Isomeric and β-decay spectroscopy of ^{173,174}Ho

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β-decay spectroscopy of ^{173,174}Ho ($Z = 67$, $N = 106{,}107$) was conducted at Radioactive Isotope Beam Factory at RIKEN by using in-flight fission of a 345-MeV/u ^{238}U primary beam. A previously unreported isomeric state at 405 keV with half-life of 3.7(12) μs and a spin and parity of $(3/2^+)$ is identified in ^{173}Ho. Moreover, a new state with a spin and parity of 9^- was discovered in ^{174}Er. The experimental log ft values of 5.84(20) and 5.25(18) suggest an allowed-hindered β decay from the ground state of ^{174}Ho to the $K^\pi = 8^-$ isomeric state in ^{174}Er. Configuration-constrained potential energy surface (PES) calculations were performed and the predictions are in reasonable agreement with the experimental results.

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I. INTRODUCTION

One of the fundamental scientific questions that remain unanswered is the origin of heavy elements in the universe. More than half of the stable isotopes of elements heavier than iron are thought to be synthesized via the rapid-neutron capture process (r process) [1,2]. Three main peaks observed in the r-process abundance distribution around $A = 80$, 130, and 195 are believed to originate from the nuclear reaction flow passing through neutron-rich nuclei at the neutron magic numbers $N = 50$, 82, and 126. In contrast to the three main r-process peaks, it is still unclear how a pygmy peak

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located around mass number $A = 165$, known as a rare-earth element (REE) peak between the neutron shell closure $N = 82$ and 126, is considered to be formed with a different mechanism than the three main peaks. Although the origin of the REE peak is still unclear, one of the possible sources is the neutron star merger ejecta in fission recycling [3]. The other possible source is suggested to arise at the later stage of r-process nucleosynthesis [1]. Recent sensitivity studies of β-decay half-lives, β-delayed neutron emission probabilities, and the nuclear masses of neutron-rich isotopes with $Z = 57$–70 and $N = 97$–115 suggest that the variation of these nuclear properties, which should be influenced by nuclear deformation, has a significant impact on the formation of REE peak in various astrophysical conditions [4–9]. In addition, the ground-state properties of nuclei taken into account in the network calculation, the presence of low-lying isomeric states was found to alter the r-process path which results in significantly different r-process final abundances [10,11]. The region of well-deformed nuclei around the double midshell ($Z = 66, N = 104$) is abundant in characteristic isomers, such as spin-trap and K isomers (K denotes the angular momentum projection on the symmetry axis of the deformed nucleus). Therefore it is necessary to identify the low-lying isomeric states and measure their lifetimes to test nuclear-structure models that are adopted in any r-process calculations.

As part of the EURICA (Euroball-RIKEN Cluster Array) project at RIBF [12], we have conducted isomeric and β-decay studies of neutron-rich rare-earth nuclei from $_{62}$Sm to $_{67}$Ho in the doubly midshell region [4]. In the previous paper, the ground-state β-decay half-lives have been measured to give experimental feedback and evaluation in the r-process REE peak formation [4]. In the current work, the low-lying states and lifetimes of ^{173,174}Ho are reported.

II. EXPERIMENTAL DETAILS

The experiment was performed at Radioactive Isotope Beam Factory (RIBF) in RIKEN, Japan [13]. The nuclei of interest near $A = 170$ were produced by in-flight fission of a ^{238}U primary beam at energy of 345 MeV/u with an average intensity of 12 pnA incident on a 5-mm-thick ^{9}Be target. The fission fragments were identified on an ion-by-ion basis through the second stage of the BigRIPS separator using the $B\rho$-ΔE-TOF method in which the magnetic rigidity ($B\rho$), energy loss (ΔE), and time-of-flight (TOF) were measured and used to determine the atomic number Z and the mass-to-charge ratio (A/q) of the individual fragment [13]. After the BigRIPS separator, the selected heavy ions were transported through the ZeroDegree spectrometer (ZDS) and subsequently implanted into a silicon array called Wide-range Active Silicon Strip Stopper Array for β and ion detection (WAS3ABi) [12] which was positioned at the end of ZDS. The WAS3ABi used in the current experiment consists of two 1-mm-thick double-sided silicon strip detectors (DSSD) with an active area of 60×40 mm^2 segmented into 40 horizontal and 60 vertical strips with 1-mm width each. All of the DSSD signals were processed through the high-gain preamplifiers to measure the energy of decay particles. Since the beam was focused on the center of DSSD, charge signals arising only from those Si strips in the middle of DSSD were split into the high- and low-gain readout systems, the latter of which was optimized to measure the energy loss of implanted heavy ions. With a low-energy threshold of ~50 keV for the high-gain setting, internal conversion (IC) electrons down to these energies were also detected in the system. The total number of identified, fully stripped ions of ^{173}Ho and ^{174}Ho implanted into WAS3ABi during the 45-h experiment were ~5600 and ~4600, respectively.

TABLE I. Theoretical internal conversion coefficients in ^{174}Er for known isomeric γ decay obtained from Ref. [14].

E_γ(keV)	$\sigma\lambda$	α_T	α_L	α_M
82	E2	6.33(9)	3.60(5)	0.878(13)
188	E2	0.310(5)	0.0890(13)	0.0213(3)
291	E2	0.0758(1)	0.01598(23)	0.00374(6)
388	E2	0.0325(5)	5.81e^{-3}(9)	1.342e^{-3}(19)
163	E1	0.0889(13)	0.01124(16)	2.49e^{-3}(4)

Discrete γ rays were detected by the EURICA γ-ray spectrometer which consists of 84 HPGe crystals arranged into 12 clusters surrounding WAS3ABi. The center of each cluster detector faced the center of WAS3ABi at a nominal distance of 22 cm. The γ-ray full-energy peak efficiency of EURICA is 9% at energy of 1 MeV with energy add-back algorithm [12]. The γ-ray measurements were carried out using a coincidence time window of up to 100 μs relative to the trigger signal generated either from a plastic scintillator placed at the end of the beam line or from WAS3ABi. There is another plastic scintillation detector with thickness of 2 cm served as a veto detector was placed at the end of WAS3ABi to reduce the light particle contamination in particle identification.

