thorium
nuclear clock

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Fraunhofer ILT

Nuclear laser spectroscopy

of ^{229}Thorium in CaF$_2$ crystals

Thorsten SCHUMM

TU Wien, Atominstitut

AQUnet
Austrian Quantum Fiber Network

FFG
Promoting Innovation.

Funded by the Austria
Research Promotion Agency

Infrastructure project 884678

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für Eich- und
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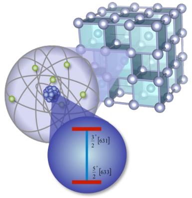
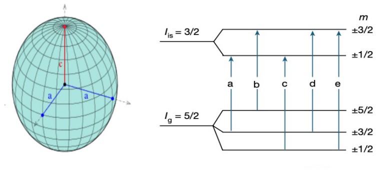
PSAS2026 18.05.2026

OUTLINE



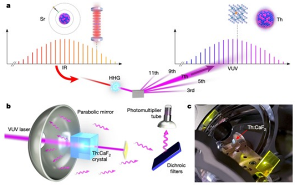
The „solid state approach“ to ^{229}Th nuclear spectroscopy

- Basic concept and implementation



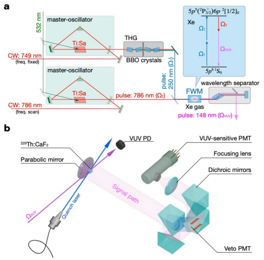
Nuclear quadrupole structure

- Nuclear – solid coupling
- Separating nuclear properties and material parameters



JILA experiment

- Absolute Mössbauer spectroscopy
- Temperature depencence
- Towards a solid-state nuclear clock



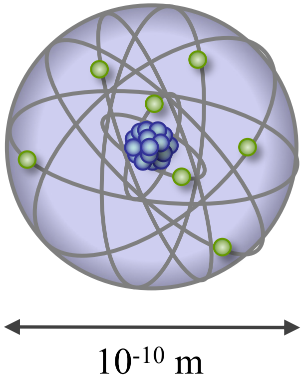
OKAYAMA experiment

- Multiple defect centers
- Site-dependent properties

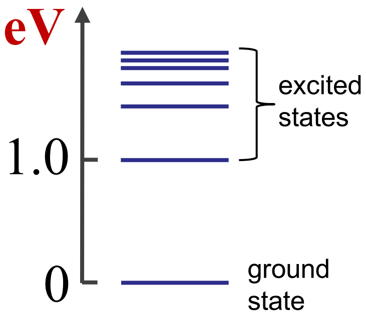
…any **questions?**…any **time!**

or contact:
thorsten.schumm@tuwien.ac.at

Concept: Nuclear laser excitation



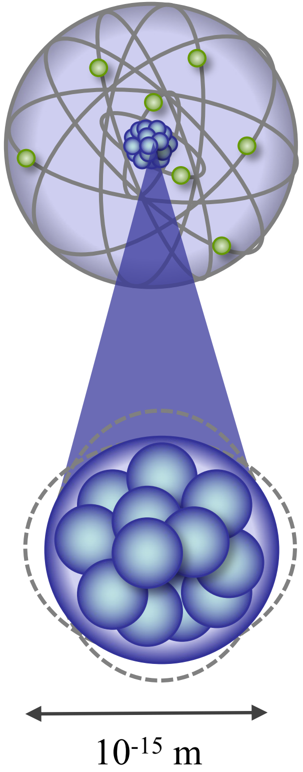
discrete energy levels



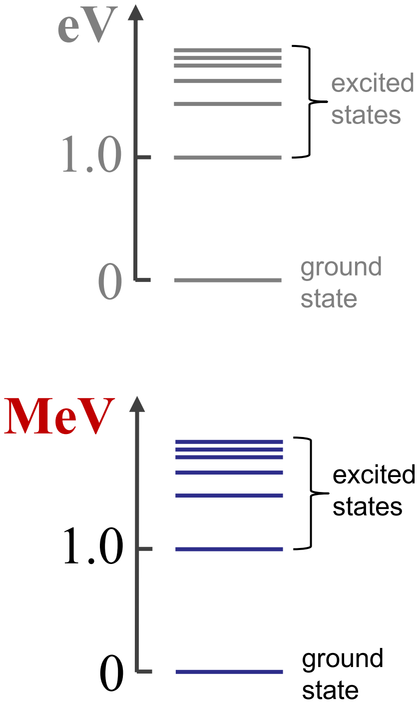
Atomic quantum state manipulation

- laser spectroscopy
- atomic clocks, quantum sensing
- quantum computation, communication
- many-body physics (BEC…)
- fundamental physics

Concept: Nuclear laser excitation



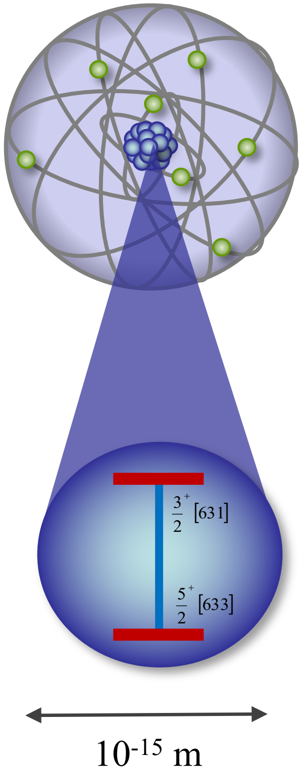
discrete energy levels

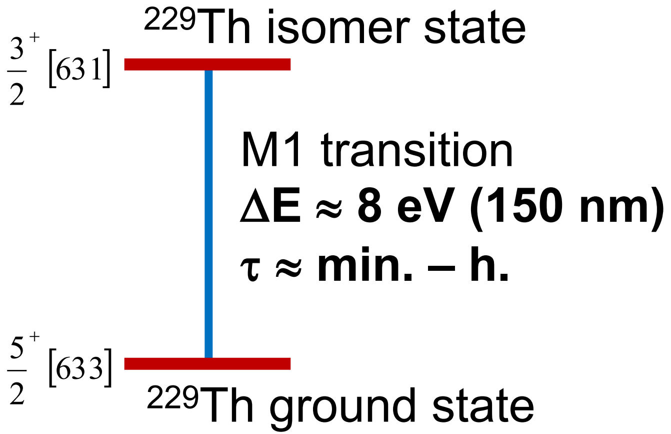


Atomic quantum state manipulation
- laser spectroscopy
- atomic clocks, quantum sensing
- quantum computation, communication
- many-body physics (BEC…)
- fundamental physics

