Ground-state β-decay spectroscopy of ^{187}Ta

M. Mukai,[1,2,*] Y. Hirayama,[3] Y. X. Watanabe,[3] H. Watanabe,[4,3,1] H. Koura,[5] S. C. Jeong,[3] H. Miyatake,[3] M. Brunet,[6] S. Ishizawa,[7,1,3] F. G. Kondev,[8] G. J. Lane,[9] Yu. A. Litvinov,[10] T. Niwase,[11,1,3] M. Oyaizu,[3] Zs. Podolyák,[6] M. Rosenbusch,[3] P. Schury,[3] M. Wada,[3] and P. M. Walker[6]

[1]*Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan*
[2]*Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305-0006, Japan*
[3]*Wako Nuclear Science Center (WNSC), Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Wako, Saitama 351-0198, Japan*
[4]*School of Physics and International Research Center for Nuclei and Particles in Cosmos, Beihang University, Beijing 100191, China*
[5]*Advanced Science Research Center, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan*
[6]*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*
[7]*Graduate School of Science and Engineering, Yamagata University, Yamagata 992-8510, Japan*
[8]*Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[9]*Department of Nuclear Physics, Research School of Physics, Australian National University, Canberra, Australian Capital Territory 2601, Australia*
[10]*GSI Helmholtzzentrum för Schwerionenforschung, 64291 Darmstadt, Germany*
[11]*Department of Physics, Kyushu University, Nishi-ku, Fukuoka 819-0395, Japan*

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Beta-decay spectroscopy of the ^{187}Ta ground state was performed at the KEK Isotope Separation System. β-delayed γ rays corresponding to the previously reported in-beam transitions were observed. The β-decay half-life of the ^{187}Ta ground state was determined to be 283(10) s by analyzing a time spectrum of β-γ coincidence events. The β-decay branching ratio and $\log(ft)$ values were evaluated for the first time. Based on the newly evaluated $\log(ft)$ values of >6.0 and a decay scheme, spin-parity values of $I^\pi = 7/2^+$ originating from the odd-proton orbit $\pi 7/2[404]$ were assigned with high confidence, which is consistent with the systematics of neighboring odd-A nuclides.

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I. INTRODUCTION

The neutron-rich nuclei with $A \approx 190$ are known as transitional nuclei which show a shape transition from well deformed to γ soft with increasing neutron number [1]. Their nuclear structures have been investigated through studies of rotational band energies, E2 transition rates, decays of K isomers, and β decays as recently reported in Refs. [2–5] and references therein. To clarify the shape transition along the isotopic chain, experimental spectroscopic studies of more neutron-rich nuclei are needed.

The ^{187}Ta ($Z = 73$, $N = 114$) was first synthesized using the fragmentation of a ^{197}Au beam at the GSI projectile-fragment separator (FRS) [6], and its isomeric states were observed in the Experimental Storage Ring (ESR) downstream of the FRS [7,8]. In their study, the half-lives and excitation energies were determined to be 2.3(6) min for the ground state, 22(9) s for the first isomeric state (^{187m1}Ta) at an excitation energy of $E_{ex} = 1789(13)$ keV, and >5 min for the second isomeric state (^{187m2}Ta) at $E_{ex} = 2935(14)$ keV. ^{187m1}Ta and ^{187m2}Ta are predicted to be high-K isomers with $K^\pi = 27/2^-$ and $41/2^+$, respectively, based on calculations of multi-quasiparticle states [7,8].

We performed β- and γ-decay spectroscopy of ^{187}Ta to clarify the nuclear structure of the ground and two isomeric states at the KEK Isotope Separation System (KISS) [9–11]. Owing to the astrophysical and nuclear physics interests in this nuclear region, systematic nuclear spectroscopy has been performed at KISS installed at the Radioactive Isotope Beam Factory (RIBF), RIKEN. KISS has unique features which can provide radioactive nuclides in their ground and long-lived isomeric states with half-lives $T_{1/2} > 0.5$ s produced by multi-nucleon transfer reactions [12–14].