III. RESULTS

A. Decay of ^{174}Ho

β-tagged γ-ray spectra measured within a time window of 10 s after implantation of ^{174}Ho are shown in Figs. 1(a), 1(c), and 1(d). In Fig. 1(a), which was obtained without restricting the range of electron energy measured in DSSDs, γ rays at 82, 188, 291, 387, and 163 keV are clearly visible. They correspond to γ transitions that were assigned previously as the $2^+ \to 0^+$, $4^+ \to 2^+$, $6^+ \to 4^+$, $8^+ \to 6^+$, and $8^- \to 8^+$ transitions, respectively, following the decay from the $K^\pi = 8^-$ isomeric state with a mean lifetime of 5.8(5) s in ^{174}Er as reported in Refs. [15,16]. The lifetime of the 8^- isomer is so long that the 163-keV γ ray de-exciting the isomer should not be observed in coincidence with any β rays within a time window up to 100 μs. Thus, the measured isomeric γ transitions are expected to be measured in prompt coincidence with the IC electrons rather than β rays. Table I summarizes the conversion coefficients of the transitions involved in the decay cascade from the 8^- isomer in ^{174}Er calculated by the BrIcc code [14]. Figure 1(b) shows an electron energy spectrum measured by DSSDs with a sum of gates on the aforementioned isomeric-decay γ rays. The energy marked in Fig. 1(b) was obtained by Ref. [14]. A prominent peak

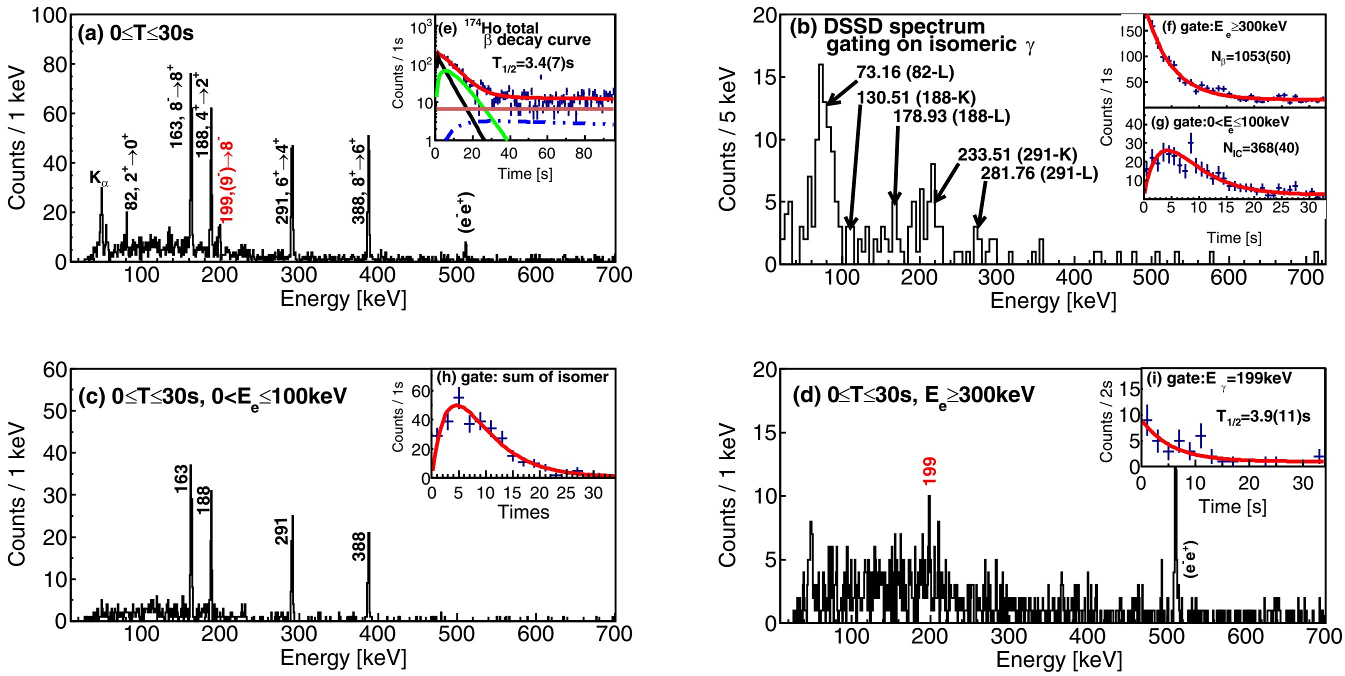

FIG. 1. (a) β-γ spectra with gate on β-decay events within a time window (T) of 10 s after implantation of ^{174}Ho. (b) DSSD spectrum measured with a sum gate of $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$, $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$, and $8^- \rightarrow 8^+$ decay transitions in ^{174}Er. Energies marked in (b) were theoretical energies from the BrIcc model [14]. The corresponding γ transitions and types of IC electrons are shown in the brackets. (c) and (d) β-γ spectra with gates and different electron energies (E_e). (e) Total decay curve of ^{174}Ho and associated fit based on decay chain of ^{174}Ho $\rightarrow$ ^{174m}Er $\rightarrow$ ^{174}Er $\rightarrow$ ^{174m}Tm $\rightarrow$ ^{174}Tm $\rightarrow$ ^{174}Yb. Total fit (red), parent component ^{174}Ho (black), daughter component ^{174m}Er (green), and background (brown) are shown in solid line. The other decay components ^{174}Er ^{174m}Tm and ^{174}Tm are shown in dot-dash line in total. (f) and (g) Time distribution of pure β-decay events ($E_{\rm DSSD} \geqslant 300$ keV) and low internal conversion electron events ($E_{\rm DSSD} \leqslant 100$ keV). (h) and (i) Time profiles of gating γ energy 199-keV transition and sum of isomeric transition.

