Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Atomic and nuclear clocks for testing fundamental physics

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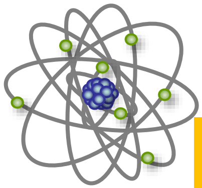
PTB, Braunschweig, Germany

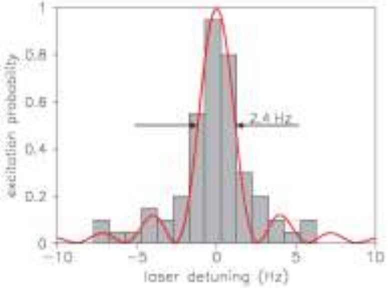
MIAPBP Workshop, Garching, 28.08.-08.09.2023

Atomic clocks and fundamental physics

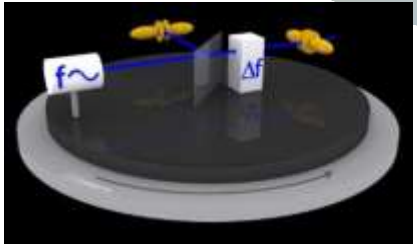


Atomic and nuclear structure, Quantum theory

Spectroscopy



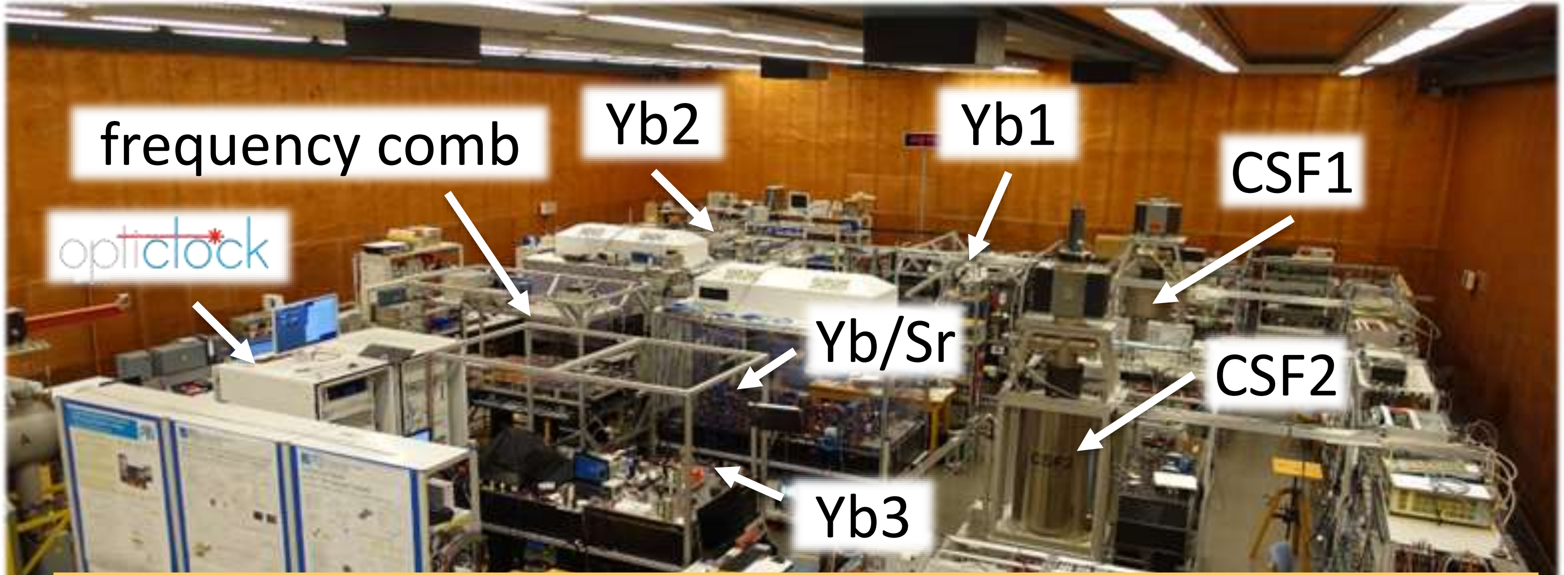
Tests of quantum theory and relativity



Clocks and Frequency Standards

PTB

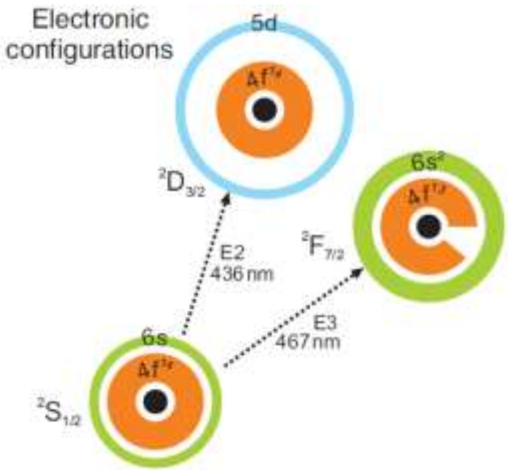
