Novel optical clocks in atoms and nuclei

676. WE-Heraeus-Seminar

July 9 - 12, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. By German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Aims and scope of the 676. WE-Heraeus-Seminar:

The goal of the seminar is to discuss conceptually novel approaches to optical frequency standards and clocks. Despite the remarkable precision already realized in current atomic clock worldwide, there is a wide range of concepts for next-generation devices, rooted in very different physical systems. The aim of the seminar is to provide a comprehensive overview on the current state of discussion and shape a community.

A special candidate for a future optical clock is the low-energy isomeric state in Thorium-229, opening the road towards nuclear clocks. The Wilhelm and Else Heraeus Seminar will resume the current state of knowledge on this exciting system and connect the worldwide community in this field. The seminar is jointly organized with the EU-FET-Open consortium of **nuClock**.

Also, we want to identify and discuss new applications of precision frequency and time standards, in particular regarding constraining possible variations of fundamental constants, clock-based geodesy, and gravitational wave detection.

Scientific Organizers:

PD Dr. Ekkehard Peik — Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, E-mail : Ekkehard.Peik@ptb.de

Prof. Thorsten Schumm — Technische Universität Wien, Austria, E-mail: thorsten.schumm@tuwien.ac.at

Prof. Simon Stellmer — Universität Bonn, Germany, E-mail: stellmer@uni-bonn.de

Program

Program

Sunday, July 8, 2018

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and get-together*	

Monday, July 9, 2018

08:00	*BREAKFAST*	
08:50 – 09:00	Scientific organizers	**Welcome & Opening**
09:00 – 10:00	Ekkehard Peik	**Th-229 as an optical nuclear clock**
10:00 – 10:30	*COFFEE & TEA*	
10:30 – 11:15	Andreas Fleischmann	**Indirect determination of the Thorium-229 isomer energy by high resolution gamma spectroscopy**
11:15 – 12:00	Christian Schneider	**Direct search for the ^{229}Th nuclear isomeric transition with Th-doped crystals**
12:00 – 12:10	**Conference photo** (in the front of the lecture hall)	
12:15	*LUNCH (followed by coffee and/or tea)*	

Program

Monday, July 9, 2018

13:45 – 14:15	Thorsten Schumm	**Two attempts to measure the Thorium-229 isomer energy**
14:15 – 14:45	Akihiro Yoshimi	**Nuclear resonant scattering of ^{229}Th for observation of radiative isomeric transition**
14:45 – 15:15	Beata Zjawin	**Analysis of optical atomic clocks readouts aimed on searches for dark-matter signatures**
15:15 – 15:45	*COFFEE & TEA*	
15:45 – 16:15	Matthias Verlinde	**Study of $^{22\,m}$Th: Laser ionization and VUV spectroscopy**
16:15 – 16:45	Petr Borisyuk	**Excitation of ^{229}Th nuclei in laser plasma: the energy and half-life of the low-lying isomeric state**
16:45 – 17:15	Adriana Pálffy-Buß	**Nuclear and atomic structure calculations for the ^{229}Th isomeric state**
17:15 -18:45	**Poster session**	
19:00	*DINNER*	

Program

Tuesday, July 10, 2018

08:00	*BREAKFAST*	
09:00 – 10:00	Peter Thirolf	**The fog disperses: What do we know about the elusive ^{229}Th isomer ?**
10:00 – 10:30	*COFFEE & TEA*	
10:30 – 11:15	Benedict Seiferle	**Internal conversion electron spectroscopy of ^{229m}Th**
11:15 – 12:00	Christoph Heyl	**Power-scaling VUV/XUV frequency combs: Recent results and prospects**
12:15	*LUNCH (followed by coffee and/or tea)*	
13:45 – 14:15	Feodor Karpeshin	**Physics of laser-assisted nuclear processes as the base for creation of the nuclear clock**
14:15 – 14:45	Julian Berengut	**Atomic calculations in multivalent ions with applications to novel clocks**
14:45 – 15:15	Martin Henriksen	**Acetylene frequency reference**
15:15 – 15:45	*COFFEE & TEA*	
15:45	**Excursion**	
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet and complimentary drinks)*	

Program

Wednesday, July 11, 2018

08:00	*BREAKFAST*	
09:00 – 10:00	Marianna Safronova	**Novel atomic clocks and the search for new physics**
10:00 – 10:30	*COFFEE & TEA*	
10:30 – 11:15	Andrew Ludlow	**High stability optical clock based on Ramsey-Borde interferometry in thermal calcium**
11:15 – 12:00	Atsushi Yamaguchi	**Laser cooling of cadmium towards an optical lattice clock**
12:15	*LUNCH (followed by coffee and/or tea)*	
13:45 – 14:15	Nils Huntemann	**$^{171}Yb^{+}$ single-ion optical clocks**
14:15 – 14:45	Stefan A. Schäffer	**Lasing on a forbidden transition in a thermal cloud of Strontium atoms**
14:45 – 15:15	Tanja Mehlstäubler	**Clocks based on complex Coulomb systems**
15:15 – 15:45	*COFFEE & TEA*	

Program

Wednesday, July 11, 2018

15:45 – 16:15	David Champion	**Pulsars as cosmic clocks**
16:15 – 16:45	Pacôme Delva	**A gravitational redshift test using eccentric Galileo satellites**
16:45 – 17:15	Jean Lautier Gaud	**Enabling the remote comparison of novel optical clock signals with state-of-the-art optical frequency standards**
17:15 -18:45	**Poster session / nuClock consortium meeting**	
19:00	*DINNER*	

Program

Thursday, July 12, 2018

08:00	*BREAKFAST*	
09:00 – 10:00	José R. Crespo López-Urrutia	**Electronic transitions in highly charged ions with possible applications to the electron-nucleus bridge mechanism**
10:00 – 10:30	*COFFEE & TEA*	
10:30 – 11:15	Viktor Flambaum	**Effects of dark matter, variation of the fundamental constants and violation of the fundamental symmetries in nuclear and atomic clocks**
11:15 – 12:00	Michal Zawada	**Dark matter searches within the intercontinental optical atomic clock network**
12:00 – 12:15	Scientific organizers	**Closing**
12:15	*LUNCH (followed by coffee and/or tea)*	

End of the seminar and departure

NO DINNER for participants leaving on Friday morning

Posters

Posters

Ines Amersdorffer	**Towards $^{229m}Th^{1+}$ lifetime measurements**
Prannay Balla Philip Pfäfflein	**Towards precision spectroscopy with VUV/XUV-frequency-combs**
Kjeld Beeks	**Excimer VUV light source for Th-229 experiments**
Pavlo Bilous	**Laser-induced electronic bridge for characterization of the Th-229 isomer transition**
Przemysław Glowacki	**Luminescence study of Ln(III) ions adsorbed on a CaF_2 surface as supplementary investigation for searching the isomeric transition in ^{229}Th solid samples**
Christoph Hotter	**A superradiant clock laser on an optical lattice with moving atoms**
Xia Hua	**Searching for the first excited nuclear state of ^{229}Th using $^{229}Th^{3+}$ coulomb crystal**
Asbjørn A. Jørgensen	**Folded-beam waist-expanding cavity for iodine based frequency reference**
Georgy Kazakov	**Possibility of laser stabilization with trapped cavity-coupled ions**
Michael Kolbe	**The MLS-IDB: A versatile beamline for applications in the UV to soft X-ray spectral range**
Sandro Kraemer	**Vacuum ultraviolet and laser ionization spectroscopy studies of ^{229m}Th**
Mustapha Laatiaoui	**Studying quenching of metastable atomic states in Th IV**

Posters

Yury Lebedinskii	**Photoelectron spectroscopy technique for the energy measuring of photons emitted from the excited ^{229m}Th nuclei**
Xinwen Ma	**A potential precision method to determine the nuclear isomeric states in 229Th at storage ring**
David-Marcel Meier	**Search for laser excitation of the low energy isomer in trapped Th^{+} ions**
Janni Moens	**Investigating the local atomic structure of Th dopants in CaF_2 using channeling techniques**
Brenden Nickerson	**The ^{229m}Th nuclear isomer in Th-doped crystal environments**
Laurin Ostermann	**Super- and subradiance of a 1D chain of clock atoms trapped inside an optical fiber**
Ilkka Pohjalainen	**Filament dispensers, recoil sources, and on-line production for ^{229}Th ion beams at IGISOL**
Jens Rauschenberger	**Spectrometers tailored for Thorium isomer emission**
Simon Stellmer	**A new quantum metrology group at the University of Bonn**
Johannes Thielking	**Laser spectroscopic characterization of the nuclear clock isomer ^{229m}Th**
Lars von der Wense	**A direct nuclear laser excitation scheme for ^{229m}Th**
Johannes Weitenberg	**XUV frequency combs**
Gregor Zitzer	**Towards sympathetic cooling of trapped $^{229}Th^{3+}$ ions**

Abstracts of Talks

(in chronological order)

Th-229 as an optical nuclear clock

E. Peik

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

The prospect of driving a low-energy nuclear gamma-ray transition in Th-229 coherently with a frequency-stable laser has stimulated numerous innovative ideas and proposals. The selection of a suitable electronic state for the nuclear excitation makes the nuclear transition frequency insensitive against field-induced systematic frequency shifts to a degree that is not obtainable in electronic transitions. A nuclear clock based on laser-cooled and trapped thorium ions will benefit from this advantage. Complementary, the obtainable isolation of the nucleus in a wide-bandgap dielectric creates the opportunity to interrogate many Th-229 nuclei as dopants in a solid. While a precise value for the Th-229 nuclear transition energy and an experimental demonstration of resonant optical excitation are still missing, experiments with Th-229 recoil ions from the alpha decay of U-233 have recently provided information on fundamental nuclear properties of the isomer [1]. I will review the ideas and concepts for highly precise Th-229 nuclear clocks [2] and the status of the experimental search for laser excitation of the nucleus in trapped ions at PTB.

References

[1] J. Thielking, M. V. Okhapkin, P. Glowacki, D. M. Meier, L. v. d. Wense, B. Seiferle, C. E. Düllmann, P. G. Thirolf, E. Peik: *Laser spectroscopic characterization of the nuclear clock isomer 229mTh*, arXiv:1709.05325 (2017)

[2] E. Peik, M. Okhapkin, C. R. Phys. **16**, 516 (2015)

Indirect determination of the Thorium-229 isomer energy by high resolution gamma spectroscopy

J. Bussmann[1], A. Fleischmann[1], J. Geist[1], L. Gastaldo[1], D. Hengstler[1], S. Kempf[1], C. Enss[1], P. Thirolf[2], C. Düllmann[3,4], G.A. Kazakov[5], S.P. Stellmer[5], and T. Schumm[5]

[1] *Heidelberg University, Germany*
[2] *LMU Munich, Germany*
[3] *Helmholtz-Institute Mainz, Germany*
[4] *JG University Mainz, Germany*
[5] *Vienna University of Technology, Austria*

The isotope Th-229 has a nuclear isomer state with the lowest presently known excitation energy, which possibly allows to connect the fields of nuclear and atomic physics with a potential application in a nuclear clock. In order to improve the accuracy of the currently most accepted energy value, (7.8±0.5) eV, we are currently performing high resolution gamma spectroscopy of transitions between the lowest 5 nuclear states of Th-229, as there are several strategies to derive the isomer energy. Resolving the 29.18 keV doublet in the γ-spectrum, corresponding to the decay into the ground and isomer state, the isomer transition energy can be determined without additional theoretical input parameters.

We present the maXs detector systems developed for this survey, consisting of arrays of metallic magnetic micro-calorimeters, optimized for photons up to 30 keV with energy resolutions which have the potential to even resolve the doublet at 29 keV which is split by the isomer energy.

We present the design considerations and the present status of the experiment. We discuss preliminary results including statistical and systematic uncertainties.

Direct Search for the ^{229}Th Nuclear Isomeric Transition with Th-doped Crystals

Christian Schneider[1], Justin Jeet[1], Eugene V. Tkalya[2,3], and Eric R. Hudson[1]

[1] *Department of Physics and Astronomy, University of California, Los Angeles, USA*
[2] *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Russia*
[3] *Nuclear Safety Institute of Russian Academy of Science, Moscow, Russia*

The nucleus of ^{229}Th has an exceptionally low-energy isomeric transition in the vacuum-ultraviolet (VUV) spectrum around $7.8 \pm 0.5\,\mathrm{eV}$ or $\approx 159\,\mathrm{nm}$ [1, 2]. While inaccessible to standard nuclear physics techniques, there are various prospects for a laser-accessible nuclear transition.

As both the transition energy and lifetime have large uncertainties, we first establish a lifetime-vs.-energy region-of-interest (ROI) [3]. This ROI is based on the currently accepted energy of the transition of $7.8 \pm 0.5\,\mathrm{eV}$ as well as phenomenological calculations for the lifetime and is the basis for our experimental searches.

Next, we report on a direct search for the nuclear isomeric transition in ^{229}Th using VUV-transparent Th-doped crystals [4, 5] as samples. Conceptually, the search is simple: A crystal is illuminated with a tunable VUV source in an attempt to excite some of the ^{229}Th nuclei into the isomeric state. Subsequently, the fluorescence off the crystal is analyzed for exponential-decay signatures compatible with a deexcitation of ^{229}Th nuclei.

In a first experiment using a synchrotron beamline at the Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory (LBNL) as a tunable light source, we were able to exclude a large portion of the lifetime-vs.-energy ROI [6].

A follow-up experiment is currently underway at UCLA. A home-built pulsed VUV laser system provides about the same photon flux as the ALS beamline, however, with significantly reduced linewidth and extended tuning range. This allows to search with orders of magnitude enhanced sensitivity over the previous search and to cover the entire ROI. We report on preliminary results and an updated lifetime-vs.-energy exclusion.