Nuclear quantum state manipulation?
- **laser spectroscopy???**
- material science
- fundamental physics
- …

Concept: ^{229}Th nuclear laser excitation





^{229}Th isomer state

$\frac{3}{2}^{+}[631]$

M1 transition

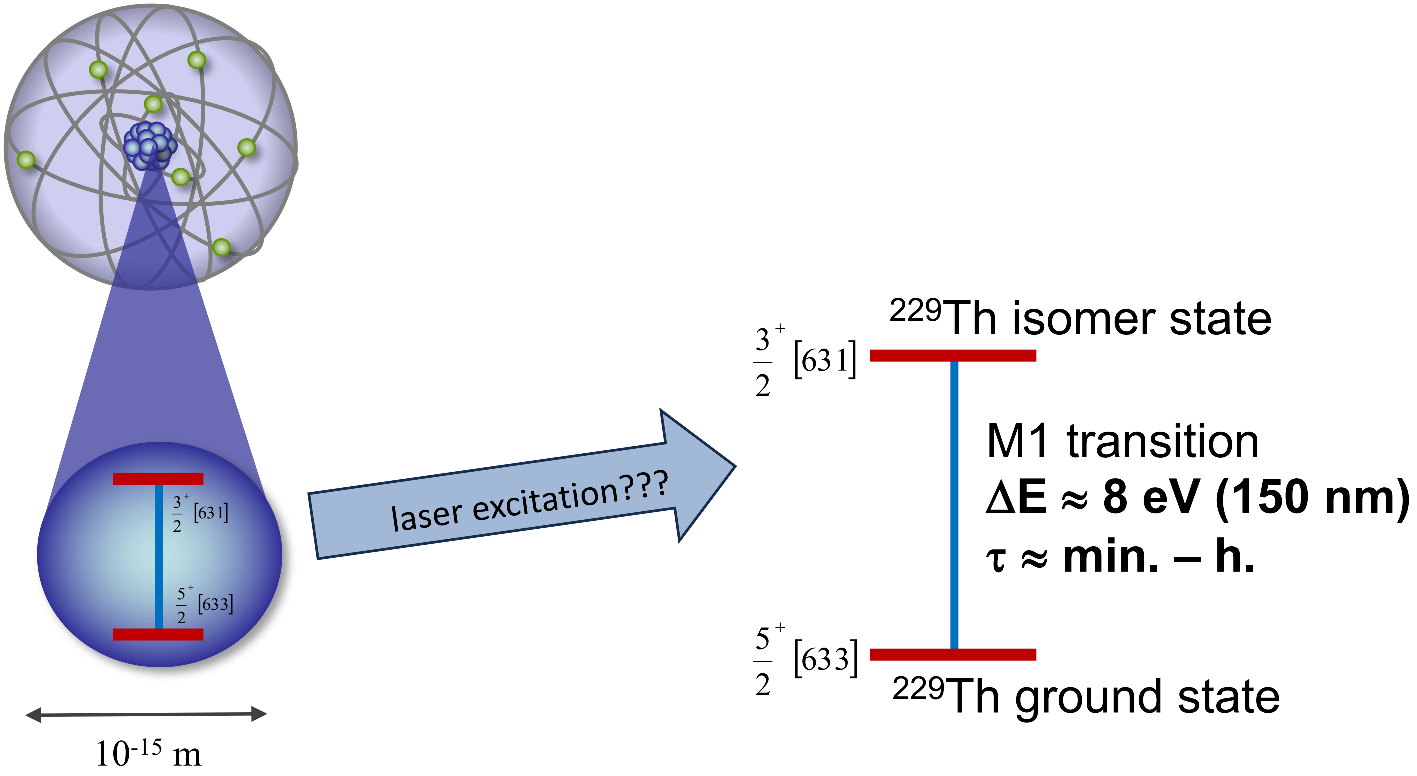
$\Delta E \approx 8$ eV (150 nm)

$\tau \approx$ min. – h.

$\frac{5}{2}^{+}[633]$

^{229}Th ground state

Concept: ^{229}Th nuclear laser excitation



laser excitation???

^{229}Th isomer state

$\frac{3}{2}^{+}$ [631]

M1 transition

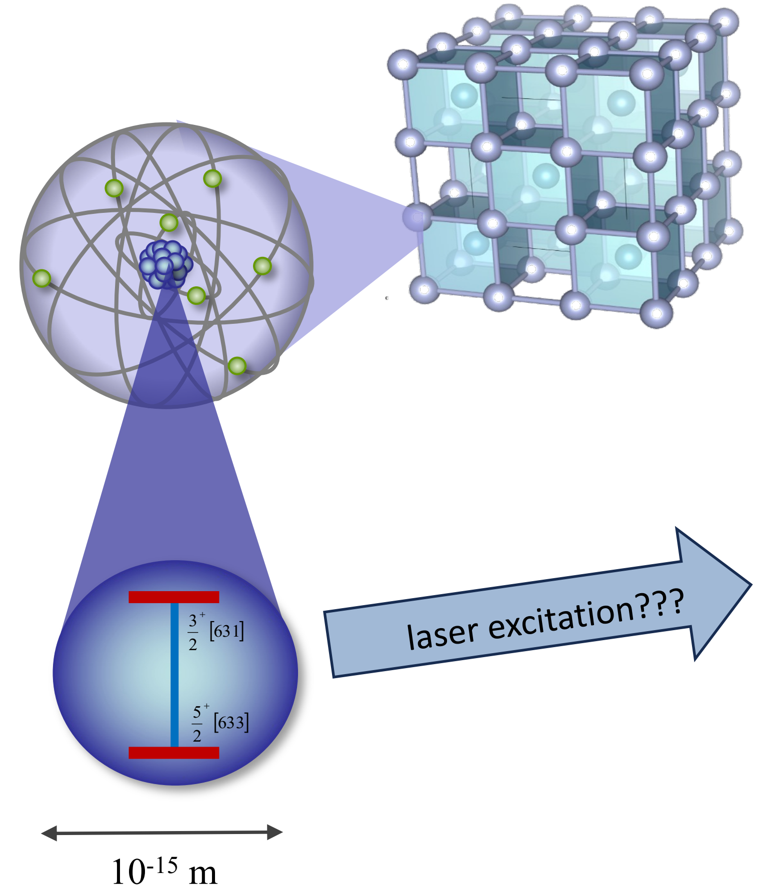
ΔE ≈ 8 eV (150 nm)

τ ≈ min. – h.

