}Tb (or ^{168}Tb) are mass-separated as the elemental ion Tb^+, they cannot be observed due to severe contamination from monoxide ions of the nuclei with the mass number 167−16 (168−16) whose fission yields are more than three orders of magnitude as large as that of ^{167}Tb (^{168}Tb). On the other hand, when they are mass-separated as the monoxide ion TbO^+, the contamination from other molecular ions are almost negligible. To enhance formation of the TbO^+ in the ion source, a small amount of oxygen gas was injected into the Ar gas-jet stream.

The mass-separated ions of interest were implanted into an aluminum-coated Mylar tape in a tape transport system, and periodically transported to a measuring position at time intervals of 64 s for ^{167}Tb and 20 s for ^{168}Tb. The measuring position was equipped with a sandwich-type plastic scintillator for β-ray measurements, a short coaxial *n*-type HPGe detector (ORTEC LOAX), and a 35% coaxial *n*-type HPGe detector (ORTEC GAMMA-X). β-γ and γ-γ coincidences between these detectors were recorded event by event together with time information used in a half-life analysis.

III. RESULTS

Figure 1 shows a β-coincident γ-ray spectrum for the mass 167+16 fraction. Dy *KX* rays originating from the β^- decay of ^{167}Tb were clearly observed, and weak Ho *KX* rays, 133.2, 250.0, 310.3, and 569.7 keV γ rays associated with the β^- decay of the daughter nuclide ^{167}Dy ($T_{1/2}$ =6.20 min) were also observed. Figure 2 shows decay curves of the Dy $K_\alpha X$ and $K_{\beta_1}X$ rays fitted by the exponential function. The half-lives of 20(4) s and 19(7) s were obtained. In the second experimental run, the Dy $K_\alpha X$ rays exhibited a 19(4) s half-life. By taking weighted average of these values, the half-life of the ^{167}Tb was determined to be 19.4(27) s. In addition, weak 57.2(2) and 69.7(2) keV γ rays exhibiting similar short half-lives of <20 s were observed. Although coincidences between these γ rays and Dy *KX* rays were not recorded due to poor statistics, these are candidates for the γ rays originating from the β^- decay of ^{167}Tb.

Figure 3 shows a β-coincident γ-ray spectrum for the mass 168+16 fraction. Dy *KX* rays from the β^- decay of ^{168}Tb were clearly observed, and weak 192.5 and 487.0 keV

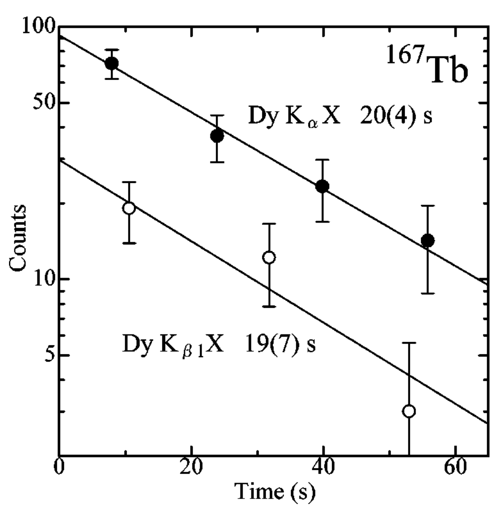

FIG. 2. Decay curves of Dy $K_\alpha X$ and $K_{\beta_1}X$ rays originating from the β^- decay of ^{167}Tb.

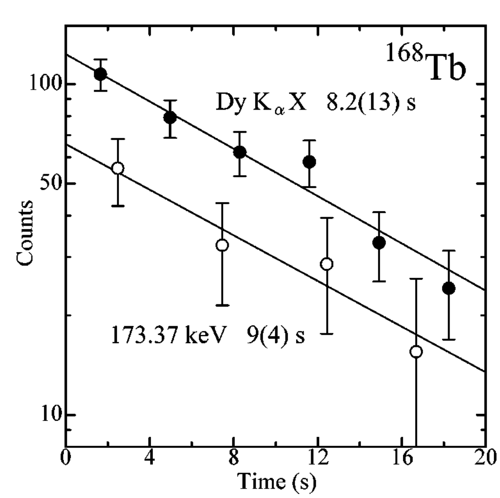

FIG. 4. Decay curves of Dy $K_\alpha X$ rays and 173.37 keV γ rays originating from the β^- decay of ^{168}Tb.

TABLE I. Energies, relative intensities, and coincidence relations of γ rays associated with the β^- decay of ^{168}Tb.