---

1. B. R. Beck et al.: Phys. Rev. Lett. **98**, 142501 (2007)
2. B. R. Beck et al.: LLNL-PROC-415170 (2009)
3. E. V. Tkalya et al.: Phys. Rev. C **92**, 054324 (2015)
4. R. A. Jackson et al.: J. Phys.: Condens. Matter **21**, 325403 (2009)
5. W. G. Rellergert et al.: Phys. Rev. Lett. **104**, 200802 (2010)
6. J. Jeet et al.: Phys. Rev. Lett. **114**, 253001 (2015)

Two attempts to measure the Thorium-229 isomer energy

Y. Shigekawa[5], Y. Kasamatsu[5], A. Shinohara[5], H. Kaser[4], M. Kolbe[4], M. Schreitl[1], V. Rosecker[1], G. Kazakov[1,3], S. Stellmer[1,2], T. Schumm[1]

[1]*Atominstitut, TU Wien, Austria*
[2]*Physikalisches Institut, University of Bonn, Germany*
[3]*Wolfgang Pauli Institute, Vienna, Austria*
[4]*Physikalisch-Technische Bundesanstalt, Berlin, Germany*
[5]*Graduate School of Science, Osaka University, Japan*
E-mail: thorsten.schumm@tuwien.ac.at

We report on two different experiments to determine the energy and lifetime of the low-energy isomeric state in Thorium-229.

The first experiment [1] attempts to optically excite ground-state Th-229, embedded in a transparent single crystal matrix by exposing it to intense VUV synchrotron radiation provided by the metrology light source (MLS) in Berlin. We report on the observed signal and background sources and the conclusions that can be drawn from this measurement concerning energy and lifetime of the isomer.

The second experiment [2] aims at determining the energy of internal conversion electrons that are emitted after U-233 decay, populating the Th-229 isomer with 2% branching ratio. Here, we employ an alpha-electron coincidence scheme and U-233 directly deposited onto an alpha detector.

[1] Stellmer et al., arXive:1803.09294
[2] Stellmer et al., arXive:1805.04929

Nuclear resonant scattering of ^{229}Th for observation of radiative isomeric transition

A. Yoshimi[1], K. Yoshimura[1], H. Hara[1], T. Hiraki[1], K. Imamura[1], H. Kaino[2], Y. Kasamatsu[7], S. Kitao[4], Y. Kobayashi[4], K. Konashi[6], R. Masuda[4], T. Masuda[1], Y. Miyamoto[1], N. Sasao[1], K. Okai[2], O. Sato[2], M. Seto[4], Y. Shigekawa[7], T. Schumm[8], S. Stellmer[8], K. Suzuki[2], R, Fujieda[2], S. Uetake[1], M. Watanabe[6], A. Yamaguchi[5], Y. Yasuda[7], Y. Yoda[3], M. Yoshimura[1]

[1]Research Institute for Interdisciplinary Science, Okayama University, Japan
[2]Graduate School of Natural Science and Technology, Okayama University, Japan
[3]Japan Synchrotron Radiation Research Institute, Japan,
[4]Research Reactor Institute, Kyoto University, Japan, [5]RIKEN, Japan,
[6]Institute for Materials Research, IRCNMS, Tohoku University, Japan,
[7]Department of Chemistry, Graduate School of Science, Osaka University, Japan,
[8]Institute for Atomic and Subatomic Physics, TU Wien, Austria.

The extraordinarily low-energy isomeric state of ^{229}Th nucleus (^{229m}Th) has attracted considerable attention recently, since a range of possible isomeric energies of 6.3 - 18.3eV was indicated through the detection of the internal conversion electrons [1]. Although such the low-energy nuclear level is expected to be the potential for ultra-precise "nuclear clock" that could be the new temporal standard, the isomeric energy and its radiative lifetime must be determined experimentally. Spectroscopic measurement of the radiative emissions from the ^{229m}Th is the best way to determine its energy and lifetime precisely. We propose an experimental procedure for populating the isomeric state using 29.19-keV Synchrotron Radiation (SR) to excite the ground state into a higher nuclear level ((a) in Fig.1), where the experimental confirmation of this excitation in advance of observing isomeric transition (c) through detection of de-excitation signal (b) is performed. This measurement, known as Nuclear Resonant Scattering (NRS), is suitable for the isomeric spectroscopies because of its independence on the uncertainties about the isomer level, but requires higher time resolution for the ^{229}Th than that of conventional NRS experiments. We will report on the developments of the experimental devices and the ^{229}Th-target system, and the present status of the ^{229}Th-NRS experiments at the SPring-8 synchrotron facility in Japan [2,3].

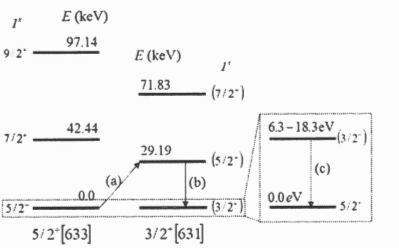


Fig.1 The lower energy level

[1] L. von der Wense et al., Nature 533, 47 (2016), B. Seiferle et al., Phys. Rev. Lett. 118, 042501 (2017).
[2] T. Masuda et al., Rev. Sci. Inst. 88, 063105 (2017).
[3] A. Yoshimi et al., Phys. Rev. C **97**, 024607 (2018).

Analysis of optical atomic clocks readouts aimed on searches for dark-matter signatures

B. Zjawin[1], P. Ablewski[1], K. Beloy[2], S. Bilicki[1,3], M. Bober[1], R. Brown[2], R. Ciuryło[1], R. Fasano[2], H. Hachisu[4], T. Ido[4], J. Lodewyck[2], A. Ludlow[2], W. McGrew[2], P. Morzyński[1,4], D. Nicolodi[2], M. Schioppo[2], M. Sekido[4], R. Le Targat[3], P. Wcisło[1], P. Wolf[3], X. Zhang[2] and M. Zawada[1]

[1]Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Poland

[2]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

[3]SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, LNE, 61 avenue de l'Observatoire, 75014 Paris, France

[4]National Institute of Information and Communications Technology 4-2-1 Nukuikitamachi, Koganei, 184-8795 Tokyo, Japan

Email: 279076@fizyka.umk.pl

Astrophysical observations indicate that the Universe contains five times more dark matter than standard matter, however its nature still remains an unsolved mystery. Dark matter candidates like topological defects and oscillating massive scalar fields can be searched for by a single optical atomic clock [1, 2]. We describe the optical atomic clocks readouts analysis and provide a recipe for analysing data from transcontinental network made of already existing optical atomic clocks. We describe, basing on Very-Long-Baseline Interferometry (VLBI) procedures, how to correlate the data obtained from already operating optical atomic clocks. We discuss methods of computing cross-correlation of more than two readouts. We present how to obtain topological defect velocity space distribution from the data. Furthermore, we discuss how to filter the readouts in order to restrict desirable frequency range and improve already existing limits on oscillating massive scalar fields couplings to standard matter. We also show how to analyse the data from a network of many clocks to exceed previously reported limits on such couplings.

References

[1] A. Arvanitaki, J. Huang, and K. Van Tilburg, "Searching for dilaton dark matter with atomic clocks", Phys. Rev. D, vol. **91**, p. 015015, 2015

[2] P. Wcisło, P. Morzyński, M. Bober, A. Cygan, D. Lisak, R. Ciuryło, and M. Zawada, "Experimental constraint on dark matter detection with optical atomic clocks", Nat. Astro., vol. **1**, p. 0009, 2016

Study of ^{229,m}Th: Laser ionization and VUV spectroscopy

M. Verlinde[1], S. Cottenier[4], L. da Costa Pereira[1], M. Huyse[1], R. Ferrer[1], S. Kraemer[1], Y. Kudryavtsev[1], M. Laatiaoui[2], S. Sels[1], P. van Duppen[1], A. Vantomme[1], E. Verstraelen[1], U. Wahl[1], S. Zadvornaya[1]

[1]IKS, KU Leuven, Leuven, Belgium
[2] Helmholtz Institute Mainz, Mainz, Germany
[4] UGent, Gent, Belgium

At KU Leuven, two complementary approaches are being developed to study the low-lying nuclear isomer in ^{229}Th. A laser spectroscopic technique, IGLIS (In-Gas-jet Laser Ionization Spectroscopy [1]), tailored to the challenges imposed by the isomer, is being refined using an offline setup that is in its final phase of development. The proof of principle of this idea was delivered when studying actinium isotopes [2]. With the IGLIS technique, we aim for high-resolution and fast laser hyperfine spectroscopy of ^{229}Th^{1+} (produced after the α decay of ^{223}U) to confirm the nuclear parameters of the isomer in the, until now, suspiciously absent charge state [3,4]. Additionally, this setup will deliver a pure, contaminant free, beam of isomeric ions.

In a second approach, the isomer's excitation energy will be determined via the detection of its nuclear gamma decay photons after implantation in a dedicated crystal host. A new production method will be used in the form of β-decaying laser-ionized ^{229}Ac ions originating from the laser-ion source at ISOLDE, CERN [6]. High ^{229}Ac production rates combined with a, based on literature, substantial branching ratio of ^{229}Ac-^{229,m}Th nuclear decay, should provide an intense source of the isomer [7,8,9]. To confirm the total β feeding of the isomer and to optimize the lattice location of ^{229}Ac and its daughter ^{229}Th, after implantation, two experiments are being developed at ISOLDE. They focus on both an efficient conversion electron detection and a study, via emission channeling, of the dependence of implantation geometry and crystal host manipulation techniques on the final lattice site of ^{229}Ac and ^{229}Th nuclei [10,11]. In a final experiment, a designated spectrometer system will analyze the obtained gamma-ray spectrum of this setup in the expected VUV range.

References

[1] Y. Kudryavtsev et al., Nucl. Instr. Meth. B376 (2016)
[2] R. Ferrer et al., Nature Comm. 8 (2017)
[3] L. von der Wense et al., Nature 533 (2016)
[4] J. Thielking et al. arXiv:1709.05325 (2018)
[5] S. Raeder et al. Hyperfine Interact. 216 (2013)
[6] E. Ruchowska et al., Phys. Rev. C 73 (2006)
[7] National Nuclear Data Center: www.nndc.bnl.gov
[8] M.R. Silva et al., Rev. Sci. Instrum. 84 (2013)

Excitation of ^{229}Th nuclei in laser plasma: the energy and half-life of the low-lying isomeric state

P.V. Borisyuk[1], E.V. Chubunova[1], N.N. Kolachevsky[2,1]

Yu.Yu. Lebedinskii[1], O.S. Vasiliev[1] and E. V. Tkalya[3,1,4]

[1]National Research Nuclear University MEPhI, Moscow, Russia
[2]P.N. Lebedev Physical Institute of the Russian Academy of Sciences,Moscow, Russia
[3]Skobeltsyn Institute of Nuclear Physics Lomonosov Moscow State University, Moscow, Russia
[4]Nuclear Safety Institute of RAS, Moscow, Russia

The results of experimental studies of the low-energy isomeric state in the ^{229}Th nucleus are presented. The work is consisted of several stages. During the first stage ^{229}Th nuclei were excited with the inverse internal conversion to the low-lying isomeric level in plasma that was formed by laser pulse at the ^{229}Th-containing target surface. Then thorium ions having excited nuclei were extracted from the plasma by an external electrical field and implanted into thin SiO_2 film grown on a silicon substrate (that is a dielectric material with about 9 eV band-gap). Gamma decay of isomeric nuclei was registered during the second stage by the general methods of the electron spectroscopy after the photonelectron emission from the silicon substrate. Substitution of the photon registration with the electron one allowed us to increase the desired signal by several orders of magnitude and detect the ^{229}Th nuclei decay. During the third stage the electron spectra from standard Xe VUV source was obtained that allowed determining the energy of photons. In order to prove that the detected signal is caused by isomeric ^{229}Th nuclei decay a series of experiments was carried. The analysis of electron spectra gives the following results: the energy of the nuclear transition is E_{is}=7.1(+0.1/−0.2) eV, the half-life of the isomeric level in bare nucleus in vacuum is T1/2=1880±170 s, the reduced probability of the isomeric nuclear transition is $B_{w.u.}(M1;3/2+\rightarrow 5/2+)=(3.3\pm0.3)\times10^{-2}$.

Nuclear and atomic structure calculations for the ^{229}Th isomeric state

P. V. Bilous[1], N. Minkov[2] and A. Pálffy[1]

[1] Max-Planck-Institut für Kernphysik, Heidelberg, Germany
[2] Institute of Nuclear Research and Nuclear Energy, Sofia, Bulgaria

The ^{229}Th actinide isotope has an isomeric state lying only 7.8 eV above the ground state. This extremely small energy renders for the first time a nuclear transition accessible to vacuum ultraviolet lasers. Novel applications such as a nuclear frequency standard with unprecedented accuracy based on this transition are anticipated.

Here we present our theoretical predictions for the reduced magnetic dipole and electric quadrupole transition probabilities for the radiative decay of the ^{229}Th 7.8 eV isomer to the ground state within a detailed nuclear-structure model approach. We show that the presence and decay of this isomer can only be accounted for by the Coriolis mixing emerging from a remarkably fine interplay between the coherent quadrupole-octupole motion of the nuclear core and the single-nucleon motion within a reflection-asymmetric deformed potential [1]. The predicted magnetic dipole transition probability which determines the radiative lifetime of the isomer is considerably smaller than presently estimated [1].

Our calculations also show that the so-far disregarded electric quadrupole component may have non-negligible contributions for the nuclear coupling to the atomic shells, for instance for internal conversion from excited electronic states and electronic bridge processes [2,3]. These findings support new directions in the experimental search of the ^{229}Th transition frequency for the development of a future nuclear frequency standard.

References

[1] N. Minkov and A. Pálffy, Phys. Rev. Lett. **118**, 212501 (2017)
[2] P. V. Bilous, G. A. Kazakov, I. D. Moore, T. Schumm and A. Pálffy, Phys. Rev. A **95**, 032503 (2017)
[3] P. V. Bilous, N. Minkov and A. Pálffy, Phys. Rev. C **97** 044320 (2018)

The fog disperses: What do we know about the elusive ^{229}Th isomer ?