at around 73 keV corresponds to the L-conversion electrons for the 82-keV, $2^+ \rightarrow 0^+$ transition. Therefore, when gating on the electron energy lower than 100 keV, a large portion of γ isomeric transition was observed in Fig. 1(c), while the 82-keV γ ray disappears. On the contrary, no isomeric γ was observed when gating on DSSD energy larger than 300 keV in which there is no IC electron [Fig. 1(d)]. Table II is a summary of total transition intensity ($I_{\rm tot}$) of γ transitions in ^{174}Er. The I_γ is corrected with γ detection efficiency concluding both types of triggers IC and β ray within a time window (T) of 30 s after implantation of ^{174}Ho. The $I_{\rm tot}$ is corrected for the IC coefficients. All the $I_{\rm tot}$ of isomeric transitions are well balanced indicating that there is no other γ decay feeding into the 2^+, 4^+, 6^+, and 8^+ states except from the 8^- state.

TABLE II. Summary of γ transitions in ^{174}Er within a time window (T) of 30 s after implantation of ^{174}Ho with DSSD energy $\leqslant$100 keV and $>$300 keV. I_γ is corrected with γ detection efficiency and $I_{\rm tot}$ is corrected with IC coefficients by $(1+\alpha_T)$. The IC coefficients are obtained from Ref. [14].

$E_{\rm DSSD}$	E_γ(keV)	$\sigma\lambda$	I_γ	$I_{\rm tot}$	$J_i^\pi \rightarrow J_f^\pi$
	82	E2	–	–	$2^+ \rightarrow 0^+$
	188	E2	314(38)	411(50)	$4^+ \rightarrow 2^+$
$\leqslant$100 keV	291	E2	312(41)	336(45)	$6^+ \rightarrow 4^+$
	388	E2	341(46)	352(47)	$8^+ \rightarrow 6^+$
	163	E1	393(42)	428(46)	$8^- \rightarrow 8^+$
$>$300 keV	199	M1	147(19)	198(26)	$9^- \rightarrow 8^-$

In addition to the known transitions below the 8^- isomer, a new γ ray was observed at 199 keV in Fig. 1(a). As demonstrated in Fig. 1(d), the 199-keV γ becomes apparent when gating on electron energy larger than 300 keV. This suggests that the 199-keV γ ray is in coincidence with β rays in the ^{174}Ho $\rightarrow$ ^{174}Er decay rather than prompt IC electrons. Because the β decay of ^{174}Ho populates the $K^\pi = 8^-$ state, the likely spin of the β-decaying state in ^{174}Ho can be restricted to 7, 8, or 9. If there is a β-decay branch to a state that decays via a prompt 199-keV γ transition to the ground state of ^{174}Er, the spin difference between this state and the β-decaying state in ^{174}Ho would be very large. Such a β-decay feeding to the presumed 199-keV state should be extremely hindered compared to the branch to the 8^- isomeric state in ^{174}Er. This is at variance with the observation of appreciable peak counts at 199 keV as demonstrated in Fig. 1(a). Therefore, we propose a previously unreported state at 1311-keV excitation energy which is located above the 8^- state of ^{174}Er. The newly observed transition in ^{174}Er is similar in excitation energy to analogous $9^- \rightarrow 8^-$ transitions in the heavier even-A $N = 106$ isotones ^{176}Yb [17], ^{178}Hf [18], ^{180}W [19], and ^{182}Os [20], as shown in Fig. 2, supporting the 9^- assignment for the 1311-keV state in ^{174}Er. In the previous study of ^{174}Er [15,16], any γ rays above the long-lived

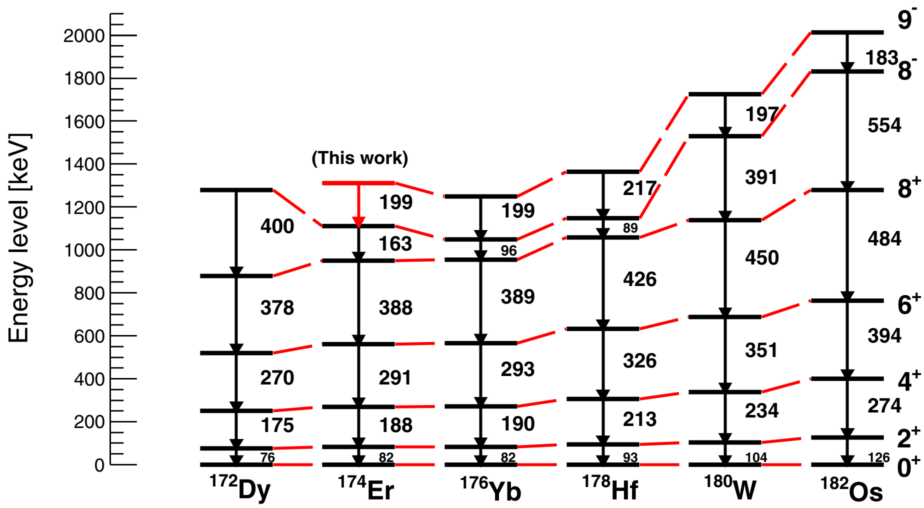

FIG. 2. Systematic study of $N = 106$ isotones near ^{174}Er, including ^{172}Dy [25], ^{176}Yb [17], ^{178}Hf [18], ^{180}W [19], and ^{182}Os [20]. Similar energy transitions are found above 8^- isomeric states of ^{176}Yb to ^{178}Hf.

$K^\pi = 8^-$ isomeric state could not be correlated with the transitions below the isomer due to the γ-ray coincidence requirements in the nanosecond range. By contrast, the previously unreported state which feeds directly into the $K^\pi = 8^-$ isomer was discovered by correlating the previously unknown 199-keV γ ray following the ^{174}Ho $\rightarrow$ ^{174}Er decay due to unambiguous isotopic separation and identification in the present work.