$\frac{5}{2}^{+}$ [633]

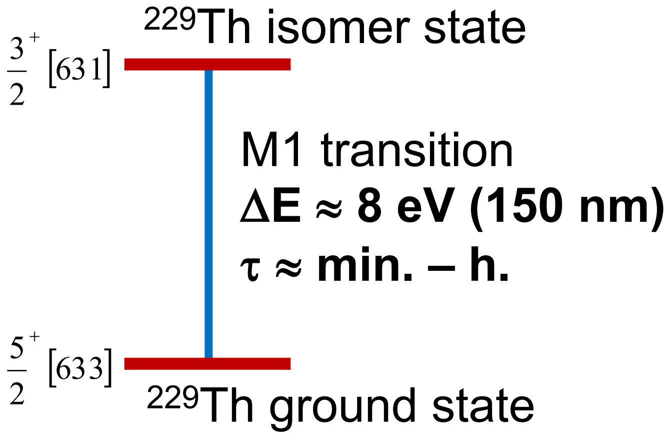
^{229}Th ground state

Concept: ^{229}Th nuclear laser excitation in CaF$_2$



The „solid state approach“:

- Th nuclei inside VUV transparent material
- large band (~10 eV) gap → fluoride crystals
- doping, implantation, diffusion…
- control of electronic environment: [Rn]
- a solid-state optical nuclear clock?



$\frac{3}{2}^{+}$ [631] ^{229}Th isomer state

M1 transition

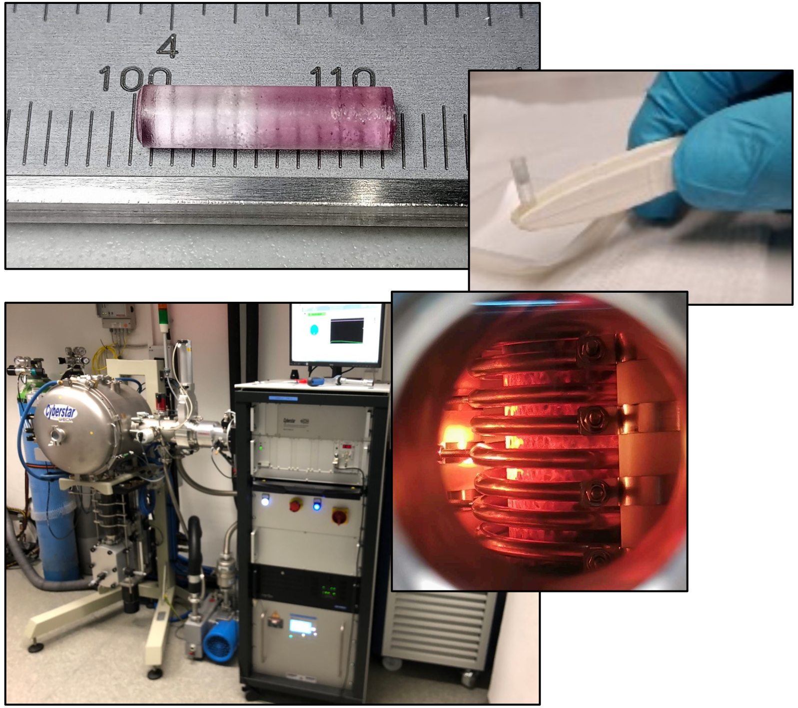
ΔE ≈ 8 eV (150 nm)

τ ≈ min. – h.

$\frac{5}{2}^{+}$ [633] ^{229}Th ground state

Fabrication of **Th:CaF$_2$** in Vienna

> 10 years of painful method development…



- dedicated lab for growth of radioactive dopants (only one in Europe)
- miniaturized crystal growth to increase doping concentration
- fluorine annealing to reduce defects
- in-house cutting + polishing
- characterization (optical, radiological)
- 1 crystal (attempt) takes 5 days

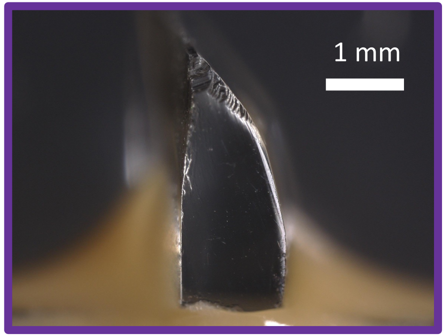
currently working on:

