Q 13: Nuclear Clocks

Time: Monday 17:00–19:00 Location: P 11

Q 13.1 Mon 17:00 P 11

Setup for Laser Excitation of the ^{229}Th Nucleus in a Cryogenic Environment — •Florian Zacherl[1], Lennart Guth[2], Jan-Hendrik Oelmann[2], Anant Agarwal[2], Tobias Heldt[2], Keerthan Subramanian[1], Srinivasa Pradeep Arasada[1], Valerii Andriushkov[3,4], Ke Zhang[1], Yumiao Wang[1,5], Darius Fenner[1], José R. Crespo López-Urrutia[2], Christoph E. Düllmann[1,3,4], Dmitry Budker[1,3,4,6], Thorsten Schumm[7], Ferdinand Schmidt-Kaler[1], and Lars von der Wense[1] — [1]Johannes Gutenberg University Mainz, Germany — [2]Max-Planck-Institut für Kernphysik, Heidelberg, Germany — [3]Helmholtz Institute Mainz, Germany — [4]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany — [5]Fudan University, Shanghai, China — [6]University of California, Berkeley, USA — [7]Vienna University of Technology, Austria

The low isomeric energy level of only 8.4 eV in ^{229}Th places the transition wavelength in the vacuum-ultraviolet (VUV) and therefore provides the unique opportunity to excite it with optical lasers. The described setup aims to excite the nuclei of Th^{4+} ions in a Th : CaF_2 crystal at around 148 nm with a VUV frequency comb. The crystal is placed and excited in a He cryogenic environment to probe for temperature dependent transition frequency shifts as well as variations in decay time at very low temperatures down to 4 K.

This work is supported by the BMFTR Quantum Futur II Grant Project *NuQuant* (FKZ 13N16295A) and DFG Project *TACTICa* (grant agreement no.495729045).

Q 13.2 Mon 17:15 P 11

Commissioning of a Low-Energy Ion Beamline for Future ^{229}Th Nuclear Clock Applications Using a Cs Ion Source as a Proxy — •Srinivasa Pradeep Arasada[1], Florian Zacherl[1], Valerii Andriushkov[2,3], Keerthan Subramanian[1], Jonas Stricker[1,2], Ke Zhang[1], Yumiao Wang[1,4], Darius Fenner[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]University of California, Berkeley, USA

The development of a ^{229}Th nuclear clock requires robust methods for extracting and preparing low-energy thorium ion beams. As a critical step toward this goal, we report the successful commissioning of a new ion beamline, comprising a buffer-gas stopping cell for thermalization and an RFQ ion guide for beam cooling. Using a stable cesium beam as a proxy for future ^{229}Th experiments, we have established and optimized the complete ion transport sequence. A MCP detector provided clear evidence that the ions were successfully extracted, guided, and detected. This work validates the core functionality of the apparatus and establishes the necessary baseline for subsequent efficiency measurements and the future integration of a ^{233}U source at the University of Mainz. This project is supported by the BMFTR Quantum Futur II Grant Project *NuQuant*(FKZ 13N16295A) and DFG Project *TACTICa*(grant agreement no.495729045).

Q 13.3 Mon 17:30 P 11

Towards lifetime measurement of the nuclear clock isomer ^{229m}Th^{3+} via hyperfine laser spectroscopy in a cryogenic Paul trap — •Georg Holthoff, Kevin Scharl, Tamila Teschler, Daniel Moritz, Markus Wiesinger, and Peter G. Thirolf — Ludwig-Maximilians-Universität München

The Thorium-229 isomer with its uniquely low lying 8.4 eV nuclear excited state is the so far most promising candidate for a nuclear frequency standard ('nuclear clock'). Due to the long lifetime of the excited state (ca. 2000 s in vacuum, expected to be measured precisely in our experiment), thus low emission rate, and ca. 148.4 nm VUV wavelength of the emitted photon, direct fluorescence detection is extremely difficult in the trapped ion approach. At LMU Munich, determining if nuclear excitation of ^{229m}Th^{3+} in our cryogenic Paul trap has occurred will therefore be performed via a double-resonance method as proposed in 2003 by Peik et al. For this we discuss predictions of the hyperfine structure of the ground and isomeric state as well as the isomer shift. Ongoing experimental work on hyperfine spectroscopy of sympathetically laser-cooled ^{229m}Th^{3+} will also be presented. The choice of hyperfine transitions to differentiate the two states and the influence of their addressing scheme is discussed for both 690 nm and 984 nm lasers. Furthermore, experimental results for different hyperfine addressing schemes using EOMs driven by voltage controlled oscillators (VCOs) are discussed. Supported by the European Research Council (ERC): Grant 856415.

