Half-life of the ^{164}Ho by the (γ, n) reaction from laser Compton scattering γ rays at the electron storage ring NewSUBARU

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The half-life of an isomer in ^{164}Ho was measured by using photodisintegration reactions. The photons were generated by Compton scattering of laser photons and relativistic electrons at the electron storage ring NewSUBARU in the super photon ring 8-GeV (SPring-8) facility. The half-life is 36.4 ± 0.3 min. This value is about 3% shorter than the previous value $37.5^{+1.5}_{-0.5}$ min reported in 1966.

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The astrophysical origin of ^{164}Er has been discussed since the 1950s [1]. This nucleus is classified as a "p nucleus," most of which are synthesized by photodisintegration reactions in supernovae (γ-process or p-process) [2–5]. The solar abundance of ^{164}Er is known to be higher than those of neighboring p nuclei by an order of a magnitude [1]. Recently, Hayakawa *et al.* [4] found the empirical abundance scaling laws between p and s nuclei with the same atomic number in the solar abundances, which are a piece of evidence that most of the p nuclei are synthesized by the γ-process. The reason why the empirical scalings appear in the solar abundances was explained by supernova model calculations [5]. However, there remains a large deviation for Er from an average value in the scalings [4]. The two deviations in the solar abundances and the scalings indicate that the origin of ^{164}Er is different from those of the other p nuclei. It was suggested that a stable isotope ^{163}Dy becomes unstable against β decay at high temperatures of $T = 10^8$–10^9 K because of an atomic effect of ionized ions. It is also suggested that ^{164}Er may be synthesized by the nuclear reaction path

$$^{163}\mathrm{Dy}^*(e^-\nu)^{163}\mathrm{Ho}(n,\gamma)^{164}\mathrm{Ho}(e^-\nu)^{164}\mathrm{Er},$$

in a slow neutron capture reaction process (s-process) as shown Fig. 1 [6–8].

An unstable isotope ^{164}Ho locates on this weak branch of the s-process (see Fig. 1). The spin and parity of the ground state of ^{164}Ho is $J^\pi = 1^+$, and there is an isomer with $J^\pi = 6^-$ at $E = 140$ keV. The half-lives of 29 ± 1 min and $37.5^{+1.5}_{-0.5}$ min have been previously recommended for the ground state and the isomer, respectively [9]. The half-life of $37.5^{+1.5}_{-0.5}$ min was measured in 1966 [10]: ^{164}Ho was populated by a (d, $2n$) reaction, and the decay γ rays were measured by a NaI(Tl) detector. After that experiment, the half-life of the isomer has never been reported with high accuracy. Thus the precise measurement of the half-life is of importance for understanding the origin of ^{164}Er. γ-ray sources, which have an advantage that a nucleus of interest can be selectively populated by the (γ, n) or (γ, γ') reaction, have been widely used [11–13]. The recent progress of the relativistic engineering (for example, see Ref. [14]) provides a new γ-ray source with a MeV energy range [15–18]. These γ rays are generated by Compton scattering of relativistic electrons and laser photons. They are powerful tools for applications in a wide range of fields such as nuclear physics [19,20], nuclear astrophysics [21,22], and atomic energy engineering [23]. In this paper, we report the half-life of the isomer in ^{164}Ho populated in (γ, n) reactions with the laser Compton scattering (LCS) γ rays at the electron storage ring facility NewSUBARU.

The LCS γ rays have the advantage that the maximum energy is sharply determined in the basic QED process and that the γ-ray flux at high energy is relatively high. The LCS γ rays are generated by the collision of relativistic electrons stored in the electron storage ring NewSUBARU [24] and laser photons provided by a Q-switch Nd:YVO$_4$ laser system. The wavelength of the laser photons is 1064 nm, and the laser system is operated at 100 kHz. The maximum laser power is about 5 W and the estimated γ-ray flux is (0.5–1.5) $\times 10^6$ photons/s with an energy range of 3.3–16.7 MeV. The details of the LCS γ rays were presented in our previous paper [25]. We already measured the half-life of the ground state of ^{184}Re by using the LCS γ rays provided by NewSUBARU [17,18], and we reported that the half-life is shorter than a previous value by about 7% [25].