- pulling single crystal fibers
- growing bulk ThF$_4$ crystals

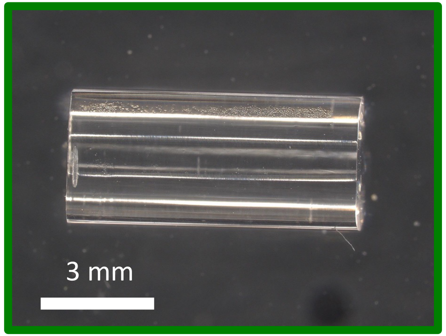
Fabrication of Th:CaF_2 in Vienna

3 crystals from Vienna with different „history“ and concentration

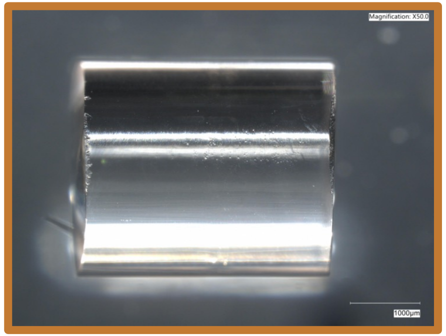
X2: 4×10^{18} cm^{-3}
19 May 2021



C13: 0.8×10^{18} cm^{-3}
7 Dec 2020



C10: 0.3×10^{18} cm^{-3}
23 Nov 2020

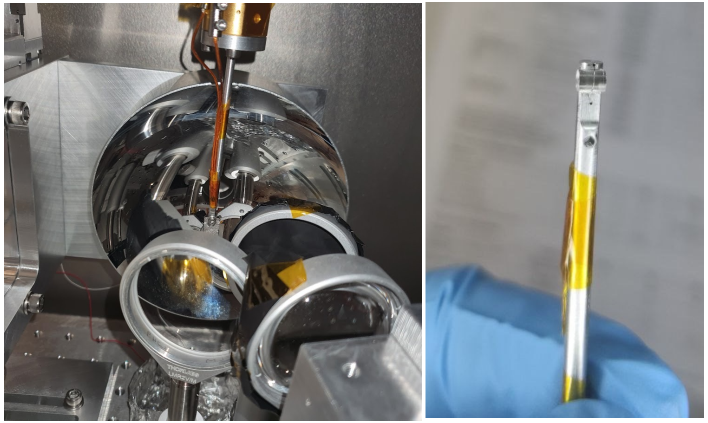


…will be used in ALL experiments shown today

* apart from the UCLA experiment on slide 4

First **laser excitation** of ^{229}Th in 2024

PTB Experiment



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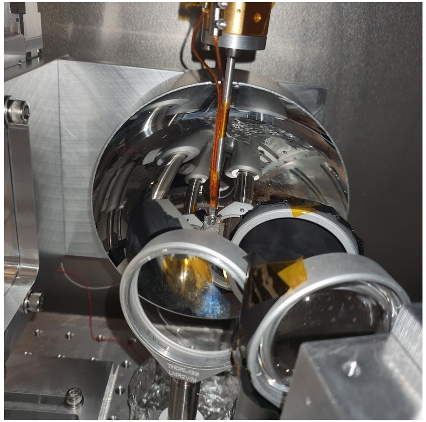
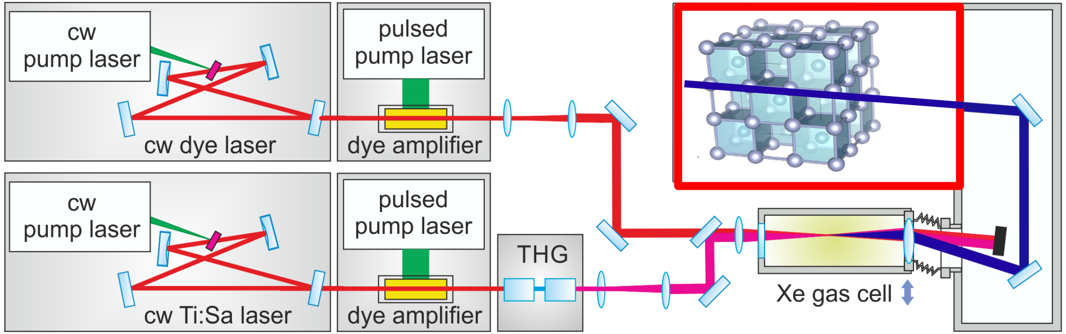
PTB Experiment





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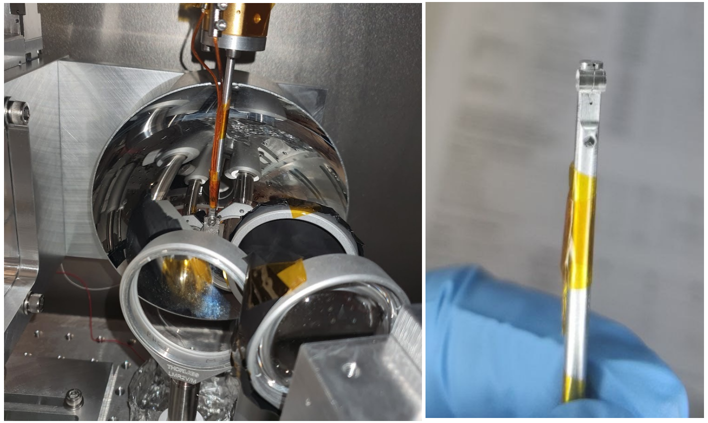
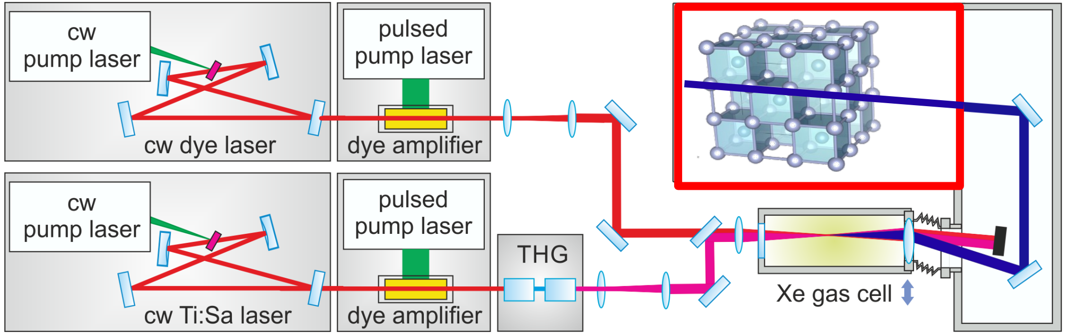
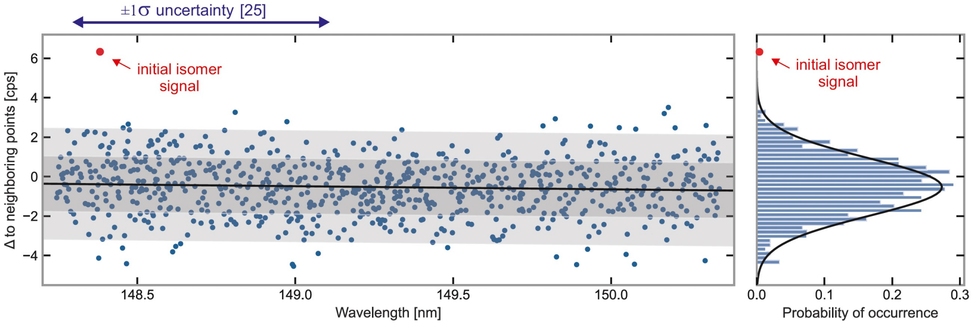


