Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Nuclear Clocks for Tests of Fundamental Physics

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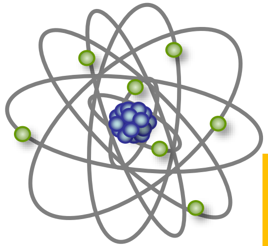
European Research Council
Established by the European Commission

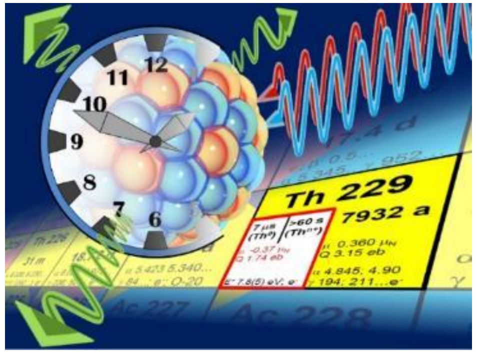
TU WIEN

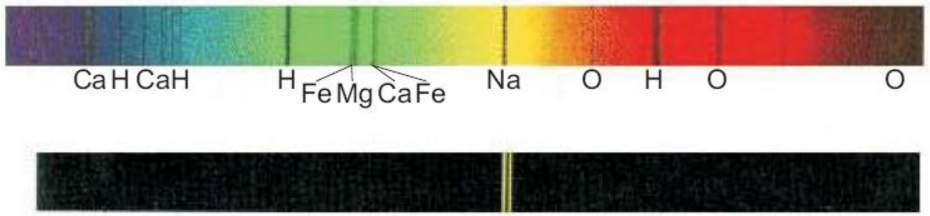
Int. Conf. on Quantum Technologies for High-Energy Physics, CERN, Geneva, 22.01.2025

Atomic clocks and fundamental physics

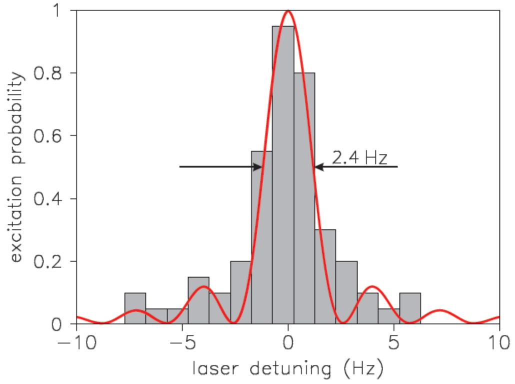


Atomic and nuclear structure, Quantum theory

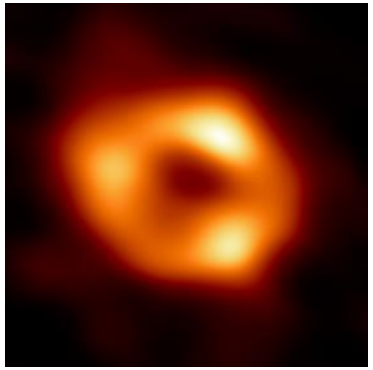


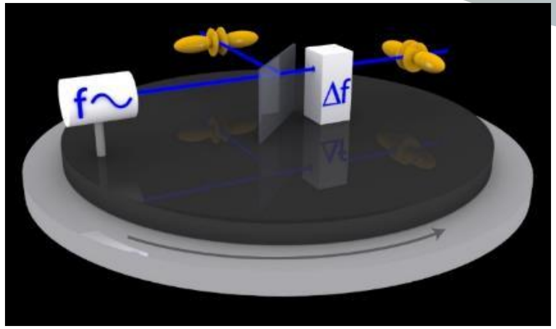


Spectroscopy



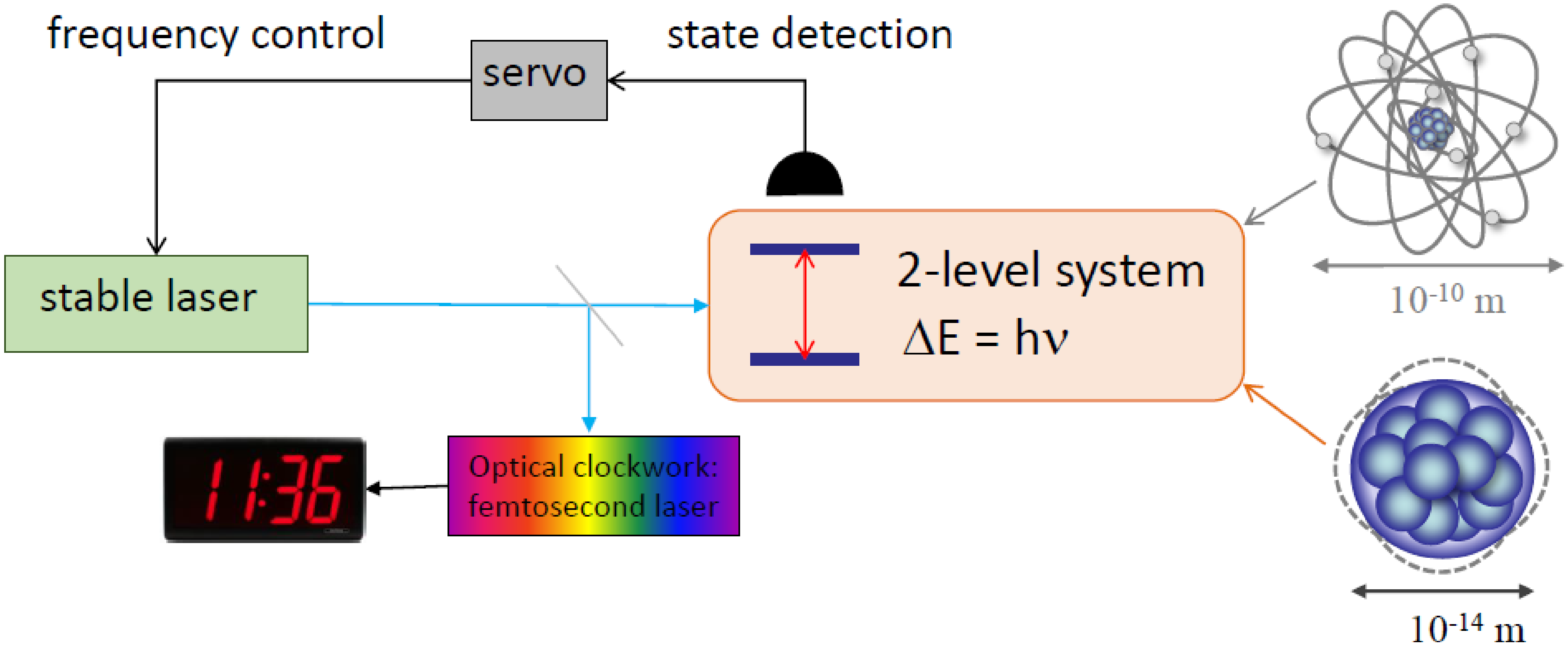
Tests of quantum theory and relativity





Clocks and Frequency Standards

From the atomic to the nuclear clock


frequency control

servo

state detection

stable laser

2-level system

$\Delta E = h\nu$

Optical clockwork:
femtosecond laser

11:36

10^{-10} m

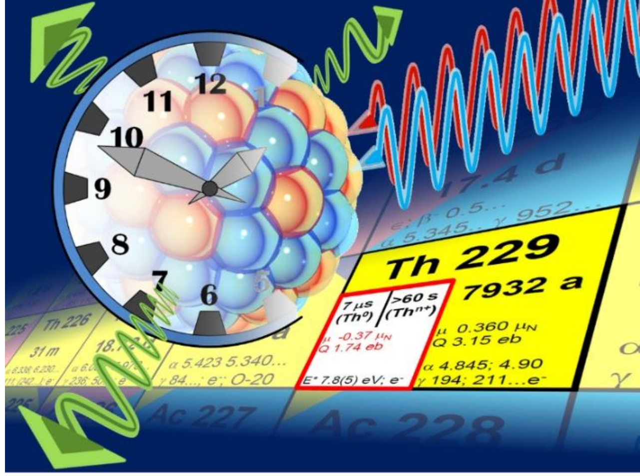
10^{-14} m

The nuclear clock promises:

- High accuracy (with laser cooled trapped ions)
- High stability (in the solid state as a laser Mössbauer system)
- High sensitivity to new physics (also to strong interaction)

Nuclear Clock:

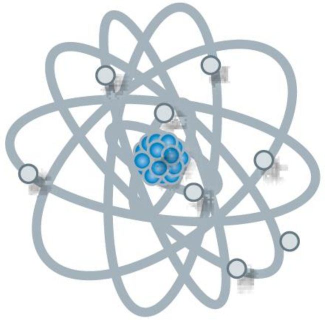
Oscillator that is frequency-stabilized
to a nuclear (γ-ray) transition



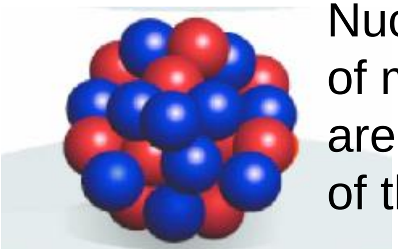
Higher accuracy:

The nuclear clock allows for a choice of a suitable electronic state
for the interrogation of the nuclear resonance.

