Quantum Metrology Laboratory
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 (FY2019) and plan (until Mar. 2025)

1. Determination of the magic wavelength of cadmium

One of the major uncertainties of optical lattice clocks is the black body radiation shift (BBR shift) which is the frequency shift caused by the black body radiation from the surrounding environment. The optical lattice clocks have achieved 18-digit accuracy by carrying out spectroscopy of the clock transition in cryogenic environment, where the BBR shift is strongly suppressed. Another way to suppress the BBR shift is to use atomic species possessing a clock transition which has smaller sensitivity to BBR. One of the candidates is cadmium. However, the magic wavelength of cadmium optical lattice clock, which is an essential parameter to operate an optical lattice clock, has not been experimentally measured so far.

In FY2019, we experimentally determined the magic wavelength of cadmium. In the scheme of an optical lattice clock, atoms are tightly confined in space by an optical lattice potential to eliminate the first-order Doppler shift. When the wavelength of the optical lattice laser is tuned to the magic wavelength, the light shift induced by the lattice laser vanishes, enabling the measurement of unperturbed resonance frequency of the clock transition of atoms trapped in an optical lattice.

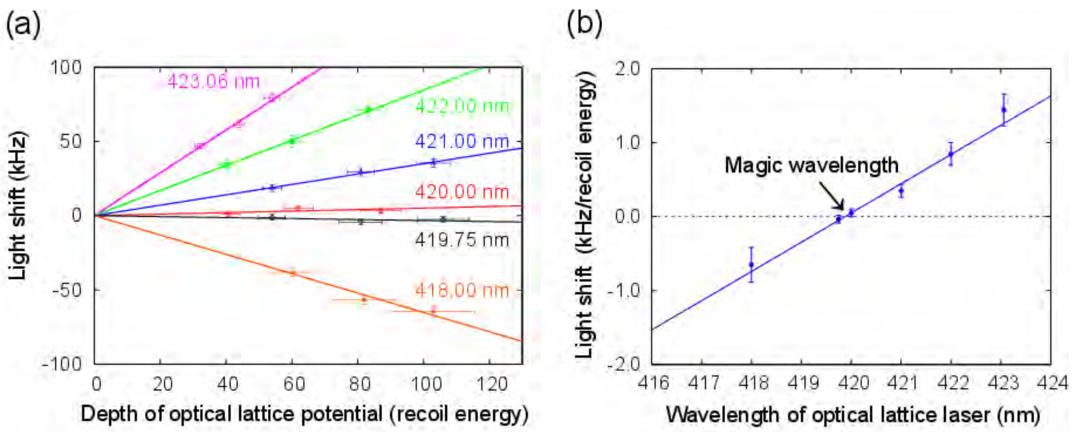

Fig. 1 Determination of magic wavelength of cadmium. (a) Dependence of light shift on depth of optical lattice potential. Numbers in figure are the wavelength of the optical lattice laser. (b) Dependence of light shift on the wavelength of optical lattice laser.

In order to trap cadmium atoms in optical lattice potential (whose trap depth is about 50 μK), we first cooled cadmium atoms down to 6 μK. We then transferred atoms in an optical lattice potential and measured the light shift as shown in Fig. 1. The magic wavelength of cadmium was determined to be 419.88(14) nm. We also theoretically calculated it to be 420.1(7) nm, which agreed with the measured value. Accuracy of the cadmium optical lattice clock will be investigated.

2. Determination of energy of the thorium-229 nuclear clock isomer

Thorium-229 has a metastable nuclear state (so-called isomer state whose lifetime is estimated to be about 1000 s) at the energy of only several eV, which can be excited by VUV laser from the ground state. So far, thorium-229 is the only nucleus known to possess an isomer state at such a low energy accessible by laser spectroscopy. One of the applications of this nuclear transition is a nuclear clock: an atomic clock based on the resonance frequency of the nuclear transition.

However, until 2018, the reported isomer energies of thorium-229 have not agreed with each other within their uncertainties. Therefore, further measurements based on different experimental techniques are important to improve the confidence in the energy of the isomer state.

In FY2019, we developed a transition edge sensor microcalorimeter which was a gamma-ray spectrometer having an energy resolution of 36 eV (FWHM) at the gamma-ray energy of 30 keV. By using it, we measured the absolute energy of gamma-rays emitted from thorium-229 and determined its isomer energy to be 8.30 (92) eV. Our result agrees with the latest two measurements based on different experimental techniques.

Towards high-resolution laser spectroscopy of the nucleus of thorium-229 by laser at 8.30 eV, the apparatus which can trap thorium-229 will be developed.

(3) Members

as of March, 2020

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(4) Representative research achievements

1. “Narrow-line Cooling and Determination of the Magic Wavelength of Cd”, A. Yamaguchi, M. S. Safronova, K. Gibble, and H. Katori, Phys. Rev. Lett. **123**, 113201 (2019).
2. “Superradiance from lattice-confined atoms inside hollow core fibre”, S. Okaba, D. Yu, L. Vincetti, F. Benabid, and H. Katori, Commun. Phys. **2**, 136 (2019).
3. “Energy of the ^{229}Th Nuclear Clock Isomer Determined by Absolute □-ray Energy Difference”, A. Yamaguchi *et al.*, Phys. Rev. Lett. **123**, 222501 (2019).
4. “X-ray pumping of the ^{229}Th nuclear clock isomer”, T. Masuda *et al.*, Nature **573**, 238 (2019).

Laboratory Homepage
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