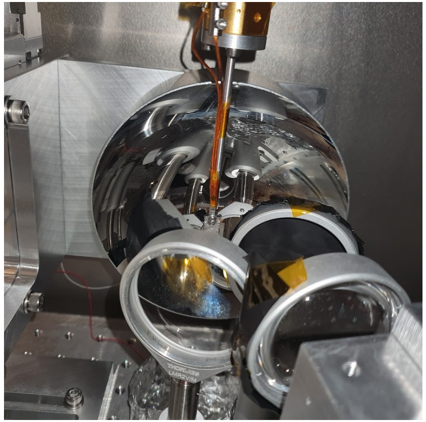


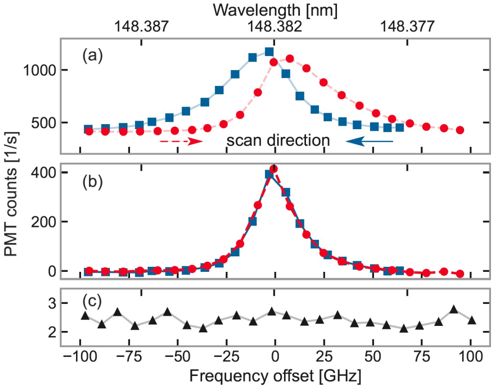


scanning for almost a year…

First **laser excitation** of ^{229}Th in 2024

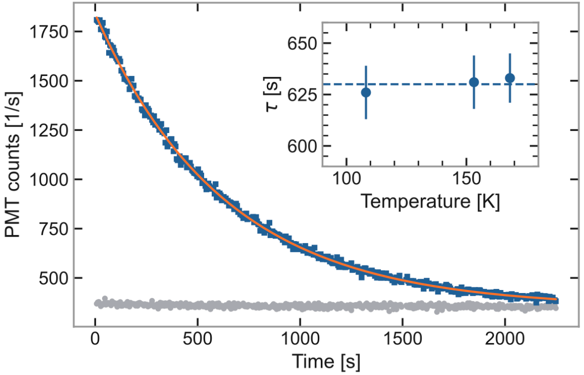
PTB Experiment



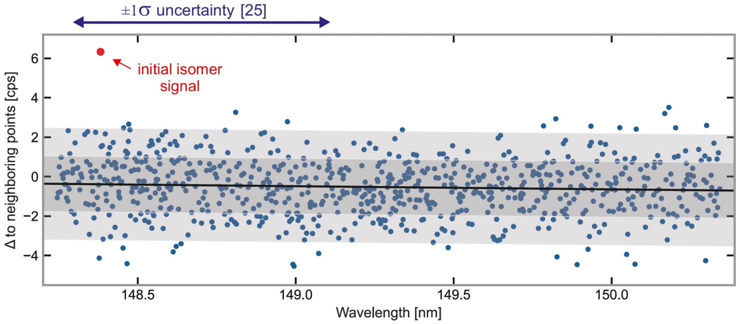


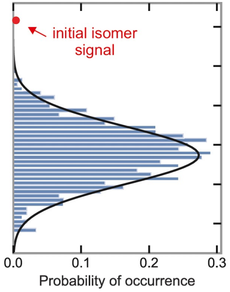
ν_{isomer}= 2020.409(7) THz

laser linewidth limited



$\tau_{\frac{1}{2}}$ = 670(102) s (in crystal)





First **laser excitation** of ^{229}Th in 2024

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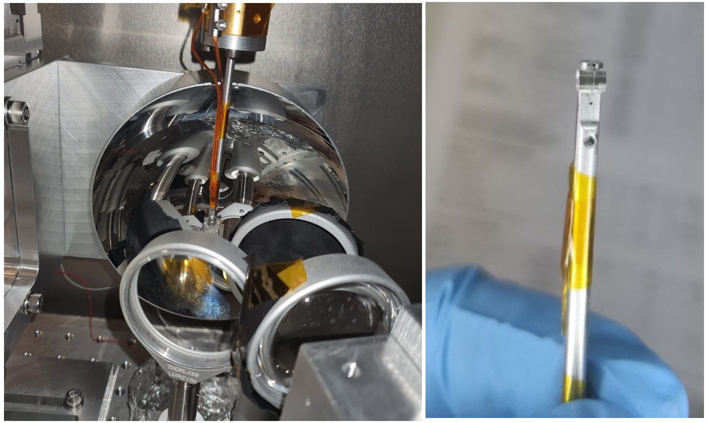
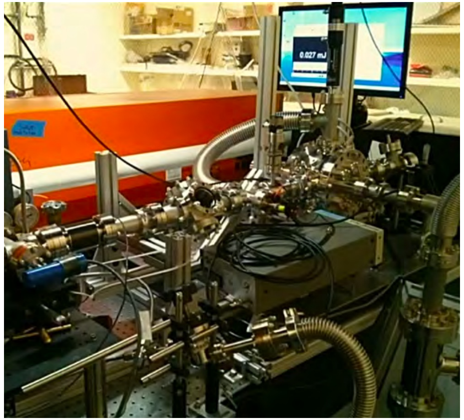
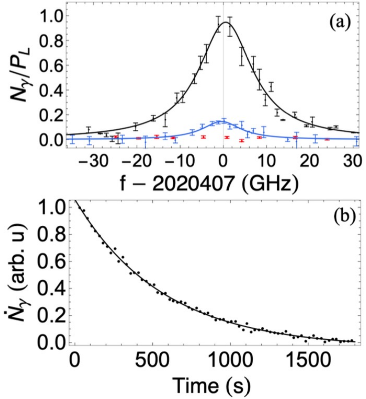


Host: CaF_2

UCLA Experiment

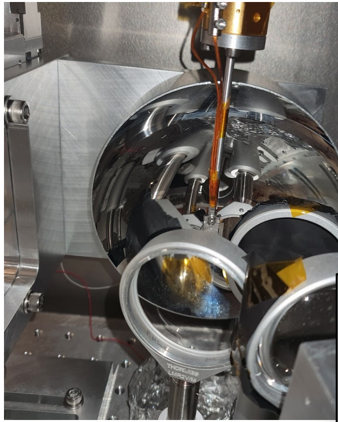


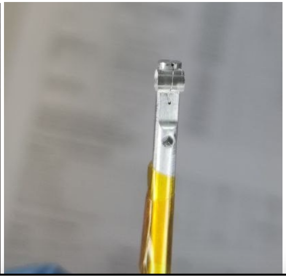


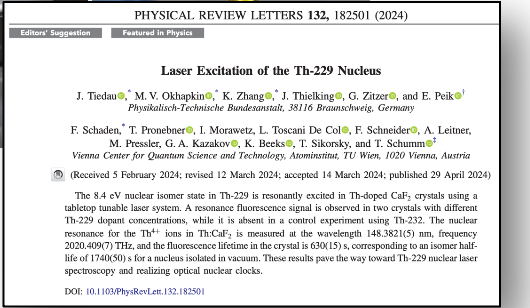
Host: $LiSrAlF_6$

First **laser excitation** of ^{229}Th in 2024

PTB Experiment







PHYSICAL REVIEW LETTERS **132,** 182501 (2024)