The partial results of the experiment on the ^{187m1}Ta were reported in Ref. [13], where the ^{187m1}Ta [$E_x = 1778 \pm 1$ keV, $T_{1/2} = 7.3(9)$ s] was interpreted as a K isomer with $K^\pi = 25/2^-$ consisting of three quasiparticles, and the ground state $I^\pi = 7/2^+$ was tentatively assigned based on the systematics of the lighter Ta nuclides [15]. The present work describes the results of β-decay measurements of the ground state ^{187g}Ta, whose spin assignment will be determined by using the $\log(ft)$ values extracted from the measured β-decay half-life and β-branching ratios. The γ rays seen in the present experiment had been observed in-beam by Shizuma *et al.* [16], but they had not been seen previously in β decay.

*momo.mukai@riken.jp

II. EXPERIMENT

The β-γ spectroscopy of ^{187g}Ta was performed in the same experiment with the γ-decay spectroscopy of the ^{186,187}Ta isomer states [13,14]. The experiment was performed using KISS [9–11], an argon-gas-cell-based laser ion source combined with an online isotope separator. Unstable tantalum nuclides were produced as targetlike fragments (TLFs) via multinucleon transfer (MNT) reactions of a ^{nat}W target (5 μm in thickness) and a ^{136}Xe primary beam (7.2 MeV/nucleon and 50 pnA), accelerated by the RIKEN Ring Cyclotron.

The TLFs were thermalized and neutralized in a gas cell filled with purified Ar gas of $\approx$1 atm and element-selectively reionized by using a laser resonance ionization technique at the exit of the gas cell. Tantalum atoms were excited via the transition of $5d^36s^2\ ^4F_{3/2} \rightarrow 3/2^\circ$ ($\lambda_1 = 248.571$ nm) [17] by irradiating with the first-step laser. The first-step laser wavelength was obtained from a dye laser (Radiant Dyes, NarrowScan) including a frequency conversion unit using a dye solution of Coumarin 500 pumped by an excimer laser (XeCl, 307.9 nm, Lambda Physik, LPX240i). The ionization of excited atoms was achieved by using 308-nm radiation obtained from the excimer laser.

The singly charged tantalum ions were accelerated to an energy of 20 keV, and their mass-to-charge ratios were chosen by using a dipole magnet with a mass resolving power of $A/\Delta A \approx 900$. The mass-analyzed ^{187}Ta ion beam was transported to a detector station which included a tape-transport device for avoiding radioactivity buildup from the decay chain of the separated nucleus under a pulsed-beam operation of KISS. The extraction yield of ^{187}Ta was about 0.7 pps. The ^{187}Ta beam was implanted in an aluminized Mylar tape of the tape-transport device, which was surrounded by β-ray detectors [18] and four super-Clover germanium detectors. The β-ray detector, a multisegmented proportional gas counter (MSPGC), consists of 32 proportional gas counters divided into two layers and covering a solid angle of 80% of 4π [18]. The four super-Clover germanium detectors were calibrated using γ rays from ^{152}Eu and ^{133}Ba and were measured to have a total absolute full-energy peak efficiency of 15% at 150 keV.

The events detected by the MSPGC were analyzed by using the multiplicity of the gas counter and by considering the energy deposition of electrons and x rays in the counter [18,19]. The events from a single inner-layer counter, referred to as $M = 1$, are sensitive to electrons with energies of about $80 \leqslant E \leqslant 100$ keV. Moreover, any single-counter events at either the inner- or outer-layer counters are sensitive to x rays through the photoelectric effect. The events from two neighboring inner- and outer-layer counters, referred to as $M = 2$, are sensitive to electrons with energies larger than 100 keV. Thus the events originating from β-ray energies larger than 100 keV are dominant in the $M = 2$ multiplicity gate.