Clock ensemble in PTB‘s clock hall



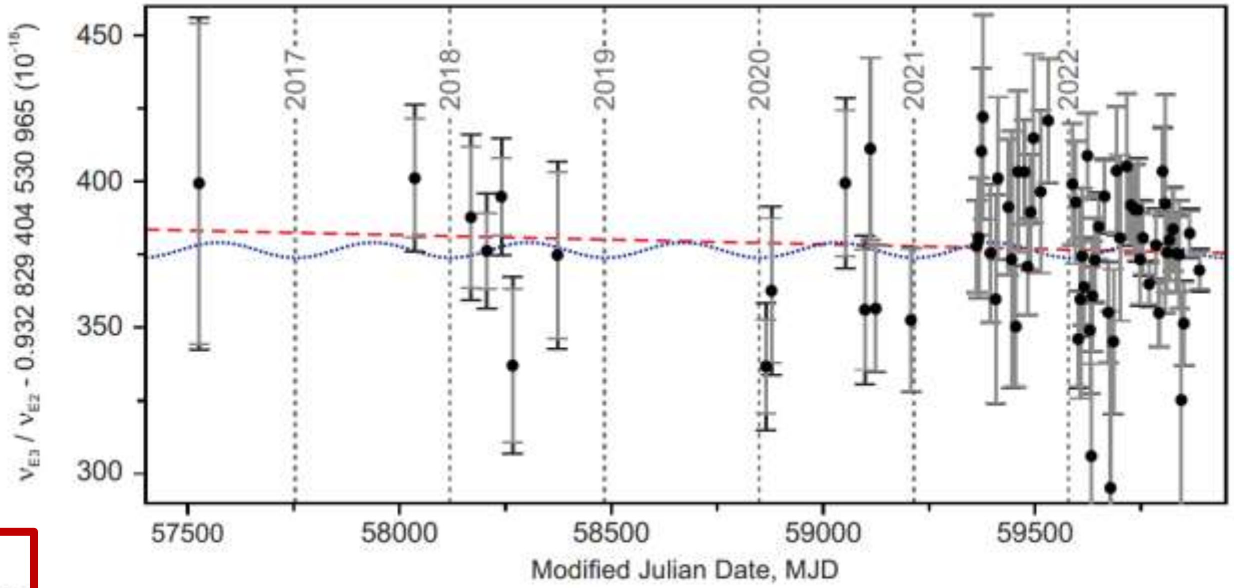
Activities on fundamental tests with these clocks:

- Optical clock with trapped $^{171}Yb^{+}$: Search for violations of LPI, LLI, search for ultralight dark matter
- Today: Towards a nuclear optical clock with $^{229}Th^{3+}$

Frequency comparisons of optical clocks at PTB



A change in the value of α would appear with enhancement ×7 in the frequency ratio of the E3 and E2 transitions of Yb^+.



Measurements from 19.05.2016 until 11.11.2022

Curve fitting:

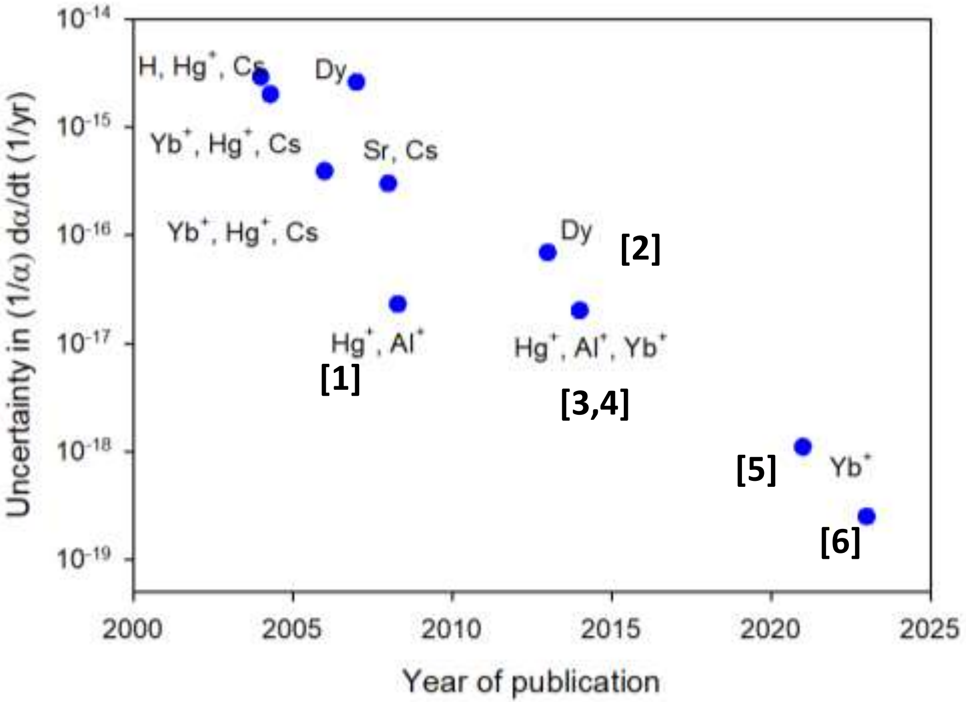
Blue: annual variation of the gravitational potential of the sun on earth

