Half-life of $^{184}\text{Re}$ populated by photodisintegration reaction with Laser Compton scattering $\gamma$-rays at NewSUBARU

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Abstract. We report a half-life of the ground state of $^{184}\text{Re}$ populated by the $^{185}\text{Re}(\gamma,n)^{184}\text{Re}$ reaction with the Laser Compton scattering $\gamma$-rays generated through relativistic engineering. The $\gamma$-rays are provided at the electron storage ring NewSUBARU. The half-life of the $3^-$ ground state of $^{184}\text{Re}$ is $38.0 \pm 0.5$ d, and this value has been taken as a recommended value, which was measured using deuteron-induced reactions. However, this half-life may include a possible contribution from the $8^+$ isomer. Therefore, one should measure the more precise half-life because the activation method based on the recommended value provides a cross section larger than the true value. Therefore, one should measure the more precise half-life of the $^{184}\text{Re}$ ground state produced selectively. The $(\gamma,n)$ reactions have an advantage that the total angular momentum transferred to populated states is lower than those of particle-induced reactions. The spin and parity of the ground state of $^{185}\text{Re}$ is $J^\pi = 5/2^+$, and thus the $3^-$ ground state of $^{184}\text{Re}$ is expected to be populated with little contamination of the $8^+$ isomer by the $^{185}\text{Re}(\gamma,n)^{184}\text{Re}$ reaction.

1 Introduction

The rare-earth element Re has two stable isotopes $^{185}\text{Re}$ (37.4%) and $^{186}\text{Re}$ (62.6%). Their nuclear data such as the half-life are important for the nuclear physics and astrophysics, for example photodisintegration nucleosynthesis in supernovae [1–6] or $^{187}\text{Re}$, $^{187}\text{Os}$ nuclear cosmochronometer [7–10]. $^{184}\text{Re}$ has a $\beta$-unstable isomer with a half-life of 169 d. The $(\gamma,n)$ production ratio of this isomer to the ground state of $^{184}\text{Re}$ was measured to study the level density and decay property in viewpoint of a statistical-model [11, 12]. An activation method has been used for measurements of nuclear reaction cross sections on Re in these studies [3, 7, 8, 10–12]. The half-life $T_{1/2}$ of the ground state of the populated nucleus is crucial for applications using the activation method since the evaluated cross section is proportional to $T_{1/2}$ of the populated nucleus.

The half-life of the $3^-$ ground state of $^{184}\text{Re}$, $T_{1/2} = 38.0 \pm 0.5$ d, was reported by measuring the decay half-life of $^{184}\text{Re}$ in 1962 [13]. This half-life has been preliminarily taken as the recommended value. We would like to stress that in 1962 the half-life of $^{184}\text{Re}$ was measured using deuteron-induced reactions. However, this half-life may include a possible contribution from the $8^+$ isomer. Therefore, one should measure the more precise half-life because the activation method based on the recommended value provides a cross section larger than the true value. Therefore, one should measure the more precise half-life of the $^{184}\text{Re}$ ground state produced selectively. The $(\gamma,n)$ reactions have an advantage that the total angular momentum transferred to populated states is lower than those of particle-induced reactions. The spin and parity of the ground state of $^{185}\text{Re}$ is $J^\pi = 5/2^+$, and thus the $3^-$ ground state of $^{184}\text{Re}$ is expected to be populated with little contamination of the $8^+$ isomer by the $^{185}\text{Re}(\gamma,n)^{184}\text{Re}$ reaction.

2 Experiment

A Nd:YVO$_4$ laser system and a nuclear experiment room with a heavy shield locate at the outside of the electron storage ring NewSUBARU [20] is shown in figure 1. The collision of the relativistic electrons and the laser photons occurs at the inside the storage ring and creates a high energy $\gamma$-ray. Its energy depends on the angle between the direction of the incident electrons and the generated $\gamma$-rays. The diameter
3 Results and discussion