Peter G. Thirolf

[1]*Ludwig-Maximilians-Universität München, Garching, Germany*

Today's most precise time and frequency measurements are performed with optical atomic clocks. However, it has been proposed that they could potentially be outperformed by a nuclear clock, which employs a nuclear transition instead of an atomic shell transition. The only known nuclear state that could serve as a nuclear frequency standard using currently available technology is the isomeric first excited state of ^{229}Th. Since 40 years nuclear physicists have targeted the identification and characterization of the elusive isomeric ground state transition of ^{229m}Th. Evidence for its existence until recently could only be inferred from indirect measurements, suggesting an excitation energy of 7.8(5) eV. In 2016, the first direct detection of this nuclear state could be realized via its internal conversion decay branch, which confirms the isomer's existence and lays the foundation for precise studies of its decay parameters [1]. Subsequently, a measurement of the halflife of the neutral isomer was achieved, confirming the expected reduction of 9 orders of magnitude compared to the one of charged ^{229m}Th [2]. Most recently, collinear laser spectroscopy was applied to resolve the hyperfine structure of the thorium isomer, providing information on nuclear moments and the charge radius [3]. Presently intense experimental efforts focus on a refined determination of the isomer's excitation energy [4], while also proof-of-principle studies of a first laser-driven nuclear excitation of ^{229m}Th based on existing laser technology are being prepared [5]. Thus a drastic increase of insight into the properties of this elusive nuclear state could be achieved in the last two years, paving the way towards an all-optical control and thus the development of an ultra-precise nuclear frequency standard. Moreover, a future nuclear clock promises various intriguing applications in applied as well as fundamental physics, ranging from geodesy and seismology to the investigation of possible time variations of fundamental constants.

References

[1] L. v.d. Wense et al., Nature 533, 47-51 (2016).
[2] B. Seiferle, L. v.d. Wense, P.G. Thirolf, Phys. Rev. Lett. 118, 042501 (2017).
[3] J. Thielking et al., Nature 556, 321-325 (2018).
[4] B. Seiferle, L. v.d. Wense, P.G. Thirolf, Eur. Phys.. Jour. A 53, 108, (2017).
[5] L. v.d. Wense et al., Phys. Rev. Lett. 119, 132503 (2017).

Internal conversion electron spectroscopy of ^{229m}Th

B. Seiferle[1], L. v.d Wense[1], I. Amersdorffer[1], S. Stellmer[2], P. Bilous[3], C. E. Düllmann[4,5], A. Pálffy[3] and P.G. Thirolf[1]

[1]LMU Munich, Garching, Germany. [2] TU Wien, Vienna, Austria, [3] Max-Planck Institute für Kernphysik, Heidelberg, Germany. [4] Johannes Guttenberg Universität, Mainz, Germany. [5] Helmholtz Institute Mainz, Mainz, Germany.

E-mail: benedict.seiferle@physik.uni-muenchen.de

The large energy uncertainty (of 0.5 eV [1]) of the first isomeric state in ^{229}Th (^{229m}Th) still hinders progress towards a nuclear clock. One possible way for a more precise energy determination is the spectroscopy of internal conversion (IC) electrons emitted during the decay of ^{229m}Th. The presence of IC as a decay channel depends on the electronic environment and is only possible in neutral ^{229m}Th [2,3].

In the presented measurements ^{229m}Th ions are produced in the ^{233}U α-decay and are extracted from a buffer-gas stopping cell with subsequent (segmented) linear Paul trap and quadrupole mass separator to form mass purified ion bunches. After neutralization of the ions and the subsequent IC decay, the kinetic energy of the emitted electrons is measured with a retarding field magnetic bottle spectrometer. For the neutralization of the ions two directions are followed:

In a first approach the ions are neutralized by collecting them on a metal surface placed in the collection region of the spectrometer. The IC electron spectrum will then reflect surface properties [4].

A second way to neutralize ^{229m}Th ions is by letting them pass through a thin carbon foil. The thereby generated neutral ^{229m}Th beam is then decaying via IC while flying through the central collection region of the magnetic bottle spectrometer. This approach allows to measure internal conversion electrons emitted from a free ^{229m}Th atom.

Experimental results from both approaches are presented.

This work was supported by DFG Grant No. Th956/3-2, by the European Union's Horizon 2020 research and innovation program under grant agreement 664732 "nuClock", and by the LMU department of Medical Physics via the Maier-Leibnitz Laboratory.

References

1. B.R. Beck et al., LLNL-PROC-415170, (2009).
2. L. v.d Wense et al., Nature 533, 47, (2016).
3. B. Seiferle et al., PRL 118, 042501, (2017).
4. B. Seiferle et al., EPJA 53, 108, (2017).

Power-scaling VUV/XUV frequency combs: Recent results and prospects

C. M. Heyl[1,2]

[1]*Helmholtz-Institute Jena, Germany*
[2]*DESY, Hamburg, Germany*
E-mail: Christoph.heyl@desy.com

The process of high-order harmonic generation enables the extension of frequency comb technology form the infrared into the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) spectral region. Following the initial demonstration of this concept in 2005, the first direct XUV comb spectroscopy was realized in 2012 [1]. Until today, the limited average power available is a major bottleneck for further applications such as direct comb spectroscopy of highly charged ions or the direct excitation of the low-energy isomeric transition in ^{229}Thorium [2]. Recent power scaling efforts have led to the generation of mW-class high-harmonics using a cavity enhanced Ytterbium frequency comb [3]. These results do not only set a new average power record for high harmonic-based XUV sources, they also raise hope for record power levels in the VUV spectral region around 7.1 eV, the energy region, where latest estimates suggest the ^{229}Thorium isomeric transition [4]. A number of different approaches targeting this transition are currently being followed, including the direct laser excitation of this transition [5].
In this contribution, I would like to discuss recent developments for XUV frequency combs and present an outlook into further power scaling possibilities in the VUV and XUV spectral region.

References

[1] A. Cingöz, D. C. Yost, T. K. Allison, A. Ruehl, M. Fermann, I. Hartl and & J.Ye, "Direct frequency comb spectroscopy in the extreme ultraviolet", Nature 482:68 (2012).

[2] L. von der Wense, B. Seiferle, and P.G. Thirolf, "Towards a ^{229}Th-based nuclear clock", Meas Tech 60:1178 (2018).

[3] G. Porat*, C.M. Heyl*, S.B. Schoun*, C. Benko, N. Dörre, K.L. Corvin, J. Ye, "Phase-matched extreme-ultraviolet frequency-comb generation", accepted for publication in Nature Photonics (2018), [* = equal author contributon].

[4] P.V. Borisyuk, E.V. Chubunova, N.N. Kolachevsky, Yu.Yu. Lebedinskii, O.S. Vasiliev, E.V. Tkalya, "Excitation of ^{229}Th nuclei in laser plasma: the energy and half-life of the low-lying isomeric state", arXiv:1804.00299 (2018).

[5] L. von der Wense, B. Seiferle, S. Stellmer, J. Weitenberg, G. Kazakov, A. Pálffy and P. G. Thirolf, „A Laser Excitation Scheme for ^{229m}Th", PRL 119:132503 (2017).

Physics of laser-assisted nuclear processes as the base for creation of the nuclear clock

F. F. Karpeshin[1], M. B. Trzhaskovskaya[2], and L. F. Vitushkin[1]

[1]D. I. Mendeleev Institute for Metrology, Saint-Petersburg, Russia
[2]National Research Center "Kurchatov Institute", Petersburg Nuclear Physics Institute, Gatchina, Russia

E-mail: fkarpeshin@gmail.com

A considerable progress during the past decades was archieved in investigation of the interrelation of the atomic structure with the nuclear processes. First of all, this concerns electromagnetic decay of the nuclei. Nuclear decay can be enhanced considerably by making use of a resonance with the electronic transitions, which can be further tuned either through changing the electron shell, or irradiating with resonance field of a laser [1]. Thus, it was predicted that the decay of the ^{229}Th isomer would be by ~700 times faster in the hydrogen-like ions. The lifetime of the nucleus in the crystal matrix also may vary. Wonderful experiments were also performed, studying the electronic shell effects on the beta decay. There is a comparative study of α decay in H-, He-like ions on the urgent agenda, with respect to that in neutral atoms.

The resonance properties of the electron shell are of extreme importance for creation of the nuclear clock. From the other side, it is generally accepted that the nuclear properties, specifically the radioactive decay constant, are essentially independent of the physical environment. Such stability against the environmental medium underlies the idea of the nuclear clock. This is in contrast with what is said above. In fact, in the case of the nuclear deexcitation through the resonance conversion (or electronic bridge), the decay probability turns out to be directly proportional to the atomic width. Therefore, it may be mastered by simple factors, such as ambient temperature and atmospheric pressure, in principle, even by a loud sound of voice [2]. Especial features of the two mechanisms of nuclear excitation through the electronic shell, reverse resonance conversion versus nonradiative electronic transitions, are discussed.

References

[1] F. F. Karpeshin, Prompt Fission in Muonic Atoms and Resonance Conversion. Saint-Petersburg: Nauka, 2006.

[2] F. F. Karpeshin and M. B. Trzhaskovskaya, Nucl. Phys. A **969**, 173 (2018).

Atomic calculations in multivalent ions with applications to novel clocks

J. C. Berengut

School of Physics, University of New South Wales, Sydney 2052, Australia

Several recent experiments have necessitated new methods of calculation of electronic spectra of complicated atoms and ions. Systems of interest include many-valence-electron atoms [1], highly charged ions with open shells [2], and atoms where hole excitations play an important role [3]. Accurate calculations are required for the design and characterization of nuclear clocks and highly-charged-ion clocks.

In this talk I will present calculations of ions that may be of interest for new clocks. The variety of highly charged ions (HCIs) available provides new opportunities for experiment. Choosing HCIs near level crossings allows optical transitions with high sensitivity to variations of the fine-structure constant, and many opportunities to control systematics. Other ions can provide electronic bridges to the low-lying nuclear transitions in Th-229 and U-235.

Our calculations are performed using AMBiT, a modern, open-source implementation of the particle-hole CI+MBPT (configuration interaction and many-body perturbation theory) method [4]. Limiting off-diagonal elements of the Hamiltonian allows the CI to achieve saturation even in difficult multivalent atoms and ions. The particle-hole formalism allows important hole configurations (where the core is unfrozen) to be treated on an equal footing with other configurations.

References

[1] N. Leefer *et al.*, Phys. Rev. Lett. **111** 060801 (2013)
[2] F. Toretti *et al.*, Phys. Rev. A **95** 042503 (2017)
[3] N. Huntemann *et al.*, Phys. Rev. Lett. **116**, 063001 (2016)
[4] J. C. Berengut, Phys. Rev. A **94**, 012502 (2016)

Acetylene frequency reference

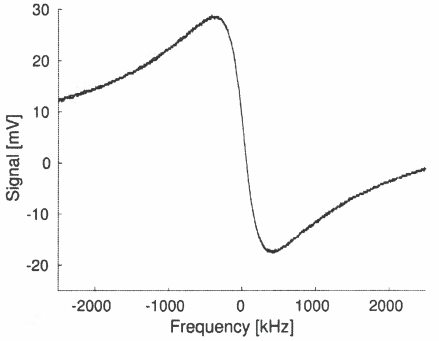
M. R. Henriksen, C. Raahauge, S. A. Schäffer, A. A. Jørgensen and J. W. Thomsen

The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 *Copenhagen, Denmark*
E-mail: name@mymail.cy

Compact optical frequency references have a number of applications within fields of metrology, coherent optical communications and spectroscopy. Here we demonstrate a scheme where cavity enhanced spectroscopy is employed in order to utilize the narrow line of an acetylene gas as a frequency discriminator. In this work we use $^{13}C_2H_2$ P(16) ($\nu_1 + \nu_3$) line at 1542,3837 nm. This is conveniently placed in the 1550 nm telecommunication band (c-band) and is a recommended frequency reference for the definition of the meter [1,2].

A low-pressure acetylene gas cell is placed in an optical cavity with a finesse of 300 and a waist radius of 0,7 mm. The NICE-OHMS (Noise Immune Cavity Enhanced Optical Heterodyne Molecular Spectroscopy) technique is used to measure the molecular induced phase shift of an interrogation laser. This is done by generating sideband on the interrogation laser at one cavity FSR (650 MHz) leading to a RF beat signal in the cavity transmission proportional to the molecular induced phase shift. By doing the measurement at a frequency of hundreds of MHz it is possible to achieve a high signal-to-noise ratio, on a signal with a high bandwidth.

The figure shows the achieved signal. The linewidth of the broadened line is approximately 700 kHz wide. The signal-to-noise ratio is measured to be greater than 1200 with a bandwidth of 2 MHz.



References

[1] R. Felder, Metrologia **42.4**, 323 (2005)
[2] J. Hald, Optics Express **19.3**, 2052-2063 (2011)

Novel atomic clocks and the search for new physics

M. S. Safronova

Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA and
Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, Maryland 20742, USA

I will give an overview of the clock proposals with highly charged ions [1] and their applications for new physics searches, such as variation of fundamental constants, violation of the local Lorentz invariance, and forces beyond the Standard Model of particle physics [2]. The selection of highly charged ions in different charge states offers narrow optical transitions that are among the most sensitive ones to the "new physics" effects. I will also discuss other recent theoretical developments in novel clock proposals [3,4].

A broadly applicable method to search for the violation of local Lorentz invariance (LLI) with atomic systems was proposed in [3]. The new scheme uses dynamic decoupling and can be implemented in current atomic clock experiments, with both single ions and arrays of neutral atoms. Moreover, the scheme can be performed on systems with no optical transitions, and therefore it is also applicable to highly charged ions which exhibit a particularly high sensitivity to Lorentz invariance violation.

A new frequency standard based on a $4f^{14}6s6p\ {}^3P_0 - 4f^{13}6s^25d$ ($J = 2$) transition in neutral Yb was proposed in [4]. The dimensionless α-variation enhancement factor for this transition was determined to be $K = -15$, in comparison to the most sensitive current clock (Yb+ E3, $K = -6$), and it is 18 times larger than in any neutral-atomic clocks (Hg, $K = 0.8$). Moreover, together with the well-established ${}^1S_0 - {}^3P_0$ transition one will have two clock transitions operating in neutral Yb, whose interleaved interrogations may further reduce systematic uncertainties of such clock-comparison experiments.

References

[1] M. G. Kozlov, M. S. Safronova, J. R. Crespo López-Urrutia, P. O. Schmidt, arxiv:1803.06532, submitted to Rev. Mod. Phys. (2018).

[2] M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson-Kimball, A. Derevianko, and Charles W. Clark, arxiv:1710.01833, in press, Rev. Mod. Phys. (2018).

[3] R. Shaniv, R. Ozeri, M. S. Safronova, S. G. Porsev, V. A. Dzuba, V. V. Flambaum and H. Häffner, Phys. Rev. Lett. **120**, 103202 (2018).