Example: Electric fields, Stark effect:



~~Electrons shield the nucleus?~~

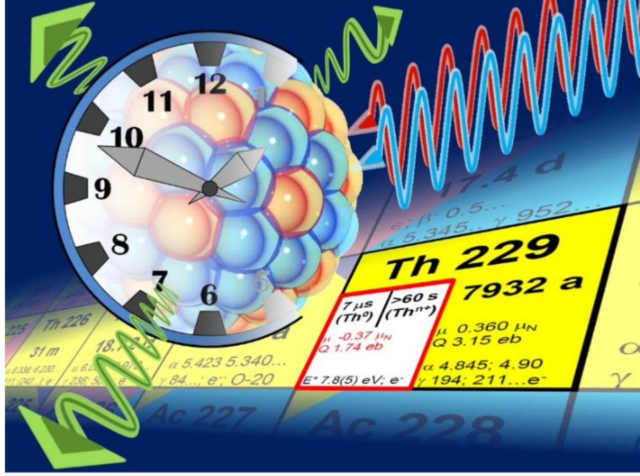


Nuclear polarizability is orders
of magnitude smaller; electronic effects
are common-mode for both states
of the transition.

Detailed analyses of suitable electronic configurations:
E. Peik, Chr. Tamm, Europhys. Lett. **61**, 181 (2003)
C. J. Campbell et al., PRL **108**, 120802 (2012)

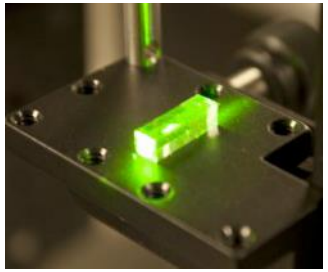
Nuclear Clock:

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

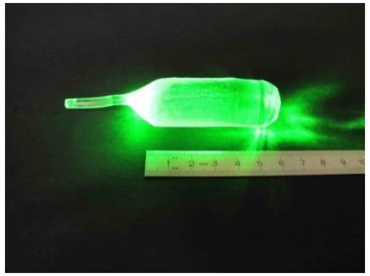


Higher stability:

In a Mössbauer solid state nuclear clock, many absorbers may be interrogated
(>10^{15} instead of ≈10^{0} (ion trap) or ≈10^{4} (optical lattice)). Systematics: Crystal field shifts.
Proposed at PTB, UCLA, TU Wien



UCLA, LiCAF



TU Vienna, CaF_2

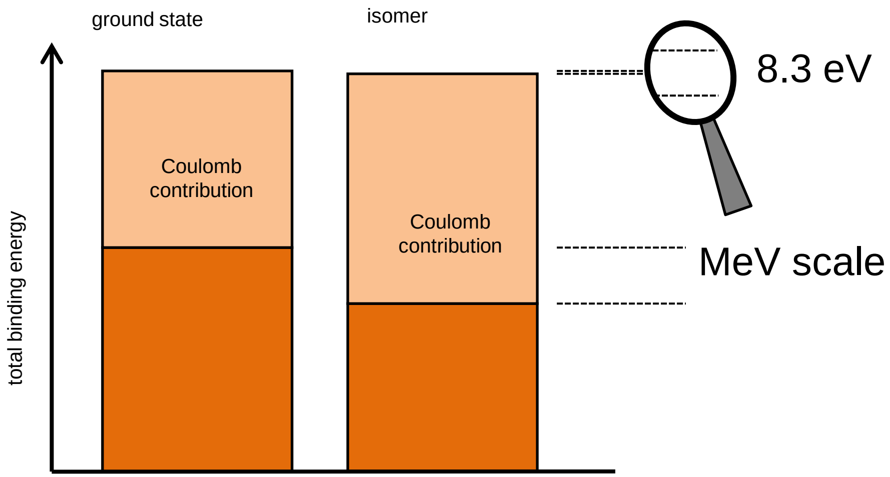
High sensitivity of a Th-229 nuclear clock in fundamental tests: Search for violations of the Einstein equivalence principle*

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

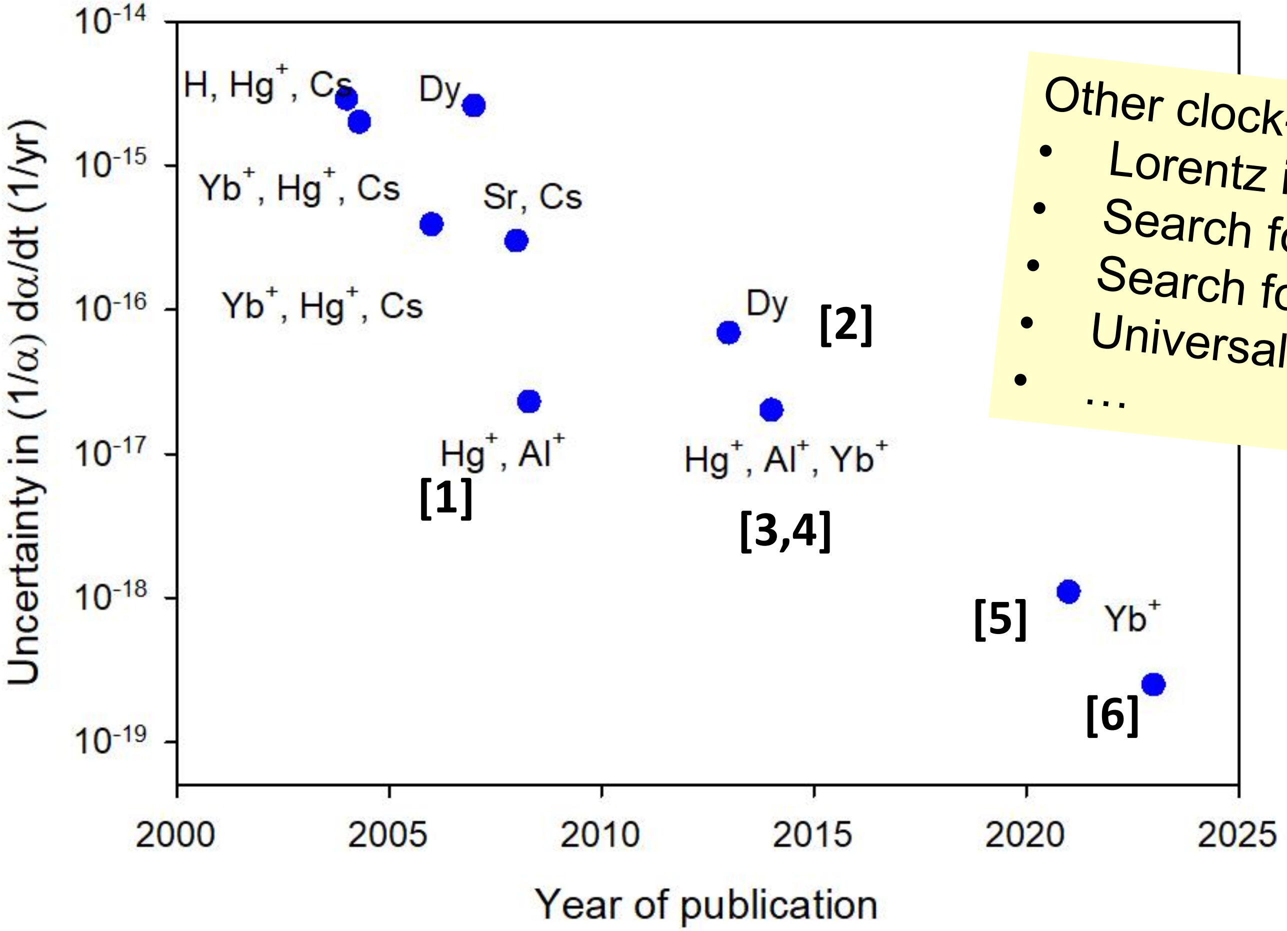
- Coulomb- and strong- contributions (MeV scale) cancel in the transition energy
  Enhanced sensitivity to variations of fundamental constants: Phys. Rev. Lett. 97, 092502 (2006)