The ^{187}Ta beam was implanted on the tape during $T_{on} = 1800$ s, and then implantation was stopped during $T_{off} = 1800$ s to measure the decay curve by changing the beam trajectory using an electric deflector installed upstream of the detector station. The beam-on and -off cycle was repeated 52 times in total. The results shown in the next section were obtained by analyzing the data from all cycles.

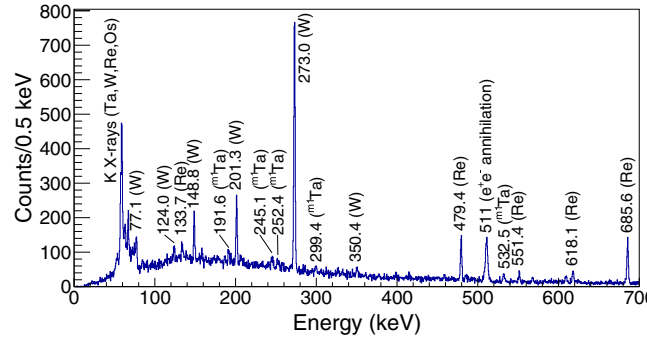

FIG. 1. Measured γ-ray energy spectrum in coincidence with the MSPGC hit pattern $M = 2$ within the prompt timing $T_{M=2} - T_\gamma = \pm 200$ ns. The figures on the peaks indicate the peak energy in keV, and the labels in parentheses indicate the possible origin of observed γ rays.

III. RESULTS

Figure 1 shows the energy spectrum of γ rays in coincidence with the MSPGC hit pattern $M = 2$. The timing gate for the coincidence was set to $T_{M=2} - T_\gamma = \pm 200$ ns to preferentially select β-delayed γ rays. The observed γ rays were identified as originating from the internal transitions of ^{187m1}Ta [13] and excited states of ^{187}W and ^{187}Re, which were populated by the β decays of ^{187}Ta and ^{187}W ($T_{1/2} = 23.809(25)$ h [20]), respectively. All identified γ rays following ground-state β decays are known from previous studies. The ^{187m1}Ta was produced by MNT reactions, and the conversion electrons with kinetic energy >100 keV emitted by the internal conversions of internal decay transitions were detected weakly with the $M = 2$ gas counter gate. The low-energy part of the spectrum was well reproduced by a fit including Os K x-rays. The Os K x-rays probably originate from the electron capture decays of ^{187}Ir ($T_{1/2} = 10.5(3)$ h [20]). The ^{187}Ir is the neutron-deficient nuclide next to the stable ^{187}Os and can be produced by the MNT reactions and extracted from KISS as ions surviving from the gas cell. The γ-ray transitions were assigned not only through comparisons with previously reported transition energies [21] but also by checking the half-lives from the energy-gated time spectra in the case of W γ rays, as described in the next paragraph, and the emission probabilities per β decay in the case of Re γ rays. All observed γ rays emitted from the excited states of ^{187}W are listed in Table I. We have also found evidence for β-delayed γ rays from the ^{187m2}Ta, which is predicted to have $K^\pi = 41/2^+$ consisting of five quasiparticles [7,8]. The results on the ^{187m2}Ta decay will be reported separately.

The growth and decay time spectra gating with each energy peak of W γ rays listed in Table I were fit considering the β decay of a single parent state and constant background without any restrictions to the fitting parameters: half-life, amplitude, and background level. The analyzed $T_{1/2}$ values listed in Table I were consistent within the error margin of one sigma from each other. Figure 2 shows the sum of the time spectra and a curve of the best fit to the experimental data. The half-life of ^{187g}Ta was determined to be $T_{1/2} = 283(10)$ s from the best fit with reduced $\chi^2 = 1.2$. The time spectrum includes

TABLE I. The measured γ-ray energy (E_γ), emission probability per β decay, and β-decay half-life ($T_{1/2}$) by gating at each γ-ray energy associated with the β decay of ^{187}Ta. The multipolarities of each transition, except for 77.3- and 123.9-keV transitions, were assumed to be E2 or M1 based on the spin-parity values of initial and final states. Unknown total conversion coefficients ($\alpha_{\rm tot}$) were calculated with the BrIcc program [22]. The branching ratios (R_β) were evaluated in two cases, assuming both pure E2 and M1 for the 148.8- and 273.0-keV transitions.

