Laser spectroscopy of triply charged ^{229}Th isomer for a nuclear clock†

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The low-energy nuclear isomer of ^{229}Th (^{229m}Th) can be excited from the nuclear ground state (^{229g}Th) using a vacuum ultraviolet laser, allowing for direct high-precision laser spectroscopy of the atomic nucleus. A nuclear clock based on the resonance frequency of this nuclear transition is expected to outperform current atomic clocks based on atomic electronic transitions.[1,2] ^{229}Th nuclear clocks have also been proposed for use in the search for new physics, such as dark matter and variations in the fine structure constant.[3]

A ^{229}Th ion in a trap is a suitable platform for an accurate nuclear clock, because the ion can be confined in an isolated environment.[2] In contrast to ions in other charge states, triply charged ^{229}Th (^{229}Th^{3+}) possesses closed electronic transitions required for laser cooling, laser induced-fluorescence detection, and state-preparation of ions. In this study, we report the trapping of the triply charged ^{229}Th isomer and determination of its nuclear decay lifetime, which is essential to specify the intrinsic linewidth of the nuclear-clock transition.

Figure 1 shows a schematic of our apparatus to trap ^{229}Th^{3+} ions. As an ion source, we use a uranium-233 (^{233}U). The ^{229}Th ions can be obtained as recoil ions from an α-decay of ^{233}U. The ^{229}Th ions are cooled by helium buffer gas (2 kPa). In this buffer gas cooling process, the charge state of ^{229}Th ions is prepared to be 3+ by charge exchange collisions. These recoil ions are extracted by a radio-frequency carpet (an ion collector),[4] transported by a quadrupole ion guide, and captured by a linear Paul trap. From the ^{233}U source, the ^{229m}Th^{3+} ions can be obtained with a branching ratio of approximately 2%.[5]

Figure 2 (left) shows electronic levels of Th^{3+} relevant to this study. We use three transitions: $^2F_{5/2} \leftrightarrow {}^2D_{3/2}$ (1088 nm), $^2F_{5/2} \leftrightarrow {}^2D_{5/2}$ (690 nm) and $^2F_{7/2} \leftrightarrow {}^2D_{5/2}$ (984 nm). The 1088-nm transition and the 690-nm + 984-nm transitions are the two closed electronic transitions. The branching ratios from $^2D_{5/2}$ to $^2F_{5/2}$ and $^2F_{7/2}$ are calculated to be 12% and 88%, respectively. We performed saturated absorption spectroscopy, where the 1088-nm laser burned a hole in the velocity distribution of the ions in the $^2F_{5/2}$ state. The 690-nm and 984-nm transitions were used to detect ions via laser-induced fluorescence at 984 nm.

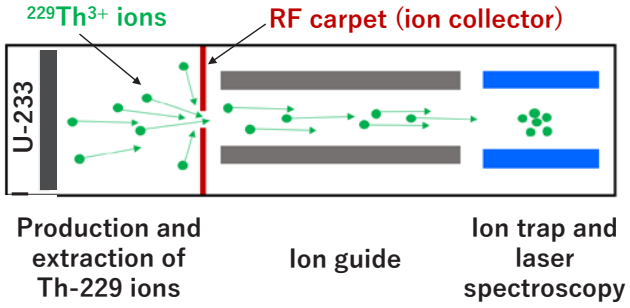

Fig. 1. A schematic of ^{229}Th^{3+} ion trap system. The ^{229}Th^{3+} ions from the ^{233}U source are collected by an RF carpet, transported by an ion guide, and captured by an ion trap where laser spectroscopy is performed.

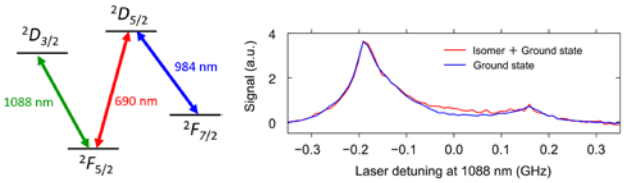

Fig. 2. (Left) Electronic level structure of a triply charged thorium ion relevant to this study. (Right) The signal from ^{229m}Th^{3+} ions can be extracted as a difference between signals from ions in the isomer and nuclear ground state (red) and those from the nuclear ground state (blue).

To selectively detect signals from ^{229m}Th^{3+} ions in a trap, we developed a nuclear-state-selective spectroscopy technique. Here, we use two different 984-nm laser frequencies to detect ions. With one frequency, ^{229g}Th^{3+} ions mainly emit fluorescence. With the other 984-nm laser frequency, both ^{229g}Th^{3+} and ^{229m}Th^{3+} ions emit fluorescence. The signal from ^{229m}Th^{3+} ions can be extracted by taking the difference between them (Fig. 2 (right)). By measuring the decay of signals from ^{229m}Th^{3+}, we determined its nuclear decay half-life to be 1400 (+600/−300) s. This corresponds to 80(20) μHz in terms of the natural linewidth of the nuclear transition, which is more than an order of magnitude narrower than the linewidth of state-of-the-art ultrastable lasers.[6] This result offers a key parameter for the ^{229}Th^{3+} nuclear clock and its applications in the search for new physics.

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