In the present experiment, 20 stacked metallic Ho foils were irradiated by the LCS γ rays for 41 min, and subsequently the targets were moved to a measurement position. The size of each Ho foil was $10 \times 10 \times 1$ mm. Eight minutes after the LCS γ-ray irradiation, decay γ rays from the foils were measured by a high-purity Ge (HPGe) detector for about 110 min. The

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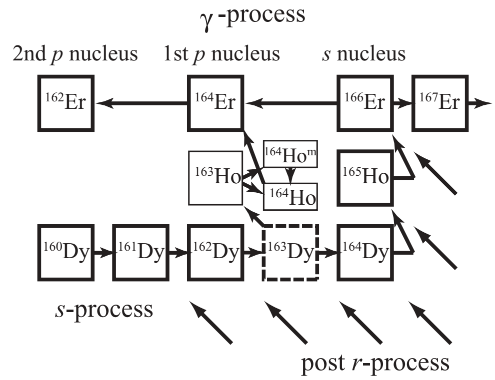

FIG. 1. Partial nuclear chart and nucleosynthesis flow around ^{164}Ho. Two isotopes of ^{164}Er and ^{162}Er are the first and second p nuclei, respectively, and ^{166}Er is an s nucleus. The p nucleus ^{162}Er is synthesized by the supernova γ-process, whereas ^{164}Er is dominantly synthesized by the weak branch of the s-process.

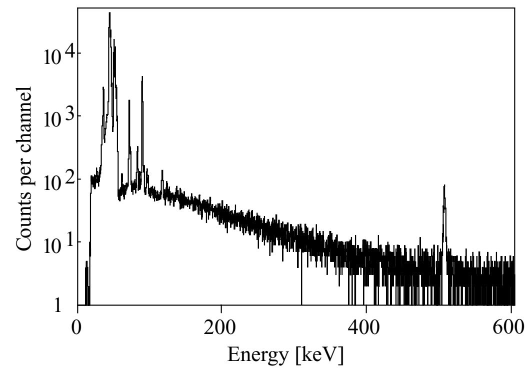

FIG. 3. Summed γ-ray spectrum measured by a HPGe detector for a period of 110 min.

20 Ho targets were located in front of the HPGe detector with lead shields to reduce the background. The efficiency of the HPGe detector was about 45% relative to a 3×3 in. NaI detector, and the energy resolution was 0.9 keV at 81 keV of ^{133}Ba. Each γ ray spectrum was recorded for 2 min by a multichannel analyzer. The spectrum was dumped, cleared, and then restarted. Each readout time was 6 s. Note that the γ-ray irradiation and measurement were performed only once to exclude the effect of the residual activities. The measurement system was stable because of the short measurement time.

The unstable isotope ^{164}Ho is dominantly populated by a photodisintegration reaction on ^{165}Ho, since natural Ho consists of a single isotope, ^{165}Ho. Figure 2 shows a schematic view of the photodisintegration reaction and a partial level scheme of ^{164}Ho. High spin states in ^{164}Ho were well studied by in-beam γ-ray spectroscopy [26]. The isomer decay was studied by γ-ray spectroscopy after the mass separation [10]. The 6^- isomer in ^{164}Ho decays to the ground state via only internal decay. The decay from the 6^- isomer to an 3^+ excited state is an $E3$ transition, and its γ decay branch is small. This 3^+ state subsequently deexcites to the ground state. Their transition energies are 94.0, 56.6, and 37.3 keV. The ground state decays to a daughter nucleus ^{164}Dy or ^{164}Er.

Figures 3 and 4 show a summed spectrum measured by the HPGe detector for a period of about 110 min. In this experiment, ^{164}Ho is dominantly populated by the photodisintegration reaction on ^{165}Ho, and most photopeaks in the observed spectra originate from the decay of ^{164}Ho. Since the spin and parity of the ground state of ^{165}Ho is $J^\pi = 7/2^-$, excited states of $J = 2$–5 in ^{164}Ho are strongly populated by the ^{165}Ho$(\gamma, n)^{164}$Ho reaction. Such excited states decay to both the 1^+ ground state and the 6^- isomer. The decay γ rays of both the states are clearly observed in the measured spectrum (see Fig. 4). The 73.4- and 91.0-keV γ rays are due to $2^+ \rightarrow 0^+$ transitions of ^{164}Dy and ^{164}Er, respectively. We also observe the γ rays following the isomer decay, whose