[4] M. S. Safronova, S. G. Porsev, Christian Sanner, and Jun Ye, Phys. Rev. Lett. **120**, 173001, (2018).

High stability optical clock based on Ramsey-Borde interferometry in thermal calcium

J. Olson[1,2], R. Fox[1], T. Fortier[1], C. W. Oates[1], and A. D. Ludlow[1,2]

[1]National Institute of Standards and Technology, Boulder, Colorado,USA
[2] Department of Physics, University of Colorado, Boulder, Colorado, USA

High-precision spectroscopy of calcium has had a rich history throughout the development of optical frequency standards based on neutral atoms. Though the experimental systems employed typically suffer from residual Doppler effects and thus cannot rival the uncertainty levels of trapped optical standards, calcium offers key benefits for realizing very high frequency stability at shorter timescales in a simple experimental apparatus. Here we highlight high-resolution Ramsey-Borde interferometry on the $^1S_0$-$^3P_1$ intercombination transition in a thermal beam of calcium. The system employs excited-state shelving detection, dual counter-propagating atomic beams, and an in-vacuum ultra-low-expansion (ULE) glass optical interferometer assembly to achieve laser stabilization of $2x10^{-16}$ in a thermal beam.

References

[1] Ch. J. Bordé, Ch. Salomon, S. Avrillier, A. Van Lerberghe, Ch. Bréant, D. Bassi, and G. Scoles, Physical Rev. A **30**, 1836-1848 (1984).
[2] R. L. Barger, J. C. Bergquist, T. C. English, and D. J. Glaze, Appl. Phys. Lett. **34**, 850-852 (1979).
[3] P. Kersten, F. Mensing, U. Sterr, F. Riehle, Appl. Phys. B **68**, 27-38 (1999).
[4] J. J. McFerran and A. N. Luiten, J. Opt. Soc. Am. B **27**, 277-285 (2010).

Laser cooling of cadmium towards an optical lattice clock

A. Yamaguchi[1]

[1]*Quantum Metrology Laboratory, RIKEN, Wako-shi, Saitama 351-0198, Japan*

The light shift caused by the blackbody radiation (BBR) is a significant source of uncertainty for optical lattice clocks based on strontium and ytterbium atoms. A cryogenic environment is one approach to reduce this systematic frequency shift [1, 2]. Another is to identify and use an atomic species whose clock transition frequency is intrinsically insensitive to the BBR, such as mercury, magnesium and cadmium (Cd) [3-5]. These species avoid the complexity of a cryogenic apparatus, enabling more compact and portable optical lattice clocks.

As a first step towards a portable cadmium optical lattice clock, we demonstrate narrow-line laser cooling of Cd. We first trapped Cd atoms in a MOT using the $^1S_0$ – $^1P_1$ transition at 229 nm [6]. These atoms were subsequently loaded into a narrow-line $^1S_0$ – $^3P_1$ MOT to further cool the atoms. We demonstrate two-stage cooling of both bosonic (^{112}Cd) and fermionic (^{113}Cd) isotopes to a temperature of 4.2(9) μK and 5.2(6) μK, respectively. Searching for the magic wavelength is in progress. The experiment and future prospects will be discussed.

References

[1] I. Ushijima *et al.*, Nat. Photonics **9**, 185 (2015).

[2] N. Nemitz *et al.*, Nat. Photonics **10**, 258 (2016).

[3] J. J. McFerran et al., Phys. Rev. Lett. **108**, 183004 (2012).

[4] K. Yamanaka *et al.*, Phys. Rev. Lett. **114**, 230801 (2015).

[5] A. P. Kulosa *et al.*, Phys. Rev. Lett. **115**, 240801 (2015).

[6] Y. Kaneda *et al.*, Opt. Lett. **41**, 705 (2016).

$^{171}Yb^{+}$ single-ion optical clocks

N. Huntemann, R. Lange, C. Sanner, M. Abdel Hafiz, B. Lipphardt, Chr. Tamm, E. Peik

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

$^{171}Yb^{+}$ provides two reference transitions that are adequate for the realization of an optical frequency standard: the $^{2}S_{1/2}(F=0) \rightarrow {}^{2}D_{3/2}(F=2)$ electric quadrupole (E2) transition at 436 nm and the $^{2}S_{1/2}(F=0) \rightarrow {}^{2}F_{7/2}(F=3)$ electric octupole (E3) transition at 467 nm [1,2]. The significantly higher sensitivity of the E2 transition to electric and magnetic fields permits diagnosis of field induced shifts of the E3 transition frequency on a magnified scale.

We employ two $^{171}Yb^{+}$ single-ion optical frequency standards that differ significantly with respect to trap geometry, control software and interrogation sequence [3]. The relative systematic uncertainty of the clocks referencing the E3 transition has been evaluated to less than 4×10^{-18} [2]. In a long-term comparison of the two clocks for a period of seven months with a duty cycle of up to 95 % per day, we found an agreement of the Yb^{+} clock frequencies within the systematic uncertainty. Due to the electronic structure of the $^{2}F_{7/2}$ state, the E3 transition frequency is very sensitive to violations of Local Lorentz Invariance (LLI) [4]. In addition, the Ytterbium ion is known for the large sensitivity of the ratio of the E3 and the E2 transition frequencies to changes of the fine structure constant α. Based on repeated measurements of this ratio, we can improve present limits on the temporal variation of α.

Beside the use of $^{171}Yb^{+}$ single-ion optical clocks in fundamental research, they are also investigated for wider applications within a pilot projects for quantum technology supported by the German Federal Ministry of Education and Research. Together with 6 industrial partners, 2 universities and a research institute, we are developing a robust, high-availability and easy-to-use optical clock, which can be operated outside a specialized laboratory [6].

References

[1] Chr. Tamm, et al., Phys. Rev. A **89**, 023820 (2014).
[2] N. Huntemann, et al., Phys. Rev. Lett. **116**, 063001 (2016).
[3] C. Sanner, et al., Phys. Rev. Lett. **120**, 053602 (2018)
[4] V. A. Dzuba, et al., Nature Physics **12**, 465 (2016).
[5] www.opticlock.de

Lasing on a forbidden transition in a thermal cloud of Strontium atoms

S. A. Schäffer, M. Tang, M. R. Henriksen, A. A. Jørgensen, J. W. Thomsen

The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark
E-mail: schaffer@nbi.dk

The intense scientific effort within atomic clocks has resulted in systems performing with a fractional frequency precision below the 10^{-18}-level [1]. Such performance demands long integration times in order to average away the white frequency noise of the oscillator. By reducing the short-term noise of the interrogation oscillator, the necessary integration time of optical lattice clocks can be reduced correspondingly.
This has sparked interest in alternative approaches to generating highly stable laser light by using an active atomic reference [2, 3]. In such a system, forbidden optical atomic transitions can be exploited to generate coherent emission via strong collective coupling in an optical cavity. By placing the system in the so-called bad cavity regime where the transition linewidth is much more narrow than the cavity linewidth, $\Gamma<<\kappa$, it is possible to ensure that the cavity frequency noise is suppressed, and the atomic characteristics dictate the spectrum of the emitted light. The realization of such systems has been investigated in the context of hot gases [4] and quasi-continuously in an optical lattice system [5,6].
Here we report on the realization of an active narrow-line atomic reference using a thermal ensemble of cooled ^{88}Sr atoms on the $^3P_1 \rightarrow {}^1S_0$ intercombination line ($\Gamma = 2\pi\cdot 7.4$ kHz). By exciting an ensemble of atoms cooled in a single-stage magneto-optical trap we observe pulses of coherent lasing into the cavity mode ($\kappa = 2\pi\cdot 620$ kHz), and measure the stability of the emitted light decrease below the natural linewidth of the transition, Γ, by measuring against a reference laser. We evaluate the pulse shape dependency on cavity detuning, and map out photon flux dependencies on the number of atoms in the cavity mode.

References

[1] S. L. Campbell et al., Science, **358**, 6359, 90-94 (2017)
[2] J. Chen, Chin. Sci. Bull., **54**, 348 (2009).
[3] D. Meiser et al., Phys. Rev. Lett., **102**, 16, 163601 (2009)
[4] Z. Xu et al., Chin. Phys. Lett., **32**, 093201 (2015)
[5] M. A. Norcia et al., Phys. Rev. X, **6**, 011025 (2016)
[6] M. A. Norcia et al., Science Adv., **2**, 10, e1601231 (2016)

Clocks based on complex Coulomb systems

T.E. Mehlstäubler

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

In order to exploit the full potential of optical ion clocks and to resolve frequencies with a fractional frequency instability of 10^{-18} and below, ion clocks need to integrate over many days to weeks. For the characterisation of systematic shifts of the clock, as well as for novel applications, such as relativistic geodesy, these long times scales pose severe limits. Scaling up the number of ions for optical clock spectroscopy is a natural way to significantly reduce integration times, but was hindered so far by poor control of the dynamics of coupled many-body systems, on-axis micromotion and systematic shifts due to interacting ions.
In this talk we will discuss novel approaches to multi-ion and multi-ensemble clocks, which are the basis for future frequency standards using quantum-correlated or cascaded clocks.

Pulsars as cosmic clocks

D. J. Champion[1]

[1]*Max-Planck Institut für Radioastronomie, Bonn, Germany*

Pulsars are often described as cosmic clocks. These diminutive, nuclear-density neutron stars are born in the supernovae of massive stars. They can spin up to 700 times a second sweeping their beams of electromagnetic radiation across the sky like a light-house, on Earth we use the largest telescopes to detect these tick-like pulses.
Some groups within the pulsar population show astonishing rotational stability. Phase-coherent analysis of observations allows precise measurement of any effect causing time variation of pulse arrival times such as: the pulsar's motion (e.g. in a binary system), chromatic delays caused by the intervening interstellar medium and General Relativistic effects.
Pulsar observations are dependent on precise time measurement on timescales of minutes but the phase-coherent analysis requires precision over years and decades. Turning this around we can create a pulsar base timescale by combining many pulsars into a timing array. Although such a timescale will not rival Earth-based systems for precision it is independent in technique and location.

A gravitational redshift test using eccentric Galileo satellites

P. Delva[1] and N. Puchades[2,1]

[1]SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire 75014 Paris France
[2] Departamento de Astronomia y Astrofisica - Valencia University

We are going to present the results of the analysis of the GREAT (Galileo gravitational Redshift test with Eccentric sATellites) experiment from SYRTE (Observatoire de Paris), funded by the European Space Agency. The General Relativity (GR) predicts that time flows differently for two clocks that have a relative speed and are placed in different gravitational potentials. It is therefore possible to test GR by comparing the frequencies of two clock, in a so-called gravitational redshift test. The best test to date was performed with the Gravity Probe A (GP-A) experiment in 1976 with an uncertainty of 1.4×10^{-4}.

An elliptic orbit induces a periodic modulation of the fractional frequency difference between a ground clock and the satellite clock, while the good stability of Galileo clocks allows to test this periodic modulation to a high level of accuracy. Galileo 201 and 202, with their large eccentricity and on-board H-maser clocks, are perfect candidates to perform this test. However, the accuracy of the gravitational redshift test is limited by the systematic uncertainty due to orbital errors, and Satellite Laser Ranging (SLR) measurements are crucial to understand them. SLR data allows us to reduce the effect of the systematics, in particular to partly decorrelate the orbit perturbations from the clock errors. By analyzing several years of Galileo satellites data we have been able to improve on the GP-A test of the gravitational redshift.

References

[1] P. Delva, A. Hees, S. Bertone, E. Richard, and P. Wolf, Class. Quantum Grav. **32(23)**, p. 232003 (2015)

[2] P. Delva et al., proceedings of the ILRS Technical Workshop, Matera, Italy, October 26-30, 2015 (2016)

Enabling the remote comparison of novel optical clock signals with state-of-the-art optical frequency standards

Fabiola Guillou-Camargo[1], Mathieu Corradini[1], Vincent Ménoret[1], Etienne Cantin[2], Anne Amy-Klein[2], Paul-Eric Pottie[3], Olivier Lopez[2], Emilie Camisard[4], Bruno Desruelle[1], Jean Lautier Gaud[1], Giorgio Santarelli[5], Christian Chardonnet[2]

[1]*Muquans, Institut d'Optique d'Aquitaine, rue François Mitterrand, 33400, Talence, France*

[2]*Laboratoire de Physique des Lasers, LPL Université Paris 13, CNRS, Villetaneuse, France*

[3]*LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC, Paris, France*

[4]*RENATER, Paris, France*

[5]*Laboratoire Photonique, Numérique et Nanoscience, LP2N Institut d'Optique d'Aquitaine, Université de Bordeaux, Talence, France*

The assessment of the performances of novel optical clocks such as ^{229}Thorium solid-state nuclear clock in terms of frequency stability and accuracy will require to compare their output signals to existing state-of-the-art optical frequency standards. A way to achieve such comparisons exploits optical frequency transfer on optical fibers.

This paper reports on the operation of the world's first optical frequency transfer link deployed at an industry level in the frame of the REFIMEVE+ project supported in France by LPL (University of Paris 13) and SYRTE (Observatory of Paris) laboratories [1], [2]. We will present our work to produce the equipment, set up and operate a link by focusing on the development and the status of the optical link between the French cities Paris and Lille - distant of 311 km. The link is based on the active compensation of the phase noise accumulated by the optical reference signal when conveyed on a dark channel of the DWDM spectrum over an existing optical fiber, in parallel of internet data traffic [2].

In terms of relative frequency stability of the transfer, the modified Allan deviation reaches a few 10^{-16} at 1 s integration time, 10^{-19} after 10^3 s of integration and the low 10^{-20} level after few 10^4 s of integration. We will also discuss the frequency offset introduced by the link and describe this segment of network in terms of operational features such as accessibility, reliability and flexibility. The latest measurement campaigns and comparisons have in particular validated the repeatability of the optical frequency transfer, the ease of use and the robustness of such technology.

The optical fiber link between Paris and Lille today meets the objective to provide a long-haul optical frequency transfer solution as a turn-key and autonomous platform to compare novel generations of optical clocks with state-of-the-art optical frequency standards. This paper will also be the occasion to describe in more details the maturity of several key technologies that can sustain Time and Frequency transfers at a continent scale.

