

## Towards a nuclear optical clock based on $^{229}\text{Th}$

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### Introduction

A precise and accurate measurement of time has influence on our everyday life in many different ways. Prominent examples are satellite-based navigation or data transfer. The most accurate clocks in the world are atomic clocks, which define the second since 1967. However, within the past decades, a drastic increase in clock accuracy was achieved, mostly triggered by the development of the nobel-prize winning frequency-comb technology, which for the first time allowed to operate optical atomic clocks [1].

In the optical atomic clock concept a narrow-band laser is stabilized onto an atomic shell transition and the frequency of the laser light is counted with the help of a frequency comb. The number of lightwaves is then converted into a time signal. Today's best optical atomic clocks achieve an accuracy that is approaching  $10^{-18}$ , which corresponds to 1 s in 30 billion years, significantly longer than the age of the universe [2]. In this range of accuracy new fields of application open up, like in relativistic geodesy or in fundamental physics, where time variation of fundamental constants and clock-based dark matter search become fields of increasing interest.

### The nuclear optical clock concept

Whenever an improved time accuracy was achieved, new and exciting applications have emerged. One particularly promising way to improve the accuracy of time measurement could be the development of a nuclear optical clock [3]. Unlike usual optical atomic clocks, which

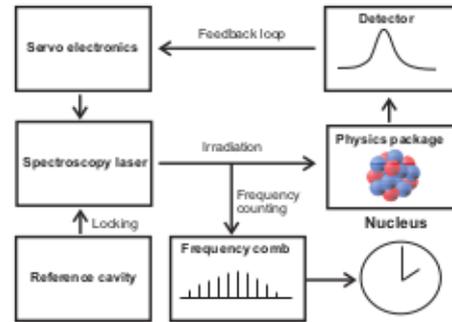


FIG. 1: The nuclear clock concept. A laser is stabilized to a nuclear transition, the frequency is counted and converted into a time signal.

are based on a transition in the atomic shell, the nuclear clock makes use of a nuclear transition for time measurement. Just like in optical atomic clocks, a narrow-band laser is stabilized to the transition, the laser frequency is counted and converted into a time signal. A conceptual sketch of the nuclear clock concept is shown in Fig. 1. A nuclear optical clock is expected to offer three advantages: (1) The nucleus is about five orders of magnitude smaller than the atom and therefore significantly more stable against external influences, (2) the transition frequency is large, potentially leading to a high stability, (3) the atomic nucleus is largely unaffected by the shell, leading to the idea of a solid-state nuclear clock providing improved statistics [4].

A central requirement for the development of a nuclear optical clock is direct nuclear laser excitation. For this purpose, the transition energy of the nuclear excitation has to match with existing narrow-bandwidth laser technology. As typical energies of nuclear transitions are in the keV to MeV range, the overlap with existing laser technology is small and by to-

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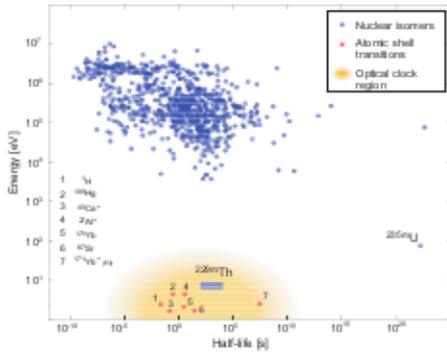


FIG. 2: Energy-half-life diagram of known metastable nuclear states.  $^{229\text{m}}\text{Th}$  is the only known nucleus that could be used for the development of a nuclear optical clock using existing laser technology. With kind permission of Nature Research [7].

day only one nuclear excited state is known which could potentially allow for direct nuclear laser excitation. This is the first nuclear excited state of the  $^{229}\text{Th}$  isotope, exhibiting an exceptionally low excitation energy of only  $(7.8 \pm 0.5)$  eV, corresponding to  $(159 \pm 11)$  nm wavelength of the laser light required for nuclear excitation [5]. The excited state is long-lived, with a radiative lifetime of expectedly about  $10^4$  s, rendering it a metastable nuclear isomer, denoted as  $^{229\text{m}}\text{Th}$ . The achievable accuracy of a  $^{229\text{m}}\text{Th}$ -based single-ion nuclear optical clock was estimated to about  $10^{-19}$  [6]. The special position of  $^{229\text{m}}\text{Th}$  is visualized in an energy-half-life diagram in Fig. 2.

### Steps towards a nuclear clock

Direct nuclear laser excitation of  $^{229\text{m}}\text{Th}$ , despite conceptually possible, remains a central challenge. The reason is, that the natural linewidth of the nuclear transition is very narrow due to the long radiative isomeric lifetime of about  $10^4$  s. This leads to prohibitively long required scanning times when searching for the nuclear excitation in thorium ions. For this reason the isomer’s excitation energy has to be constrained to higher precision, prior to  $^{229}\text{Th}$  nuclear laser excitation in a Paul trap. This has motivated a multitude of different

experimental efforts worldwide, aiming to pin down the  $^{229\text{m}}\text{Th}$  nuclear excitation energy. A recent review can be found in Ref. [8]

A first direct detection of the isomeric decay via the internal conversion (IC) decay channel in 2016 by our group [7] and a subsequent lifetime measurement [9] has opened three new paths for a precise determination of the isomeric energy. These are (1) electron spectroscopy of the IC electrons emitted in the isomeric decay [10], (2) laser-based IC-Mössbauer spectroscopy [11] and (3) a transition-edge detection technique, using a superconducting nanowire single-photon detector (SNSPD). All three paths are currently investigated by our group in collaboration with different groups worldwide.

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