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Half-life measurements of neutron-deficient isotopes using laser Compton scattering Gamma-rays at NewSUBARU

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We measure half-lives of the ground state of ^{184}Re and an isomer in ^{164}Ho, which are populated by (γ,n) reactions with laser Compton scattering (LCS) γ-ray source at NewSUBARU. These neutron-deficient isotopes are located on nucleosynthesis flows of the supernova γ process. The measured half-life of 35.4 ± 0.3 d for ^{184}Re is shorter than the previous half-life of $T_{1/2}$ = 38.0 ± 0.5 by about 7%. The half-life of the ^{164}Ho isomer is 36.4 ± 0.3 min. This is about 3% shorter than a recommended value $T_{1/2} = 37.5\,^{+1.5}_{-0.5}$ min. These results indicate that half-lives of all unstable nuclei near the β stability line may be not robust and that the LCS γ-rays are useful for precise determination of the half-lives.

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1. Introduction

The (γ,n) reactions on neutron-deficient isotopes are important for understanding nucleosynthesis by photodisintegration reactions in supernova explosions (γ process or p process) [1–7]. For this reason, the (γ,n) reaction cross-sections were measured in the rare-earth region [8–10]. An activation method has been used for measurements of nuclear reaction cross sections in these studies [8,9,11]. The half-life $T_{1/2}$ of the populated nucleus is crucial for the activation method since the evaluated cross-section is proportional to $T_{1/2}$ of the populated nucleus.

The progress of the relativistic engineering (for example see Ref. [12]) provides a new γ-ray source with a MeV energy range. These γ-rays are generated by Compton scattering of relativistic electrons by laser photons. These laser Compton scattering γ-rays (LCS γ-rays) have advantages that the maximum energy is sharply determined and that the γ-ray flux with high energy is relatively high. The Duke Free Electron Laser Laboratory at Duke University [14] and the National Institute of Advanced Industrial Science and Technology [13] have provided the LCS γ-rays in the MeV energy range and they have been widely used for applications with photon-induced reactions. Recently, a new LCS γ-ray source was installed at an electron storage ring NewSUBARU in SPring-8[15,16]. We measure half-lives of ^{184}Re[17] and ^{164}Ho isomer[18] populated by photodisintegration reactions with the LCS γ-rays at NewSUBARU.

2. Laser Compton scattering γ-ray source at NewSUBARU

A Q-switch Nd:YVO$_4$ laser system and a nuclear experiment room with a heavy shield locate at the outside of the electron storage ring NewSUBARU as shown in Fig. 1. The collision of the relativistic electrons and the laser photons creates a high energy γ-ray, whose energy depends on an angle between the direction of the incident electrons and the generated γ-rays. The energy distribution of the LCS γ-rays is determined in the basic QED process. The diameter of the LCS γ-rays is about 20 mm without a collimator at the target position, which is located at about 20 m from the collision point. The electron storage ring NewSUBARU can store electrons with an energy of 978 MeV up to 230 mA in a top-up mode. The 198 electron bunches circulate in the storage ring with a frequency of 2.5 MHz. An interval time of the electron bunches is about 2 ns. The Nd:YVO$_4$ laser system provide laser photons with a wavelength of 1064 nm at 100 kHz. A single laser pulse with a pulse length of 10 ns has a chance to collide with four or five electron bunches in the collision region. The laser power is typically 4 W and the estimated γ-ray flux is $0.5-1.5 \times 10^6$ photons/s with an energy range from 3.3 MeV to 16.7 MeV. This maximum energy of the LCS γ-rays is higher than the peak energy of the giant dipole resonance (GDR), and thus neutron-deficient isotope is effectively populated by the GDR excitation.