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

Work of **Victor Flambaum**



Clock comparison data for variations of α

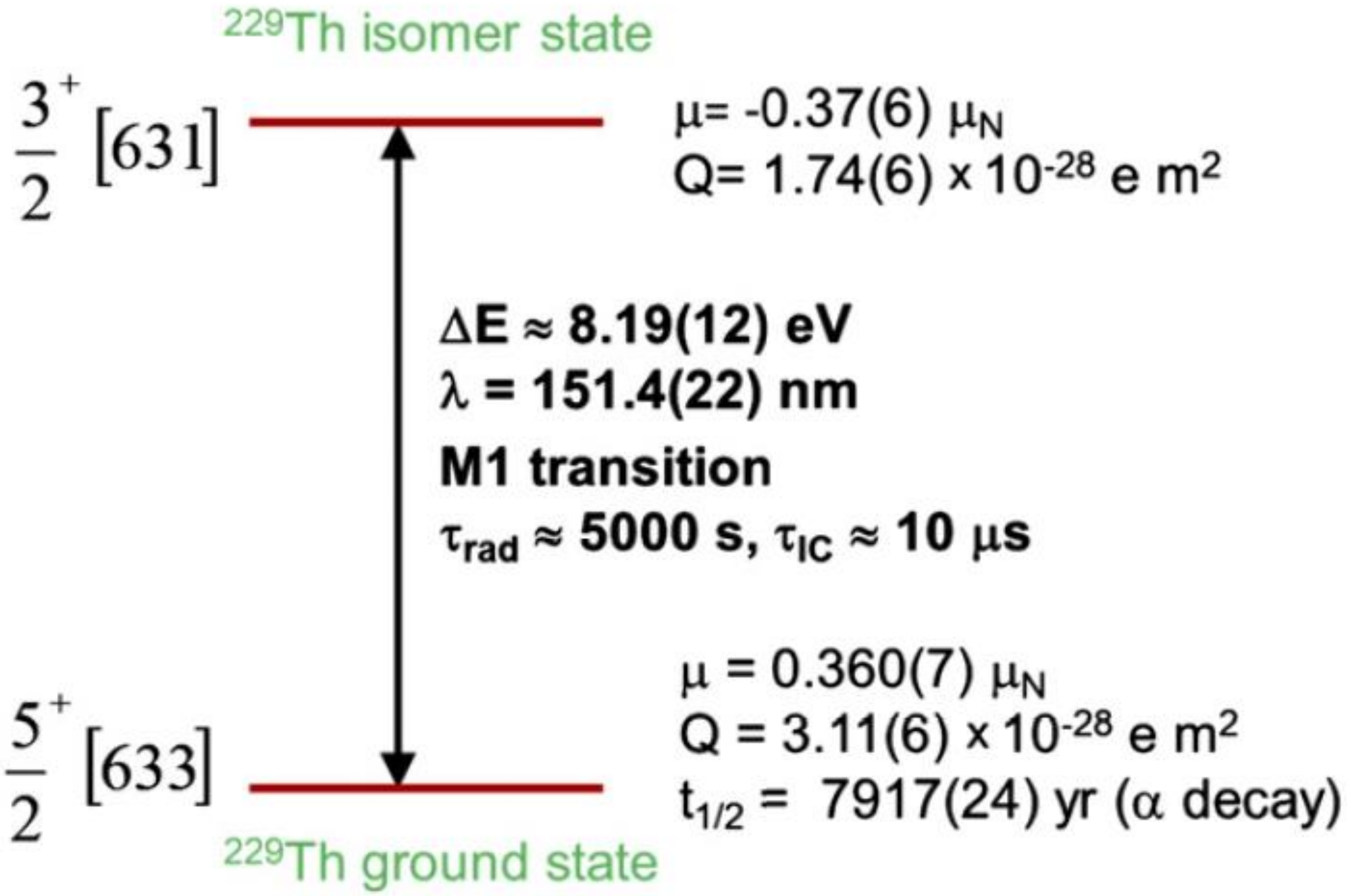


Other clock-based tests

- Lorentz invariance in the electron sector
- Search for ultralight dark matter
- Search for additional interactions / 5th force
- Universality of gravitational red shift
- …

[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)

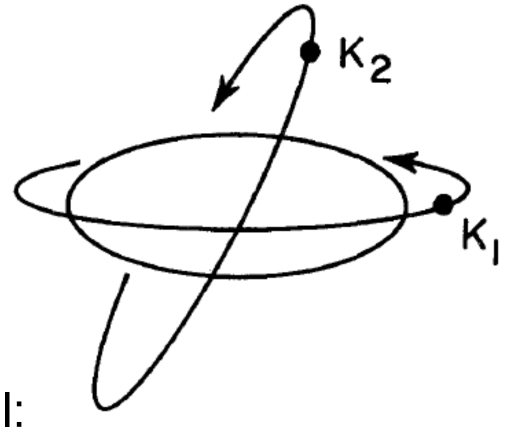
The Th-229 low-energy isomer



μ= -0.37(6) μ_N
Q= 1.74(6) x 10^{-28} e m^2

$\Delta E \approx$ 8.19(12) eV
λ = 151.4(22) nm
M1 transition
$\tau_{rad} \approx$ 5000 s, $\tau_{IC} \approx$ 10 μs

μ = 0.360(7) μ_N
Q = 3.11(6) x 10^{-28} e m^2
$t_{1/2}$ = 7917(24) yr (α decay)



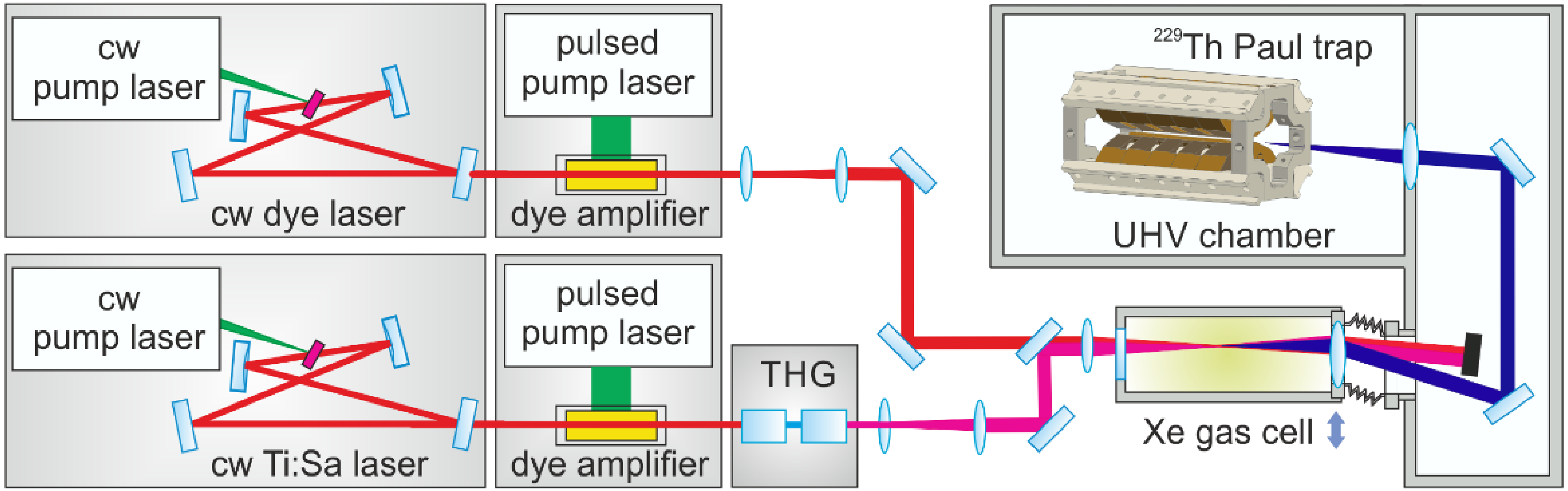
Nilsson Model:
Deformed core plus unpaired neutron

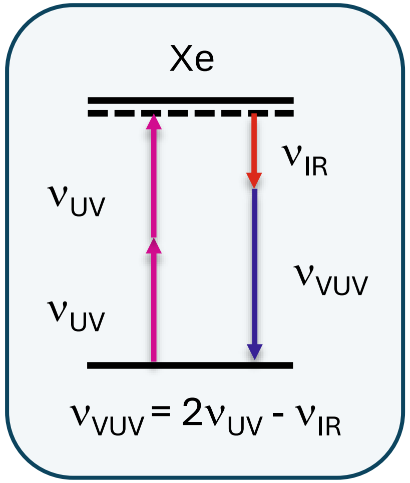
ERC Synergy Grant
Thorium Nuclear Clock
2020-2026

