Q 52: Nuclear Clocks

In 2024, direct laser excitation of the 229-Th nuclear clock transition was achieved by three research groups. These breakthroughs have led to several orders of magnitude of improvement in the energy constraint of this nuclear state. With this knowledge, the implementation of a nuclear clock has started with a rapid succession of laser, ion trap and host material developments. A nuclear clock promises very high accuracy and stability as well as interesting applications in fundamental physics. This session highlights these exciting development with two invited and four contributed talks.

Time: Thursday 11:00–13:00 Location: HS Botanik

Invited Talk Q 52.1 Thu 11:00 HS Botanik

Recent progress towards the development of a ^{229}Th-based nuclear optical clock — •Lars von der Wense — Johannes Gutenberg-Universität Mainz

The development of a nuclear optical clock based on spectroscopy of the first nuclear excited state of the ^{229}Th isotope has long been in the scientific focus[1]. Significant progress has been made in the year 2024, when three independent research groups reported success in laser spectroscopy of this previoulsy elusive nuclear state[2,3,4]. In this talk, I will provide a review of the recent developments in the field, with a special focus on the JILA experiment[4], where direct frequency comb spectroscopy of the transition was achieved. In addition, I will provide an overview on the activities underway at the University of Mainz, where we are investigating the options for cw laser spectroscopy of the nuclear transition based on light generated via quasi-phase matching in $BaMgF_4$.

[1] L. von der Wense et al., Eur.Phys.J. A, 56:277 (2020).
[2] J. Tiedau et al., PRL 132, 182501 (2024).
[3] R. Elwell et al., PRL 133, 013201 (2024).
[4] C. Zhang et al., Nature 633, 63 (2024).

This work is supported by the BMBF Quantum Futur II Grant Project "NuQuant" (FKZ 13N16295A).

Q 52.2 Thu 11:30 HS Botanik

Towards a solid-state VUV CW Laser for the ^{229}Th Nuclear Clock — •Keerthan Subramanian[1], Nutan Kumari Sah[1], Florian Zacherl[1], Srinivasa Pradeep Arasada[1], Valerii Andriushkov[2,3], Yumiao Wang[1], Ke Zhang[1], Jonas Stricker[1,2,3], Christoph Düllmann[1,2,3], Dmitry Budker[1,2,3], Ferinand Schmidt-Kaler[1], and Lars von der Wense[1] — [1]Johannes Gutenberg Universität Mainz — [2]Helmholtz Institut Mainz — [3]GSI Helmholtzzentrum für Schwerionenforschung GmbH

In the entire nuclear energy landscape consisting of nearly 3300 isotopes and 176000 energy levels, ^{229}Th is the only isotope featuring an unusually low lying isomer with an energy 8.4eV above the ground state. Recent developments have succeeded in laser exciting this 148.3 nm Vacuum UltraViolet (VUV) transition and have paved the way for the development of a nuclear clock which is expected to outperform state of the art atomic clocks. VUV radiation precludes the use of compact, commercial tunable laser sources. It also limits the number of crystals which (a) are VUV-transparent, (b) have a significant nonlinear coefficient, and (c) are amenable to some form of (quasi-)phase matching. Here we present progress towards this goal of developing a compact solid-state frequency doubled Continuous Wave (CW) laser in periodically poled $BaMgF_4$. This key technological development would enable the realization of a nuclear clock which is expected to have profound implications for tests of fundamental physics. This work is supported by BMBF Quantum Futur II Grant Project "NuQuant" (FKZ13N16295A)

Q 52.3 Thu 11:45 HS Botanik

Towards Continuous-Wave Laser Excitation of the ^{229}Th Nuclear Isomer Sympathetically Cooled with Ca Ions — •Ke Zhang[1], Valerii Andriushkov[3,4], Yumiao Wang[1,2], Keerthan Subramanian[1], Srinivasa Pradeep Arasada[1], Florian Zacherl[1], Nutan Kumari Sah[1], Jonas Stricker[1,3], Christoph E. Düllmann[1,3,4], Dmitry Budker[1,3,4,5], Ferdinand Schmidt-Kaler[1], and Lars von der Wense[1] — [1]University of Mainz, Germany — [2]Fudan University, China — [3]Helmholtz Institute Mainz, Germany — [4]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany — [5]University of California, USA

We propose an experimental scheme for the laser excitation of the nuclear isomeric state in the $^{229}Th^{3+}$ ion system, a significant challenge in nuclear and atomic physics. Thorium ions are generated from a recoil ion source and guided into a Paul trap using a radio frequency quadrupole (RFQ) guide and a mass filter. Sub-Doppler-cooled $^{40}Ca^+$ ions are used to sympathetically cool the thorium ions to their motional ground state, where the ions are deeply confined in the Lamb-Dicke regime. A continuous-wave laser, stabilized to match the nuclear transition energy, will be employed to drive the isomeric transition. This experimental scheme aims to demonstrate the feasibility of precision nuclear spectroscopy in sympathetically cooled ion systems, paving the way for ion-based nuclear optical clocks and advancing fundamental physics research. This work is supported by the DFG Project 'TACTICa' (grant agreement no. 495729045) as well as the BMBF Quantum Futur II Grant Project 'NuQuant' (FKZ 13N16295A).