References

[1] http://www.refimeve.fr/index.php/en/

[2] E. Cantin et al, "Progress on the REFIMEVE+ Project for Optical Frequency Standard Dissemination", 2017 Joint Conference of the EFTF and IEEE IFCS

[3] N. Chiodo et al, "Cascaded optical fiber link using the Internet network for remote clocks comparison", Optics Express 23, 33927-33937, 2015

Electronic transitions in highly charged ions with possible applications to the electron-nucleus bridge mechanism

José. R. Crespo López-Urrutia

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Heavy elements in ionization stages with several vacancies in open *f*-subshells and *d*-subshells display a very high density of states in their ground-state configuration. Therefore, a large number of vacuum-ultraviolet (VUV) and extreme-ultraviolet (EUV) forbidden transitions connects such states. In some cases, level crossings [1] can lead to additional degeneracies that give rise to dipole-allowed and dipole-forbidden transitions in the same energy range. Since the outer-electron wavefunction overlaps with the nucleus far more strongly in highly charged ions (HCI) than in other atomic species, the electron-nucleus coupling is expected to be much stronger. As a consequence of these properties, it is conceivably that specific HCI of ^{229}Th could exhibit properties favorable to the excitation transfer between the electronic shell and the nuclear isomeric state. Due to their high ionization potentials, HCI are impervious to electron emission through internal conversion, and thus more useful for nuclear frequency metrology. Application of HCI to the study of the nuclear clock transition requires detailed VUV and EUV spectroscopic investigations in electron beam ion traps, as those carried out in other heavy elements [2-4]. Since recently, HCI can be sympathetically cooled within Coulomb crystals down to temperatures amenable to frequency metrology [5,6]. Thus, a nuclear clock transition could be explored in a proposed combination of methods that includes quantum-logic spectroscopic detection [7] of the relevant electronic states though interrogation of co-trapped cooling ions. We are developing a VUV frequency comb for these applications [8].

References

[1] J. C. Berengut *et al.*, Phys. Rev. Lett. **106**, 210802 (2011)
[2] A. Windberger et al., Phys. Rev. Lett. **114**, 150801 (2015)
[3] A. Windberger et al., Phys. Rev. A **94**, 012506 (2016)
[4] F. Torretti et al., Phys. Rev. A **95**, 042503 (2017)
[5] L. Schmöger et al., Science **347**, 1233 (2015)
[6] L. Schmöger et al., Rev. Sci. Instrum. **86**, 103111 (2015)
[7] P. O. Schmidt et al., Science **309**, 749 (2005)
[8] J. Nauta et al., Nucl. Inst. Meth. B **408**, 285 (2017)

Effects of dark matter, variation of the fundamental constants and violation of the fundamental symmetries in nuclear and atomic clocks

V.V. Flambaum[1,2] and Y. Stadnik[2]

[1]*School of Physics, University of New South Wales, Sydney 2052, Australia*
[2] *Helmholtz Institute, J. Gutenberg University, 55099 Mainz, Germany*

Low-mass boson dark matter particles produced after Big Bang form classical field and/or topological defects. In contrast to traditional dark matter searches, effects produced by interaction of an ordinary matter with this field and defects may be first power in the underlying interaction strength rather than the second power or higher (which appears in a traditional search for the dark matter). This may give an enormous advantage since the dark matter interaction constant is extremely small.

Interaction between the density of the dark matter particles and ordinary matter produces both 'slow' cosmological evolution and oscillating variations of the fundamental constants including the fine structure constant alpha and particle masses. Atomic Dy, Rb and Cs spectroscopy measurements and the primordial helium abundance data allowed us to improve on existing constraints on the quadratic interactions of the scalar dark matter with the photon, electron, quarks, Z, W and and Higgs boson by up to 15 orders of magnitude [1,2]. Effects of scalar field produced by massive bodies on atomic clock transition frequencies have been experimentally investigated in [3].

Effects of dark matter, variation of the fundamental constants, Lorentz invariance and Einstein Equivalence violations are strongly enhanced in nuclear [4,5] and highly charged ion clocks [6].

A nuclear clock for metrology at the 19th decimal place [7], excitation of the isomeric 229mTh nuclear state via an electronic bridge process [8] and 7 orders of magnitude improvement for the anisotropy of the speed of light [9] (measured in the famous Michelson-Morley experiment) are discussed. This anisotropy leads to the anisotropy of the Coulomb interaction affecting nuclear and atomic spectra.

References

[1] Y. V. Stadnik and V. V. Flambaum. Phys. Rev. Lett. **115**, 201301 (2015)
[2] Y. V. Stadnik, V. V. Flambaum, Phys. Rev. **A 94**, 022111, (2016).
[3] N. Leefer, A. Gerhardus, D. Budker, V. V. Flambaum, Y. V. Stadnik, Phys. Rev. Lett. **117**, 271601 (2016).
[4] V.V. Flambaum. Phys. Rev. Lett. **97**, 092502 (2006).
[5] V.V. Flambaum. Phys. Rev. Lett. **117**, 072501 (2016).
[6] J. C. Berengut, V. A. Dzuba, V. V. Flambaum, Phys. Rev. Lett. **105**, 120801 (2010)
[7] C. J. Campbell, A. G. Radnaev, A. Kuzmich, V. A. Dzuba, V. V. Flambaum, A. Derevianko, Phys. Rev. Lett.**108**, 120802 (2012).
[8] S.G. Porsev, V.V. Flambaum, E. Peik, Chr. Tamm, Phys. Rev. Lett **105**,182501 (2010)
[9] V.V. Flambaum, M.V. Romalis, Phys. Rev. Lett. **118**, 142501 (2017).

Dark matter searches within the intercontinental optical atomic clock network

P. Wcisło[1], P. Ablewski[1], K. Beloy[2], S. Bilicki[1,3], M. Bober[1], R. Brown[2], R. Fasano[2], R. Ciuryło[1], H. Hachisu[4], T. Ido[4], J.Lodewyck[2], A.Ludlow[2], W. McGrew[2], P. Morzyński[1,4], D. Nicolodi[2], M. Schioppo[2,5], M. Sekido[4], R. Le Targat[3], P. Wolf[3], X. Zhang[2], B. Zjawin[1], and M.Zawada[1]

[1]Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziadzka 5, 87-100 Torun, Polandy
[2]National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA
[3]LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Universités 61 avenue de l'Observatoire, 75014 Paris, France
[4]National Institute of Information and Communications Technology 4-2-1 Nukuikitamachi, Koganei, 184-8795 Tokyo, Japan
[5]National Physical Laboratory (NPL), Teddington, TW11 0LW, United Kingdom

We report results of dark mater searches within the worldwide network made of our laboratories. We demonstrate that data routinely collected by our currently operating optical atomic clocks without any further developments of the experimental set-ups may be used to run a global program aimed at dark matter detection.

A standard optical atomic clock consists of two state-of-the-art components: an ultra-stable high-Q optical cavity which transfers stability of the length into stability of the frequency, and an atomic sample which transfers accuracy of the energy of the ultra-precise atomic clock transition into accuracy of the frequency. These two components have different susceptibilities to the external perturbations such as electric and magnetic fields, and to the possible changes of fundamental physical constants.

We use this property to derive new constraints for oscillating massive scalar fields [1] and topological defects in the scalar fields [2] couplings to standard matter exceeding previously reported limits [3] by several orders of magnitude. In this network of clocks, the technical noises (thermal noise, drift of cavities) is uncorrelated, while the effects we probe would yield correlations in remote measurements.

References

[1] A. Arvanitaki, J. Huang, K. Van Tilburg, Phys. Rev. D, **91**, 015015 (2015)

[2] A. Derevianko, M. Pospelov, Nat. Phys, **10**, 933 (2014)

[3] P. Wcisło, et al, Nat. Astron., **1**, 0009 (2016); K. Van Tilburg, et al, Phys. Rev. Lett., **115**, 011802 (2015); B. M. Roberts, et al, Nat. Commun., **8**, 1195 (2017); A. Hees, et al, Phys. Rev. Lett., **117**, 061301 (2016); T. Kalaydzhyan, N. Yu, Phys. Rev. D, **96** 075007 (2017)

Abstracts of Posters

(in alphabetical order)

Towards $^{229m}Th^{1+}$ lifetime measurements

I. Amersdorffer[1], B. Seiferle[1], L. v.d. Wense[1] and P.G. Thirolf[1]

[1]LMU Munich, Garching, Germany

In previous experiments, the isomeric lifetime of the singly charged state of ^{229m}Th extracted from a buffer gas stopping cell was found to be shorter than 10 ms (limited by the extraction time) [1].

Compared to the long lifetimes measured in $^{229m}Th^{2+}$ and $^{229m}Th^{3+}$ [2] such a short lifetime is unexpected for an isomeric energy of 7.8 eV [3] and requires further investigation.

For this reason $^{229m}Th^{2+}$ and $^{229m}Th^{3+}$ ions originating from a ^{233}U source are sent through a thin carbon foil where charge exchange occurs. The charge state distribution of the exiting ions is examined with an electrostatic analyzer consisting of a curved plate capacitor.

The performance of the analyzer is tested in simulations (using the ion optics simulator SIMION 8.1) and experiments. A clear separation of different exit charge states can be achieved which allows to select one of them for further examination.

In order to provide a new limit for the lifetime of $^{229m}Th^{1+}$, only the ions in the 1+ exit charge state are collected on a multichannel plate detector (MCP), where a signal due to the ionic impact can be observed.

If the lifetime of the isomer is longer than the time of flight between the carbon foil and the detector, an additional signal that can be attributed to the subsequent isomeric decay must be detected.

The experiment, in which the time of flight amounts to approximately 1 µs, could set a new limit for the lifetime in the singly charged state of ^{229m}Th.

This work was supported by DFG Grant No. Th956/3-2, by the European Union's Horizon 2020 research and innovation program under grant agreement 664732 "nuClock", and by the LMU department of Medical Physics via the Maier-Leibnitz Laboratory.

References

1. B. Seiferle et al., PRL 118, 042501, (2017).
2. L. v.d. Wense et al., Nature 533, 47, (2016).
3. B.R. Beck et al., LLNL-PROC-415170, (2009).

Towards ultrahigh precision spectroscopy using VUV/XUV frequency combs

P. Pfäfflein[1,2], P. Balla[1,2], I. Hart[2], C. M. Heyl[1,2]

[1]Helmholtz-Institute Jena, Germany
[2]DESY, Hamburg, Germany
E-mail: Christoph.heyl@desy.com

Frequency combs are nowadays routinely employed for precision spectroscopy in the visible and near-infrared spectral region. In contrast, the extreme ultraviolet (XUV) presents a barely explored area for precision spectroscopy studies. XUV frequency combs can be produced via high-order harmonic generation (HHG) inside a femtosecond enhancement cavity. Until today, the enhancement cavity approach is the only viable route for HHG at repetition rates above a few tens of MHz. Following the initial demonstration of this concept in 2005, first direct XUV comb spectroscopy was realized in 2012 [1]. Average power limitations present a major challenge for further applications. Recent power-scaling efforts have led to the generation of mW-power levels within single harmonics orders, corresponding to an average power of a few nW within a single continuous wave comb tooth at photon energies of up to approx.13 eV [2]. These results do not only set a new average power record for high harmonic-based XUV sources, they also raise hope for ultrahigh precision spectroscopy of challenging targets such as ^{229}Thorium [3].

Within a joined effort between the Helmholtz-Institute in Jena and DESY in Hamburg, we are currently setting up an XUV comb system at DESY. We here discuss planned experimental routes towards precision spectroscopy studies in the VUV/XUV spectral region. Envisioned targets are narrow transitions in highly charged ions as well as the ^{229}Thorium isomeric transition.

References

[1] A. Cingöz, D. C. Yost, T. K. Allison, A. Ruehl, M. Fermann, I. Hartl and & J.Ye, “Direct frequency comb spectroscopy in the extreme ultraviolet”, Nature 482:68 (2012).

[2] G. Porat*, C.M. Heyl*, S.B. Schoun*, C. Benko, N. Dörre, K.L. Corvin, J. Ye, “Phase-matched extreme-ultraviolet frequency-comb generation”, Nature Photonics (2018), [* = equal author contributon].

[3] L. von der Wense, B. Seiferle, and P.G. Thirolf, “Towards a ^{229}Th-based nuclear clock”, Meas Tech 60:1178 (2018).

Excimer VUV light source for Th-229 experiments

Kjeld Beeks[1] Simon Stellmer[1]

[1]TU Wien, Atominstitut
E-mail: Kjeld.beeks@gmaill.com

The isomer of Th-229 is the only excited nuclear state known today that could be excited by current laser technology. Owing to its long lifetime, the Th-229m isomer could form a platform of a future nuclear optical clock. Very recently, the LMU Munich experiment has observed the de-excitation of the isomer. The direct excitation of the isomer, however, still is one of the greatest challenges in this field of research.

We aim to directly excite Th-229 doped into a in a CaF2 crystal to observe the radiative decay of the isomer. Firstly, the biggest challenge of using Th-229 in a crystal is the suppression of both the non-radiative decay of the isomer and of crystal-related luminescence. Secondly, photons of the appropriate energy are needed for the direct excitation. The isomer energy is known to lie between 6.3 and 18.3 eV, which puts it in the vacuum ultraviolet (VUV) region. So far, only synchrotron radiation has been explored as a possible light source.

To excite the Th-229 in the crystal, we take a new approach by applying a commercially available excimer lamp. This light source uses a low-energy electron beam to excite noble gases to form excimer molecules. These excimers show a continuous and broad emission spectrum in the VUV region, thus forming a high-brightness VUV light source. The wavelength can be tuned to span from 110 nm to 200 nm by using different noble gas mixtures. A VUV spectrometer is used for detection and allows for spectral separation of the crystal luminescence from the anticipated isomer signal.

The excimer lamp is also used for transmission measurements of various crystals. We investigate the transmission of KBe2BO3F2 (KBBF), a non-linear laser crystal, at room and cryogenic temperatures. It is known that cooling crystals can shift the transmission edge to lower wavelengths. Indeed, a significant shift of about 5 nm is observed when cooling KBBF down to 35 K.

Details on the experimental progress along these research lines will be presented.