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

8-eV tunable VUV generation: Four wave mixing

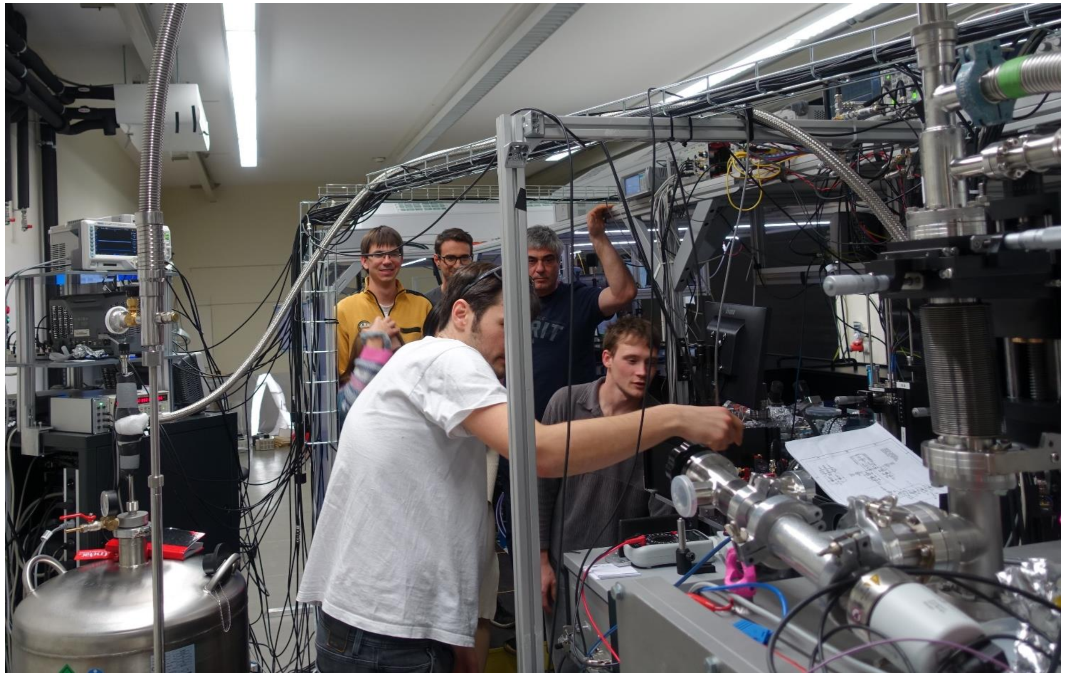
- Generating 148 nm VUV requires laser beams at 250 nm and 790 nm.
- Third order process needs high intensity to achieve suitable efficiency.
- Pulsed lasers (~10 ns, 30 Hz repetition rate) best compromise between VUV pulse energy ($>10^{13}$ photons/pulse) and linewidth (<10 GHz).
- Our setup:
  - Two cw Ti:Sa ring lasers as seed.
  - Pulsed dye amplifiers (~60 mJ/pulse, 30 Hz repetition rate).

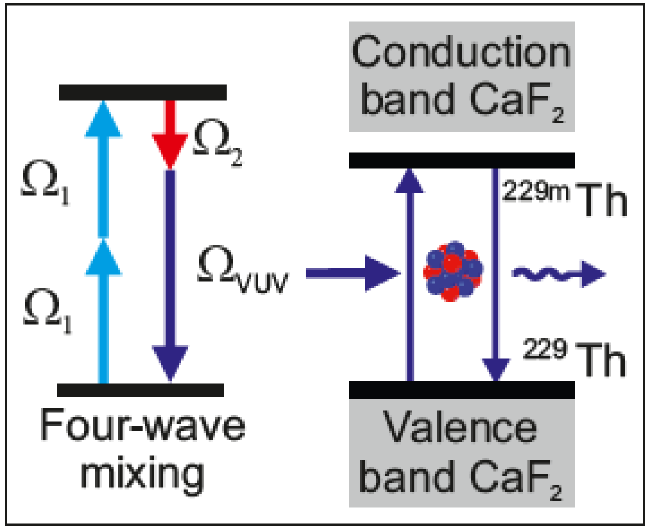


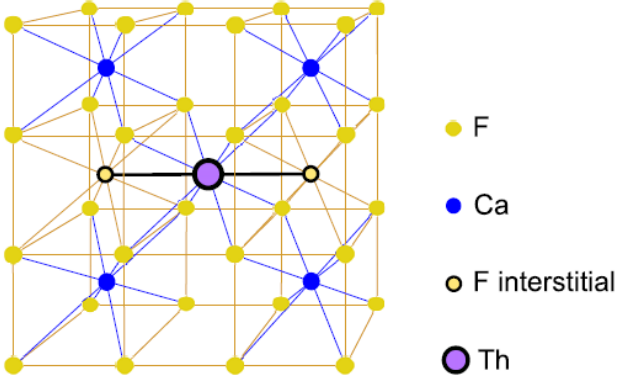


J. Thielking, K. Zhang, J. Tiedau, J. Zander, G. Zitzer, M. V. Okhapkin, E. Peik, New J. Phys. **25**, 083026 (2023)

PTB - TU Wien cooperation:
Laser excitation of ^{229}Th-doped calciumfluoride crystals



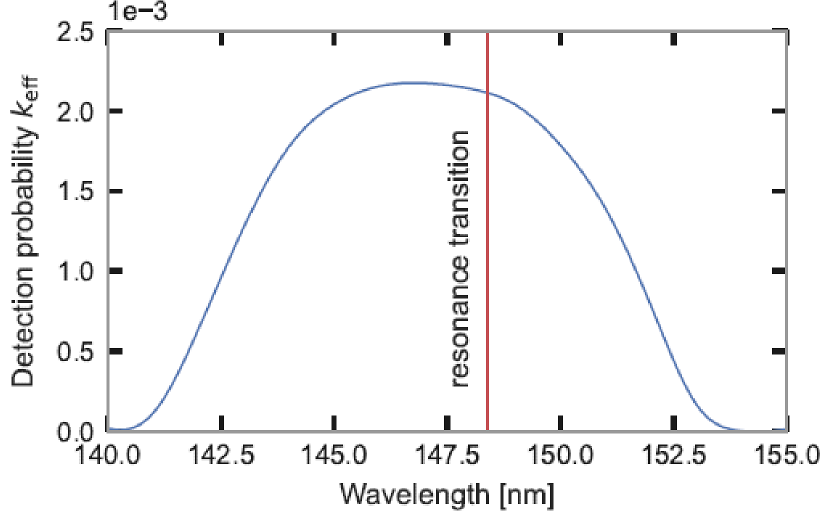




European Research Council
Established by the European Commission

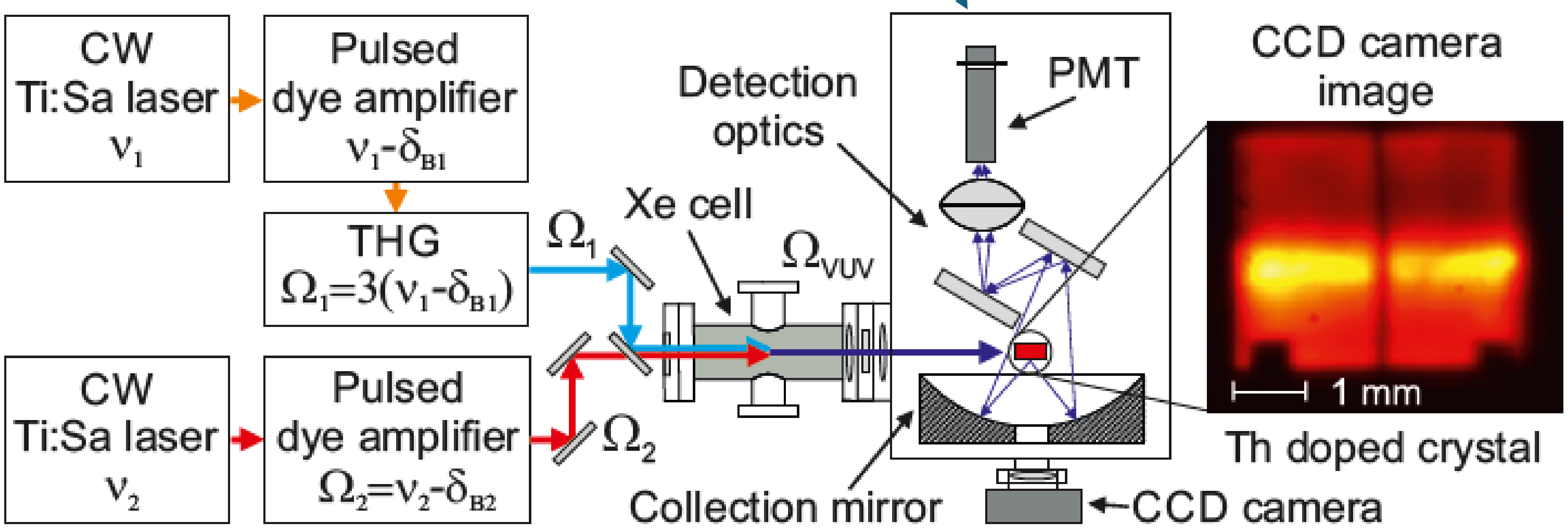
K. Beeks et al. (TU Wien), Phys. Rev. B **109**, 094111 (2024)