Q 52.4 Thu 12:00 HS Botanik

Buffer Gas Stopping Cell for Extraction of ^{229}Th Ions for Nuclear Clock Development — •Srinivasa Pradeep Arasada[1], Florian Zacherl[1], Keerthan Subramanian[1], Jonas Stricker[1,2], Valerii Andriushkov[2,3], Yumiao Wang[1,4], Nutan Kumari Sah[1], Ke Zhang[1], Ferdinand Schmidt-Kaler[1], Dmitry Budker[1,2,3,5], Christoph E Düllmann[1,2,3], and Lars von der Wense[1] — [1]Johannes Gutenberg Universität Mainz, Germany — [2]Helmholtz Institute Mainz, Germany — [3]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany — [4]Fudan University, Shanghai, China — [5]Department of Physics, University of California, Berkeley, USA

The isomeric state of ^{229}Th offers a unique opportunity for precision spectroscopy due to its exceptionally low excitation energy, making it most suitable for developing nuclear clocks with unprecedented accuracy. The isomeric state in ^{229}Th can be populated via a 2% decay branch during α decay of ^{233}U. Here we outline our plans for extracting thorium ions from a ^{233}U recoil-ion source using a buffer gas stopping cell. The system utilizes ultra-pure helium gas to minimize substantial losses caused by charge exchange or molecular formation. The extracted Th^{3+}ions are subsequently loaded into a Paul trap via a radio frequency quadrupole (RFQ) guide and Quadrupole Mass Spectrometer(QMS), where they are co-trapped with laser-cooled $^{40}Ca^+$ ions for spectroscopic interrogation.

This project is supported by the BMBF Quantum Futur II Grant Project 'NuQuant'(FKZ 13N16295A).

Q 52.5 Thu 12:15 HS Botanik

Construction and Commissioning of a Closed-Cycle Xenon-Recycling System for HHG-based VUV Lasers — •Georg Holthoff, Tim Teuner, and Peter G. Thirolf — Ludwig-Maximilians-Universität, München, Deutschland

We discuss the need for and design, construction and commissioning of a closed-cycle Helium:Xenon-recovery system designed to scavenge, filter and recompress variable mixtures of Helium and Xenon (up to 9:1) to pressures of up to 100 bar for use in High-Harmonic Generation (HHG) based Vacuum Ultraviolet (VUV) laser-light generation. The relevant components of the system, i.e. first collection from the HHG enhancement-resonator chamber where the gas is used and its filtering at ambient pressure, second, compression to the planned operating range of 60 bar in two stages and third final filtering and pressure stabilization, as well as the control system, are discussed. Subsequently, the commissioning results are presented. They include operational tests of components, leak testing using different methods and gases (aiming for a total recovery efficiency of about 98%), as well as mass-spectrometric analysis of residual gasses at different stages of the system. Characterization results are acquired in a closed-loop test setup, using a borosilicate gas-injection nozzle of dimensions similar to those in the designated VUV frequency-comb laser. Instead of the HHG enhancement resonator of this laser, the injection chamber of the test loop is comprised of an additional small vacuum chamber to not endanger the

laser components during commissioning of the gas-recycling system.
Supported by the European Research Council (ERC): Grant 856415.

Invited Talk Q 52.6 Thu 12:30 HS Botanik

Making a solid-state nuclear optical clock — •Kjeld Beeks[1,2], Luca Toscani de Col[2], Ira Morawetz[2], Rahul Singh[1], Michael Bartokos[2], Thomas Riebner[2], Fabian Schaden[2], Georgy Kazakov[2], Tomas Sikorsky[2], Thomas LaGrange[1], Fabrizio Carbone[1], and Thorsten Schumm[2] — [1]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland — [2]TU Wien, Vienna, Austria

The first nuclear excited state or isomer of ^{229}Th has an extremely low energy (8.4 eV/148 nm) and long lived (1750 s) excited state. This is a platform for a future extremely precise nuclear optical clock, on the 10^{-17} level for Th doped in CaF_2. Owing to its nuclear nature, it would be a new sensitive probe for fundamental physics. Recently, a string of successes led to nuclear spectroscopy on the 300 kHz level. The successes hinges on the development of a highly doped VUV transparent CaF_2 crystal, doped with the radioactive ^{229}Th. In this talk I will elaborate on how the crystal platform was originally developed and characterized: Crystal growth and crystal healing. More recently, an indication appeared why previous attempts of excitation in a crystal were unsuccessful: The nuclear excitation quenches through an interaction with the solid-state environment. I will further report a diverse array of new measurements and calculations characterizing the interaction and the solid-state environment of ^{229}Th:CaF_2 crystals. These measurements and calculations show we can control the interaction of the nucleus with its environment. With every characterization, and every simulation, the solid-state nuclear clock comes a step closer.