Red: linear drift of α

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = 1.8(2.5) \times 10^{-19}/\mathrm{yr}$$

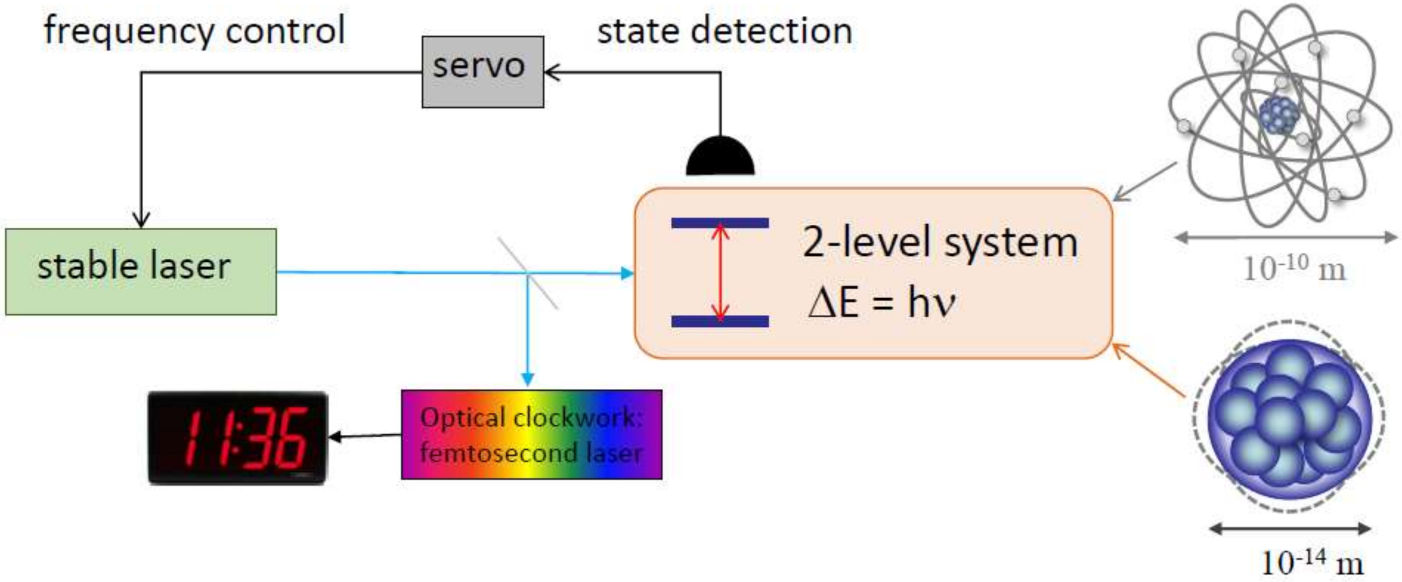
M. Filzinger, S. Dörscher, R. Lange, J. Klose, M. Steinel, E. Benkler, E. Peik, C. Lisdat, N. Huntemann: PRL 130, 253001 (2023)

Clock comparison data for variations of α



[1] T. Rosenband *et al.*, Science **319**, 1808 (2008)
[2] N. Leefer et al., PRL 111, 060801 (2013)
[3] R. Godun *et al.*, PRL **113**, 210801 (2014)
[4] N. Huntemann *et al.*, PRL **113**, 210802 (2014)
[5] R. Lange *et al.*, PRL **126**, 011102 (2021)
[6] M. Filzinger *et al.*, PRL **130**, 253001 (2023)

From the atomic to the nuclear clock

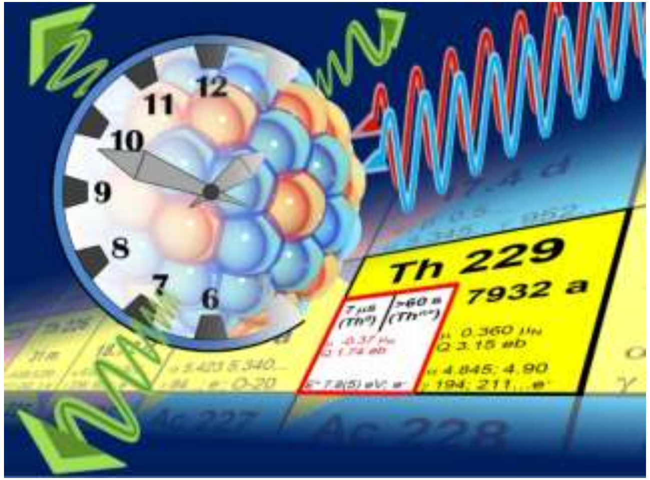


The nuclear clock promises:

