Laser Spectroscopy of Triply Charged Thorium-229 Isomer Toward a Nuclear Clock

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The nuclear isomer of ^{229}Th (^{229m}Th) attracts attention for its extremely low energy [1, 2]. The energy of ^{229m}Th was determined to be about 8.3 eV (corresponding to wavelength 149 nm) by internal conversion electron spectroscopy [3], γ-ray spectroscopy [4-6], and, more recently, vacuum-ultraviolet spectroscopy of ^{229m}Th [7]. The nuclear transition between the nuclear ground state and the isomer state of ^{229}Th offers a unique opportunity for laser spectroscopy of an atomic nucleus. One of the applications is a high-precision optical nuclear clock: an atomic clock based on this nuclear transition [8].

As a platform of the ^{229}Th nuclear clock, an ion trap with triply charged ^{229}Th ($^{229}Th^{3+}$) is suitable because $^{229}Th^{3+}$ possesses electronic transitions that enable laser cooling. In a previous study laser cooling and laser spectroscopic studies of $^{229}Th^{3+}$ ions in the nuclear ground state ($^{229g}Th^{3+}$) were demonstrated [9]. For the operation of the nuclear clock, properties of $^{229m}Th^{3+}$ also need to be known. For example, hyperfine structures of $^{229m}Th^{3+}$ should be known to confirm nuclear excitation via selective detection of $^{229g}Th^{3+}$ and $^{229m}Th^{3+}$. However, since the trapping of $^{229m}Th^{3+}$ ions has not been demonstrated yet, detailed properties of $^{229m}Th^{3+}$ remained uninvestigated.

In this study, we performed laser spectroscopy of trapped $^{229m}Th^{3+}$ ions. The $^{229m}Th^{3+}$ ions were obtained as a decay product of ^{233}U. We determined the hyperfine constants of the electronic state of $^{229m}Th^{3+}$ and derived the magnetic dipole and electric quadrupole moments of ^{229m}Th. We also investigated the nuclear decay lifetime of $^{229m}Th^{3+}$ which was a key parameter to estimate the performance of a $^{229}Th^{3+}$ nuclear clock.

References

[1] L. von der Wense, B. Seiferle, M. Laatiaoui, J. B. Neumayr, H.-J. Maier, H.-F. Wirth, C. Mokry, J. Runke, K. Eberhardt, C. E. Düllmann, N. G. Trautmann, P. G. Thirolf, "Direct detection of the ^{229}Th nuclear clock transition," Nature 533, 47 (2016).

[2] J. Thielking, M. V. Okhapkin, P. Głowacki, D. M. Meier, L. von der Wense, B. Seiferle, C. E. Düllmann, P. G. Thirolf, E. Peik, "Laser spectroscopic characterization of the nuclear-clock isomer ^{229m}Th," Nature 556, 321 (2018).

[3] B. Seiferle, *et al.*, "Energy of the ^{229}Th nuclear clock transition," Nature 573, 243 (2019).

[4] B. R. Beck, J. A. Becker, P. Beiersdorfer, G. V. Brown, K. J. Moody, J. B. Wilhelmy, F. S. Porter, C. A. Kilbourne, R. L. Kelley, "Energy Splitting of the Ground-State Doublet in the Nucleus ^{229}Th," Phys. Rev. Lett. 98, 142501 (2007).

[5] A. Yamaguchi, H. Muramatsu, T. Hayashi, N. Yuasa, K. Nakamura, M. Takimoto, H. Haba, K. Konishi, M. Watanabe, H. Kikunaga, K. Maehata, N. Y. Yamasaki, K. Mitsuda, "Energy of the ^{229}Th Nuclear Clock Isomer Determined by Absolute γ -ray Energy Difference," Phys. Rev. Lett. 123, 222501 (2019).

[6] T. Sikorsky, J. Geist, D. Hengstler, S. Kempf, L. Gastaldo, C. Enss, C. Mokry, J. Runke, C. E. Düllmann, P. Wobrauschek, K. Beeks, V. Rosecker, J. H. Sterba, G. Kazakov, T. Schumm, A. Fleischmann, "Measurement of the ^{229}Th Isomer Energy with a Magnetic Microcalorimeter," Phys. Rev. Lett. 125, 142503 (2020).

[7] S. Kraemer *et al.*, "Observation of the radiative decay of the ^{229}Th nuclear clock isomer," Nature 617, 706 (2023).

[8] E. Peik, Chr. Tamm, "Nuclear laser spectroscopy of the 3.5 eV transition in Th-229," Europhys. Lett. 61, 181 (2003).

[9] C. J. Campbell, A. G. Radnaev, A. Kuzmich, "Wigner Crystals of ^{229}Th for Optical Excitation of the Nuclear Isomer," Phys. Rev. Lett. 106, 223001 (2011).