Quantum Metrology Laboratory（2020）
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 (FY2020) and plan (until Mar. 2025)

(A) Development of a vehicle-mounted optical lattice clock for relativistic geodesy

Clocks in different gravitational potentials tick differently due to relativistic effects, with clocks in higher positions ticking faster. Precise measurement of the frequency difference between two clocks at different heights, therefore, tells us their height difference. For example, atomic clocks possessing 1×10^{-18} precision enable us to determine the height difference with 1 cm accuracy. We explore the application of such high-accuracy atomic clocks to geodetic measurements through relativistic effects. For that purpose, we are developing a vehicle-mounted optical lattice clock with an accuracy of 10^{-18}.

Figure 1 shows a picture of the vehicle-mounted clock developed in this study and the frequency comparison between the on-board clock with an optical lattice clock operated in the laboratory via an optical fiber. We found that the performance of the on-vehicle clock was similar to that of the laboratory-based clock. Such a high-performance transportable clock allows precise measurement of the spacetime affected by the gravitational field and mapping of the altitude with centimeter precision.

In the future, by transporting the on-vehicle clock to remote sites and comparing the clocks over a long baseline, we will investigate geophysical application, 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.

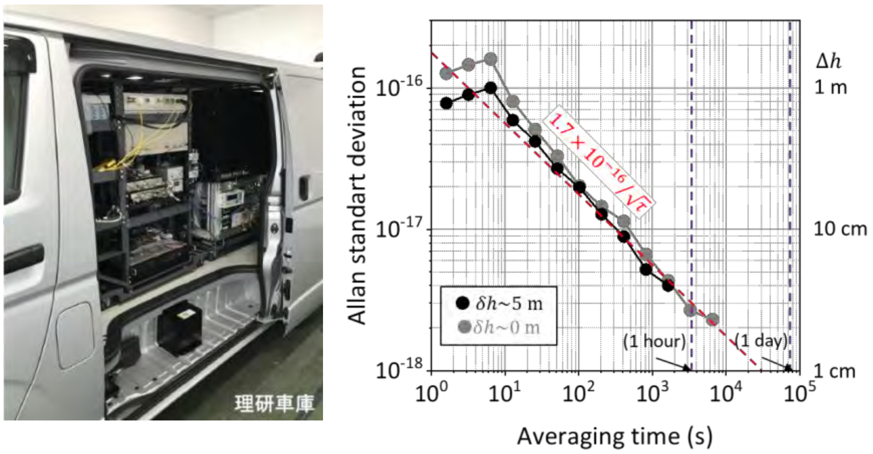

Figure 1: (Left) Vehicle-mounted optical lattice clock . (Right) Frequency comparison between an on-vehicle clock and a laboratory clock (black dots). The performance is comparable to that of the frequency comparison between two clocks in the laboratory (gray dots). Elevation differences with an uncertainty of centimeters were measured in an hour averaging time.

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

Towards an optical nuclear clock based on the low-energy nuclear transition in Th-229, we are developing a Th-229 ion trap and a technique to precisely manipulate its quantum state by lasers.

Figure 2 shows a schematic diagram of the ion trap system we are developing. First, Th-229 ions obtained as recoil ions in the alpha-decay of U-233 (Uranium233) are decelerated by collisions with helium gas (region ①). The decelerated Th-229 ions are then extracted as an ion beam by an ion collector called an RF carpet, transported (②), and trapped (③).

In FY2020, we operated all ①-③ devices together with a test ion source (cesium ion source) and established a technique for trapping ions. We also prepared a Th-229 ion source by electrodepositing U-233 onto a thin titanium plate. The intensity of the radiation emitted from this source was measured, and it was confirmed that about 10^5 Th-229 ions per second were emitted, which is a sufficient amount for our research. This Th-229 ion source was installed in the apparatus and Th-229 ions were extracted as an ion beam by ① and ②. The energy of the ion beam was measured to be 3-4 eV, which is low enough to be trapped in ③.

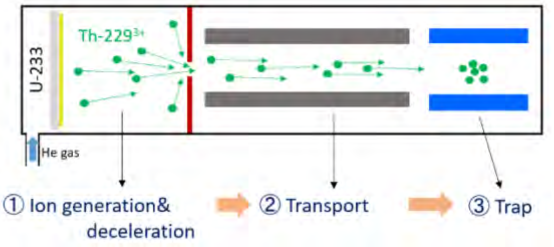

Figure 2: Th-229 ion trap system developed in this study.

In FY2021, we will introduce the low-energy Th-229 ion beam into the trapping region (③), trap Th-229 ions, and perform laser spectroscopy and laser cooling experiment. The 2% of Th-229 ions emitted from our U-233 ion source are in the isomeric nuclear state. Therefore, we will also aim to trap these ions and study the isomeric nuclear state. Such studies include lifetime measurement of the isomer state, 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 an optical nuclear clock.

(3) Members

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

(4) Representative research achievements

1. "Direct measurement of the frequency ratio for Hg and Yb optical lattice clock and closure of the Hg/Yb/Sr loop", N. Ohmae, F. Bregolin, N. Nemitz, and H. Katori, *Opt. Exp*. **28**, 15112 (2020).
2. "Test of general relativity by a pair of transportable optical lattice clocks", M. Takamoto, I. Ushijima, N. Ohmae, T. Yahagi, K. Kokado, H. Shinkai, and H. Katori, *Nat. Photon*. **14**, 411 (2020).
3. "Transportable Optical Lattice Clocks to Test Gravitational Redshift", H. Katori, *51st Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics*, Online, June (2020).
4. "Development of transportable optical lattice clocks for geodetic applications", M. Takamoto, *CLEO2020*, Online, May (2020).
5. "Energy of the Th-229 nuclear clock isomer determined by absolute γ-ray energy difference", A. Yamaguchi, *GIMRT-REMAS2020*, Online, October (2020).

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