Editors' Suggestion | Featured in Physics

Laser Excitation of the Th-229 Nucleus

J. Tiedau,* M. V. Okhapkin,* K. Zhang,* J. Thielking, G. Zitzer, and E. Peik†
Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

F. Schaden,* T. Pronebner, I. Morawetz, L. Toscani De Col, F. Schneider, A. Leitner,
M. Pressler, G. A. Kazakov, K. Beeks, T. Sikorsky, and T. Schumm‡
Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria

(Received 5 February 2024; revised 12 March 2024; accepted 14 March 2024; published 29 April 2024)

The 8.4 eV nuclear isomer state in Th-229 is resonantly excited in Th-doped CaF_2 crystals using a tabletop tunable laser system. A resonance fluorescence signal is observed in two crystals with different Th-229 dopant concentrations, while it is absent in a control experiment using Th-232. The nuclear resonance for the Th^{4+} ions in $Th{:}CaF_2$ is measured at the wavelength 148.3821(5) nm, frequency 2020.409(7) THz, and the fluorescence lifetime in the crystal is 630(15) s, corresponding to an isomer half-life of 1740(50) s for a nucleus isolated in vacuum. These results pave the way toward Th-229 nuclear laser spectroscopy and realizing optical nuclear clocks.

DOI: 10.1103/PhysRevLett.132.182501

April 2024

Host: CaF_2

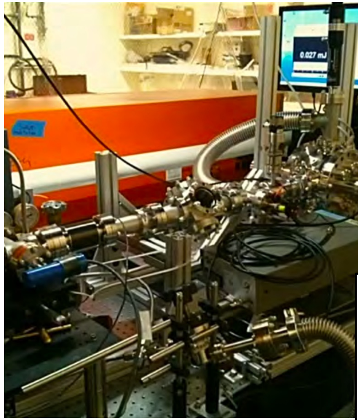
Isomer energy:

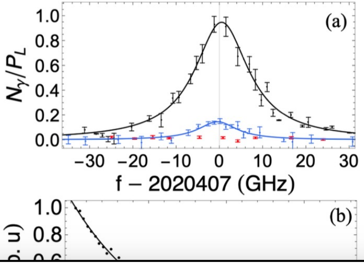
8.338(24) eV or 148.71(42) nm

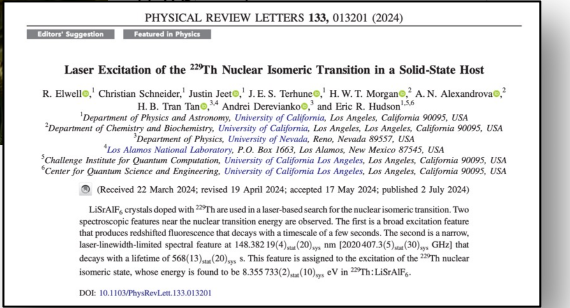
Isomer lifetime:

670(102) s (in crystal)

UCLA Experiment







PHYSICAL REVIEW LETTERS **133,** 013201 (2024)

Editors' Suggestion | Featured in Physics

Laser Excitation of the ^{229}Th Nuclear Isomeric Transition in a Solid-State Host

R. Elwell,[1] Christian Schneider,[1] Justin Jeet,[1] J. E. S. Terhune,[1] H. W. T. Morgan,[2] A. N. Alexandrova,[2]
H. B. Tran Tan,[3,4] Andrei Derevianko,[3] and Eric R. Hudson[1,5,6]
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
[2]*Department of Chemistry and Biochemistry, University of California, Los Angeles, Los Angeles, California 90095, USA*
[3]*Department of Physics, University of Nevada, Reno, Nevada 89557, USA*
[4]*Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA*
[5]*Challenge Institute for Quantum Computation, University of California Los Angeles, Los Angeles, California 90095, USA*
[6]*Center for Quantum Science and Engineering, University of California Los Angeles, Los Angeles, California 90095, USA*

(Received 22 March 2024; revised 19 April 2024; accepted 17 May 2024; published 2 July 2024)

$LiSrAlF_6$ crystals doped with ^{229}Th are used in a laser-based search for the nuclear isomeric transition. Two spectroscopic features near the nuclear transition energy are observed. The first is a broad excitation feature that produces redshifted fluorescence that decays with a timescale of a few seconds. The second is a narrow, laser-linewidth-limited spectral feature at $148.382\,19(4)_{\mathrm{stat}}(20)_{\mathrm{sys}}$ nm [$2020\,407.3(5)_{\mathrm{stat}}(30)_{\mathrm{sys}}$ GHz] that decays with a lifetime of $568(13)_{\mathrm{stat}}(20)_{\mathrm{sys}}$ s. This feature is assigned to the excitation of the ^{229}Th nuclear isomeric state, whose energy is found to be $8.355\,733(2)_{\mathrm{stat}}(10)_{\mathrm{sys}}$ eV in $^{229}Th{:}LiSrAlF_6$.

DOI: 10.1103/PhysRevLett.133.013201

July 2024

Host: $LiSrAlF_6$

Isomer energy:

148.38219(4)stat (20)sys nm

Isomer lifetime:

568(13)stat (20)sys s (in crystal)

...any **questions?**...any **time!**

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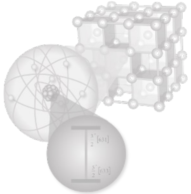
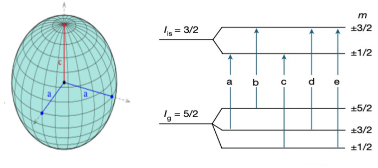
OUTLINE



The „solid state approach“ to ^{229}Th nuclear spectroscopy

- Basic concept and implementation



Nuclear quadrupole structure

- Nuclear – solid coupling
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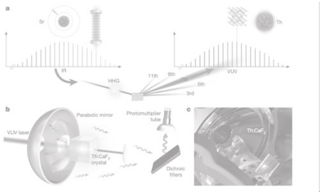