Energy (keV)	Intensity	Coincident γ rays
Dy $K_\alpha X$	184(28)	KX, 75.0, 173.4, 227.0
74.96(6)	50(10)	KX, 173.4, 227.0
173.37(8)	100(19)	KX, 75.0, 227.0
227.03(16)	56(15)	KX

γ rays from the daughter nuclide ^{168}Dy ($T_{1/2}$=8.7 min) were seen. In addition, 74.96(6), 173.37(8), and 227.03(16) keV γ rays were observed. Figure 4 shows decay curves of the Dy $K_\alpha X$ rays and 173.37 keV γ rays. The half-life of the ^{168}Tb was determined to be 8.2(13) s from that of the Dy $K_\alpha X$ rays. The 74.96, 173.37, and 227.03 keV γ rays also exhibited similar half-lives of 8(4), 9(4), and 6(4) s, respectively. These γ rays were coincident with Dy KX rays and coincident each other. Therefore, it is concluded that these three γ rays originate from the β^- decay of ^{168}Tb. γ-ray energies, intensities, and coincidence relations are summarized in Table I.

IV. DISCUSSION

A. β-decay half-lives

Experimental and theoretical β-decay half-lives of ^{159}Pm, ^{161}Sm, ^{165}Gd, and ^{166,167,168}Tb are summarized in Table II. The half-lives of ^{159}Pm, ^{161}Sm, ^{165}Gd, and ^{166}Tb were determined in our previous experiments [7–9]. The theoretical half-lives were taken from the calculations by Tachibana *et al.* with the second generation of the gross theory (GT2) [11] and by Staudt *et al.* with the proton-neutron quasiparticle random-phase approximation (*pn*-QRPA) [12].

For the gross theory, two different half-lives calculated by the version in 1992 (GT2-1992) [13] and that in 1996 (GT2-1996) [14,15] are listed in Table II. In the gross theory, the one-particle strength function D_Ω which represents the distribution of β-decay strength of one particle plays a crucial role in the calculation of the total β-strength function $|M_\Omega|^2$. Here, Ω denotes the type of β-decay operator; the Fermi, Gamow-Teller, and first-forbidden transitions are taken into account in the model. In the GT2-1996, these functions D_Ω were modified against those of the GT2-1992 to reproduce more reasonable β-strength functions. Details of the improvements and the form of the new function for the Gamow-Teller transition are described in Ref. [15]. In addition to this modification, input parameters of the Q_β value used in the calculations were changed. The Q_β values of ^{159}Pm, ^{161}Sm, ^{165}Gd, and ^{166,167,168}Tb in the GT2-1992 were taken from the mass formula by Tachibana *et al.* [16] improved by following Ref. [17], while those in the GT2-1996 were from the systematics by Audi and Wapstra in their atomic mass evaluations [18]. For the *pn*-QRPA, three different half-lives are listed in Table II, which were calculated using three different input parameters of the Q_β value and deformation taken from the mass formulas by Hilf *et al.* [19], Groote *et al.* [20], and Möller *et al.* [21]. The Q_β values used in the calculations are also listed in Table II.

As shown in Table II, the GT2-1992 and the *pn*-QRPA systematically overestimate the half-lives for these nuclei. In particular, the calculated half-lives for ^{166,167,168}Tb are 3–8 times longer than the experimental ones. On the other hand, the calculated half-lives of the GT2-1996 were greatly improved against those of the GT2-1992, especially for ^{166,167,168}Tb, and are in good agreement with the experimental ones.

The modification of the β-strength functions in the GT2-1996 made the calculated half-life shorter; if the same Q_β value is used as the input parameter, the GT2-1996 estimates the half-life about 0.5 times as short as that of the GT2-1992. The Q_β values for ^{159}Pm, ^{161}Sm, ^{165}Gd used in the GT2-

TABLE II. Comparison between experimental and calculated β-decay half-lives of ^{159}Pm, ^{161}Sm, ^{165}Gd, ^{166}Tb, ^{167}Tb, and ^{168}Tb. The Q_β values listed together are the input parameters used in the calculations.

