【Grant-in-Aid for Scientific Research (S)】

Nuclear Clock: Exploring Fundamental Physics with an Innovative Probe

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Project Information	Project Number : 25H00397 Keywords : Nuclear clock, thorium-229, frequency standard, constancy of physical constants, ultralight dark matter	Project Period (FY) : 2025-2029

Purpose and Background of the Research

●Outline of the Research

Recent advances in atomic clock technology have enabled light and electromagnetic wave frequency measurements with a relative precision exceeding 10^{-18}, the highest in physical measurements. This ultra-precise technology has led to various investigations in fundamental physics. Among these, testing the constancy of physical constants has drawn attention, potentially offering insight into dark energy. Improving probe sensitivity requires surpassing atomic clock precision, and a promising approach is the "nuclear clock," which uses atomic nuclei less affected by external fields.

Although most nuclear excitations are too high for laser excitation, thorium-229—with its 8.4 eV excited state—is a unique exception. If laser manipulation becomes feasible, it would not only enable the realization of a nuclear clock with precision beyond that of traditional atomic clocks, but also allow us to test the constancy of the fine-structure constant with 3 to 4 orders of magnitude greater sensitivity, thanks to the uniqueness of thorium-229. The present research aims to develop two types of nuclear clocks such as a solid-state nuclear clock and a trapped-ion nuclear clock by integrating the related technologies we have cultivated through thorium-229 studies. Our goal is to use these nuclear clocks to investigate the constancy of the fine-structure constant, thereby driving breakthroughs in fundamental physics

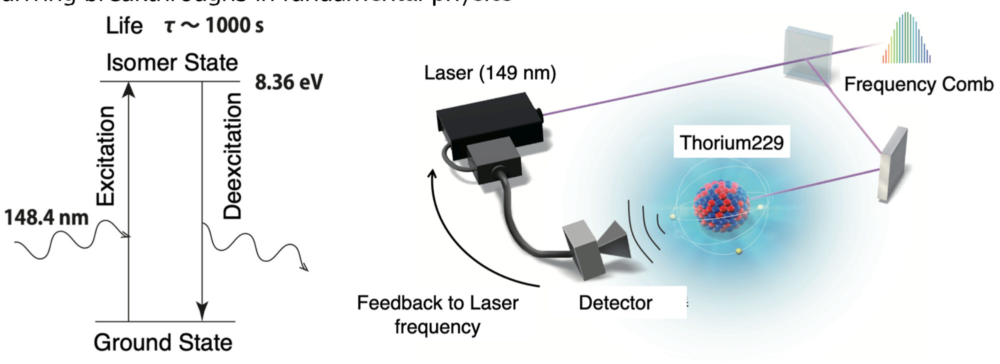

Figure 1. Conceptual image of a nuclear clock using thorium229

●Research Background

Thorium-229's unique properties have been studied since the 1970s, but many aspects remained unclear. Since 2014, our team has made key advances, including the first artificial production of its isomeric state in 2019 and the observation of vacuum ultraviolet emission in 2024, which allowed precise energy measurement. We also reported the isomer's lifetime in an ion trap, and in the same year, German and Austrian teams achieved laser excitation—an important step toward nuclear clocks.

In response, we formed an "All-Japan" team combining experts in ion-trap, solid-state clocks, and radiochemistry to realize nuclear clocks and advance fundamental physics.

●Research Methodology

we will simultaneously develop two types of nuclear clocks (Figure 2): ion-trap and solid-state nuclear clocks. Common efforts will be made in detail study of the isomer transition and developing lasers, with the goal of realizing nuclear clocks as probes for fundamental physics.

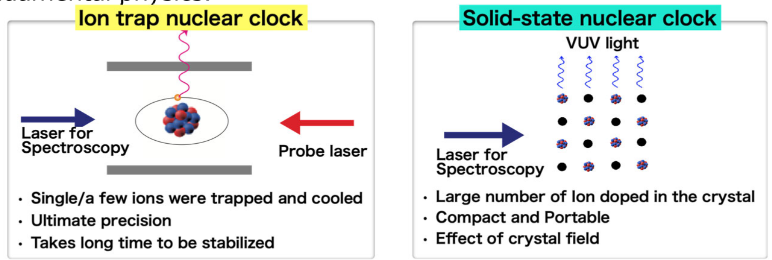

Figure 2. Two types of nuclear clocks developed in this Research (Ion Trap and Solid-State).

Expected Research Achievements

●Understanding and Controlling the Nuclear Decay Mechanism of Thorium-229

To realize nuclear clocks, we will investigate the decay mechanisms of thorium-229 and observe the yet-undetected process such as electronic bridge (Figure 3), aiming to efficiently control of excitation and de-excitation.

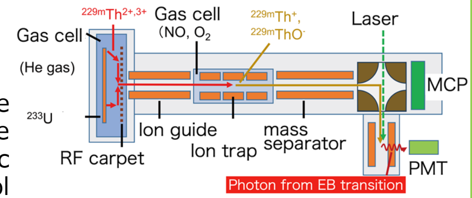

Figure 3. Electronic bridge transition detection System

●Realization of an Ion-Trap Nuclear Clock

We will develop a continuous-wave (CW) laser with a wavelength of 148 nm in the vacuum ultraviolet (VUV) region. By irradiating thorium-229 ions captured and cooled in an ion trap with this laser to excite nuclear transitions, we will perform spectroscopy and realize an ion-trap nuclear clock (Figure 4).

●Realization of a Solid-state Nuclear Clock

To achieve good performance, we will fabricate candidate crystals and test them using X-rays and lasers. Using the VUV CW laser, we aim to perform spectroscopy and realize a solid-state nuclear clock (Figure 5).

●Test of Variation of Fine-Structure Constant and Search for Ultralight Dark Matter

Using the developed nuclear clocks, we will measure temporal variation in frequency measurement to test the constancy of the fine-structure constant. We will also perform the search for ultralight dark matter.

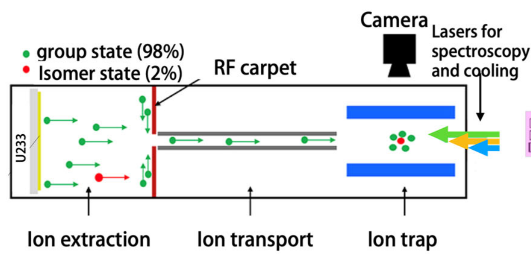

Figure 4. Ion trap nuclear clock

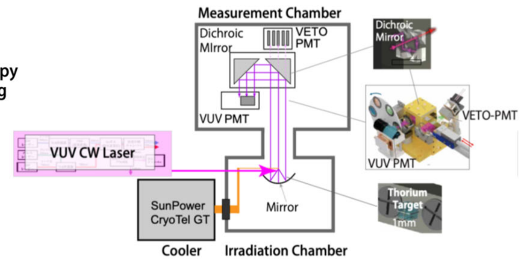

Figure 5. solid-state nuclear clock

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