Experimental setup



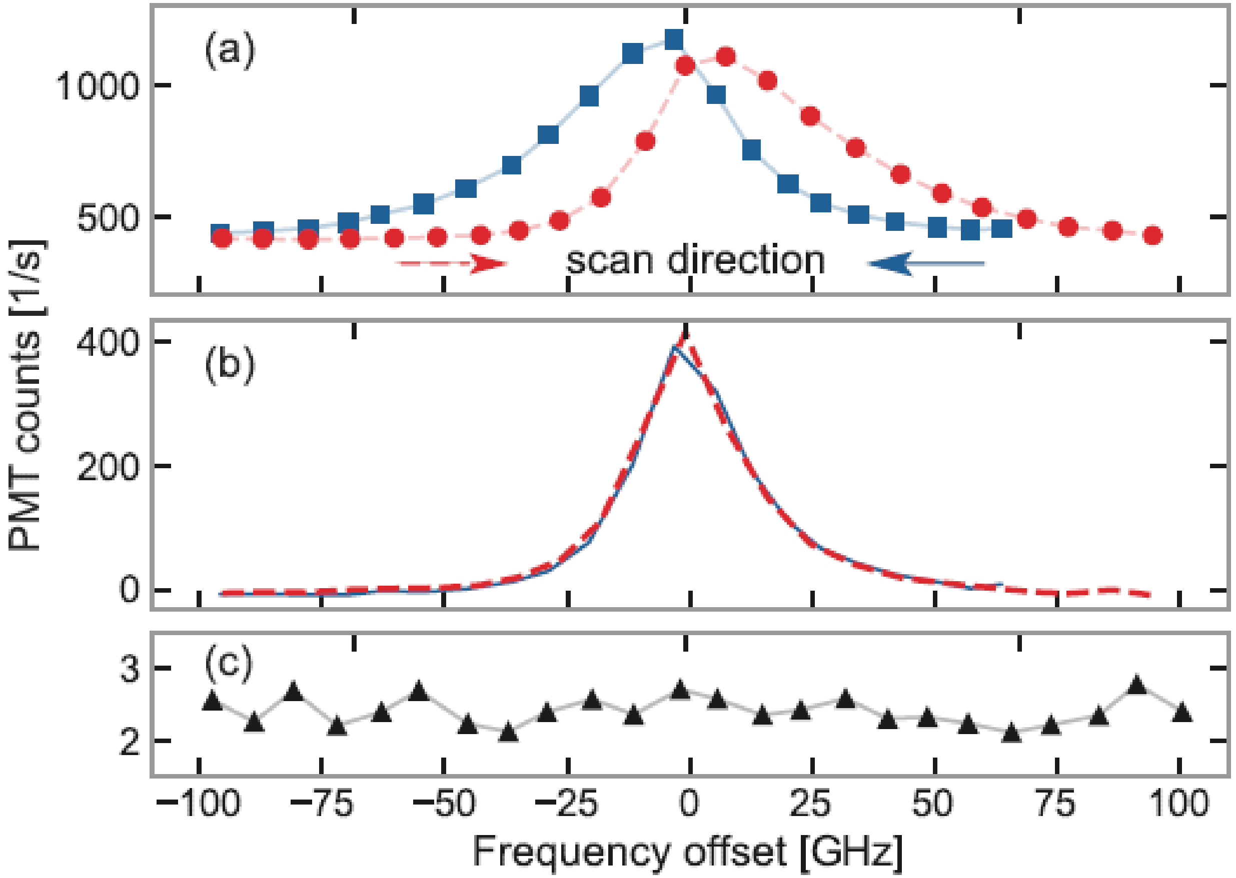
overall photon detection efficiency

VUV-sensitive
Cs-I photomultiplier



Si-CCD detects
photoluminescence
in the vis. range

Resonant laser excitation, detected in VUV fluorescence



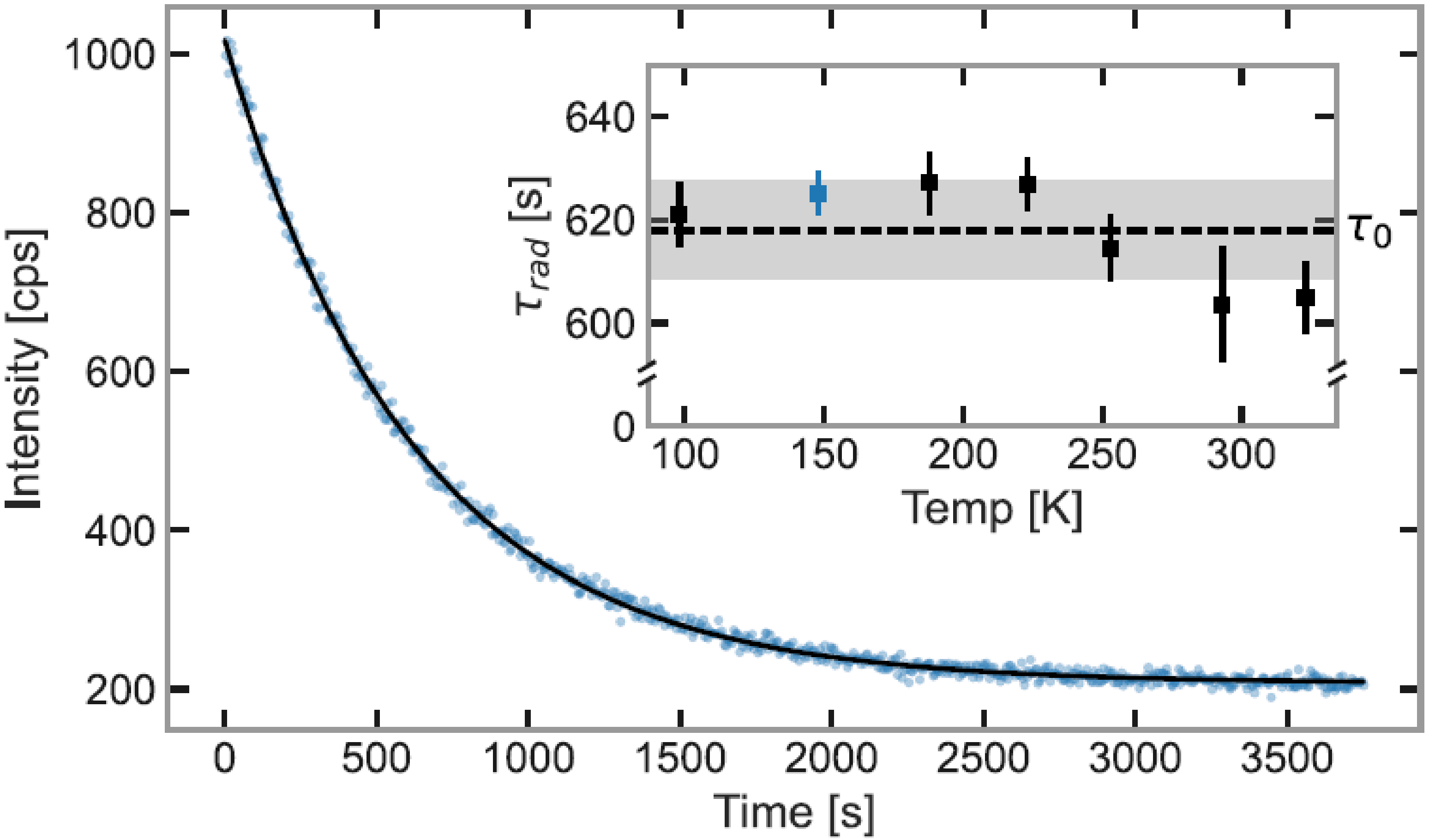
Excitation spectra at 148 nm: Hitting a narrow line with a broad laser.
(each point: 120 s excitation, 150 s detection)