The β-decay half-life of ^{174}Ho was obtained from a least-square fit of total decay curve [Fig. 1(e)] using the Bateman equations [21], in which the daughter decay, granddaughter decay, and background components are taken into account. It was assumed that there are two decay paths, one of which consists of isomeric decay of ^{174}Er.

(A)^{174}Ho $\rightarrow$ ^{174m}Er $\rightarrow$ ^{174}Er $\rightarrow$ ^{174m}Tm $\rightarrow$ ^{174}Tm $\rightarrow$ ^{174}Yb

(B) ^{174}Ho $\rightarrow$ ^{174}Er $\rightarrow$ ^{174m}Tm $\rightarrow$ ^{174}Tm $\rightarrow$ ^{174}Yb

Because the 199-keV γ ray from the proposed $I^\pi = 9^-$ state to the $K^\pi = 8^-$ isomer is prompt with respect to the β^--detection tag, the β^--decay path to the $I^\pi = 9^-$ state is included in path A. The half-lives of ^{174m}Er[4.0(3)s] [16], ^{174}Er[3.2(2)min] [22], ^{174m}Tm[2.29(1)s] [23], and ^{174}Tm[5.4(1)min] [24] were obtained and were set as fixed parameters. The fitted branching ratios of path A and path B were 99.8%(1) and 0.2%(2), respectively, suggesting that the latter branch has a negligible contribution to the β decay of ^{174}Ho. Excluding branch B, the half-life of ^{174}Ho was determined to be 3.4(7) s, in good agreement with 3.2(11) s obtained in our earlier work [4]. The systematic error came from the uncertainties of half-lives in ^{174m}Er, ^{174}Er, ^{174m}Tm, and ^{174}Tm. The fitted time profile of the 199-keV γ transition is 3.9(11) s as shown in Fig. 1(i) which is consistent with the fitted value from total decay curve of ^{174}Ho in Fig. 1(e) and different from the decay curve gating on isomeric γ rays in Fig. 1(h). This agreement also supports the fact that the 199-keV γ transition is from 9^- to 8^- states following the β decay of ^{174}Ho.

The β-decay branching ratios to the 9^- and 8^- states in ^{174}Er were evaluated based on the measured γ-ray intensities summarized in Table II. The total intensity of the 199-keV transition $I_{\mathrm{tot}}(199)$, which is derived from the measured γ-ray intensity corrected for the full-energy peak efficiency and the calculated total IC coefficient, can be expressed using the branching ratio R(9^-) as

$$I_{\mathrm{tot}}(199) = Y \times R(9^-) \times \varepsilon_\beta = N_\beta \times R(9^-), \qquad (1)$$

where Y and ε_β represent the number of the implanted ^{174}Ho ions and the efficiency of DSSDs for $E_e \geqslant 300$-keV electrons that are dominated by β rays, respectively. Assuming that all of the implanted ^{174}Ho ions undergo β decay either towards the 8^- or 9^- states, i.e., $R(8^-) + R(9^-) = 1$, the total number of β particles detected with a gate on $E_e \geqslant 300$ keV, $N_\beta = Y \times \varepsilon_\beta$, is equal to the integral of the ^{174}Ho $\rightarrow$ ^{174}Er decay component in the decay curve shown in Fig. 1(f), $N_\beta = 1053(50)$. On the other hand, the total intensity of a transition below the long-lived $K^\pi = 8^-$ isomer, obtained with a gate on $E_e \leqslant 100$ keV as shown in Fig. 1(c), can be written as

$$I_{\mathrm{tot}}(\mathrm{iso}) = Y \times \frac{\alpha_T(82) - \alpha_K(82)}{1 + \alpha_T(82)} \times \varepsilon_{\mathrm{IC}} = N_{\mathrm{IC}}, \qquad (2)$$

where $\varepsilon_{\mathrm{IC}}$ denotes the DSSD efficiency for electron energies lower than 100 keV that contain predominantly the L and higher shell IC electrons. $\varepsilon_{\mathrm{IC}}$ should be smaller than ε_β because of the threshold of the high-gain readout system. The factor consisting of the IC coefficients for the 82-keV ($E2$) transition, $\frac{\alpha_T(82)-\alpha_K(82)}{1+\alpha_T(82)}$, has to be taken into account to correct for the conversion process in the gating transition. Because the DSSD threshold is around 50 keV, the K-shell IC electrons at 24.51 keV for the 82-keV γ transition were not detected. Therefore, the $\alpha_K(82)$ is not included. A fit to the decay curve measured in coincidence with electrons lower than 100 keV yields $N_{\mathrm{IC}} = 368(40)$, as shown in Fig. 1(g).

Based on Table II, Eqs. (1) and (2), the β-decay branching ratio of the 9^- and 8^- states was estimated to be 18(3)% and 82(3)%, respectively. Using $T_{1/2} = 3.4(7)$ s from this work and $Q_\beta = 6260.0(422)$ keV of ^{174}Ho from Ref. [26], the β-branching ratios yield the log ft values of 5.84(20) and

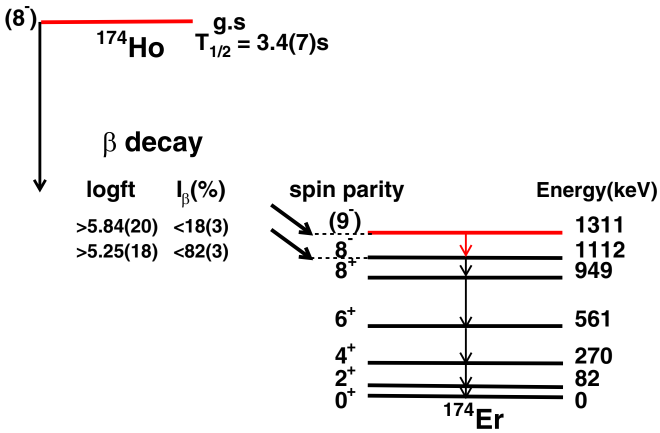

FIG. 3. β-decay scheme of ^{174}Ho proposed from this experiment. Apparent beta feedings I_β and the corresponding log ft values are given on the left-hand side of the level scheme. The states and transitions marked in red are previously unreported. Other black γ transitions were previously reported in Ref. [15].