- High accuracy (with laser cooled trapped ions)
- High stability (solid state reference like Th:CaF2)
- High sensitivity to new physics

Nuclear Clock:

Oscillator that is frequency-stabilized to a nuclear (γ-ray) transition



Motivation:

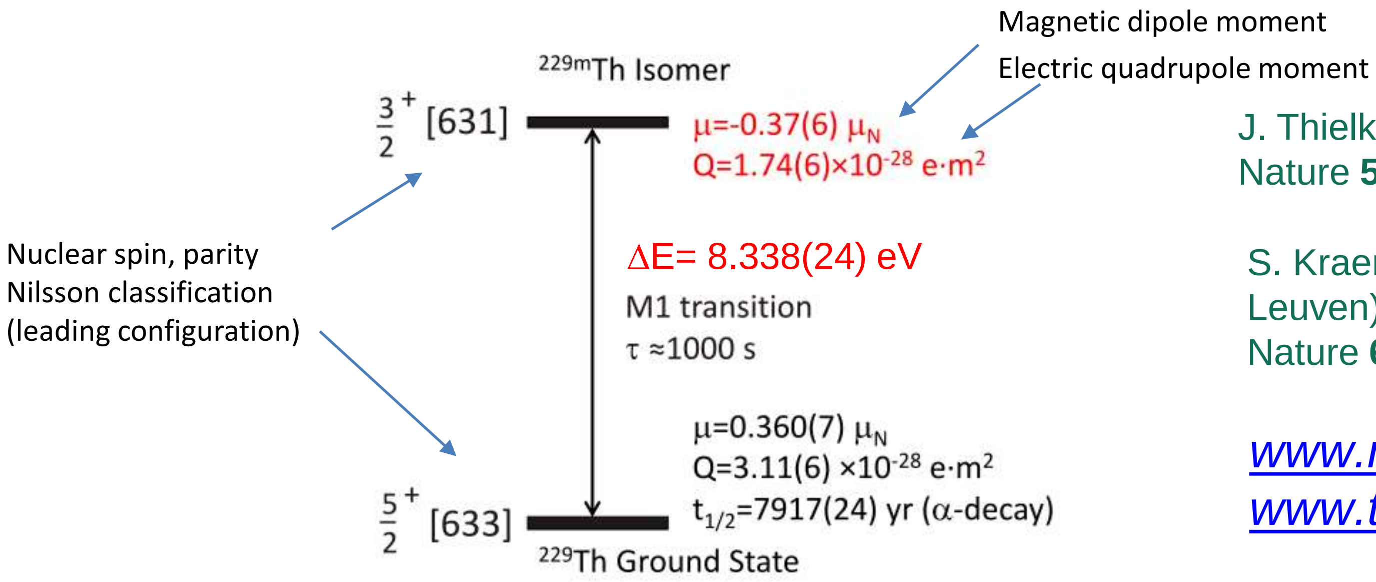
Higher precision: In many of the advanced optical clocks (trapped ion and optical lattice) field-induced shifts make a dominant contribution to the uncertainty budget. These can be reduced in a nuclear clock.

Higher stability: In a Mößbauer solid state nuclear clock, many absorbers may be interrogated ($>10^{10}$ instead of $\approx 10^{0}$ (ion) or $\approx 10^{4}$ (lattice)).

Higher frequency: → higher stability. EUV or even X-ray transitions may be used when suitable radiation sources become available.

Low-energy transition in Th-229 as a reference for a nuclear clock

accessible for laser excitation at ≈ 150 nm



J. Thielking et al. (PTB, LMU)
Nature **556**, 321 (2018)

S. Kraemer et al. (KU Leuven)
Nature **617**, 706 (2023)

www.nuclock.eu
www.thoriumclock.eu

Advantage of the nuclear over the atomic clock: (nearly) free choice of a suitable electronic state for the interrogation of the nuclear resonance.

E. Peik, Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

K. Beeks et al., Nat. Rev. Phys. **3**, 238 (2021)

News from other labs

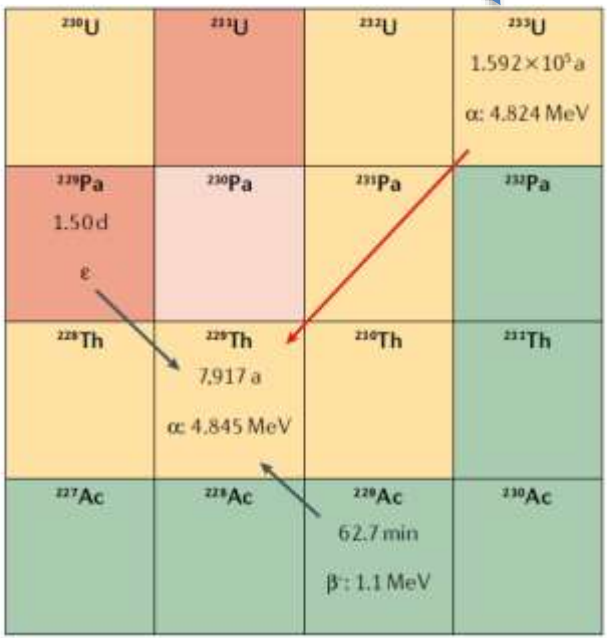
Production of ^{229m}Th through β-decay of ^{229}Ac

