nuClock Report Summary
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Periodic Reporting for period 2 - nuClock (Towards a nuclear clock with Thorium-229)

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Summary of the context and overall objectives of the project

"The quest for a more precise way of measuring time is a theme that prevails through the history of mankind. In turn, clocks have always reflected humanity's state of knowledge. As we briefly recall the evolution of man-made clocks, we find that most of them did not measure time directly, but the frequency of oscillations. With every generation of newly developed clocks, the oscillating objects used for reference gradually reduced in size, spanning from the largest structures in the universe to the smallest ones. Early researchers went from observing the (apparent) annual motion of the Sun or the night sky (e.g. observatories such as Stonehenge) and the motion of Earth around Sun (e.g. sundials) to the fabrication of mechanic pendulums and, later, to the development of quartz crystals in electronic watches. Today's best clocks employ single atoms or ions in atom clocks, which loose or gain less than a fraction of a second over the age of the universe. Within the nuClock project, we are advancing one step further: Employing the nucleus of an atom (1000-times smaller than the atom itself) might allow us to improve the performance of today's clocks even further.

Only very few types of atomic nuclei (referred to as isotopes) are suitable for such a "nuclear clock": Candidate nuclei need to possess a certain well-defined, long-lived excited state of low energy (a so-called isomer); this is true for only very few isotopes. Taking into account the range of currently available lasers (used for manipulation of the nuclei), there is only one single isotope suitable for such a nuclear clock: Thorium-229.

A clock based on Th-229 would "tick" faster compared to today's atomic clocks, it would be less sensitive to external perturbations, and it might prove to be smaller and more robust by design. It might therefore supersede atomic clocks in a number of applications. The most prominent application of highly precise clocks is the generation of timing signals that are used by navigation systems, such as GPS. Apart from these navigation systems, which are built into billion cars and cell phones, modern society heavily relies on precise synchronization and timekeeping in power grids, telecommunication networks, and financial markets.

While the operation of a nuclear clock cannot anticipated for the near future, work within the nuClock project will lay the foundations for such a device. Three major challenges are tackled within the consortium: (1) A thorough characterization of the Th-229 isotope, (2) Designing the hardware components of the future clock, and (3) development of suitable laser sources. To advance at the maximum possible speed, these three strands of research are pursued in parallel."

Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far
The nuClock project is now 2.5 years into its 4-year duration. Significant advances in technology development have been made, accompanied by ground-breaking, first-ever basic research findings.

As a first scientific break-through, the LMU Munich group was able to present the first-ever direct observation of the isomeric state in Th-229. This discovery marks an important step towards the development of a nuclear clock and was published in the highly reputed journal Nature. This work included the introduction of a new detection method, which will be used to measure important properties of the isomeric state. As an example, this detection method was used to measure the lifetime of the isomeric state under the internal-conversion decay channel. This experiment is very important, as the lifetime cannot be computed theoretically.

Based on joined expertise in the LMU Munich and PTB Braunschweig groups, the first-ever optical spectroscopy of thorium ions in the isomeric state have been performed. Optical addressing and manipulation of ions in the excited nuclear state is an important step towards the nuclear clock. The spectroscopy investigated the hyperfine structure of electronic transitions, which allowed researcher to draw conclusions on properties of the excited nucleus. Such information is important to design protocols for nuclear clock operation.

In addition, theory investigations and technology development pushed towards the realization of the new type of clock. Theory work included the development of improved nuclear structure models to predict properties of the excited nucleus, and the development of a new scheme for optical spectroscopy at an intermediate level in resolution. In terms of technology development, works spans across fields as diverse as SQUID development for cryogenic detectors, development of laser sources in the VUV wavelength range, and characterization of radioactive samples at the µm scale.

Progress beyond the state of the art and expected potential impact (including the socio-economic impact and the wider societal implications of the project so far)

The nuClock project is the first and only consortium with a clear mission to develop a nuclear clock. While previous experiments were carried out by single isolated groups from various disciplines of physics, the nuClock consortium presents the only aggregation of researcher from all relevant fields of physics (atomic and nuclear physics, quantum optics, laser development, theory support) that is required to tackle the problem in a broad and well-thought-out fashion. The success of this strategy is evidenced by the vivid teamwork between the eight partners of the consortium. The scientific work already led to dozens of publications and earned world-wide reputation.

For the remaining 1.5 years of the project, we expect a measurement of the isomer energy to better than 0.1 eV (corresponding to about 1 nm in wavelength) using at least two different approaches. Cross-checking results with different approaches is very important to exclude systematic uncertainties, and we are currently following at least five different approaches to ensure that at least two of them are successful in the end. With an uncertainty below 0.1 eV, the stage is set for optical spectroscopy. Two types of laser systems are currently being developed, and depending on the transition wavelength, one of the two will be chosen for direct optical spectroscopy.

Once the resonance frequency is found, its value can be compared to other reference frequencies with the help of a frequency comb. Such a device then includes all major parts of an optical clock. Spectroscopy of the clock transition allows to search for drifts in fundamental constants, a hot topic in astrophysics and cosmology. A future nuclear clock might have the potential to outperform today’s best optical clocks and could contribute to international timekeeping. When cast into a rigid design, nuclear clocks could be operated on navigation satellites to improve the precision of navigation (GPS and the like). Improved and highly reliable synchronization of networks is a prerequisite for today’s industry and society.

Related information