5.25(18) for the 9^- and 8^- states, respectively. Because of the pandemonium effect [27], the β-decay branching ratios and log ft values are upper and lower limits, respectively. The β-decay scheme of ^{174}Ho is proposed as shown in Fig. 3. Based on the systematic study of log ft values in Ref. [28] and in Table III, the log ft values imply that β decay of ^{174}Ho to the 9^- and 8^- states of ^{174}Er is an allowed-hindered β transition which satisfies the selection rule $\Delta K = \Delta N$=0, $\Delta\Lambda = \Delta n_z = \pm 1$ or 0. The quasiparticle configuration of isomeric $K^\pi = 8^-$ was assigned as $\nu 9/2^+[624] \otimes 7/2^-[514]$ [16]. Based on the selection rules for an allowed-hindered β transition, the quasiparticle configuration of the ground state in ^{174}Ho can be deduced as $\nu 9/2^+[624] \otimes \pi 7/2^-[523]$, which is illustrated as Fig. 4. The β decay of ^{174}Ho $\rightarrow$ ^{174}Er proceeds via the transformation of the $7/2^-[514]$ neutron to the $7/2^-[523]$ proton. As a result, we assign the ground state of ^{174}Ho as $K^\pi = 8^-$.

Considering the single-particle orbitals near the $Z = 66$ and $N = 108$ Fermi surfaces (see Fig. 4), it is likely that the first-forbidden unhindered transition from $\nu 9/2^+[624]$ to $\pi 7/2^-[523]$ competes with the aforementioned allowed-hindered transition. The forbidden transition of this type is known to take place in the ^{175}Er to ^{175}Tm β decay, where the $J^\pi = 11/2^-$ member of the rotational band built on the $\pi 7/2^-[523]$ state in ^{175}Tm is populated with log ft $\sim$ 6.3

TABLE III. Systematic study of known experimental log ft values with near ^{174}Ho [22,31–35].

Decay channel	Log ft value	$J_i^\pi \rightarrow J_f^\pi$
^{168}Ho $\rightarrow$ ^{168}Er	5.45	$3^+ \rightarrow 2^+$
^{171}Er $\rightarrow$ ^{171}Tm	6.382	$5/2^- \rightarrow 7/2^-$
^{174}Tm $\rightarrow$ ^{174}Yb	4.73	$(4^-) \rightarrow (5^-)$
^{178}Lu $\rightarrow$ ^{178}Hf	6.53	$1^{(+)} \rightarrow 0^+$
^{176}Tm $\rightarrow$ ^{176}Yb	5.65	$(4^+) \rightarrow (3^+, 4^+)$
^{173}Er $\rightarrow$ ^{173}Tm	4.5	$(7/2^-) \rightarrow (9/2^-)$

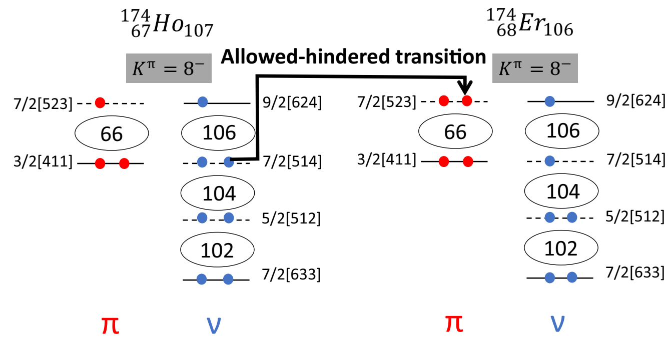

FIG. 4. Schematic diagrams of two-quasiparticle configurations of ^{174}Ho and ^{174}Er. The solid and dash lines are the Nillson orbitals with positive and negative parities, respectively. The red and blue dots are protons and neutrons. The bold black arrow represents the β-decay path in ^{174}Ho $\rightarrow$ ^{174}Er.

from the $\nu 9/2^+[624]$ ground state of ^{175}Er [29,30]. As the log ft value of this microscopic transition is much larger than observed log ft values, it is unlikely that the β feedings towards the 9^- and 8^- states in ^{174}Er are characteristic of the forbidden transition.

B. Decay of ^{173}Ho

Figure 5(a) exhibits a γ-ray energy spectrum measured within a time window of 2 μs after ^{173}Ho implanting into WAS3ABi. A γ-ray peak is clearly visible at 405 keV in Fig. 5(a). A half-life of 3.7(12) μs was obtained from a least-squares fit of the 405-keV γ-ray gated time spectrum

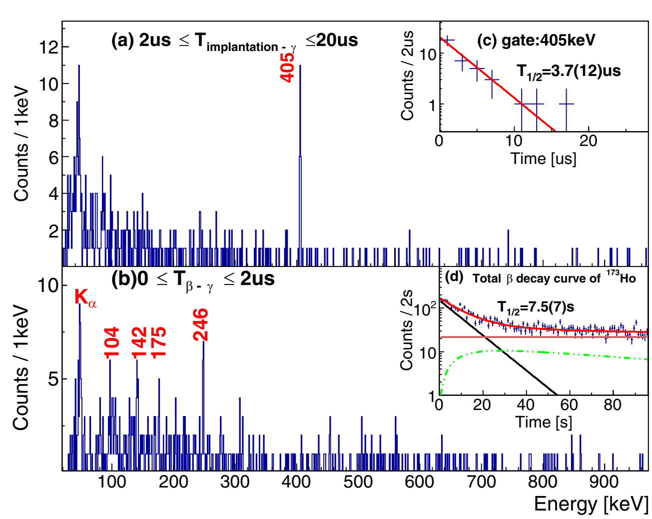

FIG. 5. (a) Delayed γ spectrum with gate on 2 μs after ^{173}Ho implantation. (b) β-γ spectra measured with 5-s time difference between implantation and β events. The time window for β and γ is with 2 μs. Energy peaks marked in red are newly discovered γ transitions in β decay of ^{173}Ho to ^{173}Er. (c) Time distribution of 405 keV after implantation of ^{173}Ho. (d) Total β curve of ^{173}Ho and associated fit based on decay of ^{173}Ho $\rightarrow$ ^{173}Er $\rightarrow$ ^{173m}Tm $\rightarrow$ ^{173}Tm $\rightarrow$ ^{173}Yb. Total fit (red), parent component ^{173}Ho (black), and background (brown) are shown in solid line. The decay components of ^{173}Er and ^{173}Tm are shown in dash-solid line in green.

as shown in Fig. 5(c). The spin and parity of the 405-keV isomeric state in ^{173}Ho will be discussed in Sec. IV.