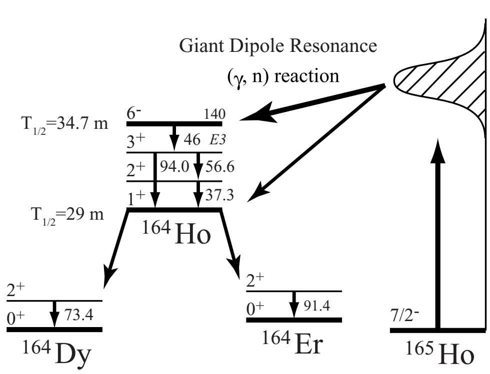

FIG. 2. Partial level scheme of ^{164}Ho and a schematic view of the photodisintegration reactions on ^{165}Ho. The ground state of $J^\pi = 1^+$ and the isomer of $J^\pi = 6^-$ are populated by the photodisintegration reactions.

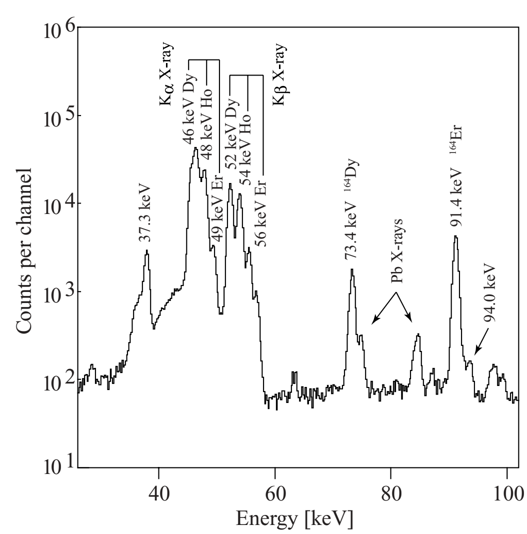

FIG. 4. Summed γ-ray spectrum measured by a HPGe detector for a period of 110 min. The decay γ rays of both the ground state and the isomer are clearly observed. The K_α and K_β x rays of three elements of Dy, Ho, and Er are also observed.

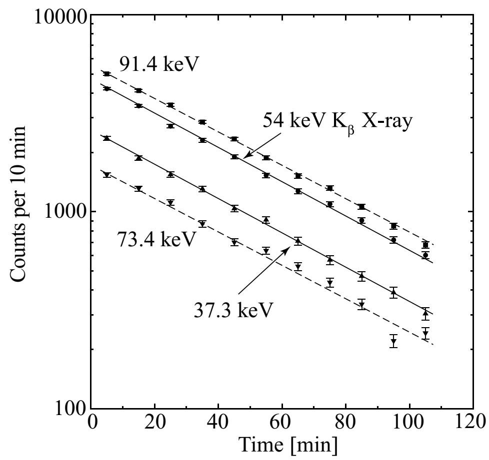

FIG. 5. Decay curve of yields of 37.3-, 54-, 73.4-, and 91.4-keV photons following the decay of the ground state and the isomer in ^{164}Ho. The half-lives of the 37.3-keV γ ray and 54-keV K_β x ray following the isomer decay are 34.4 ± 0.4 and 34.7 ± 0.4 min, respectively. These half-lives are identical within the uncertainty. Two γ rays of 73.4 and 91.4 keV are due to the $2^+ \rightarrow 0^+$ transitions of ^{164}Dy and ^{164}Er, respectively. We could not obtain the population ratio of the isomer to the ground state and the half-lives of the ground state and the isomer from the two decay curves (see text).

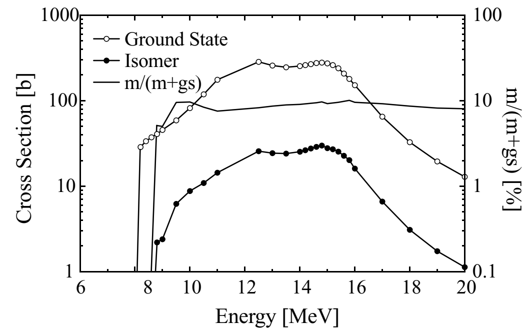

FIG. 6. Calculated cross sections on the ^{165}Ho$(\gamma, n)^{164}$Ho reaction and their ratio.

energies are 37.3, 56.6, and 94.0 keV. There are K_α and K_β x rays from three elements of Dy, Ho, and Er.