Line shapes after correction for the slow exponential fluorescence decay

Control experiment with Th-232: no signal

J. Tiedau et al. (PTB – TU Wien cooperation), Phys. Rev. Lett. **132**, 182501 (2024)

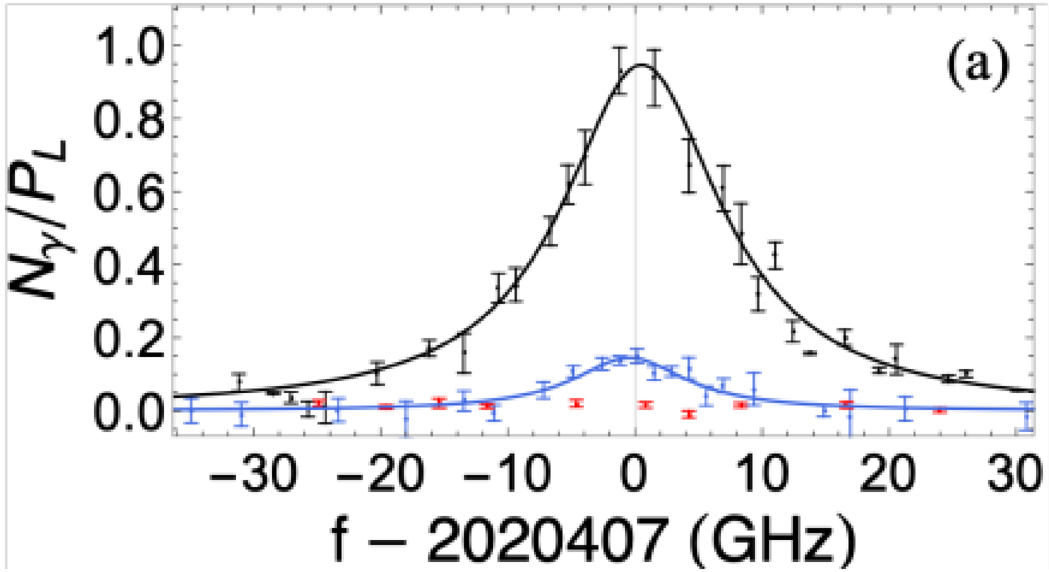
Fluorescence decay curves



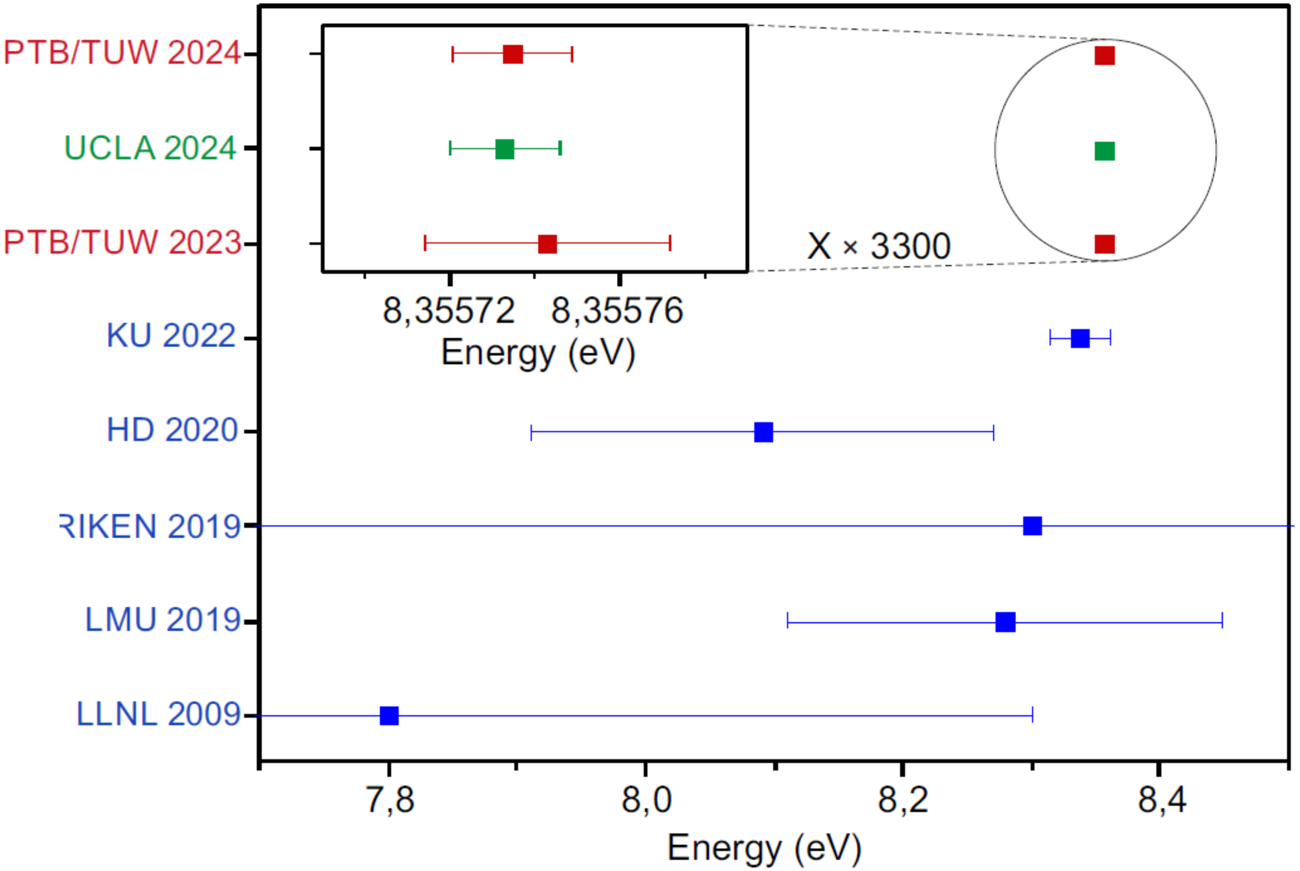
Decay time constant: 618(9) s:
- Identical for differently doped X2 and C10 crystals
- Identical for C10 before and after refluorination with CF_4
- Independent of crystal temperature 100 – 320 K

F. Schaden et al. (TU Wien, & PTB), arXiv:2412.12339

Th-229 excitation in Th:LiSAF at UCLA



R. Elwell et al., Phys. Rev. Lett. 133, 013201 (2024)




Article

Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock

https://doi.org/10.1038/s41586-024-07839-6

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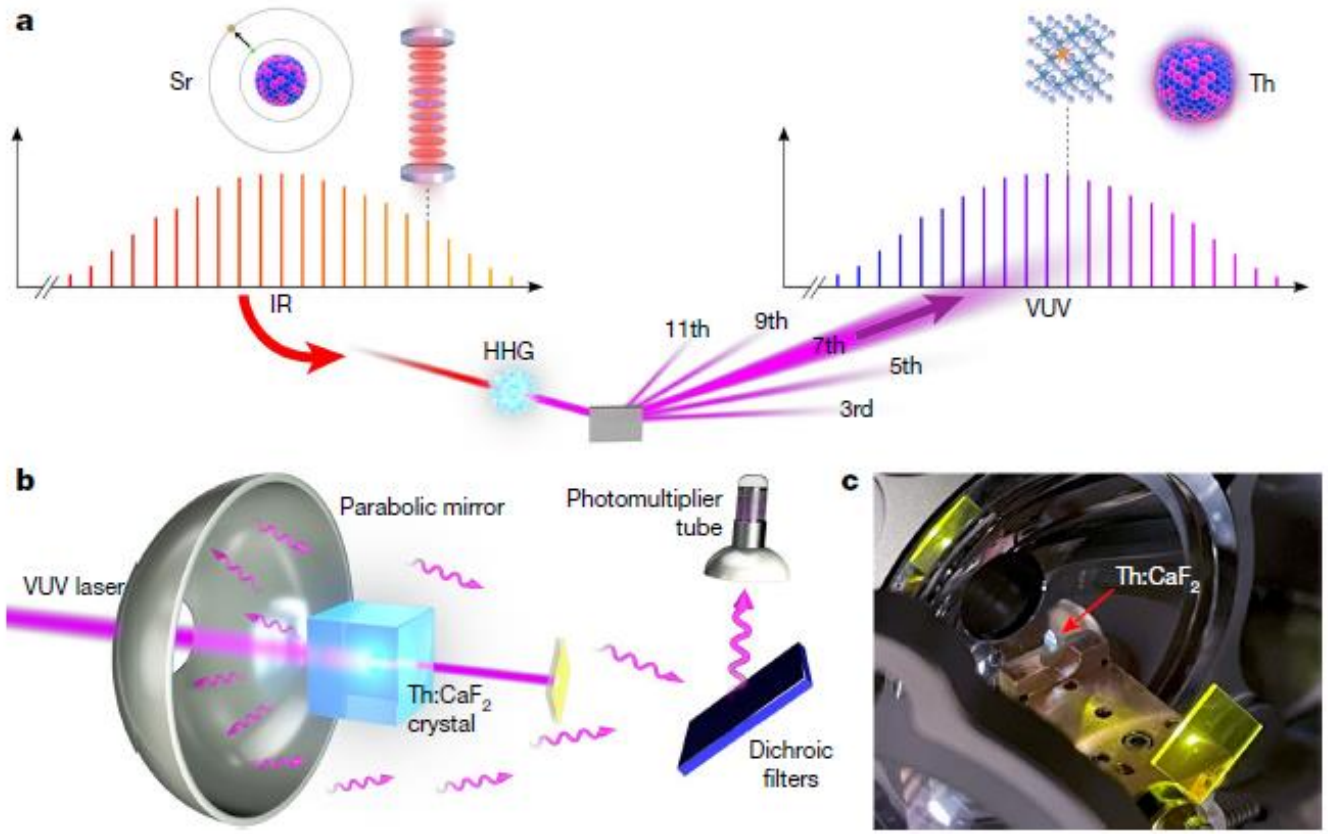
Accepted: 17 July 2024

Chuankun Zhang[1,2,3]✉, Tian Ooi[1,2,3], Jacob S. Higgins[1,2,3], Jack F. Doyle[1,2,3], Lars von der Wense[1,2,3,7], Kjeld Beeks[4,8], Adrian Leitner[4], Georgy A. Kazakov[4], Peng Li[5], Peter G. Thirolf[6], Thorsten Schumm[4] & Jun Ye[1,2,3]✉



Nature **633**, 63 (2024)