- First optical observation of the isomer decay
- First optical wavelength measurement
- First observation of Th-229 nuclear photon emission from solids (MgF_2, CaF_2)

Online experiment at CERN ISOLDE
Lead: KU Leuven, Piet van Duppen
S. Kraemer et al., arXiv:2209.1027
Nature **617**, 706 (2023)

Wavelength 148.71(42) nm
excitation energy 8.338(24) eV
The half-life of ^{229m}Th embedded in MgF_2 is determined to be 670(102) s.

At LMU, PTB, LANL et al.



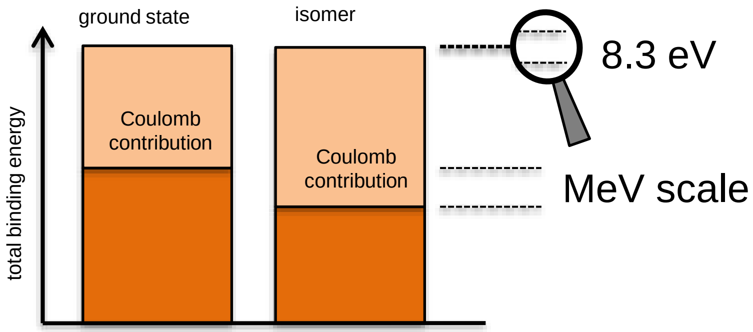
At CERN

High sensitivity of a Th-229 nuclear clock for violations of the equivalence principle

- Transition frequency is sensitive to the strong interaction (in addition to electromagnetism)

- Coulomb- and strong- contributions (MeV scale) cancel in the transition energy
  Enhanced sensitivity to variations of fundamental constants:
  V. Flambaum, Phys. Rev. Lett. 97, 092502 (2006)

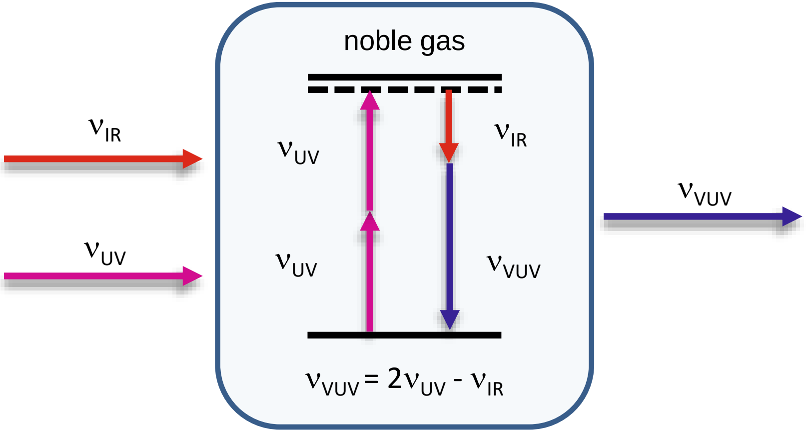
- Bound system of massive particles (n, p) at high energies
  Enhanced effect of LLI violation:
  V. Flambaum, Phys. Rev. Lett. 117, 072501 (2016)



E. Peik, T. Schumm, M. Safronova, A. Pálffy, J. Weitenberg, P.G. Thirolf, Quant. Sci. Tech. 6, 034002 (2021)

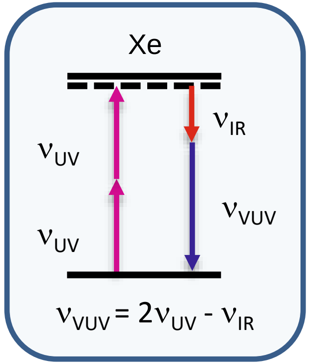
8-eV VUV generation: Four wave (difference) mixing principle

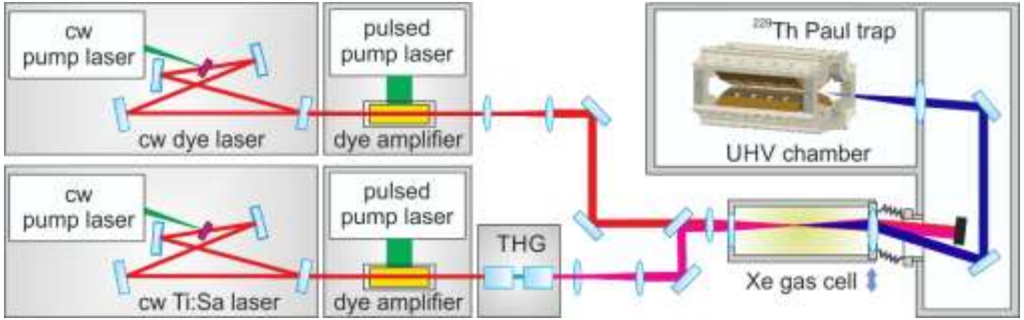
- Near-resonantly driving of 2-photon transition in noble gas.
- Supplying one photon with ν_{IR} yields fourth photon with $\nu_{VUV} = 2\nu_{UV} - \nu_{IR}$.
- Two-photon transition in Xe at 2 x 250 nm is suitable for VUV tunability from 167 nm to 148 nm, i.e. 7.42 eV to 8.38 eV.