The β-delayed γ-ray spectrum measured within a time window of 5 s after implantation of ^{173}Ho is shown in Fig. 5(b). The 48.2- and 49.1-keV peaks are the K_α x rays emitted from Er atoms [24]. The γ peaks marked in red at 140, 175, and 246 keV are γ transition candidates in ^{173}Er. Because of low statistics, no γ-γ coincidence analysis can be made to deduce the level scheme of ^{173}Er.

The β-decay half-life of ^{173}Ho is extracted by fitting the total decay curve of ^{173}Ho as demonstrated in Fig. 5(d). The proposed decay path of ^{173}Ho is

^{173}Ho $\rightarrow$ ^{173}Er $\rightarrow$ ^{173m}Tm $\rightarrow$ ^{173}Tm $\rightarrow$ ^{173}Yb.

^{173}Yb is stable. The β of ^{173}Er will feed to the $7/2^-$ isomer state in ^{173m}Tm with 15-μs half-life while no direct feeding to the ground state of ^{173}Tm [35]. The order of magnitude in the half-life of ^{173}Ho is in seconds which is observed from the total decay curve of ^{173}Ho in Fig. 5(d). Therefore, the 405-keV isomeric state is not taken into account since its half-life 3.7(12) μs is 6 order magnitude smaller than the β-decay half-life of ^{173}Ho, resulting a negligible contribution to β decay of ^{173}Ho half-life. In the fitting, the half-lives of ^{173}Er[1.4(1)min] [35], ^{173m}Tm[15(3)μs] [36], and ^{173}Tm[8.24(8)h] [37] are set as fixed parameters and the half-life of ^{173}Ho, initial activities, and the background are set as free parameters. The half-life of ^{173}Ho 7.5(7)s was obtained. The systematic error is coming from the uncertainties of half-lives in ^{173}Er, ^{173m}Tm, and ^{173}Tm.

IV. DISCUSSION

Configuration-constrained potential-energy-surface (PES) calculations [38] have been performed to study the deformations and excitation energies of quasiparticle states in ^{173,174}Ho and ^{173,174}Er. Single-particle levels are obtained from the nonaxial deformed Woods-Saxon potential [39]. For a given quasiparticle, the single-particle orbitals are always occupied while changing the deformation. This was achieved by calculating and identifying the average Nilsson quantum numbers for every orbit involved in the configuration. The calculations were performed in (β_2, γ, β_4) deformations and the equilibrium deformation is determined by minimizing the obtained PES. The results are summarized in Table IV.

As discussed in the β decay of ^{174}Ho, a new state at 1311 keV was identified in ^{174}Er with spin-parity assignment of 9^- which is proposed as the $I^\pi = 9^-$ member of the $K^\pi = 8^-$ rotational band. In addition, the likely spin parity for the ground-state configuration of ^{174}Ho can be restricted to 8^- by the deduced log ft values in the current work. In the PES calculation, the calculated energy level of the 8^- isomeric state in ^{174}Er is 1020 keV which is comparable to the experimental data 1113 keV [15]. The ground-state configuration of ^{174}Ho is described as one-neutron and one-proton quasiparticle configuration $\nu 9/2^+[624] \otimes \pi 7/2^-[523]$ while the $K^\pi = 8^-$ isomeric state in ^{174}Er is interpreted as a two-neutron configuration based on the $\nu 9/2^+[624] \otimes 7/2^-[514]$. The β decay from the 8^- ground state in ^{174}Ho to the $K^\pi = 8^-$ isomeric state in ^{174}Er can proceed with an allowed-hindered transition through the transformation of a neutron in the $7/2^-[514]$ orbit to a proton in the $7/2^-[523]$ orbit with the neutron $9/2^+[624]$ being a spectator. This interpretation is consistent with the argument based on the measured log ft values for the β decay of ^{174}Ho $\rightarrow$ ^{174}Er.

TABLE IV. Low-lying quasiparticle states in ^{173,174}Ho and ^{173,174}Er predicted by configuration-constrained potential-energy-surface calculations.

J^π	Configuration	β_2	γ	β_4	E_x(keV)
^{173}Ho					
$7/2^-$	$\pi 7/2^-[523]$	0.281	0	−0.032	0
$1/2^+$	$\pi 1/2^+[411]$	0.278	0	−0.032	125
$3/2^+$	$\pi 3/2^+[411]$	0.283	0	−0.032	507
$5/2^+$	$\pi 5/2^+[413]$	0.284	0	−0.032	1146
$1/2^-$	$\pi 1/2^-[514]$	0.299	0	−0.009	1451
^{173}Er					
$7/2^-$	$\nu 7/2^-[514]$	0.282	0	−0.032	0
$9/2^+$	$\nu 9/2^+[624]$	0.284	0	−0.031	160
$5/2^-$	$\nu 5/2^-[512]$	0.284	0	−0.031	304
$7/2^+$	$\nu 7/2^+[633]$	0.276	0	−0.032	510
$1/2^+$	$\nu 1/2^+[651]$	0.301	0	−0.015	1095
^{174}Ho					
8^-	$\nu 9/2^+[624] \otimes \pi 7/2^-[523]$	0.276	0	−0.032	0
5^+	$\nu 9/2^+[624] \otimes \pi 1/2^+[411]$	0.274	0	−0.032	117
9^-	$\nu 9/2^+[624] \otimes \pi 9/2^-[514]$	0.285	0	−0.033	1538
^{174}Er					
g.s	0^+	0.279	0	−0.032	0
8^-	$\nu 9/2^+[624] \otimes 7/2^-[514]$	0.279	0	−0.032	1020
9^-	$\nu 11/2^+[615] \otimes 7/2^-[514]$	0.285	0	−0.033	2501
9^-	$\nu 9/2^+[624] \otimes 9/2^-[505]$	0.267	−1.5	−0.03	3755