3. Measurements of half-lives of ^{164}Ho isomer and ^{184}Re

In an experiment of Re, we used three natural Re metallic foils. The individual Re foil had a thickness of 0.2 mm and a size of 25 mm × 25mm. The three stacked natural Re metallic foils were

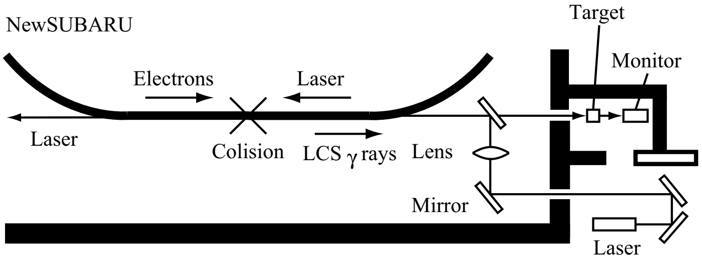

Figure 1: The laser Compton scattering γ-ray source at NewSUBARU

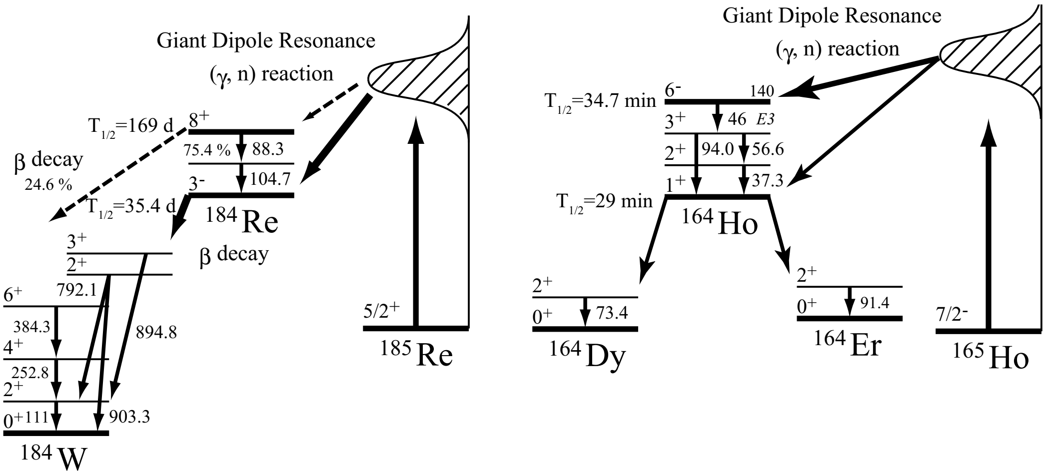

Figure 2: Nuclear reactions and decay scheme of ^{184}Re (left) and ^{164}Ho isomer (right).

irradiated by the LCS γ-rays for about 9 hours. The irradiated targets were cooled for a period of 23 days to reduce the background from short-lived radioactivities such as ^{186}Re ($T_{1/2}$=90.64 h) and to obtain the stability of the electronics system. To evaluate the half-life of ^{184}Re, time dependence of γ-ray intensities from the activities was measured for a period of 83 days. The γ-rays emitted after the β decay were measured by a HPGe detector with lead shields. The three Re foils were located on a plain in the front of the HPGe detector. The efficiency of the HPGe detector was larger than 70% relative to a 3" × 3" NaI detector and its energy resolution was 2.1 keV at 1.3 MeV. The measurement system was almost stable and the peaks of the γ-rays shifted by only one or two channel/s relative to about 3000 channels during the measurement of 83 days.

In an experiment of Ho, twenty 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 mm × 10 mm × 1 mm. After 8 min from the LCS γ-ray irradiation, decay γ-rays from the foils were measured by a HPGe detector for 110 min. The twenty Ho targets were located on a plain in the front of the HPGe detector with lead shields. The efficiency of the HPGe detector was about 45%.

Three γ-rays of 792.1, 894.8 and 903.3 keV of ^{184}Re are clearly observed. The half-life was