Q 13.4 Mon 17:45 P 11

A cryogenic Paul trap for spectroscopy of the nuclear clock isomer ^{229m}Th^{3+} — •Markus Wiesinger, Georg Holthoff, Kevin Scharl, Tamila Teschler, Daniel Moritz, and Peter G. Thirolf — Ludwig-Maximilians-Universität München

The ^{229}Th nucleus has the unique property of an extremely low lying isomeric first excited state (denoted ^{229m}Th). With an excitation energy of 8.356 eV – corresponding to a wavelength of 148.4 nm – and an expected lifetime of the ionic thorium isomer in vacuum of about 2000 s, the isomeric state can be directly excited with laser light from state-of-the-art VUV laser systems. Consequently, ^{229}Th is the ideal candidate for a nuclear optical clock. Furthermore, the nuclear clock transition has an about 10^3 times larger sensitivity to time variation of the fine structure constant compared to transitions in other atoms.

While the isomeric state was recently directly excited with laser light in ^{229}Th doped CaF_2 and other solid-state crystals, the nuclear clock project at LMU focusses on the trapped ion approach with laser-cooled ^{229}Th^{3+}, which features suitable electronic transitions for fast nuclear state readout and extremely low systematic uncertainties.

This talk will give an overview of the cryogenic Paul trap apparatus routinely applied for sympathetic laser-cooling of $^{229(m)}$Th^{3+} ions embedded in mixed-species $^{229(m)}$Th^{3+}/^{88}Sr^{+} Coulomb crystals. We will show simultaneous fluorescence imaging of trapped ^{88}Sr^{+} ions at 422 nm and ^{229}Th^{3+} ions at 690 nm using two cameras, laying the foundations for measuring the lifetime of ^{229m}Th^{3+} in vacuum and for quantum state readout after VUV excitation of the nuclear transition.

Q 13.5 Mon 18:00 P 11

Towards Continuous-Wave Laser Excitation of the Th-229 Nuclear Isomer Sympathetically Cooled with Ca Ions — •Ke Zhang[1], Valerii Andriushkov[2,3], Yumiao Wang[1], Darius Fenner[1], Keerthan Subramanian[1], Florian Zacherl[1], Srinivasa Pradeep Arasada[1], Jonas Stricker[1,2], Christoph E. Düllmann[1,2,3], Dmitry Budker[1,2,3,4], Ferdinand Schmidt-Kaler[1], and Lars von der Wense[1] — [1]Johannes Gutenberg University Mainz, Germany — [2]Helmholtz Institut Mainz, Germnay — [3]GSI Helmholtzzentrum für Schwerionenforschung — [4]Department of Physics, University of California, Berkeley, USA

We investigate an experimental scheme for the continuous-wave laser excitation of the nuclear isomeric state in ^{229}Th^{3+}. Thorium recoil ions are extracted from a radioactive source, mass-selected to obtain purified ^{229}Th^{3+}, and injected into a linear Paul trap via an RF quadrupole guide. Inside the trap, the ^{229}Th^{3+} ions are sympathetically cooled through Coulomb interaction with sub-Doppler-cooled ^{40}Ca^{+} ions, reaching the motional ground state in the Lamb–Dicke regime. A continuous-wave laser stabilized to the expected nuclear transition energy will coherently drive the isomeric transition. This approach aims to demonstrate the feasibility of precision nuclear spectroscopy in a sympathetically cooled trapped-ion system, enabling the way for ion-based nuclear optical clocks and advancing fundamental research in nuclear and atomic physics. The work is supported by the DFG Project *TACTICa* (grant agreement no. 495729045) and the BMFTR Quantum Futur II Project *NuQuant* (FKZ 13N16295A).