3.1 Population ratio of the isomer to the ground state of $^{184}\text{Re}$

Before the evaluation of the half-life of the observed three $\gamma$-rays, we discuss the contribution of the isomer populated via the $^{185}\text{Re}(\gamma,n)^{184}\text{Re}$ reaction since the half-life of the isomer is different from that of the ground state. If the isomer is populated in the nuclear reactions, the decay curve of the radioactivity has two components. Figure 2 shows a partial level scheme. The 3$^+$ ground state of $^{184}\text{Re}$ decays mainly to 2$^+$ and 3$^+$ excited states in $^{184}\text{W}$. In contrast the 8$^+$ isomer deexcites through two decay paths of internal $\gamma$-decay and $\beta$-decay. The isomer decays to the ground state of $^{184}\text{Re}$ by $\gamma$-decay cascades, whose branching ratio is about 75.4%. The ground state of $^{184}\text{Re}$ subsequently decays to $^{184}\text{W}$. Therefore most $\gamma$-rays including the three $\gamma$-rays measured in this experiment can be observed in both the decay of the ground state and the isomer, and the half-lives of these $\gamma$-rays may both be affected by the decay. In contrast, the $\gamma$-rays from a 7$^-$ excited state in $^{184}\text{W}$ were observed only in the decay of the isomer because the 7$^-$ excited state is not populated by the decay of the ground state of $^{184}\text{Re}$ (see fig. 2). Therefore, the intensities of the decay $\gamma$-rays, for example 216.5, 536.7, 920.9 keV, are of importance to evaluate the population ratio of the isomer in $^{184}\text{Re}$. In fact these $\gamma$-rays were clearly observed from $^{184}\text{Re}$ produced by the $^{184}\text{Re}(n,2n)^{183}\text{Re}\alpha$ reaction with neutrons provided from a nuclear reactor in our previous experiment [7].

We cannot observe these $\gamma$-rays in the present experiment (see fig. 3). We take an example of the 920.9 keV $\gamma$-ray, which cannot be observed as shown in figure 4. This fact indicates that the population ratio of the isomer is negligibly small in the present $(\gamma,n)$ reaction. We estimate the upper limit of the population ratio of the isomer by taking into account the statistical error of the background around the three $\gamma$ rays and we obtain the upper limit $\sim 3\%$. Our experimental result is consistent with previously measured ratios, 1.9% measured by using bremsstrahlung photons whose endpoint energy is 22 MeV [12] and 0.45 - 4.5% in an energy range of 10 – 20 MeV [11].

We perform a Hauser-Feshbach statistical-model calculation. We use a combination of OPTMAN [22] and GNASH [23] codes. The OPTMAN is a coupled-channel code which gives transmission coefficients to be used in the statistical-model calculation. The optical potential was adjusted to reproduce the cross sections, total and proton and neutron scattering.
3.2 Half-life of the ground state of $^{184}\text{Re}$

Three $\gamma$-rays of 792.1, 894.8 and 903.3 keV are clearly observed in the measured spectra (see fig. 4). The half-life was evaluated from the decay curves of the three $\gamma$-rays. The fraction of the ground state is larger than 97% in $^{184}\text{Re}$ activities and the decay curves are well fitted by a straight line as shown in figure 6. The individual spectrum is recorded for a period of three days. The lack of data in the period of 31 ∼ 38 days is due to the maintenance power cut. We obtain the half-life of the individual $\gamma$-ray by using $\chi^2$ fitting and the results are $35.1 \pm 0.5$, $36.0 \pm 0.9$ and $35.6 \pm 0.5$ d for 792.1, 894.8 and 903.3 keV $\gamma$-rays, respectively. These three half-lives are identical within the uncertainty. Finally we obtain the half-life of $35.4 \pm 0.7$ d as the average value of these three $\gamma$-rays.

Historically, the measurement of the half-life, $38 \pm 1$ d, was reported in 1960 [27]. The most precise half-life, $38.0 \pm 0.5$ d, was reported in 1962 [13] 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 [13,27] may include the isomer, but the effect of the isomer was not taken into account. After the discovery of the isomer, two half-lives, 33 ± 5 [28], were reported but their uncertainties are so large that the value of 38.0 ± 0.5 d is within the uncertainty range. In these two measurements, the 185Re(n,2n)184Re reaction [14] and a α+186W reaction with an incident energy of 42 MeV [28] were used and both the ground state and the isomer were populated. It is noted that the half-life measured in the present experiment is consistent with these previous values [14,28] within the uncertainty.

4 Conclusion

We report a half-life of the 184Re ground state populated via the 185Re(n,n)184Re reaction generated by Laser Compton scattering at electron storage ring NewSUBARU. The ground state of 184Re is dominantly populated in this reaction. The result of the statistical-model calculation is consistent with the present observation. The measured half-life is 35.4 ± 0.7 d. This is about 7% shorter than a recommended value T1/2 = 38.0 ± 0.5 d, which was reported in 1962 before a discovery of an isomer with Jπ = 8+ in 184Re. The present 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. It is inferred that measured half-lives of some unstable nuclei near the β-stability line have never been robust. The LCS γ-rays are useful for a precise half-life measurement.

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