Reported state [21]		Present work								
			I_γ (%)		$E_\gamma^{149}/E_\gamma^{273}$ = E2/E2		$E_\gamma^{149}/E_\gamma^{273}$ = M1/M1			
E_x (keV)	I^π	E_γ (keV)	/β decay	$T_{1/2}$ (s)	R_β (%)	log(ft)	R_β (%)	log(ft)	Multipolarity	$\alpha_{\rm tot}$
0.0	$3/2^-$	–	–	–	3(13)	>8.4	0(4)	>9	–	–
77.3	$5/2^-$	77.2(1)	6.8(8)	355(66)	0(8)	>7.3	0(0)	–	M1+E2	10.17 [21]
201.4	$7/2^-$	123.9(2)	3.1(5)	252(102)	9(3)	7.1(2)	3(2)	7.6(3)	M1+E2	2.01 [21]
		201.3(1)	12.6(6)	289(28)					E2	0.30
350.4	$7/2^-$	148.8(1)	8.8(4)	256(29)	87(16)	6.05(9)	97(11)	6.00(7)	M1/E2	1.52/0.86
		273.0(1)	61(2)	287(15)					M1/E2	0.28/0.11
		350.5(2)	2.1(5)	239(122)					E2	0.05

the contribution from the β decay of ^{187g}Ta populated by the internal decay of ^{187m1}Ta, in addition to the direct population by the MNT reactions. However, the decay half-life of ^{187m1}Ta is relatively short, $T_{1/2} = 7.3(9)$ s [13], and thus its internal decay could not affect the fitting result.

The measured half-life $T_{1/2} = 283(10)$ s is more than twice as long as $T_{1/2} = 2.3(6)$ min previously measured at the ESR [7]. In that experiment, fully ionized ^{187}Ta^{73+} ions were observed in settings on ^{190}W and ^{184}Hf central fragments. Only short observation times of <10 s and ≈50 s were employed [8]. The half-life was deduced based on the losses of particles from the ESR. Since these ESR settings were not optimized for $A = 187$ isobars, unwanted losses due to reasons other than radioactive decay could cause the discrepancy compared to our new and more precise result.

The β-decay branching ratio (R_β) from ^{187g}Ta to each state in ^{187}W was evaluated from the β-decay transition intensity to each excited state obtained by analyzing the γ-ray intensities. The total β-decay transition intensity was obtained by analyzing the time spectrum of the MSPGC events as described below. The intensity ($I_{\gamma,j}$) of a γ-decay transition (j) was obtained by fitting the time spectrum measured in coincidence with the MSPGC hit pattern $M = 2$ (β-ray event). Here, a single decay component (exponential function) and constant background were taken into account in the fitting function. Then the internal transition intensity ($I_{{\rm IT},j}$) was calculated to be $I_{{\rm IT},j} = I_{\gamma,j}/\varepsilon_{{\rm Ge},j} \times (1 + \alpha_{{\rm tot},j})$ from the corrected γ-decay transition intensity $I_{\gamma,j}/\varepsilon_{{\rm Ge},j}$ by accounting for the γ-ray detection efficiency ($\varepsilon_{{\rm Ge},j}$) and the total conversion coefficient ($\alpha_{{\rm tot},j}$). The β-decay transition intensity ($I_{\beta,i}$) to each excited state i was derived by subtracting the total incoming $I_{{\rm IT},j}$ to the state i from the total outgoing $I_{{\rm IT},k}$ from the state i. When the subtracted values become less than zero, the values were defined to be zero and the upper limit values were defined from the corresponding uncertainty. Independently, the total intensity of β-decay transitions ($I_{\beta,{\rm MSPGC}}$) from ^{187g}Ta was evaluated from the time spectrum of the $M = 2$ events detected by the MSPGC. Here, a single decay component and constant background were taken into account in the fitting function. The MSPGC detection efficiency [19] was identical for all the β-decay transitions because of the similar Q_β. Finally, the R_β values were derived as $I_{\beta,i}/I_{\beta,{\rm MSPGC}}$ in the case $\Sigma I_{\beta,i} < I_{\beta,{\rm MSPGC}}$ ($E_\gamma^{149}/E_\gamma^{273}$ = E2/E2) and $I_{\beta,i}/\Sigma I_{\beta,i}$ in the case $\Sigma I_{\beta,i} > I_{\beta,{\rm MSPGC}}$ ($E_\gamma^{149}/E_\gamma^{273}$ = M1/M1). The β-decay transition intensity from ^{187g}Ta to ^{187g}W was deduced to be 3(13)% ($E_\gamma^{149}/E_\gamma^{273}$ = E2/E2), as shown in Table I, by subtracting the sum of $I_{\beta,i}$ from $I_{\beta,{\rm MSPGC}}$. This value might include unobserved internal transitions to ^{187}W states and the intensity of β-delayed neutron emissions.