We obtain the half-life from decay curves of yields of these γ and x rays. Unfortunately, the 56.6-keV γ ray and K_β x ray of Er are a doublet, and the intensity of the 94.0-keV γ ray is too weak to obtain the decay curve. Thus, we obtain the decay curves of the 37.3-keV γ ray and 54-keV K_β x rays of Ho, as shown in Fig. 5. We obtain the photon yields from summed spectra for about 10 min. The half-lives obtained by χ square fitting are 36.1 ± 0.4 and 36.6 ± 0.4 min for the 37-keV γ ray and 54-keV x ray, respectively. The errors include only statistical errors. The systematic errors caused by the dead time of the multichannel analyzer is lower than 0.1%, since the dead time of individual measurements is lower than 1%. We take the average value of 36.4 ± 0.3 min as the half-life of the ^{164}Ho isomer in the present experiment. This half-life is about 3% shorter than the previous value of $37.5^{+1.5}_{-0.5}$ min, which was measured by a NaI(Tl) detector in 1966 [10]. After the measurement in 1966, half-lives of 37.3 ± 0.5 [27] and 36.7 ± 1.0 min [28] have been reported as the half-life of the isomer. However, the decay curves were not clearly presented in their articles [27,28], and these two half-lives have not be taken as the recommended value [9]. Therefore we conclude that the present result is the only report in which the decay curves of γ and x rays of the isomer are measured by the Ge detector with a high energy resolution.

Two γ rays of 91.4 and 73.4 keV following the decay of the ground state of ^{164}Ho are clearly observed (see Fig. 4). The ground state of ^{164}Ho are populated by the direct population by the photodisintegration reaction and the internal decay of the isomer (see Fig. 2). Thus the decay curves of yields of 91.4 and 73.4 keV are a function of three parameters: the population ratio of the ground state to the isomer and the half-lives of the ground state and the isomer. Tasi *et al.* [29] measured population ratios of individual excited states by using the ^{165}Ho$(\gamma, n)^{164}$Ho reaction with neutron capture γ rays provided from a nuclear reactor. This result shows that both the ground state and the isomer are populated by the (γ, n) reaction. In addition, we calculate the population ratio of the isomer to the ground state using a statistical model. Similar calculations were carried out in our previous studies [25,30]. The calculated ratios are about 10% over a wide energy range (see Fig. 6). The half-life of the ground state can be evaluated by χ-square fitting by taking into account the isomer decay and the direct population. However, we could not obtain the half-life of the ground state from these decay curves, since the statistics of the yields of these γ rays are not enough to reduce the three parameters of the decay function (see Fig. 5).

The unstable nucleus ^{164}Ho locates on a weak branch of the s-process. Hayakawa *et al.* suggested that abundance ratios of three isotopes of ^{162}Er, ^{164}Er, and ^{166}Er based on the scalings [4] can be used as a thermometer to evaluate the temperature of the s-process environment [31]. The result using this thermometer [31] supports the s-process model calculation [32]. The weak branch from ^{163}Dy has been studied experimentally. The change of the half-life of the ionized ^{163}Dy was measured [7], and a neutron capture cross-section on an unstable isotope ^{163}Ho was measured [8]. The present measured half-life is shorter than the previous value by about 3%, but this reduction of the half-life does not affect the s-process abundance of ^{164}Er and supports the s-process origin of ^{164}Er.

In summary, we report a half-life of an isomer in ^{164}Ho populated by a ^{165}Ho$(\gamma, n)^{164}$Ho reaction with γ rays generated by laser Compton scattering at the electron storage ring NewSUBARU in the super photon ring 8-GeV (SPring-8) facility. The measured half-life is 36.4 ± 0.3 min. This is about 3% shorter than the recommended value $T_{1/2} = 37.5^{+1.5}_{-0.5}$ min, which was measured by a NaI(Tl) detector in 1966.

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