Quantum Metrology Laboratory（2021）
Chief Scientist: Hidetoshi Katori (D.Eng.)

(0) Research field
CPR Subcommittee: Physics and Engineering

Keywords: Quantum electronics, Atomic clock, Quantum metrology, Optical lattice clock, Relativistic geodesy

(1) Long-term goal of laboratory and research background

The quest for the superb precision of atomic spectroscopy contributed to the birth of quantum-mechanics and to progress of modern physics. Highly precise atomic clocks, which are outcomes of such research, are indeed key technologies that support our modern society, such as the navigation with GPS and synchronization of high-speed communication networks. In 2001, we proposed a new atomic clock scheme, "optical lattice clock", which may allow us accessing to 18-digit-precision time/frequency in a measurement time of seconds. Armed with such high precision atomic clocks, we investigate fundamental physics such as the constancy of fundamental constants as well as application of such clocks to relativistic geodesy. In parallel, we explore quantum information technology and quantum metrology to investigate the quantum feedback scheme and quantum simulator/computation.

(2) Current research activities (FY2021) and plan (until Mar. 2025)

(A) Development of a transportable optical lattice clock for relativistic geodesy

Due to relativistic effects, clocks in different gravitational potentials tick differently. A clock with 10^{-18} uncertainty can measure the gravitational redshift caused by a height difference of 1 cm, thus making it a high-precision geodetic device. To develop such “relativistic geodesy” applications, networks of optical lattice clocks connected via optical fibers are required. To this end, development of highly transportable optical lattice clocks is essential.

In FY2021, we have developed a compact optical lattice clock system whose volume is 49 L (weight is 45 kg). This corresponds to one-sixth the volume (one-quarter the weight) of the device used in our measurements performed at Tokyo Skytree in 2019. We have confirmed that fractional frequency stability of the newly developed compact optical lattice clock system reached 5×10^{-18} after an averaging time of 1 hour.

In the future, we will connect them to long-distance optical fiber links and demonstrate practical applications to relativistic geodesy such as monitoring of uplift in the earth's crust. Further downsizing and networking of the clocks will allow the clocks to be used as geopotential sensors that are complement to GNSS (Global Navigation Satellite System) and gravimeters.

(B) Development of Th-229 ion trap towards an optical nuclear clock

The first-excited nuclear state of Th-229 attracts attention for its extremely low energy which was measured to be 8.3 eV (corresponding to the wavelength of 149 nm). The nuclear transition between the ground state and the first-excited state of Th-229 thus offers unique opportunities for direct high-precision laser spectroscopy of an atomic nucleus. One of the applications is an optical nuclear clock: an atomic clock based on this nuclear transition. Towards a Th-229 optical nuclear clock, we are developing a Th-229 ion trap apparatus.

We are aiming to trap triply charged Th-229 ions because they possess electronic transitions suitable for laser cooling. Figure 1 shows a schematic diagram of the ion trap system we are developing. The Th-229 recoil ions emitted from a U-233 source are cooled by collisions with helium (He) buffer gas and extracted as a low-energy ion beam by an RF-carpet. The transported Th-229^{3+} ions are trapped in a linear Paul trap and used for laser cooling experiments.

In FY2021, we have developed the apparatus by using Th-232 isotope instead of Th-229 because Th-232 isotope is much easier to handle due to its large natural abundance and less radioactivity than Th-229. We installed a Th-232 plate instead of the U-233 source. The Th-232^{3+} ions are obtained by laser ablation. By operating an ion transport part (②) as a quadrupole mass spectrometer of ions, we confirmed that Th-232 ions in the charge state 1, 2, and 3 were generated. We also trapped Th-232^{+} ions and performed laser spectroscopy of them by the electronic transition at 402 nm.

In the future, we will demonstrate trapping and laser cooling of Th-229^{3+} ions towards a Th-229 nuclear clock. The 2% of Th-229 ions emitted from the U-233 ion source are in the isomeric nuclear state (the first nuclear excited state at 8.3 eV). Therefore, we will also aim to trap them to study the isomeric nuclear state. Such studies include lifetime measurement of the isomer state and precise isomer energy determination by measuring the energy of the photon emitted when the isomer nucleus decays to the ground state, which is important for the study of the Th-229 nuclear clock.

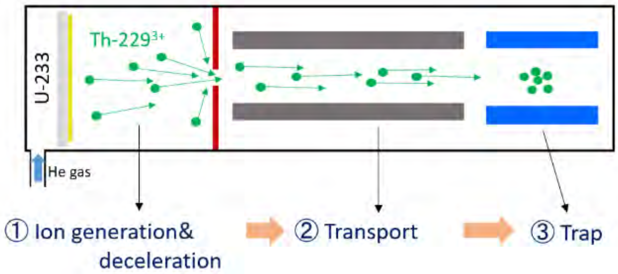

Figure 1: Th-229 ion trap system developed in this study.

(3) Members

(Chief Scientist) Hidetoshi Katori
(Senior Research Scientist) Masao Takamoto, Atsushi Yamaguchi
(Assistant) Megumi Kobayashi

(4) Representative research achievements

1. "Transportable Strontium Optical Lattice Clocks Operated Outside Laboratory at the Level of 10^{-18} Uncertainty", N. Ohmae, M. Takamoto, Y. Takahashi, M. Kokubun, K. Araki, A. Hinton, I. Ushijima, T. Muramatsu, T. Furumiya, Y. Sakai, N. Moriya, N. Kamiya, K. Fujii, R. Muramatsu, T. Shiimado, and H. Katori, *Adv. Quantum Technol.* **4**, 2100015 (2021).

2. (Plenary Talk) "Transportable Optical Lattice Clocks to Test and Use Gravitational Redshift", Hidetoshi Katori, *IMEKO XXIII World congress (IMEKO2021)*, August 30 - September 3, 2021, online virtual conference.

3. "Test of gravitational redshift with optical lattice clocks and their applications to relativistic geodesy", Masao Takamoto, *Sixteenth Marcel Grossmann Meeting*, Online, July (2021).

4. "Development of an RF-carpet gas cell to obtain an ion beam of thorium-229", A. Yamaguchi, Y. Shigekawa, H. Haba, M. Wada, and H. Katori, *ViCPEAC2021*, Online, July (2021).

5. "Estimation of radiative half-life of ^{229m}Th by half-life measurement of other nuclear excited states in ^{229}Th", Y. Shigekawa, A. Yamaguchi, K. Suzuki, H. Haba, T. Hiraki, H. Kikunaga, T. Masuda, S. Nishimura, N. Sasao, A. Yoshimi, and K. Yoshimura, *Phys Rev C* **104**, 024306 (2021).

Laboratory Homepage
https://www.riken.jp/en/research/labs/chief/qtm_metrol/index.html
http://www.amo.t.u-tokyo.ac.jp/e_index.html