Th:CaF$_2$ crystal from Vienna,
Femtosecond frequency comb and high harmonic generation (JILA)
≈100 kHz linewidth
≈2 kHz uncertainty relative to Sr optical clock

$$\nu_{\mathrm{Th}} = \frac{1}{6}(\nu_a + 2\nu_b + 2\nu_c + \nu_d) = 2,020,407,384,335(2)\,\mathrm{kHz}.$$

Conclusion and Outlook

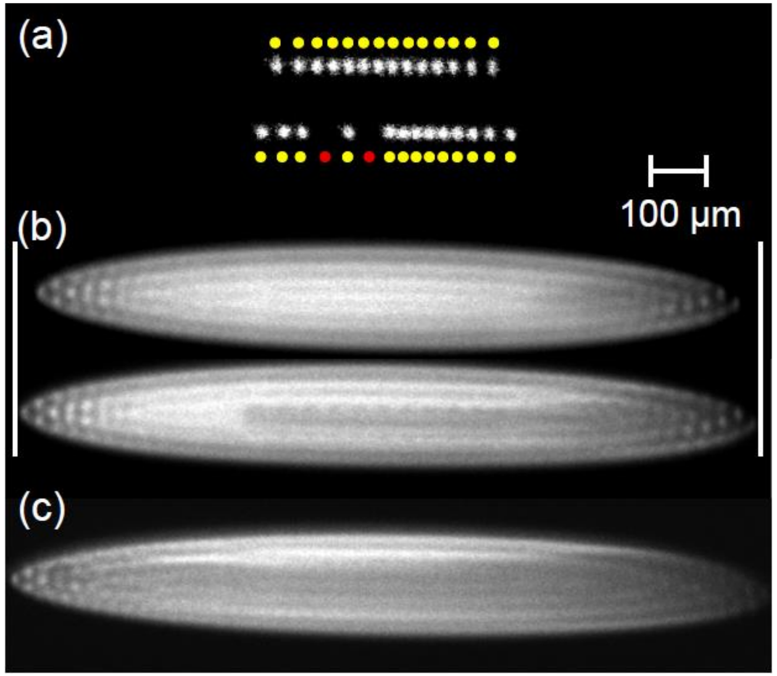
- We obtained laser excitation of the Th-229 nucleus.
- There is rapid progress now in nuclear laser spectroscopy (see also UCLA, JILA, …).
- Th-229 promises high sensitivity for fundamental tests, also involving the strong interaction.

What‘s next?

- Building a narrow-linewidth VUV laser
- Exciting the nuclear transitions in trapped Th ions

- „Quantum nucleonics“
- Nuclear clock for fundamental tests

$^{229}Th^{3+}$ sympathetically cooled with $^{88}Sr^{+}$



G. Zitzer et al., Phys. Rev. A **109**, 033116 (2024)

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Established by the European Commission

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A. Leitner

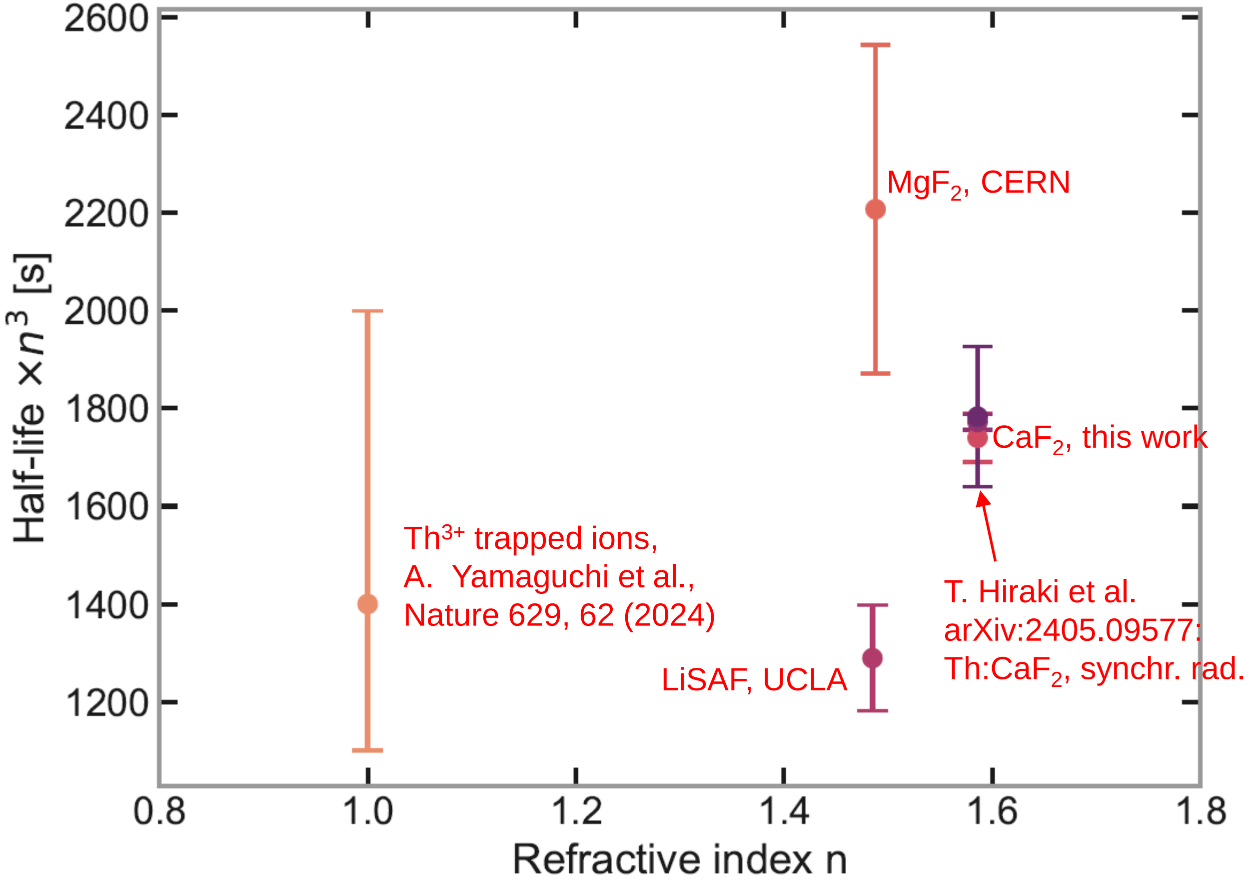
M. Pressler
G. Kazakov
K. Beeks
T. Sikorsky
T. Schumm

The electromagnetic mode density in the dielectric medium is enhanced relative to vacuum, leading to a n^3 enhancement of the M1 spontaneous transition rate:
G. Nienhuis, C. Th. J. Alkemade, Physica (Amsterdam) 81, 181 (1976).

With this correction, the half-life becomes: 1740(50) s

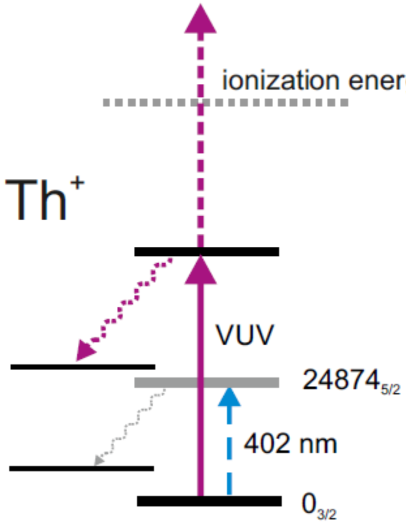
In Weisskopf units
(nuclear oscillator strength):
B(M1)=0.022 W.u.

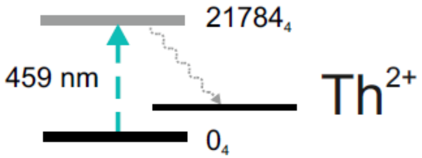
Nuclear structure predictions
(E. Tkalya, N. Minkov, et al.):
B(M1)= 0.006 - 0.05 W.u.