		$T_{1/2}$ (s)	(R^a)	Q_β (MeV)	$T_{1/2}$ (s)	(R^a)	Q_β (MeV)	$T_{1/2}$ (s)	(R^a)	Q_β (MeV)
		^{159}Pm			^{161}Sm			^{165}Gd		
Experimental		2 ± 1			4.8 ± 0.8			10.3 ± 1.6		
GT2-1996 [14]		3.08	(1.54)	5.52	6.72	(1.40)	4.80	16.0	(1.55)	4.19
GT2-1992 [13]		6.54	(3.27)	5.44	16.0	(3.33)	4.64	30.7	(2.98)	4.18
pn-QRPA [12]	(Hilf)	2.93	(1.47)	5.12	10.7	(2.23)	4.71	20.6	(2.00)	3.92
	(Groote)	2.54	(1.27)	4.89	13.0	(2.71)	4.51	27.4	(2.66)	3.77
	(Möller)	2.80	(1.40)	5.29	12.6	(2.63)	4.98	18.4	(1.79)	4.14
		^{166}Tb			^{167}Tb			^{168}Tb		
Experimental		21 ± 6			19.4 ± 2.7			8.2 ± 1.3		
GT2-1996 [14]		33.6	(1.60)	4.89	18.2	(0.94)	4.10	7.25	(0.88)	5.97
GT2-1992 [13]		114	(5.43)	4.50	82.6	(4.26)	3.61	34.9	(4.26)	5.26
pn-QRPA [12]	(Hilf)	83.7	(3.99)	4.80	67.3	(3.47)	3.54	37.1	(4.52)	5.74
	(Groote)	166	(7.90)	4.54	130	(6.70)	3.41	68.4	(8.34)	5.37
	(Möller)	82.8	(3.94)	4.81	63.0	(3.25)	3.86	28.6	(3.49)	5.78

[a] $R=T_{1/2}(\text{calc.})/T_{1/2}(\text{exp.})$.

TABLE III. Inertial parameters ($\hbar^2/2\mathcal{J}$) and decoupling parameters (a) of the $\nu 1/2^-[521]$ rotational bands in $N=99$, 101, and 103 odd-mass isotones. These parameters were extracted from the level energies of the $1/2^-$, $3/2^-$, and $5/2^-$ states in this band.

Nucleus ($N=99$)	$\hbar^2/2\mathcal{J}$ (keV)	a	Nucleus ($N=101$)	$\hbar^2/2\mathcal{J}$ (keV)	a	Nucleus ($N=103$)	$\hbar^2/2\mathcal{J}$ (keV)	a
			^{175}W	14.03	0.797	^{177}W	14.91	0.795
^{171}Hf	12.57	0.777	^{173}Hf	12.94	0.818	^{175}Hf	13.44	0.747
^{169}Yb	11.76	0.791	^{171}Yb	12.24	0.850	^{173}Yb	12.29	0.671
^{167}Er	11.09	0.699	^{169}Er	11.93	0.831	^{171}Er	11.67	0.623
^{165}Dy	10.32	0.567	^{167}Dy	10.82	0.769			

1992 and the GT2-1996 are about the same. Thus the improvements of the calculated half-lives for these nuclei are mostly due to the modification of the β-strength functions. On the other hand, the large deviations of more than a factor of 4 for ^{166,167,168}Tb in the GT2-1992 are not only due to the β-strength functions but also due to the small Q_β values; the Q_β values for ^{166,167,168}Tb in the GT2-1992 are 400–700 keV as small as the evaluated ones by Audi and Wapstra which were employed in the GT2-1996. The corrections of input Q_β values in the GT2-1996 for ^{166,167,168}Tb, in conjunction with the modified β-strength functions, made the calculated half-lives shorter by a factor of 3–5, and consequently agree well with the experimental ones.

The overestimates by the *pn*-QRPA are also partly due to the input Q_β values. The half-lives of ^{166,167,168}Tb calculated by the *pn*-QRPA (Groote) are 7–8 times as long as the experimental ones. These large deviations result from the small Q_β values used in the calculations. The Q_β values in the *pn*-QRPA (Hilf) and (Möller) for ^{166,167,168}Tb are also smaller than the evaluated ones by Audi and Wapstra. However, even if the evaluated Q_β values are used in the *pn*-QRPA calculation, it is estimated that the calculated half-lives for ^{161}Sm, ^{165}Gd, and ^{166,167,168}Tb are still longer by a factor of 2–3 [7].