Laser-induced electronic bridge for characterization of the Th-229 isomer transition

P. Bilous and A. Pálffy

Max Planck Institute for Nuclear Physics, Heidelberg, Germany

The isotope Th-229 is unique among the other nuclei due to its long-lived first excited state at the energy of 7.8 eV. Its radiative decay to the ground state has very narrow width and high stability to external perturbations, rendering Th-229 a candidate for a first nuclear clock at unprecedentedly high relative accuracy of 10^{-19}. Precise knowledge of the transition parameters such as energy and γ-decay rate is however needed for its implementation.

In this work a method for determining the energy of the Th-229 isomeric state using a tunable optical or UV laser is considered theoretically [1]. The approach is based on the process of laser-induced electronic bridge (LIEB), in which the excited nuclear state decays by transfering its energy to the outer electrons. The electronic shell is then promoted to a high-lying bound state by absorption of a laser photon and a virtual photon coming from the nucleus. The process is allowed if the laser photon energy is chosen such that the two-photon resonance condition is satisfied. We calculate the LIEB rates and show that depending on the value of the nuclear transition energy, the enhancement factor compared to the radiative nuclear decay can achieve up to 10^8 if the isomer energy happens to be close to an M1 transition energy in the electronic shell.

References

[1] P. V. Bilous, E. Peik, and A. Pálffy, New J. Phys. 20, 013016 (2018).

Luminescence study of Ln(III) ions adsorbed on a CaF_2 surface as supplementary investigation for searching the isomeric transition in ^{229}Th solid samples

P. Głowacki[1,2] and E. Peik[1]

[1]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2]Poznań University of Technology, Poznań, Poland
E-mail: przemyslaw.glowacki@put.poznan.pl

The thorium isotope 229 is a unique system as far as its nuclear structure is concerned. There are several ideas and concepts for a clock based on a γ-transition in the nucleus as a reference - instead of a transition in the electron shell – which offers many advantages [1]. The fundamental issue is the search for the clock transition.

One of the approaches are the experiments with solid samples and synchrotron radiation. The PTB group developed a novel adsorption technique which deposits $^{229}Th^{4+}$ ions on a surface of CaF_2 from an aqueous solution. The CaF_2 surface doped by the ^{229}Th ions (areal density $1x10^{13}$ mm^{-2}) was exposed to high-intensity undulator radiation in the wavelength range between 130 and 320 nm. After the excitation no clear fluorescence signal related to the nuclear transition was observed [2]. Various reasons of this state of affairs were possible. The isomer excitation energy or lifetime may be outside of the set detection range, or nonradiative decay may prevent the observation of fluorescence.

In order to test the process of the preparation of the samples following the technique developed in [2] and to study the luminescence properties of ions in aqueous and surface-doped solid samples, we chose the lanthanide elements ions Eu^{3+} and Tb^{3+}, well known for their strong luminescence [3]. In this work the luminescence spectra for both elements were recorded and the selected optical properties are presented. Additionally, the radiative lifetime (τ_R), as well as the luminescence quantum efficiency (Φ_{Ln}) of europium ions, based on the information from observed luminescence times (τ_{obs}) and corrected emission spectra - are calculated following the method described in [4] and discussed.

References

[1] E. Peik, M. Okhapkin, C. R. Physique **16**, 516-523 (2015)
[2] A. Yamaguchi,M. K olbe, H. Kaser, T. Reichel, A. Gottwald and E. Peik, New J. Phys. **17**, 053053 (2015)
[3] K. Binnemans, Coordination Chemistry Reviews **295**, 1-45 (2015)
[4] M. H. V. Werts, R. T. F. Jukes and J. W. Verhoeven, Phys. Chem. Chem. Phys. **4**, 1542-1548 (2002)

A superradiant clock laser on an optical lattice with moving atoms

C. Hotter[1], D. Plankensteiner[1], L. Ostermann[1] and H. Ritsch[1]

[1] Institute for Theoretical Physics, University of Innsbruck
Technikerstrasse 21, A-6020 Innsbruck, Austria

It is theoretically well described that an ideal supperradiant laser on an optical clock transition with fixed positions of the atoms features an extreme frequency stability and accuracy. To obtain a more realistic description we extent this model by adding classical positions and momenta of the atoms to the system as dynamic variables. We study the properties of the spectrum of such a laser as well as its stability. For well chosen parameters we predict a stable atom configuration inside the cavity. Further, the atoms are simultaneously cooled via stimulated cavity cooling and thus the trapping in the cavity direction is achieved by the system itself. The dynamics of the atoms does not depend that much on their initial positions and momenta as soon as they are initially cold enough. We find that the shape of the laser spectrum is only weakly shifted when compared to the case of atoms at fixed positions.

Searching for the first excited nuclear state of ^{229}Th using $^{229}Th^{3+}$ coulomb crystal

X. Hua[1], L. Li[1], Z. Lu[2] and X. Tong[1]

[1]State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Science, Wuhan, 430071, China

[2] University of Science and Technology of China, Hefei, 230026, China

E-mail: huaxia@wipm.ac.cn

In 2011, C. J. Campbell and colleagues produced laser-cooled Wigner crystals of $^{229}Th^{3+}$ in a linear Paul trap [1]. We are proposed to measure the energy of this first excited nuclear state of ^{229}Th based on $^{229}Th^{3+}$ coulomb crystals in vacuum chamber. The procedure includes 1) Preparation of $^{229}Th^{3+}$; 2) Confinement of $^{229}Th^{3+}$ using radio frequency quadrupole ion trap, together with Doppler laser cooling and high vacuum technology. Obtaining long lifetime and stabilized confined $^{229}Th^{3+}$ coulomb crystals; 3) Illuminating the $^{229}Th^{3+}$ Coulomb crystal with tunable lasers. Determine the energy range and lifetime of the first excited nuclear state of ^{229}Th.

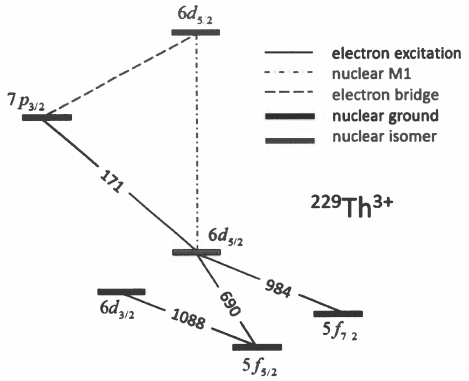


Figure 1: Electron excitation, nuclear M1 and electron bridge existed in $^{229}Th^{3+}$

The probability of first excited nuclear state of ^{229}Th (red in Figure 1) is small, makes it difficult to observe and measure directly. Alternate method is to measure the electron bridge (green in Figure 1) to obtain information of the first excited nuclear state of ^{229}Th indirectly.

References

[1] C. J. Campbell, et al. Physical Review Letters **106**, 223001 (2011)

Folded-beam waist-expanding cavity for iodine based frequency reference

A. A. Jørgensen[1] , M. R. Henriksen[1], S. A. Schäffer[1] and J. W. Thomsen[1]

[1]The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, Copenhagen, Denmark
E-mail: asbjorn.arvad@nbi.ku.dk

Optical frequency references commonly use atoms or molecules with ultra narrow linewidth transitions. To minimize the broadening mechanisms the atoms or molecules are often laser cooled and trapped using multiple lasers and ultra high vacuum systems. We aim to create a compact molecular frequency reference using an $^{127}I_2$ gas cell and implementing a heterodyne cavity enhanced spectroscopy technique (NICE-OHMS[1]) on the P(13)43-0:a_3 transition. $^{127}I_2$ is chosen because the transition is easily accessible at 514.673 nm and is a recommended transition for the representation of the meter[2].

The NICE-OHMS technique allows us to measure the phase shift induced by the molecules and achieve much better signal to noise than ordinary saturated absorption spectroscopy. It is still limited by the transition time broadening which is inversely proportional to the waist size:

$$\Delta\nu_{transit} = \frac{1}{2\pi} 2\sqrt{2ln2} \sqrt{\frac{2k_B T}{\pi m}} \frac{1}{w(z)}$$

To decrease the transit time broadening we propose to use a folded cavity with a mirror with a short focal length (F = 25 mm) together with a lens (F = 150mm), to create a beam expanding telescope.

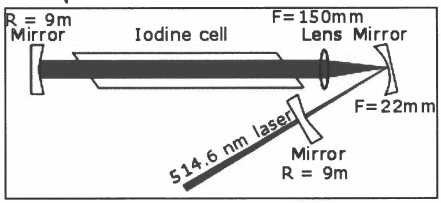


Figure 1 Illustration of the folded beam expanding cavity

This creates a cavity with a waist w ~ 1 cm which reduces the transit time broadening significantly compared to a typical cavity waist size on the order of millimeters. Other compact setups have demonstrated lasers locked to this transition with relative instabilities on the order of $10^{-13}/\sqrt{\tau}$ [3] without cavity enhancement. Because the finesse of the cavity increases the signal to noise ratio we believe we can achieve similar or better stabilities.

References

[1] L.-S.Ma, J. Ye, P. Dub, J.L. Hall, J. Opt Soc. Am. B **16**, 2255-2268 (1999)

[2] R. Felder, Metrologica **42**, 323-325 (2003)

[3] C. Philippe, D. Holleville, R. Le Targat, P. Wolf, T. Leveque, R. Le Goff, E. Martaud, O. Acef, Proc. SPIE 10562, International Conference on Space Optics — ICSO 2016, 1056253 (2017)

Possibility of laser stabilization with trapped cavity-coupled ions

G.A. Kazakov

University of Vienna and Wolfgang Pauli Institute, Vienna, Austria

The concept of an active optical frequency standards was proposed about 10 years ago [1,2]. The idea is to use optically trapped alkaline-earth atoms as a gain medium to build an extremely narrow-line laser, whose frequency will be robust to fluctuations of the cavity length. The main challenge towards the realization of this concept is the limited trap lifetime of the atoms. Recently we showed [3], that in such a laser, neutral atoms may be replaced by charged ions in a radio-frequency Paul trap with much longer lifetime. Our idea is based on the effect of synchronization of radiating dipoles and on the possibility to compensate (in leading orders) micromotion-induced shifts for some ion species in specially designed traps.

Here we discuss in detail the perspectives of creating of the bad cavity laser based on a Coulomb crystal in the linear Paul trap. We consider compensation of the micromotion-induced shifts, coupling of the quadrupole transition with the cavity mode in different geometries, various ion species and clock transitions as well as pumping schemes, and estimate attainable characteristics of different trapped-ion bad-cavity lasers.

The author acknowledge financial support by the (Austrian Science Foundation) FWF under grant No F41 (SFB "VICOM").

References

[1] J. Chen, X. Chen, Proceedings of the 2005 IEEE International Frequency Control Symposium and Exposition, 608 (2005)

[2] D. Meiser *et al*, Phys. Rev. Lett. **102**, 163601 (2009)

The MLS-IDB: A versatile beamline for applications in the UV to soft X-ray spectral range

Hendrik Kaser, Alexander Gottwald, Gerhard Ulm, Michael Kolbe

Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany
Hendrik.Kaser@ptb.de and Michael.Kolbe@ptb.de

The Physikalisch-Technische Bundesanstalt (PTB) operates its own electron storage ring Metrology Light Source (MLS) [1] in Berlin-Adlershof. The main purpose is to provide best conditions for metrological applications in the energy range from soft X-ray to THz. An insertion device beamline (IDB) at the MLS U125 undulator has been put into operation, which delivers high flux in combination with high spectral purity in the range from 4.4 nm to 800 nm (280 eV to 1.55 eV). By a switching mirror unit behind the beam shutter, the undulator radiation can be directed into three different branches. In the central branch the direct undulator radiation is available without any beamline optics. The second branch utilizes the deflected undulator beam for applications which need a moderate spectral resolution ($\Delta E = 2E/N$ as given by the width of the 1. undulator harmonic with the number of undulator periods N=30.5). Different experiments in the search for the low-energy nuclear transition in ^{229}Th were applied at this beamline branch [2,3].

In the third branch mainly used for analytical purposes, the undulator radiation is monochromatized by a normal incidence – grazing incidence (NI-GI) hybrid plane grating monochromator covering the whole wavelength range. In the NI mode (40 nm to 800 nm), two different coated laminar gratings with 600 lines/mm are used, while the GI mode (4.4 nm to 50 nm) is covered by a blazed grating with 1200 lines/mm. The beamline is optimized for highest suppression of unwanted contributions (i.e. higher orders from the diffraction gratings) and highest reliability of the on-line monitoring of the radiation intensity (photon flux). Thus, it can provide quantitative photon numbers for traceable measurements.

Currently, it is mainly used for investigations of interfaces and nanostructures by various experimental techniques, such as photoelectron spectroscopy [4] as well as variable angle spectroscopic ellipsometry [5].

[1] A. Gottwald et al., Metrologia **49**, S146 (2012)

[2] A. Yamaguchi, M. Kolbe, H. Kaser, T. Reichel, A. Gottwald, E. Peik, New J. Phys. **17**, 053053 (2015) DOI: 10.1088/1367-2630/17/5/053053

[3] S. Stellmer, G. Kazakov, M. Schreitl, H. Kaser, M. Kolbe, T. Schumm, submitted, arXiv:1803.09294v1.

[4] F. Roth, T. Arion, H. Kaser, A. Gottwald, W. Eberhardt; J. El. Spec. Rel. Phen. **224**, 84 (2018) DOI:10.1016/j.elspec.2017.05.008

[5] M. D. Neumann, C. Cobet, H. Kaser, M. Kolbe, A. Gottwald, M. Richter, N. Esser; Rev. Sci. Instrum. **85**, 055117 (2014) DOI:10.1063/1.4878919

Vacuum Ultraviolet and Laser Ionization Spectroscopy Studies of ^{229m}Th

S. Kraemer[1], M. Verlinde[1], S. Cottenier[2], L. da Costa Pereira[1], R. Ferrer[1], M. Huyse[1], Y. Kudryavtsev[1], M. Laatiaoui[3], V. Manea[1], S. Sels[1], P. Van Duppen[1], A. Vantomme[1], E. Verstraelen[1], U. Wahl[1], S. Zadvornaya[1]

[1]IKS, KU Leuven, Leuven, Belgium
[2]Center for Molecular Modeling, UGent, Gent, Belgium
[3]Helmholtz Institute Mainz, Mainz, Germany

Two complementary approaches to study the low-lying isomer in ^{229}Th and its decay to the ground state are pursued:

In a first approach, the beta decay of ^{229}Ac, in view of a novel production method of isomer in ^{229Th}, will be studied. Produced online by proton irradiation on a uranium carbide target at the ISOLDE facility at CERN, ^{229}Ac will be laser-ionized and implanted into a suitable host material. According to literature, an isomeric state feeding of at least 14% is expected [1,2].