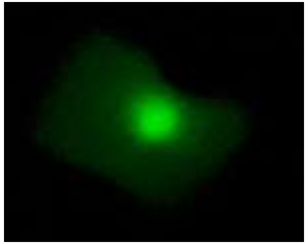
8-eV VUV generation: Four wave (difference) mixing principle

- Tuning over the range 7.9 eV to 8.3 eV requires laser beams at 250 nm and 610-759 nm.
- Third order process needs high intensity to achieve suitable efficiency.
- Pulsed lasers (~10 ns, 30 Hz repetition rate) best compromise between VUV pulse energy (>10^{13} photons/pulse) and Fourier transform limited bandwidth (<1 GHz).
- Our setup:
  - Two cw ring lasers as seed: 750 nm Ti:Sa laser, 610-759 nm tunable dye laser.
  - Pulsed dye amplifiers (~60 mJ/pulse, 30 Hz repetition rate).
  - Third harmonic generation to achieve 250 nm for two-photon transition.

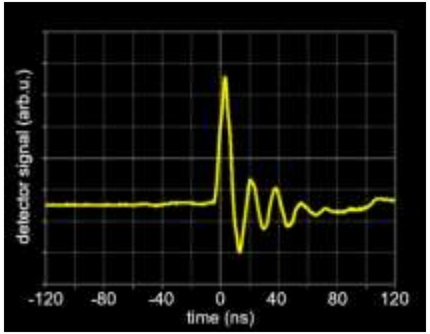




FWM laser system at PTB

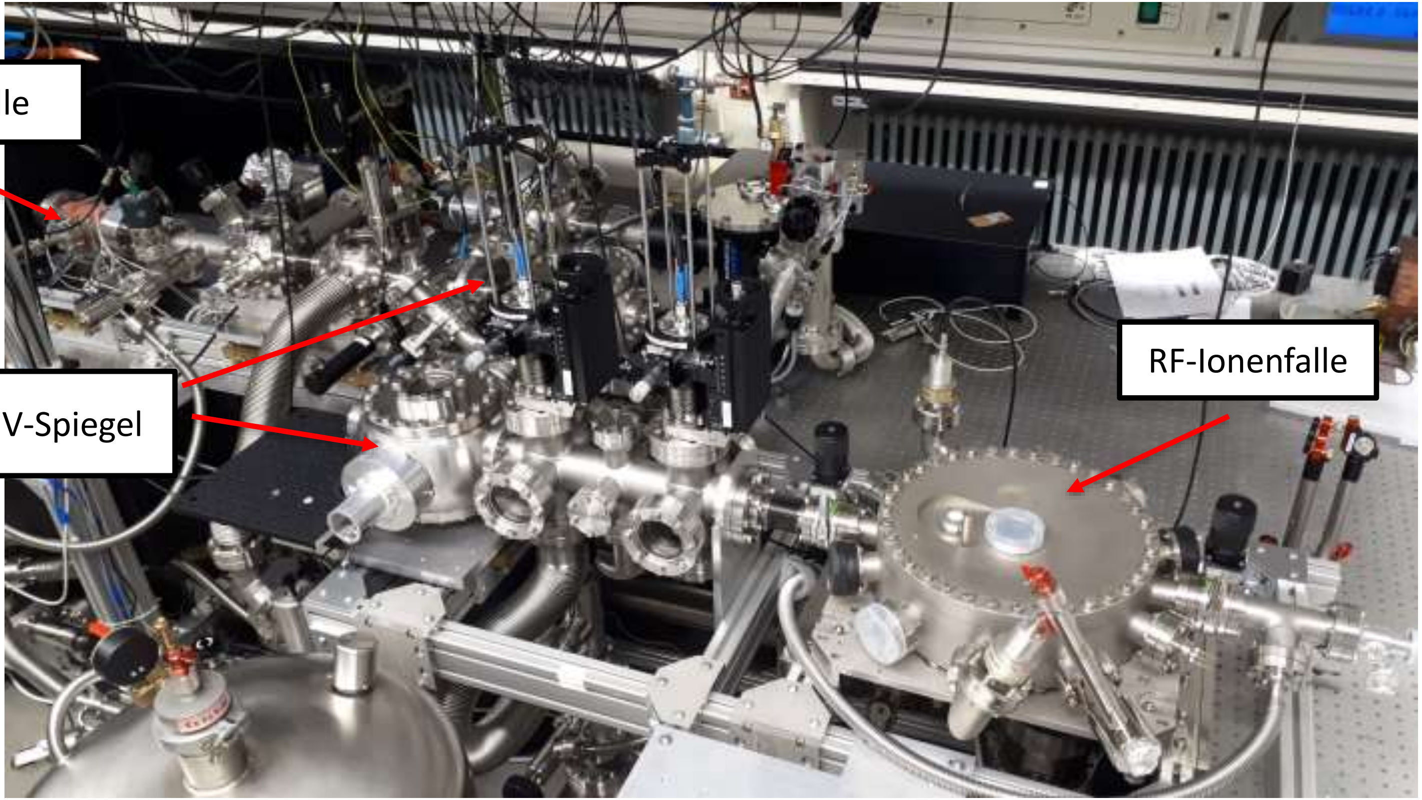


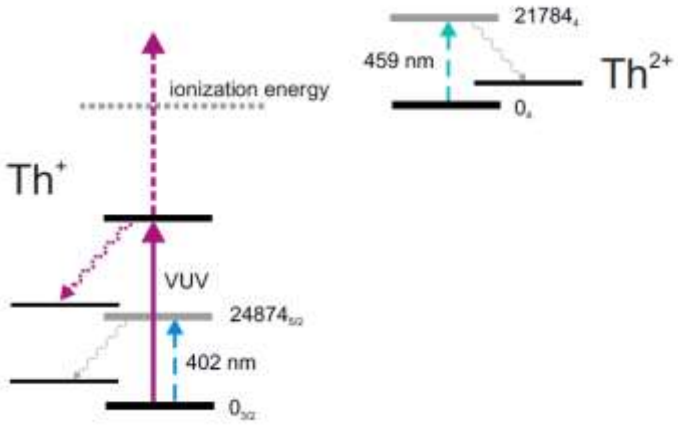
VUV beam visualization on Ce:YAG phosphor



- Relative power measurements with Cu-based photo-electron detector.
- Absolute measurements with pyro-electric power meter show $E_{pulse} > 5$ µJ.

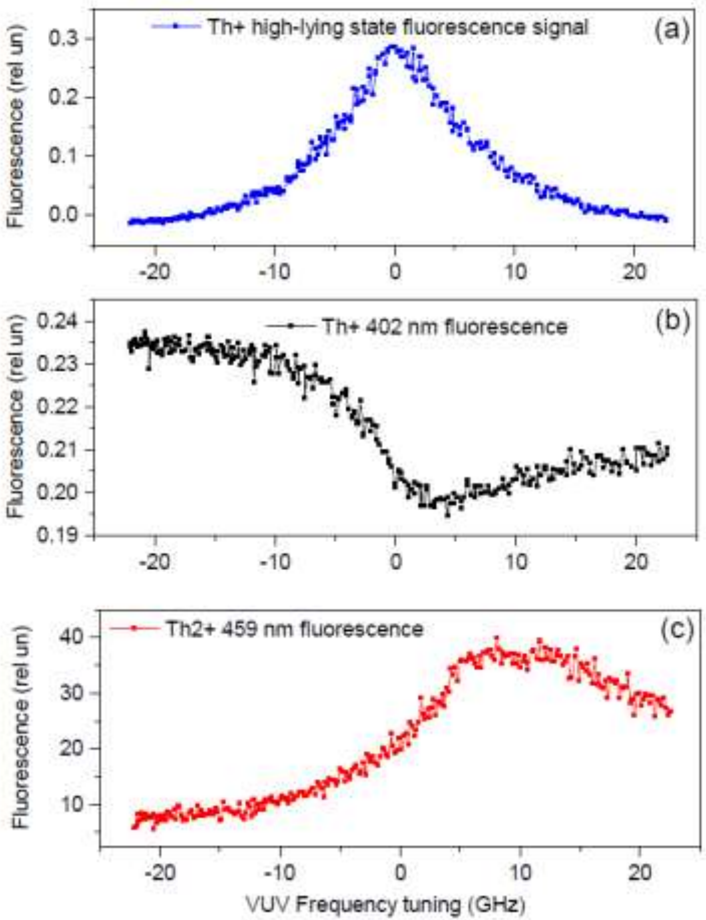
VUV Beam Line





First VUV laser excitation of trapped Th^{+} ions

Detection:
in Th^{+} : provides laser spectral profile
in Th^{2+} : sensitive to the integrated excitation rate