B. Excited states of ^{167}Dy

The observed 57.2 and 69.7 keV γ rays tentatively assigned to γ transitions in ^{167}Dy are considered as the $3/2^- \rightarrow 1/2^-$ and the $5/2^- \rightarrow 1/2^-$ intraband transitions in the $\nu 1/2^-[521]$ band as shown in Fig. 5(a). Low-energy states in $^{169}Er_{101}$, $^{171}Yb_{101}$, $^{173}Hf_{101}$, and $^{175}W_{101}$ isotones show quite similar structure consisting of rotational bands built on the $1/2^-[521]$, $5/2^-[512]$, and $7/2^+[633]$ Nilsson states [22]. The ground state configuration of these isotones is the $1/2^-[521]$, which is also expected in ^{167}Dy. Intensities of β feedings to levels in ^{167}Ho are also consistent with the $1/2^-$ assignment for the ground state of ^{167}Dy [23]. On the other hand, the ground state configuration of ^{167}Tb is expected to be the $\pi 3/2^+[411]$, as well as that of neighboring odd-mass Tb isotopes. If the ground state spin and parity of the ^{167}Tb is $3/2^+$, its β^- decay and following γ transitions could strongly populate the $3/2^-$ and $5/2^-$ states in the $1/2^-[521]$ band and the $5/2^-[512]$ bandhead. Energies of the 57.2 and 69.7 keV γ rays are fairly consistent with the expected energies for the $3/2^-$ and $5/2^-$ states in the $1/2^-[521]$ band in ^{167}Dy as described below. Level energies of a $K=1/2$ band are represented by the following equation:

$$E(I)=E_0+\frac{\hbar^2}{2\mathcal{J}}[I(I+1)+a(-1)^{I+1/2}(I+1/2)],$$

where $E(I)$ is the excitation energy of the spin I state, E_0 is the bandhead energy, and $\hbar^2/2\mathcal{J}$ and a are the inertial parameter and the decoupling parameter, respectively. The $\hbar^2/2\mathcal{J}$ and a of the $1/2^-[521]$ bands in $N=99$, 101, and 103 isotones extracted from the excitation energies of the $1/2^-$, $3/2^-$, and $5/2^-$ states [22] are summarized in Table III. These parameters show smooth change with both proton and neutron number; the $\hbar^2/2\mathcal{J}$ monotonously decreases from tungsten to dysprosium, and both the $\hbar^2/2\mathcal{J}$ and a of the $N=101$ isotones are larger than those of the $N=99$ isotones. The parameters of ^{167}Dy extracted from the 57.2 and 69.7 keV γ-ray energies follow the above tendency.

From the systematics of the $N=101$ isotones, it is expected that the $5/2^-[512]$ bandhead in ^{167}Dy lies at $\sim$100 keV, and a transition to the $3/2^-$ state in the $1/2^-[521]$ band should be observed [22]. In the γ-ray spectrum, a 40.6(2) keV γ-line was weakly observed, which is a candidate for this transition. Further measurements are needed to assign this transition.

C. Excited states of ^{168}Dy

Figure 5(b) shows a proposed decay scheme of ^{168}Tb. The 74.96 and 173.37 keV γ rays were assigned to the $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ transitions in the ground state band, respectively, by considering their energies and intensities. According to the systematics of the Nilsson orbit assignments, the 65th proton and the 103rd neutron of the ^{168}Tb ground state are expected to occupy the $\pi 3/2^+[411]$ orbital and the $\nu 5/2^-[512]$ orbital, respectively; $^{171}Er_{103}$, $^{173}Yb_{103}$, $^{175}Hf_{103}$, and $^{177}W_{103}$ isotones have a ground state configuration of $5/2^-[512]$ [22]. Thus the ground state spin and parity of ^{168}Tb is expected to be 4^- by following the Gallagher and Moszkowski coupling rule [24]. The relative intensities of the $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ transitions are not contradictory to the 4^- assignment.

The 227.03 keV γ ray is expected to be an interband transition because its energy does not match with intraband transitions from low-spin states. In ^{160,162,164,166}Dy, the $K^\pi=2^-$ octupole band and the $K^\pi=2^+ \gamma$ band are found at excitation energy around $\sim$1 MeV, and intense γ transitions from the octupole band to the γ band are observed [22]. Considering the systematics of level energies, branching ratios of γ transitions, and the observed coincidence relations

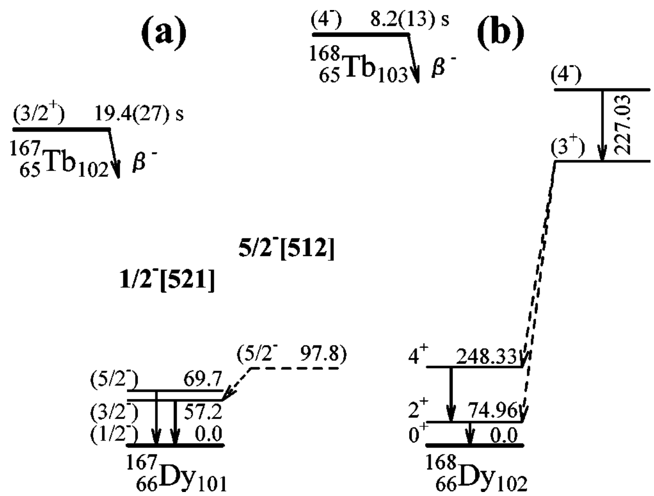

FIG. 5. Proposed decay schemes for the β^- decay of (a) ^{167}Tb and (b) ^{168}Tb.