For ^{173}Ho, an isomeric state at energy of 405 keV with 3.7(12) μs was discovered in ^{173}Ho. As odd-A Ho isotopes ^{165}Ho to ^{171}Ho have even neutrons, the ground-state spin parity is determined by the configuration of the unpair proton. Therefore, the ground-state spin parity of ^{173}Ho is expected to be $J^\pi = 7/2^-$ which is the same as ^{165}Ho to ^{171}Ho [44]. Several isomers have been identified in odd-A Ho isotopes. These isomers in ^{159}Ho, ^{161}Ho, and ^{163}Ho with half-life of 8.30(8)s, 6.76(7)s, and 1.09(3)s, respectively, are built on $\pi 1/2^+[411]$ decaying to ground state via the E3 transition. In ^{165}Ho and ^{167}Ho, isomeric states with $K^\pi = 3/2^-$ and half-lives of 1.625 and 6.0 μs, respectively, are found. These are interpreted as being built on the π $3/2^+[411]$ configurations which decay to their respective ground states via M2 electromagnetic transitions. To confirm which configuration contributes to the 405-keV state in ^{173}Ho, one can compare the hindrance factor F_W of neighboring nuclei [45].

The hindrance factor F_W is defined as the experimental partial half-life relative to the single-particle Weisskopf estimate [45]:

$$F_W = \frac{T^{\gamma}_{1/2}}{T^{W}_{1/2}}. \tag{3}$$

TABLE V. Weisskopf hindrance factors; F_W factors for low-lying isomeric states in odd-A Ho isotopes. Data from Refs. [40–43].

A	Configuration	$\sigma\lambda$	E_γ(keV)	$T_{1/2}^{\text{exp}}$	$T_{1/2}^{W}$	F_W
159	$\pi 1/2^+[411]$	E3	205.9	8.30(8) s	0.0529 s	390(15)
161	$\pi 1/2^+[411]$	E3	211.2	6.76(7) s	0.0432 s	347(16)
163	$\pi 1/2^+[411]$	E3	297.9	1.09(3) s	0.00379 s	369(8)
165	$\pi 3/2^+[411]$	M2	361.7	1.512(5) μs	0.106 μs	18(3)
167	$\pi 3/2^+[411]$	M2	259.3	6.0(5) μs	0.557 μs	20(5)

$T_{1/2}^W$ is the single-particle estimation in which

$$T_{1/2}^W(E3) = \frac{2.1\times 10^{-2}}{A^2 \times E_\gamma^7}, \quad (4)$$

$$T_{1/2}^W(M2) = \frac{1.98\times 10^{-8}}{A^{2/3} \times E_\gamma^5}. \quad (5)$$

The F_W factors of low-lying isomeric states in odd-A Ho isotopes are listed in Table V. If the configuration of the 405-keV state in ^{173}Ho is built on $\pi 1/2^+[411]$, the F_W equals to $9.42\times 10^{-3}(28)$. On the other hand, if the configuration is $\pi 3/2^+[411]$, the F_W is 63(12). Compared to the F_W factors in Table V, it is suggested that the 405-keV state is built on $\pi 3/2^+[411]$.

In the PES calculation of odd-A Ho isotopes $^{159-173}$Ho, the configurations of the ground state were predicted as $\pi 7/2^-[523]$, giving the spin parity of $7/2^-$ being consistent with experimental data [32,44]. The PES calculation of ^{173}Ho also predicts that the energy of $3/2^+$ as 507 keV which is close to the experimental result 405 keV.

V. SUMMARY

Isomeric and β-decay coincidence studies of ^{173,4}Ho have been performed at RIBF, RIKEN. An isomeric state at 405 keV with half-life of 3.7(12) μs was found in ^{173}Ho. The spin parity of this state was assigned as $\frac{3}{2}^+$ from the systematics of F_w factors in its neighboring odd-A Ho isotopes. For the β decay of ^{174}Ho to ^{174}Er, a new excited state of ^{174}Er at 1311 keV was discovered which was suggested to be 9^- based on the systematics of the neighboring $N = 106$ isotones. The experimental log ft values of 5.25(18) and 5.84(20) for the decays from ^{174}Ho to the populations to the $K^\pi = 8^-$ and $I^\pi = 9^-$, respectively, indicate that this decay is an allowed-hindered β decay and constrains the likely ground-state spin parity of ^{174}Ho to 8^-. The configuration-constrained potential-energy-surface (PES) calculation with (β_2, γ, β_4) as parameters was performed. The configurations of the 8^- state in ^{174}Er and ground state in ^{174}Ho are interpreted as $\nu 9/2^+[624] \otimes 7/2^-[514]$ and $\nu 9/2^+[624] \otimes \pi 7/2^-[523]$, respectively. These two configurations fulfill the allowed-hindered β-decay transition rule ($\Delta K = \Delta N = 0$, $\Delta\Lambda = \Delta n_z = \pm 1$ or 0) which is in agreement with the result deduced from the experimental log ft values. Moreover, the PES calculation predicts the ground state and isomeric state in ^{173}Ho as $\pi 7/2^-[523]$ and $\pi 3/2^+[411]$, respectively, which are consistent with the results extrapolated from the systematics of F_W factors. Understanding these structures is crucial for r-process nucleosynthesis, as the lifetimes of low-lying isomeric states are considered to change the final abundance.

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[1] G. J. Mathews and J. J. Cowan, Nature (London) **345**, 491 (1990).

