Title: Coulomb Crystals for Clocks

Abstract

The combination of ion trapping and laser-cooling enables high precision measurements which are especially relevant for optical clocks. Trapping the ions of interest together with ions that are suitable for laser cooling results in a Coulomb-coupled solid-like state allowing for measurements with improved single particle sensitivity and reduced systematic frequency shifts. However an improved understanding of the origins and the control of systematic frequency shifts, including the development of novel reference transitions are needed.

Keywords

optical clock, nuclear clock, ion trap, laser cooling.

Background to the Metrological Challenges

Optical clocks with trapped ions are among the most precise frequency standards available today. However further improvements are needed to enable applications and to strengthen the high-level metrological infrastructure for the measurement of time and frequency. Improvements in reliability and precision of optical clocks with trapped atoms can provide input to the redefinition of the SI second, facilitate the exchange of technology and know-how between groups specialised in high-precision optical frequency metrology and groups at nuclear physics laboratories and make high precision methods developed for optical frequency standards in National Metrology Institutes available to a wider class of systems of scientific interest.

Coulomb crystals of many ions offer the opportunity to increase the stability of an optical clock through the simultaneous interrogation of many ions. Trapping the ions of interest together with ions that are suitable for laser cooling results in a Coulomb-coupled solid-like state would allow for measurements with improved single particle sensitivity and reduced systematic frequency shifts. Currently, the most precise trapped-ion optical clocks with an evaluated systematic uncertainty range of 10^{-18} are based on single highly charged ions (e.g. Al^+, In^+, Yb^+, Th^{3+}, Th^{4+}). In the case of Al^+, a second, so called logic ion is used for sympathetic cooling and state detection of the Al^+ ion via quantum logic. The structure and dynamics of the laser-cooled Coulomb crystals of ions need to be investigated to minimise the effects of kinetic energy and interaction between the ions. Also of relevance are the charge-to-mass ratios (that influence the spatial arrangement and motional coupling between the ions), and the cooling wavelengths, (ideally the cooling lasers radiation should not perturb the interrogation of the clock reference transition). A new approach to use several ions as a linear string on the field-free axis has been shown to attain below 10^{-18} uncertainty and improved stability.

Improved understanding of the origins and the control of systematic frequency shifts requires novel reference systems with higher immunity to field-induced systematic shifts. These novel systems include a low-energy nuclear transition in Th-229 and transitions in highly charged ions. The Th-229 trapped ion nuclear clock is a promising candidate for optical clocks as it features low sensitivities to field-induced systematic frequency shifts and the highest sensitivities in several clock-based tests of fundamental physics. A major obstacle for further work is the absence of a direct optical observation of the transition between nuclear ground state and isomer and a more precise value for the transition wavelength. The recent detection of the decay of the isomeric state via internal conversion electrons from Th-229 recoil ions from the U-233 activity opens a route towards experiments with trapped Th-229 ions in the isomeric state.

The main contributions to the systematic uncertainty with trapped ions arise from the chemical reactions and collisions of trapped ions with neutral atoms and molecules of the background gas. Important for the highly reactive Th ions is the ability to identify and eliminate causes of ion loss through the formation of molecular ions. This is also important for the uninterrupted long-term operation of all trapped-ion clocks. Experiments on collisional frequency shifts need to detect "soft" collisions that do not transfer sufficient energy to be detected in the fluorescence signal during laser cooling, but that may nevertheless perturb the phase during the clock interrogation. These experiments require the measurements of minute collision rates and will therefore benefit from the simultaneous use of many target ions.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on the traceable measurement and characterisation of Coloumb crystal ions for high precision optical clocks.

The specific objectives are

1. To minimise the effects of kinetic energy and interaction between the ions of laser-cooled Coulomb crystals to reduce systematic frequency shifts in optical clock applications by investigation of the structure and dynamics of laser-cooled two-species Coulomb crystals of ions of different masses and charge states.
2. To implement sympathetic cooling of highly charged clock relevant ions with suitable coolant ions to reduce systematic frequency shifts.
3. To develop efficient sources of Th-229 ions in charge states Th^{3+} and Th^{4+}, based on recoil ions from U-233. This should allow loading of an ion trap in ultrahigh vacuum from a source of less than 10 kBq U-233 activity.
4. To provide reliable estimates on collisional frequency shifts in trapped ion optical clocks by investigating chemical reactions and collisions of trapped ions with neutral atoms and molecules of the background gas. To identify and eliminate causes of ion loss through the formation of molecular ions.
5. To develop transportable equipment for laser cooling, high resolution spectroscopy and precision optical frequency measurements that enable common experiments to be carried out at nuclear physics laboratories and optical metrology laboratories.

Proposers shall give priority to work that aims at excellent science exploring new techniques or methods for metrology and novel primary measurement standards, and brings together the best scientists in Europe and beyond, whilst exploiting the unique capabilities of the National Metrology Institutes and Designated Institutes.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMRP project SIB04 and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.5 M€, and has defined an upper limit of 1.8 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 40 % of the total EU Contribution to the project.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the “end user” community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the “end user” community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,

You should detail other impacts of your proposed JRP as specified in the document “Guide 4: Writing Joint Research Projects (JRPs)”

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.