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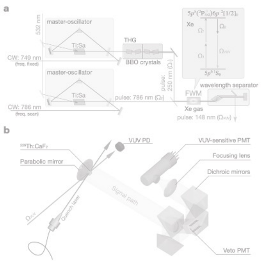
JILA



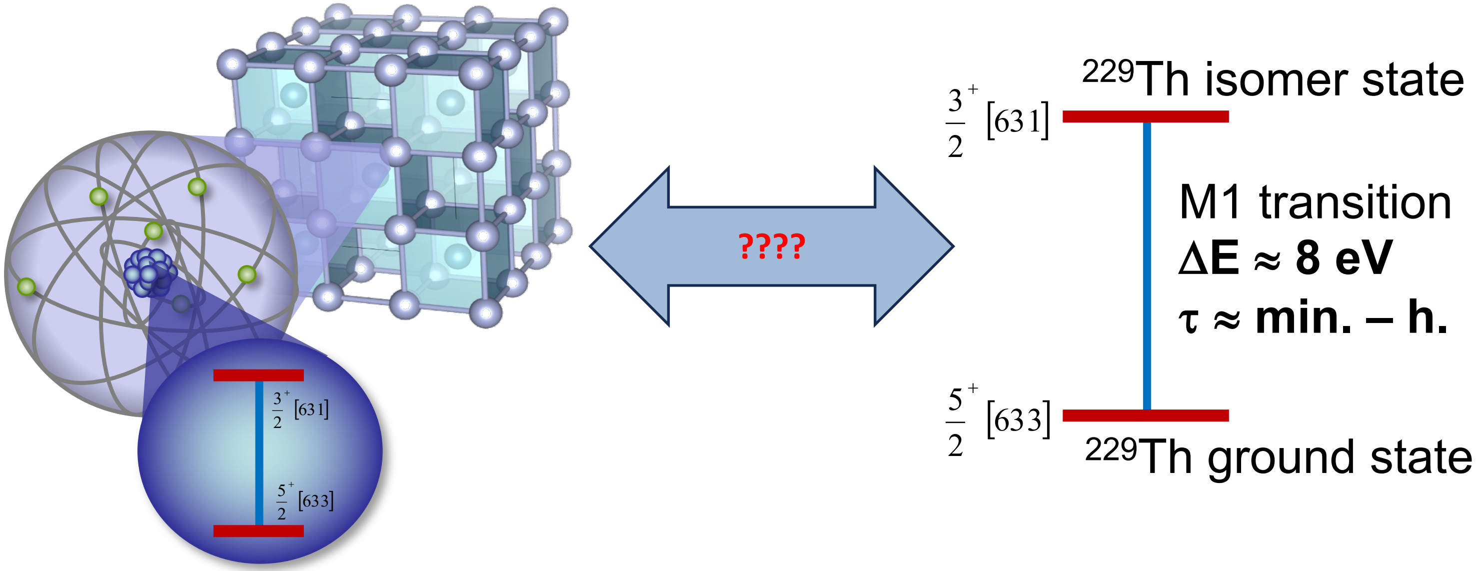
OKAYAMA experiment

- Multiple defect centers
- Site-dependent properties

OKAYAMA UNIVERSITY

Nuclear quadrupole structure in ^{229}Th:CaF$_2$

What about interactions between crystal and nuclear levels?



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M1 transition

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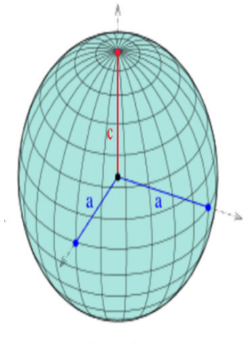
$\tau \approx$ min. – h.

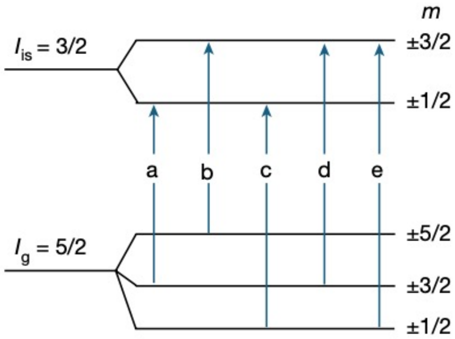
^{229}Th ground state

Nuclear quadrupole structure in ^{229}Th:CaF$_2$

Quadrupole structure determined by **nuclear** and **material parameters**



Prolate



$$H = \frac{QV_{zz}}{4I(2I-1)}\left[3I_z^2 - \mathbf{I}^2 + \eta\left(I_x^2 - I_y^2\right)\right]$$

Q – (intrinsic) quadrupole moment „universal“

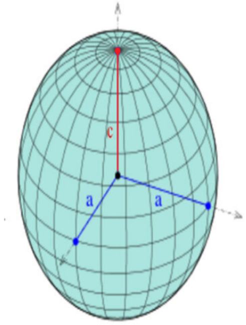
V_{zz} – electric field gradient (EFG)

η – anisotropie parameter

$\left.\right\}$ host-specific

Nuclear quadrupole structure in ^{229}Th:CaF$_2$

Quadrupole structure determined by **nuclear** and **material parameters**



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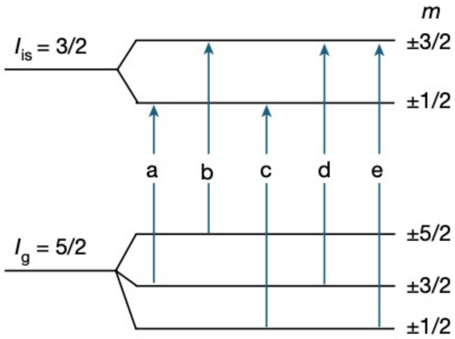

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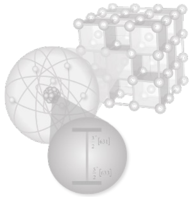
} host-specific

can we see these quadrupole levels…?