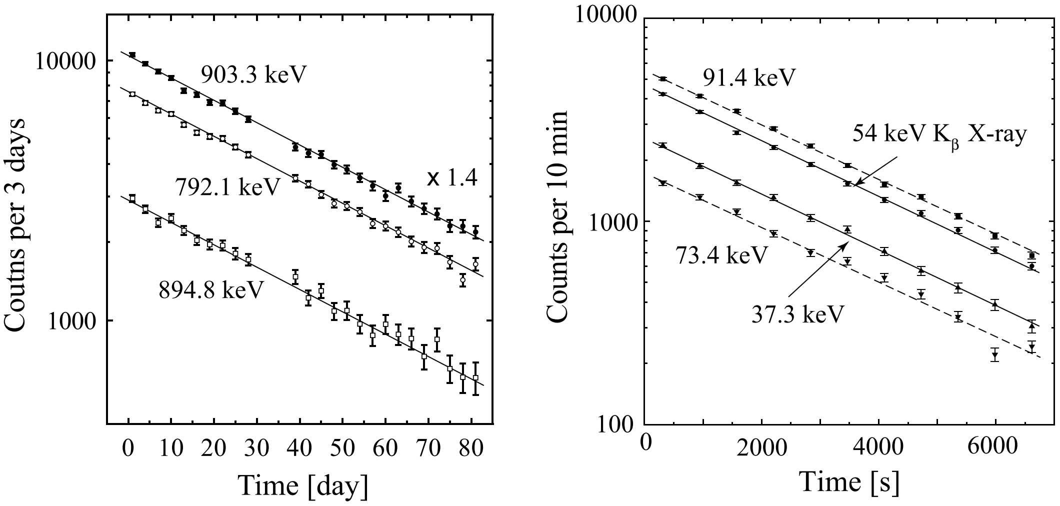

Figure 3: Measured decay curves of γ-rays of ^{184}Re (left) and ^{164}Ho isomer (right).

evaluated from the decay curves of these three γ-rays. Since the γ-rays following the decay of the isomer on ^{184}Re were not observed the ground state of ^{184}Re is dominantly populated in this reaction. The decay curves are well fitted by a straight line as shown in Fig. 3. The individual spectrum is recorded for a period of three days. We obtain the half-life of the individual γ-ray by using χ-square fitting and the results are 35.1 ± 0.5, 36.0 ± 0.9 and 35.6 ± 0.5 d for 792.1, 894.8 and 903.3 keV γ-rays, respectively. These three half-lives are identical within the uncertainty. Finally we obtain the half-life of 35.4 ± 0.3 d as the average value of these three γ-rays.

Historically, the measurement of the half-life, 38 ± 1 d, was reported in 1960 [19]. The most precise half-life, 38.0 ± 0.5 d, was reported in 1962 [20] and this was widely taken as the recommended value. In these two studies, Re activities were prepared by using deuteron-induced reactions. After these studies, the isomer with a half-life of 169 d was found by a measurement of decay of activities populated by the neutron-induced reactions in a nuclear reactor. Therefore radioactive samples in the two historical studies [19,20] may include the isomer, but the effect of the isomer was not taken into account.

We obtain the decay curves of the 37.3-keV γ-ray and 54-keV K$_\beta$ X rays of Ho as shown in Fig. 3. The half-lives obtained by χ square fitting are 36.1 ± 0.4 min and 36.6 ± 0.4 min for 37 keV γ ray and 54 keV X ray, respectively. 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 [22]. Note that the decay curves of 91.4 keV and 73.4 keV from the decay of ^{164}Ho must be composed of feeding from the ^{164}Ho isomer and β-decay.

4. Conclusion

We report half-lives of the ^{184}Re ground state and ^{164}Ho isomer, which are populated via photodisintegration reactions with laser Compton scattering (LCS) γ-rays at electron storage ring

NewSUBARU. The ground state of ^{184}Re is dominantly populated in this reaction. The measured half-life is 35.4 ± 0.3 d. This is about 7% shorter than a recommended value $T_{1/2}$ = 38.0 ± 0.5, which was reported in 1962 before a discovery of an isomer with $J^{\pi} = 8^{+}$ in ^{184}Re. Our result provides essential information for applications using an activation method because the cross-section should be smaller by about 7% than that based on the previous value. The measured half-life of the ^{164}Ho isomer is 36.4 ± 0.3 min. This is about 3% shorter than a recommended value $T_{1/2}$ = 37.5 $^{+1.5}_{-0.5}$ min, which was measured by a NaI(Tl) detector in 1966. These experiments indicate that measured half-lives of all unstable nuclei near the β stability line may be not robust and that the LCS γ rays are useful for a precise measurement even if a high spin isomer exists in a nucleus of interest.

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