Estimation of radiative half-life of ^{229m}Th by half-life measurement of other nuclear excited states in ^{229}Th[†]

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The first excited state in the ^{229}Th nucleus (^{229m}Th) has an excitation energy of ∼8 eV.[1–4] This low-lying isomeric state allows the laser excitation and spectroscopy of the nucleus, potentially leading to an ultraprecise optical nuclear clock.[5] This radiative half-life of ^{229m}Th, which determines the natural linewidth of the nuclear transition between the ground state and ^{229m}Th, is an important parameter to estimate the performance of the nuclear clock. The radiative half-life has yet to be determined experimentally; however, it can be estimated from the reduced transition probabilities $B(X\lambda)$ of the inter-band transitions between the $5/2^+[633]$ and $3/2^+[631]$ rotational bands beginning with higher excited states than ^{229m}Th by applying the Alaga rule.[6] The Alaga rule states that the ratio of two $B(X\lambda)$ values for a pair of intra- or inter-band transitions equals the ratio of the squares of Clebsch-Gordan coefficients based on the assumption of the separable rotational motion of a nucleus. In this study, we measured the half-lives of the excited states in the $5/2^+[633]$ and $3/2^+[631]$ bands to determine the $B(X\lambda)$ values required to estimate the radiative half-live of ^{229m}Th.

To determine the half-lives, we performed a coincidence measurement between γ rays and α particles emitted from a ^{233}U source, as described in Ref. 7). First, we obtained the time trace of the 42.43-keV γ rays following the 4783.5-keV α particles (see Fig. 1 in this paper and Fig. 2 in Ref. 7)). By fitting a single exponential decay function convoluted with a Gaussian function to the time trace, the half-life of the 42.43-keV state was determined to be 169(4) ps, which is consistent with the value of 172(6) ps reported previously.[8] Next, we performed fitting to the time trace of the 54.70-keV γ rays following the 4729-keV α particles, yielding a half-life of 103(12) ps. Moreover, by selecting the 97.14-keV γ rays, we obtained a half-life of 88(9) ps. From the weighted average of these values, the half-life of the 97.14-keV state was determined to be 93(7) ps. In the same manner, the half-life of the 71.82- and 163.25-keV states were determined for the first time to be 120(40) and 220(30) ps by fitting to the time traces of the 71.82- and 66.12-keV γ rays following the 4754-keV and 4664-keV α particles, respectively.

We derived the $B(X\lambda)$ values using the obtained half-lives, experimental γ branching ratios,[1,9,10] mixing ratios,[9,10] and internal conversion coefficients.[10,11] First, for the intra-band transitions, we found that the B(M1) and B(E2) values of the transitions starting with the 29.19-, 42.43-, 71.83-, and 97.14-keV states were consistent with the values estimated from the Alaga rule. By contrast, for the transitions starting with the 163.25-keV state, the B(M1) and B(E2) values deviated from the estimation based on the Alaga rule, as it often appears with increasing nuclear spins. Next, to investigate the validity of the Alaga rule for the inter-band transitions, we calculated the B(M1; ^{229m}Th→^{229g}Th) values from the B(M1) values of the 29.19→0, 71.83→42.43, and 97.14→71.83 keV transitions based on the Alaga rule. The values obtained from the 29.19→0 and 71.83→42.43 keV transitions agreed with each other (0.014(4) and 0.013(4) $\mu_N{}^2$, respectively). This indicates that the contribution of the Coriolis interactions is insignificant and the Alaga rule is applicable for the inter-band transitions between those low-spin states. The weighted average of B(M1; ^{229m}Th→^{229g}Th) obtained from these transitions was 0.014(3) $\mu_N{}^2$, from which we estimated the radiative half-life of ^{229m}Th to be $5.0(11) \times 10^3$ s.

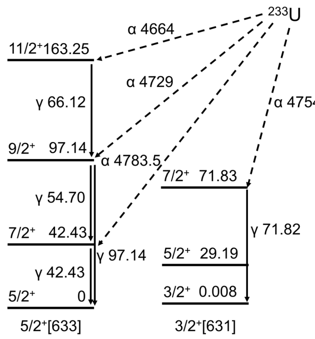

Fig. 1. Energy levels of the ^{229}Th nucleus grouped into rotational bands, as well as the α and γ transitions used for determining the half-lives of the excited states (units: keV).

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