Q 13.6 Mon 18:15 P 11

A solid-state VUV laser at 148.4 nm for the ^{229m}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], Darius Fenner[1], Gaurav Jha[1], Jonas Stricker[1,2,3], Christoph E. Düllmann[1,2,3], Dmitry Budker[1,2,3,4], Ferdinand Schmidt-Kaler[1], and Lars von der Wense[1] — [1]Johannes Gutenberg Universität Mainz — [2]Helmholtz Institut Mainz — [3]GSI Helmholtzzentrum für Schwerionenforschung — [4]University of California, Berkeley

The recent laser excitation of ^{229m}Th has ushered in a new era with the prospect of building a nuclear clock with unprecedented stability and susceptibility to the variation of fundamental constants. A continuous-wave (cw) clock laser at 148.4 nm is indispensable for the realization of such a clockwork based ^{229m}Th.

$BaMgF_4$ (BMF) is a suitable candidate for second harmonic generation (SHG) due to its second order non-linearity, high VUV transparency and ferroelectric properties making it amenable to periodic poling (pp). In order to reach reasonable powers, ppBMF is placed inside an enhancement resonator and intracavity SHG is performed. The projected powers make it a viable scheme for the realization of a compact all solidstate cw laser necessary for the realization of a solid-state as well as a single-ion nuclear clock. Recent progress towards this goal will be presented. This work is supported by BMFTR Quantum Futur II Grant NuQuant under grant agreement no FKZ 13N16295A.

Q 13.7 Mon 18:30 P 11

Design and optimization of a VUV beamline for nuclear laser excitation of a single ^{229}Th^{3+} ion — •Tamila Teschler[1], Georg Holthoff[1], Daniel Moritz[1], Kevin Scharl[1], Markus Wiesinger[1], Johannes Weitenberg[2], Stephan H. Wissenberg[2], and Peter G. Thirolf[1] — [1]Ludwig-Maximilians-Universität München (LMU) — [2]Fraunhofer Institute for Laser Technology (ILT), Aachen

Direct frequency-comb spectroscopy represents an advanced technique for achieving narrowband nuclear laser excitation. Within an ERC Synergy project, a VUV frequency comb developed at Fraunhofer ILT will be combined with a cryogenic Paul trap system at LMU Munich to enable the excitation of the isomeric state in ^{229}Th using laser radiation at $\lambda \approx 148\,\text{nm}$. This is a major milestone toward the implementation of a nuclear clock based on the unique nuclear properties of the nuclear isomer ^{229}Th, enabling highly precise timekeeping and providing insights into new physics beyond the Standard Model. The approach relies on frequency-comb interrogation of a single, sympathetically laser-cooled ^{229m}Th^{3+} ion. To ensure sufficient excitation probability, a VUV focus diameter of about $3\,\mu$m is required, imposing strict limitations on the optical beamline design to minimize aberrations and transmission loss. The procedures for the design and optimization of a VUV beamline from the VUV laser source to the trapped-ion environment will be presented. Funding: Thorium Nuclear Clock ERC Synergy project, Grant Agreement No. 856415.

Q 13.8 Mon 18:45 P 11

Towards nuclear laser excitation of ^{229}Th ions — •Vishal Lal, S. Sagar Maurya, Gregor Zitzer, Niels Irwin, Johannes Tiedau, Maksim V. Okhapkin, and Ekkehard Peik — Physikalisch-Technische Bundesanstalt, Braunschweig

The recently demonstrated laser excitation of low-energy nuclear transition in ^{229}Th using table-top laser systems, has opened prospects for a new generation of optical clocks based on a nuclear transition. Since the nucleus itself is much smaller, much less polarizable and very well shielded by the electrons around, the effect of external electric fields and field gradients are expected to be significantly smaller compared to electronic transition used in most of the state-of-the-art optical atomic clocks (trapped ions and optical lattice clocks). The laser excitation of the nucleus can be detected efficiently in a double-resonance method by probing the hyperfine structure of a transition in the electron shell.

We here report our experimental setup and advances in laser excitation of the ^{229}Th nucleus and relevant hyperfine structure suitable for nuclear spectroscopy in buffer gas cooled of ^{229}Th^{1+}, ^{229}Th^{2+}, and sympathetically laser cooled ^{229}Th^{3+} ions.