Production of singly charged ^{229m}Th by charge exchange reaction in an ion trap

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The first excited state of the ^{229}Th nucleus, ^{229m}Th, has an excitation energy of only 8.3 eV,[1)] which leads to the variation of the decay modes of the isomer depending on the electronic states. The internal conversion (IC) process[2)] and γ-ray emission[1)] of ^{229m}Th have been recently observed. However, the electron bridge (EB) process, which is the higher-order γ-ray emission through the transition of atomic electrons, is yet to be observed. One of the candidates that may decay by the EB process is the singly charged ^{229m}Th (^{229m}Th$^+$).[3)] The half-life of ^{229m}Th$^+$ is theoretically estimated to be approximately 1 s when the atomic electrons of ^{229m}Th$^+$ is in the ground state ([Rn]7s6d^2).[3)] In previous studies, the Munich group extracted the ion beams of ^{229m,g}Th^{3+}, ^{229m,g}Th^{2+}, and ^{229m,g}Th$^+$ recoiling from a ^{233}U source using an RF-funnel gas cell.[2,4)] When they extracted ^{229m,g}Th$^{3+,2+}$ to the surface of a microchannel plate detector (MCP), ^{229m}Th ions were neutralized on the MCP and the IC electrons of ^{229m}Th were observed. However, no IC electrons were observed upon the extraction of ^{229m,g}Th$^+$. In their experiment, the electrons of ^{229m}Th$^+$ may have been excited during the stopping process of the high-energy ^{229m}Th ions in the RF-funnel gas cell; hence, there is a possibility that the dominant decay mode was the IC process ($T_{1/2} \sim 7$ μs), not the EB process. Therefore, we aim to produce ^{229m}Th$^+$ via a different method: charge exchange reactions between low-energy ^{229m}Th^{2+} and gaseous molecules (*e.g.*, NO) inside an ion trap. In this study, we report the production of ^{229m}Th$^+$ using the impurities contained in an Ar gas toward the half-life determination of ^{229m}Th$^+$ and the direct observation of the EB process.

We extracted low-energy ion beams of ^{229m,g}Th^{2+} (isomer 2%[6)]) using the setup presented in Ref. 5). In this study, we introduced an Ar gas (purity: 99.9999%) into the ion trap through a variable leak valve, and the pressure around the ion trap was stabilized at 0.2 or 0.5 Pa via the control of the Ar pressure of the upstream of the leak valve. The voltage applied to each electrode was optimized to maximize the number of ^{229m,g}Th^{2+} extracted to the MCP.

First, we continuously extracted ions to the MCP detector and obtained a mass spectrum (Fig. 1), where $\sim 2 \times 10^4$ ions/s of ^{229m,g}Th^{2+} were extracted (extraction efficiency: $\sim$20%). Subsequently, we accumulated ions in the trap for 0.8 s, trapped them for 1 s after stopping the accumulation, and then extracted them to the MCP detector. In this case, we observed the mass peak of ^{229m,g}Th$^+$ (Fig. 1), which was produced by charge exchange reactions with gaseous impurities contained in the Ar gas (NO or other molecules).

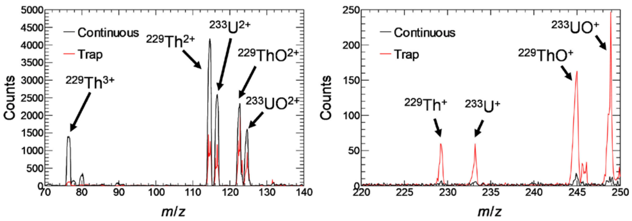

Fig. 1. Mass spectrum for ions continuously extracted (black) and extracted after accumulation and trapping (red).

We created short ion bunches of ^{229m}Th$^+$ by 0.8 s ion accumulation and 0.1 s trapping to confirm whether the IC electrons of ^{229m}Th were observable when ^{229m,g}Th$^+$ were placed on the MCP. The surface voltage of the MCP was set to -2000 V for only ion detection or -35 V for both ion and IC-electron detection. Figure 2(a) shows the time traces of the MCP counts, where the decay curve for -35 V exhibits a longer lifetime than that for -2000 V. Comparable measurements using ^{233}U$^+$ showed no clear difference between -2000 and -35 V (Fig. 2(b)). Thus, the decay curve observed for -35 V included the IC-electron signals of ^{229m}Th. This indicates that ^{229m}Th$^+$ survived in the ion trap during the 0.1 s trapping time.

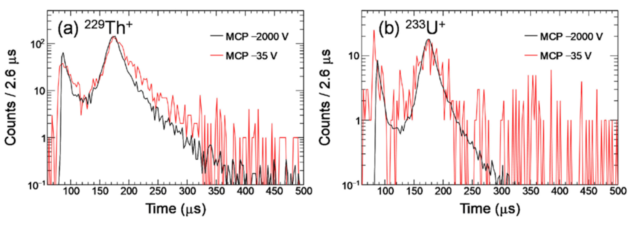

Fig. 2. MCP counts as a function of the time at MCP surface voltages of -2000 V (black) and -35 V (red) for ^{229}Th$^+$ (a) and ^{233}U$^+$ (b). The plots for -2000 V are arranged so that their peak tops are matched to those for -35 V.

The ion counts as a function of the trap time measured at a MCP voltage of -2000 V exhibited a growth

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DOI:10.34448/RIKEN.APR.57-124

and decay curve. Thus, ^{229m,g}Th^{+} produced from ^{229m}Th^{2+} was converted to molecular ions such as ^{229m,g}ThO^{+}. We can measure the half-life of ^{229m}Th^{+} by measuring the growth and decay curve for IC-electron counts (number of ^{229m}Th^{+}) at a MCP voltage of -35 V and comparing it with the curve for ^{229m,g}Th^{+} ions. However, such measurements require more ^{229m}Th^{+} ions. We recently attempted to mix a small amount of NO gas with the Ar gas and observed the increase in the counts of ^{229m,g}Th^{+}. Hence, the half-life measurement of ^{229m}Th^{+} will soon be accomplished.

References

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