The branching ratio to the isomer will be measured in a dedicated experiment with actinium implanted into a metal. Taking advantage of the internal conversion channel and its short lifetime, a low-energy electron detection will enable to distinguish between ground- and isomeric state feeding.

Emission channeling measurements deliver valuable information on the lattice positions after implantation and after decay to thorium. A suitable annealing procedure can be developed to improve actinium lattice positions, taking advantage of the low recoil energy in the beta decay towards thorium.

These studies together with improved background control will eventually make VUV spectroscopy of the gamma decay and the precise determination of the transition energy at an improved signal-to-background ratio and with suppressed internal conversion feasible.

In a second approach, laser ionization spectroscopy of the hyperfine structure in $^{229m}Th^{1+}$ will be performed using the IGLIS (In-Gas-jet Laser Ionization and Spectroscopy) offline-setup at KU Leuven in combination with a gas-cell adapted to the requirements of a ^{233}U source [3]. This technique has successfully been applied to heavy elements and can potentially serve as a basis for a contaminant-free pure-isomeric source of ^{229m}Th ions [4].

References

[1] E. Ruchoska et al., Phys Rev C **73**, 044326 (2006)
[2] National Nuclear Data Center. Available at www.nndc.bnl.gov
[3] Y. Kudryavtsev et al., Nucl. Instr. Meth. B 376, 382-387 (2016)
[4] R. Ferrer et al., Nature Comm. **8**, 14520 (2017)

Studying quenching of metastable atomic states in Th IV

M. Laatiaoui[1]

[1]*Helmholtz Institute Mainz, Mainz, Germany*
[2] *Johannes Gutenberg University, Mainz, Germany*

The first direct detection and characterization of the ^{229}Th isomer [1, 2], has opened up new and promising avenues in developing precise nuclear frequency standards. Thorium atoms in a 3+ charge state exhibits a simple level scheme that can be exploited for both laser cooling and resonance fluorescence spectroscopy. The optical access to the $^2S_{1/2}$ metastable state of this ion enables the elimination of most systematic frequency shifts in future ^{229}Th-based nuclear clocks once the nuclear transition has been found [3, 4].
In my contribution I will present an experimental setup, which enables studying the lifetime and the quenching mechanisms of this metastable state.

References

[1] L.v.d. Wense et al., Nature **533**, 47-51 (2016)
[2] J. Thielking et al., Nature **556**; 321-325 (2018)
[3] E. Peik and Chr. Tamm, EPL **61**, 181-186 (2003)
[4] M. Safronova et al., PRA **74**, 042511 (2006)

Photoelectron spectroscopy technique for the energy measuring of photons emitted from the excited ^{229m}Th nuclei

Yu.Yu. Lebedinskii[1], P.V. Borisyuk[1], E.V. Chubunova[1], N.N. Kolachevsky[2,1], O.S. Vasiliev[1] and E. V. Tkalya[3,1,4]

[1] *National Research Nuclear University MEPhI, Moscow, Russia*
[2] *P.N. Lebedev Physical Institute of the Russian Academy of Sciences,Institute, Moscow, Russia*
[3] *Skobeltsyn Institute of Nuclear Physics Lomonosov Moscow State University, Moscow, Russia*
[4] *Nuclear Safety Institute of RAS, Moscow, Russia*

In this presentation, we describe the methodology of using electron spectroscopy for energy measuring of photon emitted in γ decay of excited ^{229}Th nuclei. The Si substrate covering SiO_2 layer with implanted Th ions was used as a photocathode. The modeling of the spectral line shape for such photocathode is a complex task, that requires determination of many parameters, including the ones related to device. In order to avoid labour-intensive and probably non correct model calculations within the framework of this work we use a simple empirical method that is based in the comparison of the right edge of the photoelectron spectra obtained for the studied samples and VUV sources with known spectral characteristics. We used two sources (Kr and Xe discharge lamps) for modeling photoionization from Th:SiO_2/Si. The analysis of electronic spectra obtained with the help of radiation from an external source with known energy makes it possible to calibrate the spectra obtained as a result of the decay of the excited isomeric state ^{229}Th and determine the energy of the emitted photons (see Fig.1).

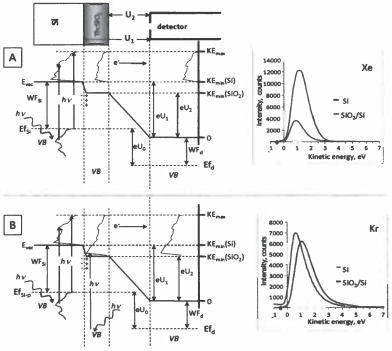


Fig.1 The scheme of the photoelectron spectra formation for the ^{229}Th:SiO_2/Si structure and clean Si substrate during irradiation by the xenon lamp (A) and the krypton lamp (B).

A potential precision method to determine the nuclear isomeric states in 229Th at storage ring

X. Ma[1,2], W. Q. Wen[1], Z. K. Huang[1,2], H. B. Wang[1,2], L. J. Dou[2],Y. J. Yuan[1], M. Wang[1], Z. Y. Sun[1], L. J. Mao[1], J. C. Yang[1], H. S. Xu[1], and W. L. Zhan[1]

[1]Institute of Modern Physics, CAS, Lanzhou, 730000, China
[2] University of Chinese Academy of Sciences, 100049, Beijing, China

Precision determination of the predicted lowest isomeric state of ^{229m}Th has been a hot topic for nuclear physics and atomic physics after E. Peik et al [1] suggested that the isomeric state of the ^{229}Th can be used to construct a nuclear clock. C. J. Campbell et al [2] estimated that this nuclear clock will have an accuracy of 19th decimal, which has at least one to two orders higher precision than the current best optical clocks. The indirectly measurement gives the value of 7.8 ± 0.5 eV by advanced x-ray microcalorimeter [3]. However, there was no direct measurement of the energy splitting of 229Th until a recent measurement confirms the existence of the isomer and the measured energy is constrained to between 6.3 and 18.3 eV [4]. The development of a ^{229}Th-based nuclear clock is reviewed in [4].

The first international workshop of the "Nuclear Isomer Clock" about ^{229}Th was held at GSI, Darmstadt in Sep. 2012 [5]. Dielectronic recombination (DR) has been successfully used to study the atomic (hype)-fine structures at storage rings [6, 7]. It has been proposed by using DR technique to investigate the process of the nuclear excitation by electron capture [8]. Proposals to determine the nuclear isomeric states were planned at CSRe of IMP [9] and at the ESR of GSI, respectively.

At CSR the 229Th will be produced by 232Th PF reaction and are stacked and electron cooled in CSRe, by detuning the electron beam energy from the cooling point, hopefully the resonant transition can be found with a precision better than a few milli-eV. The investigation will be carried out in DR-collaboration.

Project is supported by NSFC 91336102 and GJHZ1305.

References

[1] E. Peik, Europhys. Lett., **61**, 181 (2003).
[2] C.J. Campbell, et al., PRL, **108**, 120802 (2012).
[3] B.R. Beck, et al., PRL 98, 142501 (2007).
[4] L. v. d. Wense et al., Nature (London) 533, 47 (2016), Meas. Tech. 60, 1178(2018)
[5] EMMI Workshop-The 229mTh "Nuclear Isomer Clock", GSI, Darmstadt, Germany, 25-27 Sep. 2012.
[6] M. Lestinsky, et al., PRL 100, 033001 (2008), C. Brandau, et al., PRL 100, 073201 (2008)
[7] Z. K. Huang, et al., Astrophysical Journal Supplements Series, 235, 2 (2018)
[8] A. Pálffy, et al., Phys. Lett. B 661, 330 (2008)
[9] X Ma, et al., Phys. Scr. T166 (2015) 014012

Search for laser excitation of the low energy isomer in trapped Th^+ ions

D.-M. Meier, J. Thielking, G. Zitzer, M. V. Okhapkin and E. Peik

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
E-mail: david-marcel.meier@ptb.de

Among all known isotopes ^{229}Th possesses a uniquely low-lying metastable nuclear excitation state at 7.8(5) eV with a lifetime of about ~1000 s. Since the energy of 7.8 eV corresponds to a wavelength in the VUV region of about ~160 nm, laser excitation of the nucleus would be feasible. But to this end a more precise knowledge on the transition frequency is needed.

For the search of the transition's frequency we attempt to excite the nucleus in a two-photon process via the NEET [1] or electronic bridge [2] mechanisms which rely on the hyperfine coupling between electron shell and nucleus. Since the Th^+ ion is a three valence electron system, it possesses a dense electronic level structure [3] which makes it likely to observe an enhanced coupling to an electronic level in close proximity to the nuclear resonance. This would lead to a higher excitation probability and strong decrease of the lifetime of the isomeric state.

After investigating the energy range from 7.3 eV to 8.3 eV for an indication of NEET excitation we now extend our search to the $+3\sigma$ energy range from 7.8 to 9.8 eV.

For this reason, detailed knowledge about the electronic level structure of Th^+ in this range is necessary. In our experiment we investigate two-photon laser excitation of high-lying levels in $^{232}Th^+$ ions. Our latest results include 177 previously unknown energy levels with angular momenta from J = 1/2 to 7/2.

References

[1] F.F. Karpeshin, *et al.*, Nucl. Phys. A, **654**, 579 (1999)
[2] S. G. Porsev *et al.*, Phys. Rev. Lett. **105**, 185501 (2010)
[3] O. A. Herrera-Sancho et al., Phys. Rev. A **88**, 012512 (2013)

Investigating the Local Atomic Structure of Th Dopants in CaF_2 Using Channeling Techniques

J. Moens[1], S. Cottenier[3], L. da Costa Pereira[1], M. Huyse[1], R. Ferrer[1], S. Kraemer[1], Y. Kudryavtsev[1], M. Laatiaoui[2], S. Sels[1], P. van Duppen[1], A. Vantomme[1], M. Verlinde[1], E. Verstraelen[1], U. Wahl[1], S. Zadvornaya[1]

[1] IKS, KU Leuven, Leuven, Belgium
[2] Helmholtz Institute Mainz, Mainz, Germany
[3] UGent, Gent, Belgium

^{229}Th-doped CaF_2 has been proposed as a platform to study the ^{229}Th low-energy isomer state (e.g. based on nuclear spectroscopy) as well as in application scenarios, such as a solid-state nuclear clock [1,2]. The suitability and performance of this solid-state system strongly depends on the atomic environment of the Th atoms in the CaF_2 crystal lattice [3], which is yet to be experimentally assessed. In this poster we present two approaches to experimentally determine the lattice site occupied by Th atoms (substituting for a Ca atom, an interstitial site in crystalline CaF_2, or in a disordered environment). One approach is based on the electron emission channeling technique, involving ion implantation of a suitable parent isotope (e.g. ^{231}Ac) that decays by β- emission into a suitable Th isotope (e.g. ^{231}Th) which also decays by β- emission. By measuring the channeling anisotropy of the emitted β-particles, it is possible to determine the lattice location of both the parent and the Th species. This approach is particularly attractive in the context of complementing vacuum ultraviolet (VUV) spectroscopy experiments that require the implantation of a parent isotope that feeds the ^{229}Th isomer state (e.g. ^{229}Ac), as proposed by the KU Leuven group. In this case, the ^{231}Ac/^{231}Th decay mimics the ^{229}Ac/^{229}Th decay in terms of recoil and its potential impact on the local atomic structure. The other approach is based on ion channeling techniques, in which the lattice location of Th dopants in CaF_2 can be directly investigated using an external (stable) ion beam (e.g. He^+ MeV beam for Rutherford backscattering spectrometry). This approach is particularly attractive, for example, in the context of characterizing CaF_2 crystals doped with Th during growth, and is compatible with any Th isotope.

References

[1] S.Stellmer, Scientific Reports **5**, 15580 (2015)
[2] G.A. Kazakov, New Journal of Physics **14**, 083019 (2012)
[3] P. Dessovic, Journal of Physics: Condensed Matter **26**, 105402 (2014)

The ^{229m}Th nuclear isomer in Th-doped crystal environments

B.S. Nickerson and A. Pálffy
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Current efforts in the development of a nuclear frequency standard based on the isomeric state of ^{229m}Th have been centered around precisely determining its state energy. The unique lowest transition in the ^{229}Th nucleus with frequency in the vacuum ultraviolet (VUV) range and very narrow linewidth promises enhanced precision and amazing stability [1]. This level is a nuclear isomeric state at $\approx$ 7.8 eV that can be reached by VUV lasers. A very exact measurement of the isomeric transition energy has been elusive, with the first confirmation of the level decay coming only recently [2].

As a starting point, a typical nuclear forward scattering (NFS) setup [3] is considered where by resonant photons are scattered through ^{229}Th:CaF_2. Numerical results for excitation schemes using one or two VUV pulses in different configurations are presented. The result of nuclear excitation with a pulse trains are investigated along with the interplay between phase relation, detuning and pulse spacing. By taking advantage of such effects we aim to design a more sensitive nuclear excitation scheme to resolve not only the transition energy but provide a clear signature of the excitation.

[1] W. G. Rellergert *et al.*, Phys. Rev. Lett. 104, 200802 (2010).
[2] L. von der Wense *et al.*, Nature 533, 47-51 (2016).
[3] W.-T. Liao *et al.*, Phys. Rev. Lett. 109, 262502 (2012).