Th-229 isomer lifetime data from different systems

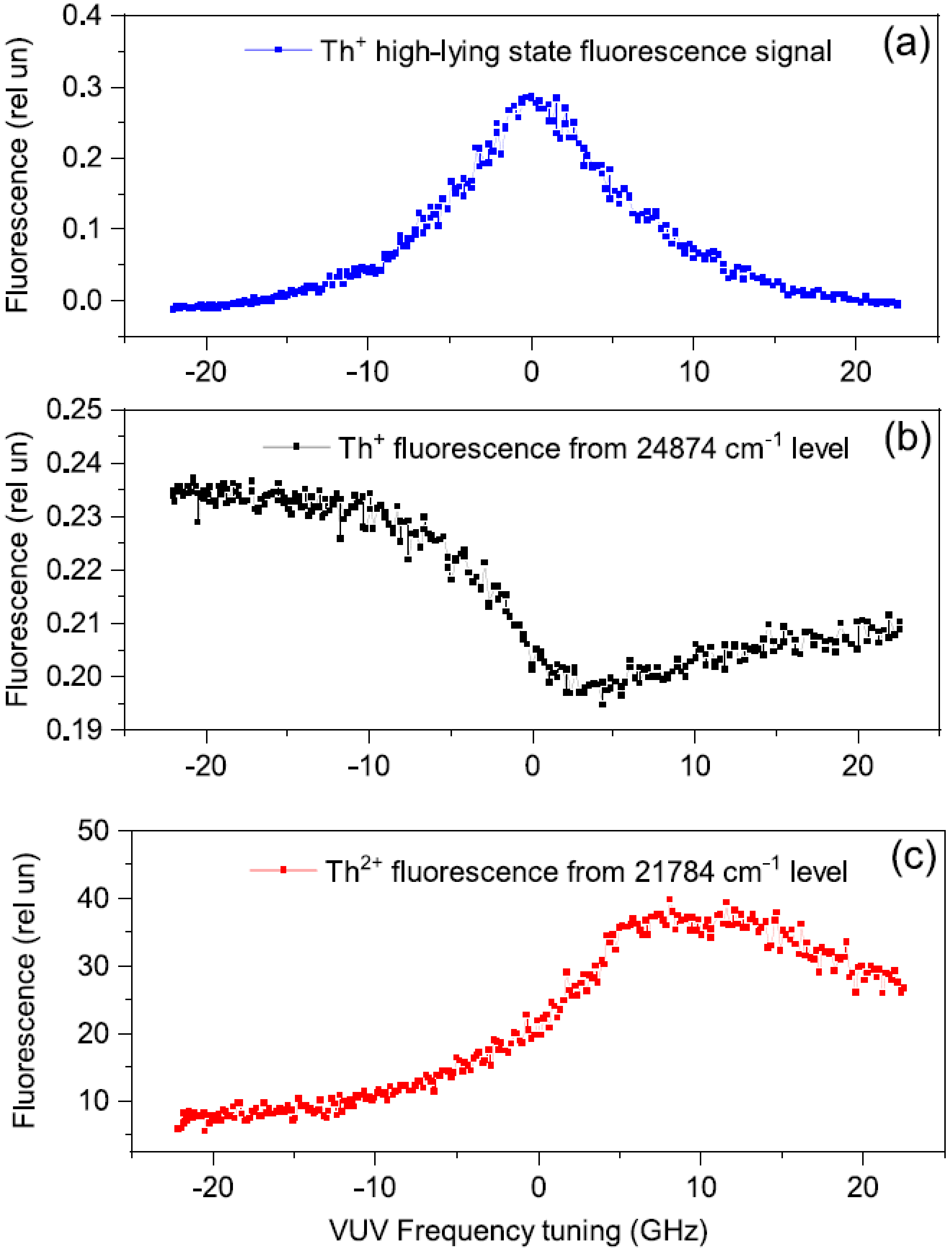
VUV laser spectroscopy of trapped Th$^+$ ions (electronic resonance lines)





Excitation wavelength	Level
148.8122(5) nm	67 198.8(2) cm^{-1}
148.6675(5) nm	67 264.2(2) cm^{-1}
148.2033(5) nm	67 474.9(2) cm^{-1}

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



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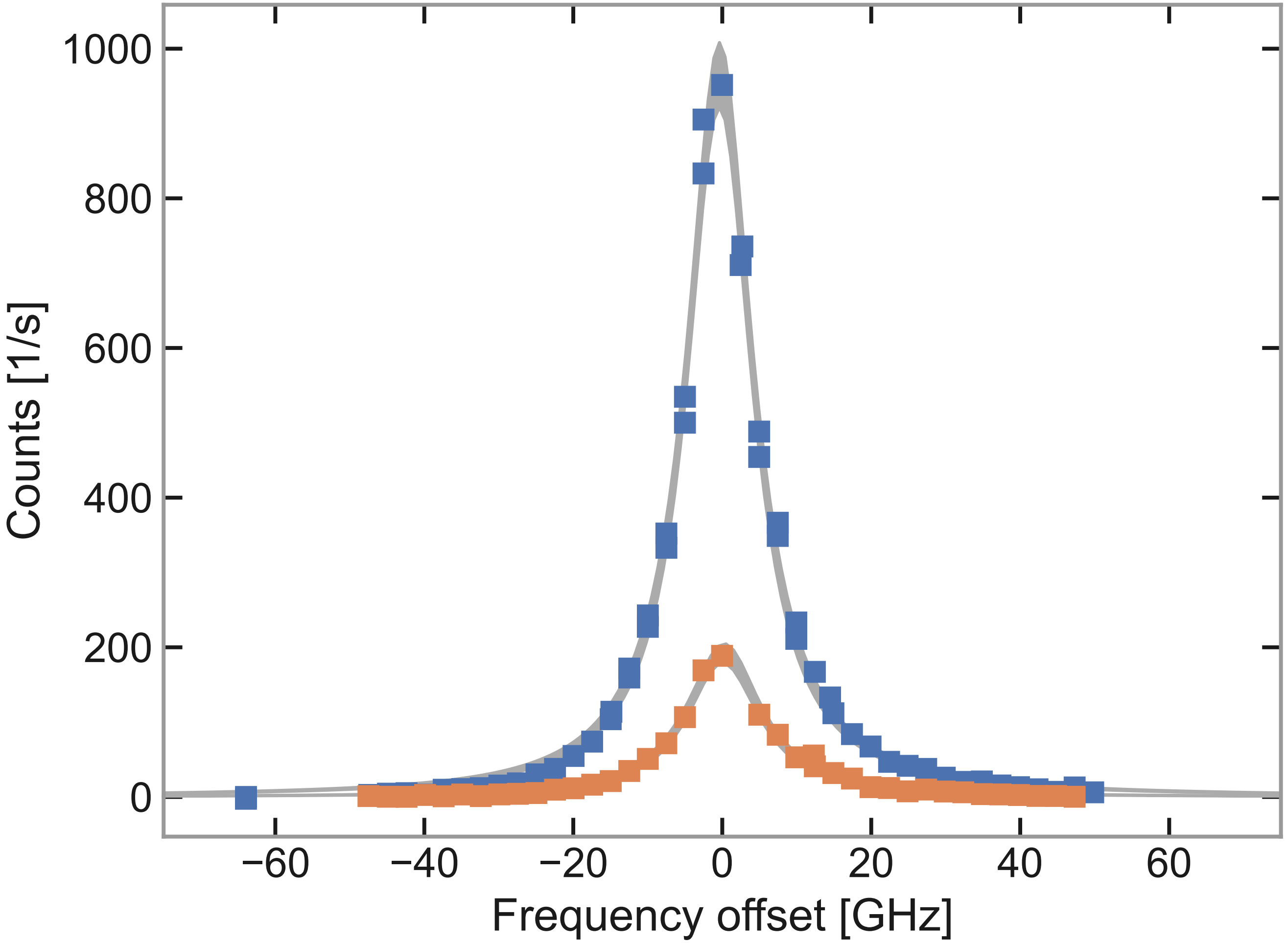
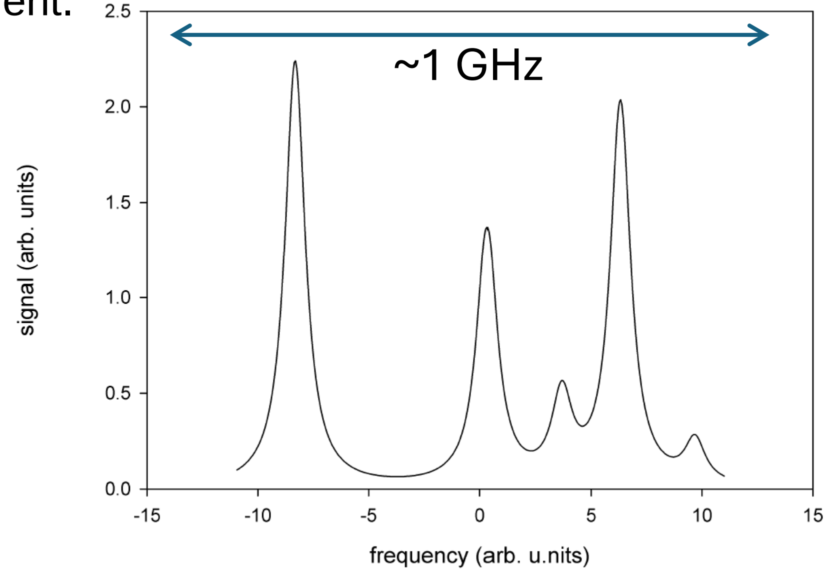


Line splitting from the interaction of the nuclear quadrupole moments with the electric crystal field gradient.



Crystal Code	X2	C10
Dopant isotope	Th-229	Th-229
Th activity [kBq]	66	22
Concentration [cm^{-3}]	5×10^{18}	3×10^{17}
Column density [mm^{-2}]	8×10^{15}	1×10^{15}

Lineshape (FWHM: 12(1) GHz) and resonance frequency (2020.4079(35) THz) are consistent for two differently doped crystals.