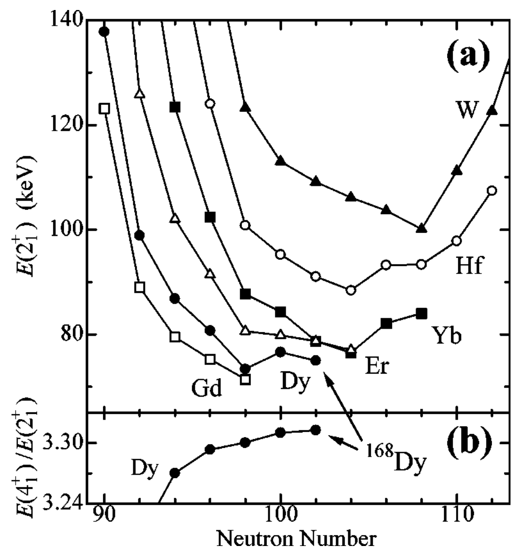

FIG. 6. (a) Level energies of the first 2^+ states in even-even Gd, Dy, Er, Yb, Hf, and W isotopes. (b) Energy ratios between the 4_1^+ and 2_1^+ states $E(4_1^+)/E(2_1^+)$ for even-even Dy isotopes.

and intensities, the $4^- \rightarrow 3_\gamma^+$ assignment is likely for this transition. Owing to poor statistics, the $3_\gamma^+ \rightarrow 2_1^+$ and $3_\gamma^+ \rightarrow 4_1^+$ transitions could not be observed in the present experiment.

Figure 6(a) shows excitation energies of the 2_1^+ states in even-even Gd, Dy, Er, Yb, Hf, and W isotopes. The 2_1^+ energy of Dy isotopes takes the minimum at ^{164}Dy, and then rises at ^{166}Dy. This tendency has been interpreted that the maximum deformation occurs at $N=98$ (^{164}Dy) in Dy isotopes as suggested in Ref. [25]. However, the present result revealed that the 2_1^+ state again decreases in energy at ^{168}Dy. The energy of the 4_1^+ states also shows the same tendency. This indicates that the second energy minimum exists around $N\approx 104$ as in Er, Yb, and Hf isotopes, which is reasonably explained as the maximum deformation at the $N=104$ neutron midshell. In contrast to the 2_1^+ energy, the energy ratio between the 4_1^+ and 2_1^+ states $E(4_1^+)/E(2_1^+)$ for Dy isotopes increases smoothly with neutron number toward the $N\approx 104$ neutron midshell as shown in Fig. 6(b). Thus the energy minimum at $N=98$ is considered to be a rather irregular behavior. This implies the existence of some local effect to enhance nuclear deformation around ^{164}Dy.

V. SUMMARY

β-decay half-lives of new neutron-rich isotopes ^{167}Tb and ^{168}Tb have been determined to be 19.4(27) s and 8.2(13) s, respectively. The present half-lives and those of the recently identified nuclei ^{159}Pm, ^{161}Sm, ^{165}Gd, ^{166}Tb were compared with the calculated ones. The GT2-1992 and the *pn*-QRPA systematically overestimate the half-lives for these nuclei. On the other hand, the calculated half-lives of the GT2-1996 were greatly improved against those of the GT2-1992, especially for ^{166,167,168}Tb, and are in good agreement with the experimental ones. This improvement is not only due to the new one-particle strength functions employed in the GT2-1996 but also due to the corrections of input Q_β values which were taken from the systematics by Audi and Wapstra.

Excited states of the daughter nuclides ^{167}Dy and ^{168}Dy have been established for the first time. The excited states observed in ^{167}Dy were assigned to the $3/2^-$ and $5/2^-$ states in the $\nu 1/2^-[521]$ rotational band. Level energies of the 2_1^+ and 4_1^+ states in ^{168}Dy were found to be lower than those in ^{166}Dy. It indicates that the second energy minimum of the 2_1^+ states in Dy isotopes exists around the $N\approx 104$ neutron midshell, which is reasonably explained as the maximum deformation at the midshell. On the other hand, the first minimum at $N=98$ implies the existence of some local effect to enhance nuclear deformation around ^{164}Dy.

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