Super- and subradiance of a 1D chain of clock atoms trapped inside an optical fiber

L. Ostermann[1], C. Genes[2] and H. Ritsch[1]

[1] *Institute for Theoretical Physics, University of Innsbruck, Austria*
[2] *Max Planck Institute for the Science of Light, Erlangen, Germany*

Atoms resonantly coupled to the transversely confined propagating field modes of a optical nanofiber will exchange energy via virtually infinite range fiber mediated and free space dipole dipole interaction. For a sufficiently large number of emitters regularly arranged in a magic wavelength lattice, fiber interaction dominates free space coupling and emission. We predict drastic modifications of the atomic decay and shifts of the emission frequency. We study the example of superradiant forward decay from the fully inverted state including free space emission and coupling to transverse fiber modes of a hollow core fiber. Using various levels of approximation starting from a solution of the full master equation to different orders of mean field expansions we study systems from a few to experimentally relevantly many particles.

Filament dispensers, recoil sources, and on-line production for ^{229}Th ion beams at IGISOL

I. Pohjalainen[1], I.D. Moore[1] , S. Geldhof[1], M. Reponen[1],T. Schumm[2] A. Voss[3]

[1]University of Jyvaskyla, Department of Physics, P.O. Box 35 (YFL), Finland
[2]Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria

E-mail: ilkka.pohjalainen@jyu.fi

High optical resolution spectroscopy of actinide elements is the current focus of the collinear laser spectroscopy facility at the Accelerator Laboratory, University of Jyväskylä [1]. The recent detection [2] and measurement of hyperfine structure of ^{229m}Th [3] has prompted new questions of the ^{229m}Th such as the life time of the singly charged ion. To produces ^{229}Th ion beams several ideas are being investigated. For the thorium-229 ion beam production by in-gas cell laser resonance ionization several types of filament dispensers have been studied of which the electro deposited thorium with a zirconium layer for reduction had the most favorable characteristics.

^{233}U can be used also to produce ^{229}Th also in the isomer for the Two different ^{233}U alpha recoil sources has been analyzed extensively with direct and implantation foil gamma- and alpha-ray spectroscopy. Also series of Rutherford back scattering spectroscopy measurements have been performed to study the source composition.

The first on-line experiment for the production of ^{229}Th from a light-ion fusion-evaporation reaction on ^{232}Th targets has also been performed. Although the identification of ^{229}Th was not directly possible due to the long half-life (7932 years), several alpha-active reaction products were detected and a yield of about 400 ions/s/μA for ^{229}Th was deduced from the ^{227}Pa yield. The challenge of on-line production is in the competing fission channel that is expected to cause strong ionization of the buffer gas. Also significant target damage was observed during the experiment. This has prompted new target manufacturing concepts which are current being considered.

References

[1] A. Voss et al., Phys. Rev. **A 95**, 032506 (2017)
[2] L. von der Wense et al., Nature, **533**, 47 (2016)
[3] J. Thielking et al. Nature **556** 321 (2018)

Spectrometers tailored for Thorium isomer emission

R. Hörlein[1] and J. Rauschenberger[1]

[1]H+P SPECTROSCOPY, Mannheim, Germany

Several approaches have been proposed and tested to populate the few-eV isomer in ^{229}Th, most of them relying on doped crystals. Common to all experiments is the fact that the VUV gamma emitted during de-excitation of the isomer is to be measured spectrally resolved with a VUV spectrometer.

The required spectral range at 7.8(5) eV, corresponding to a wavelength of 160(10) nm is very accessible. However, the signal to be measured is expected to be very weak with an estimated 10^3-10^5 photons per second reaching the spectrometer entrance, notably with a very large angular distribution due to the spatially extended source [1, 2].

As a further complication, the narrow-line emission (width below a few THz) is contained in a Cherenkov radiation background. The isomer signal is expected to rise above the noise of the Cherenkov background after a few hours (depending on approach chosen) of illumination / detection cycles [1, 2].

Hitherto, only standard off-the-shelf spectrometers or monochromators were used for the isomer emission detection. Yet, the abovementioned particular requirements of the Thorium experiments make a tailored spectroscopy solution necessary. We present recent advances in spectrometers specifically tailored for this task.

References

[1] S. Stellmer et al, Towards a measurement of the nuclear clock transition in ^{229}Th, Journal of Physics: Conference Series **723** (2016) 012059

[2] P. V. Borisyuk et al, Excitation of ^{229}Th nuclei in laser plasma: the energy and half-life of the low-lying isomeric state, arXiv:1804.00299

A new quantum metrology group at the University of Bonn

S. Stellmer[1]

[1]*Physikalisches Institut, University of Bonn, Germany*
E-mail: stellmer@uni-bonn.de

A new group in the field of quantum metrology has been established at the University of Bonn. We will follow two research lines: one is targeted at very fundamental questions in physics, the other one seeks to develop advanced technologies for quantum communication and network synchronization.

The first research line is about a measurement of the electric dipole moment (EDM) of mercury atoms. The current best measurements of any EDM have been performed with room-temperature, cm-sized gases of mercury. We will bring these experiments into the ultracold regime, where we profit from the small system size, long coherence time, and supreme control over the system. Using an ultracold ensemble of atoms might allow for the exploitation of quantum effects to enhance measurement sensitivity.

In the second research line, we will develop and optimize individual components that will be essential for a future quantum communication network. We will start out with a network of robust optical clocks, operating at telecom wavelengths and reaching an uncertainty in the 10^{-15} to 10^{-16} range. Such clocks will be used to phase-stabilize the nodes of a future quantum communication network. Alternatively, they can be used for optical synchronization of networks, such as arrays of radio telescopes.

The flying qubits of large-scale networks will have to be at telecom wavelengths, whereas all candidate platforms for stationary qubits (atoms, ions, or solid state) are in the visible wavelength range. Therefore, we will also develop robust and highly efficient wavelength conversion modules to convert visible into IR photons at the single-photon level.

Laser spectroscopic characterization of the nuclear clock isomer ^{229m}Th

J. Thielking[1], M. V. Okhapkin[1], P. Głowacki[1], D.-M. Meier[1], L. v. d. Wense[2], B. Seiferle[2], C. E. Düllmann[3,4,5], P. G. Thirolf[2], E. Peik[1]

1 Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
2 Ludwig-Maximilians-Universität München, Garching, Germany
3 GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
4 Helmholtz-Institut Mainz, Mainz, Germany
5 Johannes Gutenberg-Universität, Mainz, Germany

E-mail: johannes.thielking@ptb.de

We present the first measurement of fundamental nuclear properties of the isomer ^{229m}Th, namely the magnetic dipole and electric quadrupole moments and the nuclear charge radius, using precision hyperfine spectroscopy of Th^{2+} recoil ions, loaded from the α decay of ^{233}U [1]. The hyperfine splittings and isomer shifts of two electronic transitions have been analyzed. The main findings can be summarized as follows: The nuclear magnetic moment was determined to be $\mu^m = -0.37(6)\mu_N$, which deviates significantly from the theoretical Nilsson model prediction of $-0.076\mu_N$. The intrinsic nuclear quadrupole was determined as $Q^m = 8.7(3)$eb. To within the experimental uncertainty it is identical to the intrinsic quadrupole moment of the nuclear ground state, in agreement with theoretical predictions. From the amplitude of the hyperfine resonances, the 2% branching ratio into the isomer following the α decay of ^{233}U was verified experimentally for the first time. The change of the mean square charge radius was determined from the isomer shift in relation to the isotope shifts between ^{229}Th and ^{232}Th, and is given as $\langle r^2\rangle^{229m} - \langle r^2\rangle^{229} = 0.012(2)$ fm^2.
We can now apply this data to the known Th^+ hyperfine structure [2] to achieve an efficient direct detection method for our experiment, which is searching for the optical excitation of the isomer in Th^+ ions via the electronic bridge [3] and NEET process [4].

References

[1] J. Thielking et al., Nature **556**, 321-325 (2018)
[2] M.V. Okhapkin et al., Phys. Rev. A **92**, 020503 (2015)
[3] S. G. Porsev et al., Phys. Rev. Lett. **105**, 185501 (2010)
[4] F.F. Karpeshin et al., Nucl. Phys. A, **654**, 579 (1999)

A direct nuclear laser excitation scheme for ^{229m}Th

L. von der Wense[1], B. Seiferle[1], S. Stellmer[2], J. Weitenberg[3], G. Kazakov[2], A. Pálffy[4], and P. G. Thirolf[1]

[1]*Ludwig-Maximilians-Universität München, Garching, Germany*
[2]*Technische Universität Wien, Vienna , Austria*
[3]*Max-Planck-Institut für Quantenoptik, Garching, Germany*
[4]*Max-Planck-Institut für Kernphysik, Heidelberg, Germany*

E-mail: L.Wense@physik.uni-muenchen.de

Direct nuclear laser excitation of the low-lying nuclear isomer ^{229m}Th has been a long-standing objective. Until recently it was assumed that reaching this goal would require a significantly reduced uncertainty of the isomer's excitation energy. However, a new direct nuclear laser excitation scheme was proposed, which circumvents this requirement [1]. The scheme makes use of the isomer's internal conversion (IC) decay channel [2] and the recently confirmed short isomeric IC lifetime [3]. Further, it is based on already existing laser technology, thereby paving the way for a first nuclear laser excitation and the determination of the isomeric transition energy to a precision of 10^{-5} eV. This energy precision would be sufficient for the development of a single-ion nuclear clock based on ^{229}Th.
In the presentation the proposed concept of nuclear laser excitation will be detailed and the current status of experimental preparation will be given. Experiments will start this summer in collaboration with the University of Hannover.

References

[1] L. v.d.Wense et al., PRL **119** 132503 (2017).
[2] L. v.d.Wense et al., Nature **533** 47 (2016).
[3] B. Seiferle et al., PRL **118** 042501 (2017).

Supported by DFG Grant TH956/3-2, by the European Union's Horizon 2020 research and innovation programme under grant agreement 664732 "nuClock" and by the LMU department for Medical Physics via the Maier-Leibnitz-Laboratory.

XUV Frequency Combs

J. Weitenberg[1,2], A. Ozawa[1], F. Schmid[1], Th. Udem[1], and Th. W. Hänsch[1,3]

[1]Max-Planck Institute of Quantum Optics MPQ, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
[2] Fraunhofer Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany
[3]Ludwig-Maximilians University LMU, Schellingstr. 4/III, 80799 München, Germany

XUV frequency combs allow for precision spectroscopy of transitions with wavelength below 200 nm. Spectroscopy has been performed by other groups on argon (82 nm), neon (63 nm) [1] and xenon (147 nm) [2]. We aim for spectroscopy of the 1s-2s transition in He^+, which permits an experimental test of bound-state QED in simple atomic systems [3]. A mayor challenge compared to spectroscopy of atomic hydrogen is the small wavelength of 60.8 nm to excite the transition. A frequency comb at this wavelength can be generated by high-harmonic generation (HHG) of an IR comb around 1033 nm (H17). At repetition rates >10 MHz an enhancement resonator can be employed which helps to reach the required intensity and boosts the conversion efficiency. We require >100 µW at 60.8 nm for a reasonable excitation rate of He^+. We expect to reach this by scaling demonstrated results [4] by a factor >10. This will be achieved by using a femtosecond Innoslab amplifier with 400 W average power [5] and employing a new nonlinear pulse compression scheme suitable for these parameters, which overcomes the limitation due to self-focusing [6,7]. We use a geometrical output coupling scheme of the harmonics from the enhancement resonator, which is power-scalable because it avoids limitations due to an additional element, such as bandwidth, thermal effects, dispersion and nonlinearity [8]. A quasi-imaging resonator with a slit in a resonator mirror [9] and a circulating field distribution avoiding the slit allows a large output coupling efficiency also at low harmonics [4,10]. The source can possibly be adapted to excite the ^{229}Th isomer nuclear transition.

References

[1] A. Cingöz et al., Nature **482**, 68-71 (2012).
[2] A. Ozawa et al., Phys. Rev. A **87**, 022507 (2013).
[3] M. Herrmann et al., Phys. Rev. A **79**, 052505 (2009).
[4] I. Pupeza et al., PRL **112**, 103902 (2014).
[5] P. Rußbüldt et al., JSTQE **21**, 3100117 (2015).
[6] J. Schulte et al., Opt. Lett. **41**, 4511-4514 (2016).
[7] J. Weitenberg et al., Opt. Express **25**, 20502-20510 (2017).
[8] I. Pupeza et al., Nat. Photon. **7**, 608-612 (2013).
[9] D. Esser et al., Opt. Express **21**, 26797-26805 (2013).
[10] J. Weitenberg et al., J. Opt. **7**, 025609 (2015).

Towards sympathetic cooling of trapped $^{229}Th^{3+}$ ions

G. Zitzer, J. Thielking, D.-M. Meier, M. Okhapkin and E. Peik

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
E-mail: gregor-alexander.zitzer@ptb.de

Because of its relatively simple and convenient electronic level structure the $^{229}Th^{3+}$ ion is a favored charge state for the realization of an optical nuclear clock with laser-cooled trapped ions. Direct laser cooling of $^{232}Th^{3+}$ and $^{229}Th^{3+}$ has been experimentally demonstrated and large Coulomb crystals of these ions have been observed [1,2]. The narrow natural linewidth of the cooling transitions (≈ 200 kHz) and the high number of hyperfine components (e.g. six hyperfine levels for the ground state) in $^{229}Th^{3+}$ limits the rate of cyclic laser excitation and therefore the achievable laser cooling power.

For the further investigation of thorium ions in the charge state 3+ and the future clock operation we are developing a new setup. We plan to investigate sympathetic laser cooling of $^{229m}Th^{3+}$ with $^{88}Sr^{+}$. $^{88}Sr^{+}$ possesses a convenient level structure for Doppler cooling and sideband cooling. Both ions have a similar charge to mass ratio, so that in a linear radiofrequency ion trap a central prolate distribution of $^{229m}Th^{3+}$ will be surrounded by a shell of $^{88}Sr^{+}$. We plan to extract the $^{229}Th^{3+}$ ions generated by a ^{233}U source via α-decay [3] and guide them to a segmented linear Paul trap in an ultrahigh vacuum environment. Here we present concept, design and status of the upcoming experiment on $^{229}Th^{3+}$.

References

[1] C. J. Campbell et al., Phys. Rev. Lett. **102**, 233004 (2009)
[2] C. J. Campbell et al., Phys. Rev. Lett. **106**, 223001 (2011)
[3] L. v. d. Wense, On the direct detection of ^{229m}Th, Springer International Publ., DOI: 10.1007/978-3-319-70461-6 (2018)