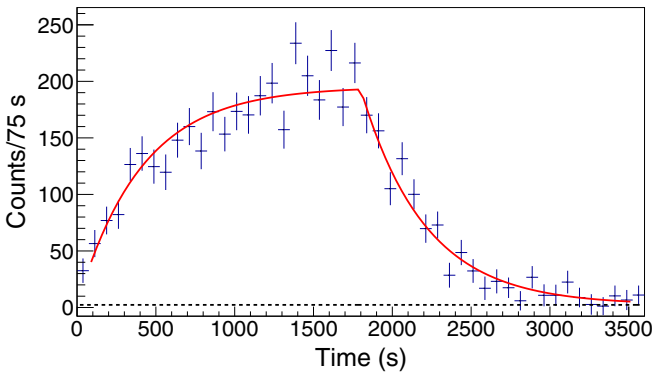

FIG. 2. Growth and decay time spectrum of γ rays associating with the β decay of ^{187g}Ta listed in Table I measured in coincidence with the MSPGC hit pattern $M = 2$. The beam was implanted during $T_{\rm on} = 1800$ s and switched off during the subsequent $T_{\rm off} = 1800$ s. The solid red line indicates the best fit to the experimental data, including the β decay of ^{187g}Ta and a constant background [2(1) counts/75 s/52 cycle] shown as the black dotted line.

The total conversion coefficients have been previously evaluated only for the 77.3- and 123.9-keV transitions to be 10.17 and 2.01(13) [21], respectively, which were calculated based on measured conversion electron data. The $\alpha_{\rm tot}$ values of other transitions were calculated by using the BrIcc program [22] with assumed multipolarity based on the known spin-parity values of the initial and final states. The 201.3- and 350.5-keV transitions with $\Delta I = 2$ were assumed to be E2 transitions. For the 148.8- and 273.0-keV transitions with $\Delta I = 1$, both pure M1 and E2 transitions, were considered in the analysis since the mixing ratios are unknown. The pure