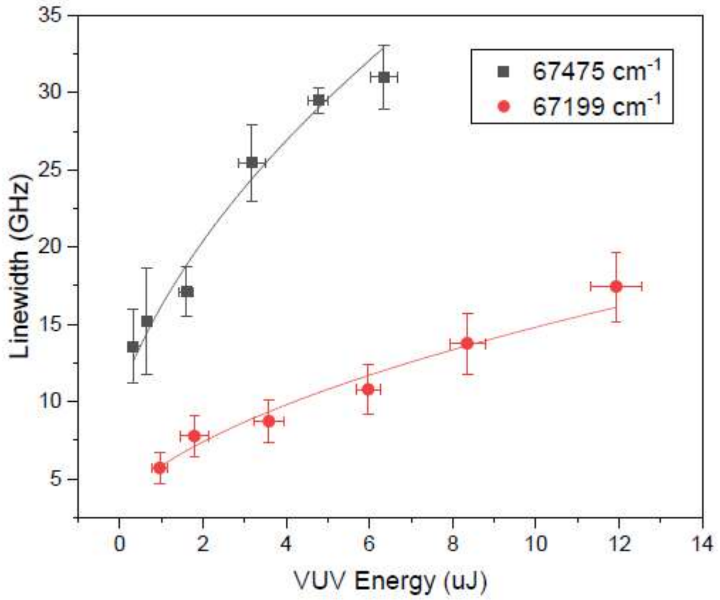
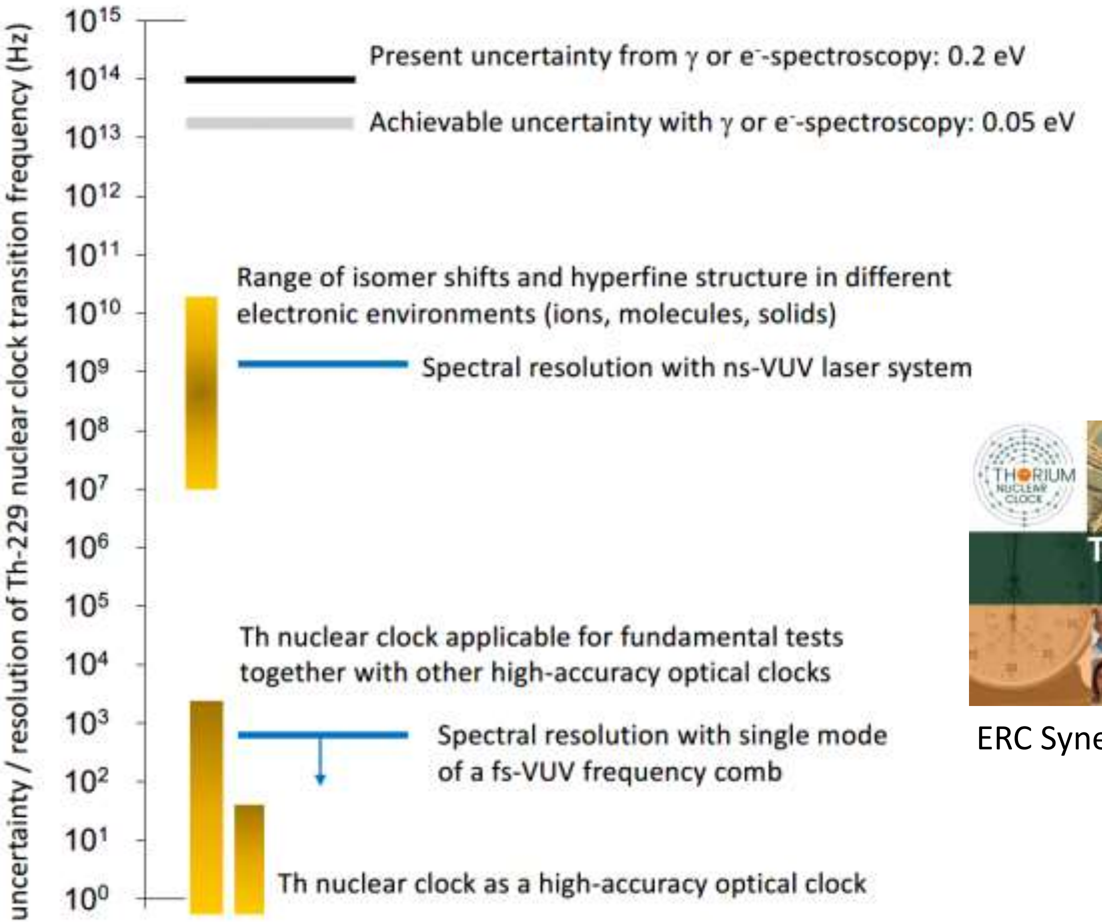


Figure 7. Width of the resonances vs. VUV pulse energy for two transitions. A contribution from Doppler broadening of 2.7 GHz is subtracted from the observed resonance widths.

Linewidth of the VUV source:
≤6 GHz
(phase noise from the amplifiers gets upconverted in THG and FWM processes)

J. Thielking, K. Zhang, J. Tiedau, J. Zander, G. Zitzer, M. V. Okhapkin, E. Peik, New J. Phys. **25**, 083026 (2023)

„Roadmap“ in frequency uncertainty for the Th-229 nuclear transition



ERC Synergy Project 2020

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European Research Council
Established by the European Commission

<u>PTB Working Group
Laser Nuclear Spectroscopy</u>

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Positions available !

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