[2] R. Surman, J. Engel, J. R. Bennett, and B. S. Meyer, Phys. Rev. Lett. **79**, 1809 (1997).

[3] S. Goriely, J.-L. Sida, J.-F. Lemaître, S. Panebianco, N. Dubray, S. Hilaire, A. Bauswein, and H.-T. Janka, Phys. Rev. Lett. **111**, 242502 (2013).

[4] J. Wu *et al.*, Phys. Rev. Lett. **118**, 072701 (2017).

[5] M. R. Mumpower, G. C. McLaughlin, and R. Surman, Phys. Rev. C **85**, 045801 (2012).

[6] M. R. Mumpower, G. C. McLaughlin, and R. Surman, Phys. Rev. C **86**, 035803 (2012).

[7] M. R. Mumpower, R. Surman, D.-L. Fang, M. Beard, P. Möller, T. Kawano, and A. Aprahamian, Phys. Rev. C **92**, 035807 (2015).

[8] M. Mumpower, J. Cass, G. Passucci, R. Surman, and A. Aprahamian, AIP Adv. **4**, 041009 (2014).

[9] M. R. Mumpower, R. Surman, G. C. McLaughlin, and A. Aprahamian, Prog. Part. Nucl. Phys. **86**, 86 (2016).

[10] K. Langanke and G. Martínez-Pinedo, Rev. Mod. Phys. **75**, 819 (2003).

[11] S. Sarkar and M. Saha Sarkar, Astrophysical implication of low $E(2_1^+)$ in neutron-rich Sn isotopes, in *Proceedings of the Fourth International Workshop on Nuclear Fission and Fission-Product Spectroscopy*, edited by A. Chatillon, H. Faust, G. Fioni, D. Goutte, and He. Goutte, AIP Conf. Proc. Vol. 1175 (AIP, Melville, 2009), p. 182.

[12] S. Nishimura, Prog. Theor. Exp. Phys. **2012**, 03C006 (2012).

[13] N. Fukuda *et al.*, Nucl. Instrum. Methods Phys. Res. B **317**, 323 (2013).

[14] T. Kibédi, T. W. Burrows, M. B. Trzhaskovskaya, P. M. Davidson, and C. W. Nestor, Nucl. Instrum. Methods Phys. Res. A **589**, 202 (2008).
[15] G. D. Dracoulis *et al.*, Phys. Lett. B **635**, 200 (2006).
[16] G. D. Dracoulis *et al.*, Phys. Rev. C **79**, 061303(R) (2009).
[17] N. J. Ncapayi *et al.*, Eur. Phys. J. A **26**, 265 (2005).
[18] S. M. Mullins *et al.*, Phys. Lett. B **393**, 279 (1997).
[19] J. Pedersen *et al.*, Z. Phys. A **321**, 567 (1985).
[20] T. Kutsarova *et al.*, Nucl. Phys. A **587**, 111 (1995).
[21] H. Bateman, Proc. Cambridge Philos. Soc. **15**, 423 (1908).
[22] K. Becker *et al.*, Nucl. Phys. A **522**, 557 (1991).
[23] R. S. Chakrawarthy *et al.*, Phys. Rev. C **73**, 024306 (2006).
[24] T. Tuurnala, V. Pursiheimo, and E. Liukkonen, Z. Phys. A **247**, 436 (1971).
[25] H. Watanabe *et al.*, Phys. Lett. B **760**, 641 (2016).
[26] M. Wang *et al.*, Chin. Phys. C **36**, 1603 (2012).
[27] J. C. Hardy, L. C. Carraz, B. Jonson, and P. G. Hansen, Phys. Lett. B **71**, 307 (1977).
[28] J.-I. Fujita, G. T. Emery, and Y. Futami, Phys. Rev. C **1**, 2060 (1970).
[29] G. Løvhøiden, P. H. Andersen, D. G. Burke, E. R. Flynn, and J. W. Sunier, Nucl. Phys. A **327**, 64 (1979).
[30] X. Zhang, S. Yuan, W. Yang, Z. Li, W. Mou, X. Yu, and J. Zhong, Z. Phys. A **353**, 353 (1996).
[31] R. M. Chasteler, J. M. Nitschke, R. B. Firestone, K. S. Vierinen, and P. A. Wilmarth, Phys. Rev. C **42**, R1796(R) (1990).
[32] R. M. Chasteler, J. M. Nitschke, R. B. Firestone, K. S. Vierinen, and P. A. Wilmarth, Phys. Rev. C **42**, R1171 (1990).
[33] C. J. Orth, W. R. Daniels, D. C. Hoffman, and F. O. Lawrence, Phys. Rev. C **8**, 718 (1973).
[34] S. C. Gujratht and S. K. Mukherjee, Indian J. Phys. **41**, 633 (1967).
[35] V. Pursiheimo, T. Tuurnala, and T. Raunemaa, Z. Phys. A **252**, 283 (1972).
[36] R. O. Hughes *et al.*, Phys. Rev. C **86**, 054314 (2012).
[37] C. J. Orth, M. E. Bunker, and J. W. Starner, Phys. Rev. **132**, 355 (1963).
[38] F. R. Xu, P. M. Walker, J. A. Sheikh, and R. Wyss, Phys. Lett. B **435**, 257 (1998).
[39] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. A **435**, 397 (1985).
[40] J. S. Geiger, R. L. Graham, and M. W. Johns, Nucl. Phys. A **161**, 263 (1971).
[41] J. Borggreen, H. J. Frahm, N. J. Sigurd Hansen, and S. Bjørnholm, Nucl. Phys. **77**, 619 (1966).
[42] G. Mauron, J. Kern, and O. Huber, Nucl. Phys. A **181**, 489 (1972).
[43] T. Tuurnala, R. Katajanheimo, and E. Hammarén, Z. Phys. A **280**, 309 (1977).
[44] G. Løvhøiden, D. G. Burke, E. R. Flynn, and J. W. Sunier, Nucl. Phys. A **315**, 90 (1979).
[45] P. Walker and G. Dracoulis, Nature (London) **399**, 35 (1999).