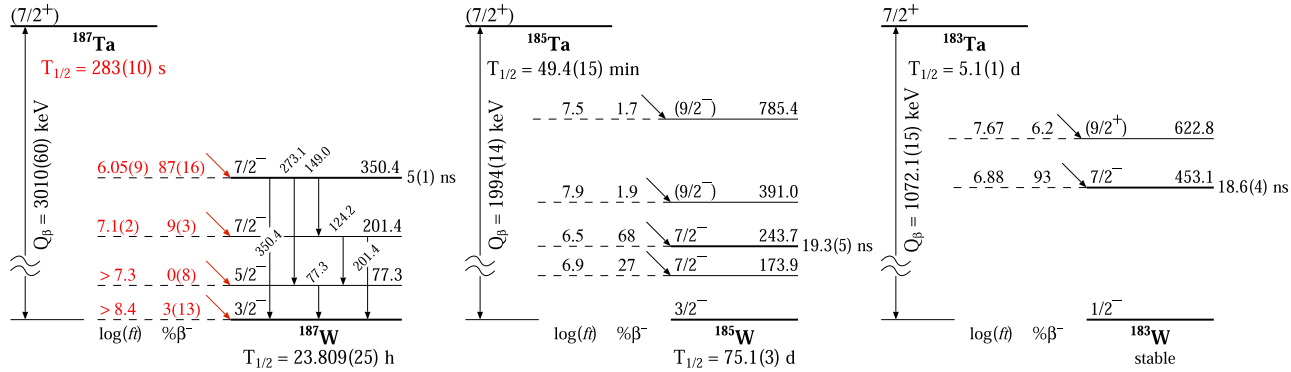

FIG. 3. The β-decay schemes of ^{183,185,187}Ta ground states. The nuclear structure data, half-lives, and masses are taken from the Nuclear Data Sheets [21,25,26], the NUBASE2020 [20], and the AME2020 [27], respectively. The excited states populated by the β-decay transitions with branching ratio more than 1% are shown. The γ-ray transitions in ^{183,185}W are omitted. The newly determined branching ratios, log(ft) values, and β-decay transitions are shown in red. The branching ratios and log(ft) values for ^{187}Ta are shown in the case of pure E2 character for both the 149- and 273-keV γ transitions.

M1 or E2 assumption for these two transitions gives the upper or lower limit of the β-decay transition to the 350.4-keV state, respectively.

The log(ft) values were calculated from the evaluated R_β values and newly determined $T_{1/2}$ value by using the LOGFT program [23,24]. The obtained R_β and log(ft) values are listed in Table I. According to the tentative spin-parity assignment of $7/2^+$ for ^{187g}Ta, the unique and nonunique first-forbidden transitions were considered for the transitions to ^{187g}W and excited states, respectively. The lower limit log(ft) values of the ground and first excited states were calculated by assuming $R_\beta + 1\sigma$ as the upper-limit branching ratio.

IV. DISCUSSION

A. Decay scheme of ^{187}Ta

Figure 3 shows the newly determined β-decay scheme of ^{187}Ta together with those of ^{183,185}Ta. These Ta nuclides dominantly decay to the $I^\pi = 7/2^-$ isomers in the corresponding W nuclide via first-forbidden transitions. The R_β values to the ground and first excited states with $I^\pi = 3/2^-$ and $5/2^-$, respectively, were determined to be zero or negligibly small by accounting for the uncertainty. The $I^\pi = 7/2^-$ isomers are suggested to be the $\nu 7/2[503]$ Nilsson configuration forming the $K^\pi = 7/2^-$ band head for these W nuclides [28]. The other $I^\pi = 5/2^-$ ($E_x = 77.3$ keV) and $7/2^-$ ($E_x = 201.4$ keV) states populated in the β decay of ^{187}Ta are band members of the ground-state $\nu 3/2[512]$ band [28]. The possible spin-parity values of the ^{187g}Ta are $I^\pi = 5/2^+$ or $7/2^+$ by accounting for the first-forbidden transitions of $\Delta I = 0$ and ± 1 suggested from the evaluated log(ft) values and the dominant transitions to the $I^\pi = 7/2^-$ states. From the systematics of the excited single-proton states of lighter Ta nuclides [15] and the decay properties of ^{187m1}Ta [13], the most probable spin-parity values could be determined to be $I^\pi = 7/2^+$ as the $\pi 7/2[404]$ Nilsson configuration for ^{187g}Ta. This spin-parity assignment is consistent with the systematic similarity of the β-decay schemes of ^{183,185,187}Ta.

B. Half-lives of neutron-rich Ta nuclides

Figure 4 shows the comparison of experimental half-lives of neutron-rich Ta nuclides with theoretical values. The theoretical half-lives were obtained from three types of large-scale calculations; the gross theory [29] using the Q_β values obtained from the Koura-Tachibana-Uno-Yamada (KTUY) mass formula [30,31], the quasiparticle random-phase approximation (QRPA) with inputs from the FRDM (2012) model [32], and the proton-neutron relativistic QRPA (*pn*-RQRPA) based on the relativistic Hartree-Bogoliubov (RHB) calculations with the D3C* parametrization [33]. The characteristic features on the comparison are summarized below.

In the calculations of the KTUY + gross theory, the allowed transitions and first-forbidden transitions with rank $L = 0$, 1, and 2 are considered. The predicted half-life is two orders of magnitude longer than the experimental value at $A = 185$. It could originate from the smaller transition strength in

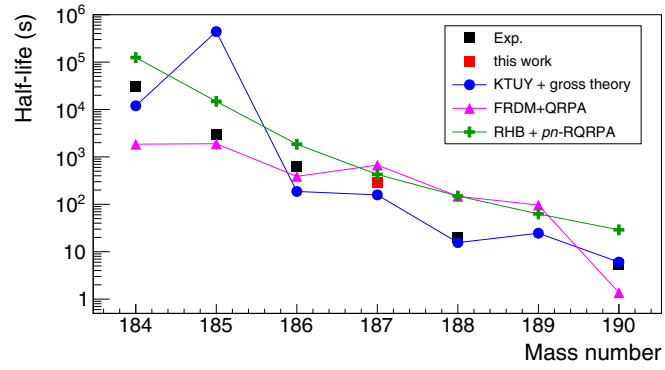

FIG. 4. Comparison between experimental and theoretical half-lives of neutron-rich Ta nuclides. The experimental data are taken from the NNDC [35]. There is no experimental value at $A = 189$. The theoretical half-lives are obtained from KTUY + gross theory [29–31], FRDM + QRPA [32], and RHB + *pn*-RQRPA [33] calculations.

the Q_β decay window as a result of the predicted smaller Q_β compared to the experimental value ($Q_\beta = 1.994(14)$ MeV [27]) by 0.8 MeV.

In the FRDM + QRPA calculations, the first-forbidden transitions are treated by taking into account the second-order gross theory similar to the KTUY + gross theory, and the Q_β values are taken from the experimental data where available ($A < 187$) [34]. The larger discrepancy at $A = 184$ is probably due to the difficulty of accurate predictions with very few transitions in small Q_β decay windows close to stable nuclei.

In the fully self-consistent RHB + *pn*-RQRPA calculations, the nuclear ground-state properties are described by RHB calculations using the D3C* parametrization and excited states are obtained using the *pn*-RQRPA [33]. This framework can treat the first-forbidden transitions with rank $L = 0$ and 1 on the same footing as the Gamow-Teller transitions. The calculation gives overestimated values by factors of 1.5 to 8. The origin of this overestimation is not clear. The calculation predicts systematically a larger fraction of first-forbidden decay rate in the total decay rate of $N = 126$ isotones in comparison to other theoretical models as shown in Fig. 11 in Ref. [33]. The overestimation of the fraction of first-forbidden transitions might be a reason for the predicted longer half-lives.

In spite of the consideration of the first-forbidden transitions in the theoretical calculations, there are still deviations between experimental and theoretical half-lives. The systematic experimental study in this nuclear region is important to improve the theoretical predictions.

V. SUMMARY

We performed β-decay spectroscopy of ^{187g}Ta at KISS. Known γ-ray transitions of ^{187}W from in-beam work were here identified as β-delayed γ rays for the first time. The β-decay half-life of ^{187g}Ta was determined to be 283(10) s. The proposed decay scheme of ^{187g}Ta is similar to those of ^{183,185}Ta. Based on the newly evaluated $\log(ft)$ values of >6.0 and the decay scheme, the spin-parity values of $I^\pi = 7/2^+$ originating from the odd-proton orbit $\pi 7/2[404]$ were assigned with high confidence, consistent with the systematics of neighboring odd-A nuclides.

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Correction: Entries that should have appeared in the last two columns of Table I were incorrectly placed during the production process and have been fixed.