OUTLINE



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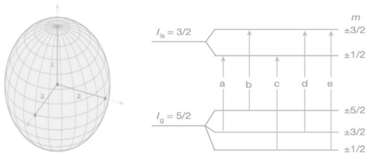

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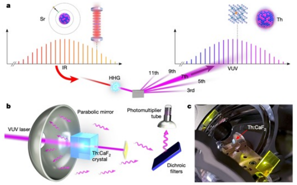
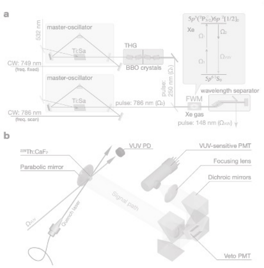
- Nuclear – solid coupling
- Separating nuclear properties and material parameters



JILA experiment

- Absolute Mössbauer spectroscopy
- Temperature depencence
- The EFG "mystery“

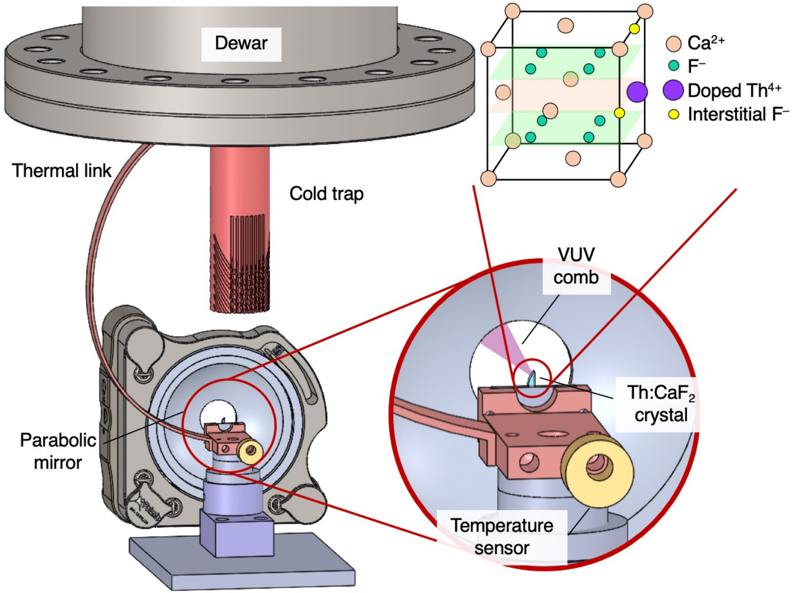


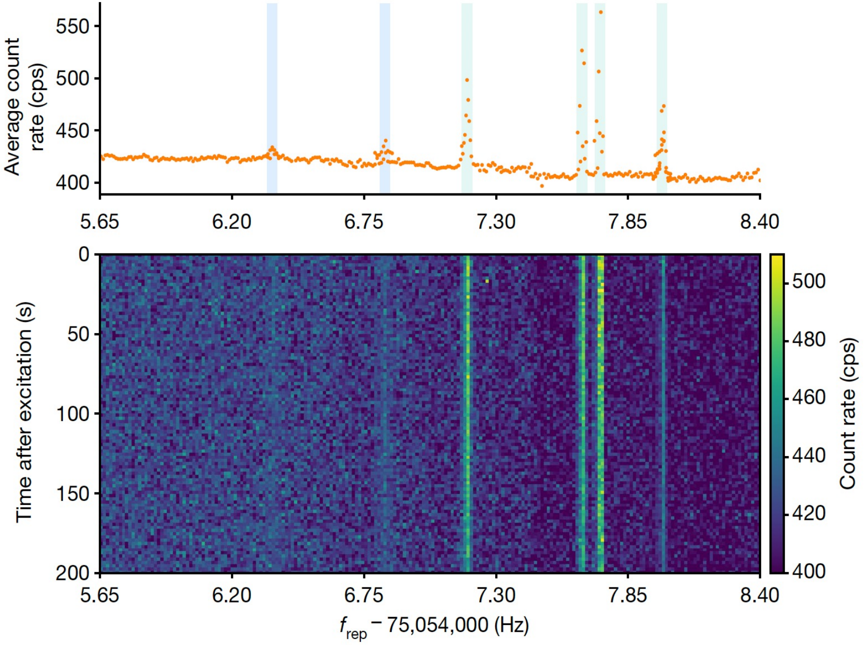
OKAYAMA experiment

- Multiple defect centers
- Site-dependent properties

VUV frequency comb precision spectroscopy

JILA experiment

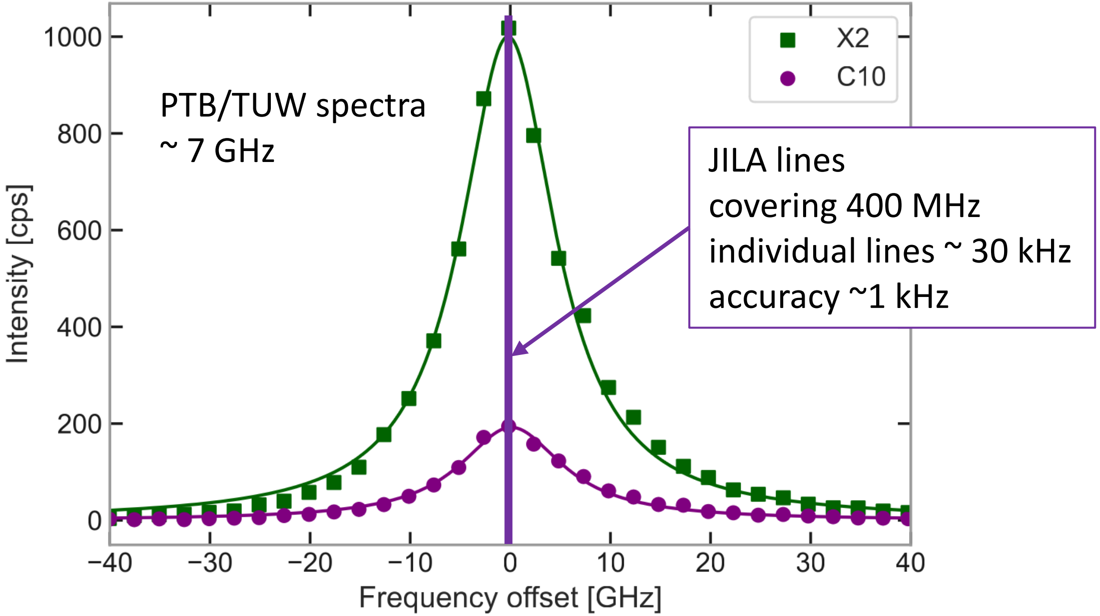




- 4 strong, 2 weak lines observed
- absolute frequency determination with reference to Sr clock

VUV frequency comb precision spectroscopy

JILA experiment vs. PTB/UCLA



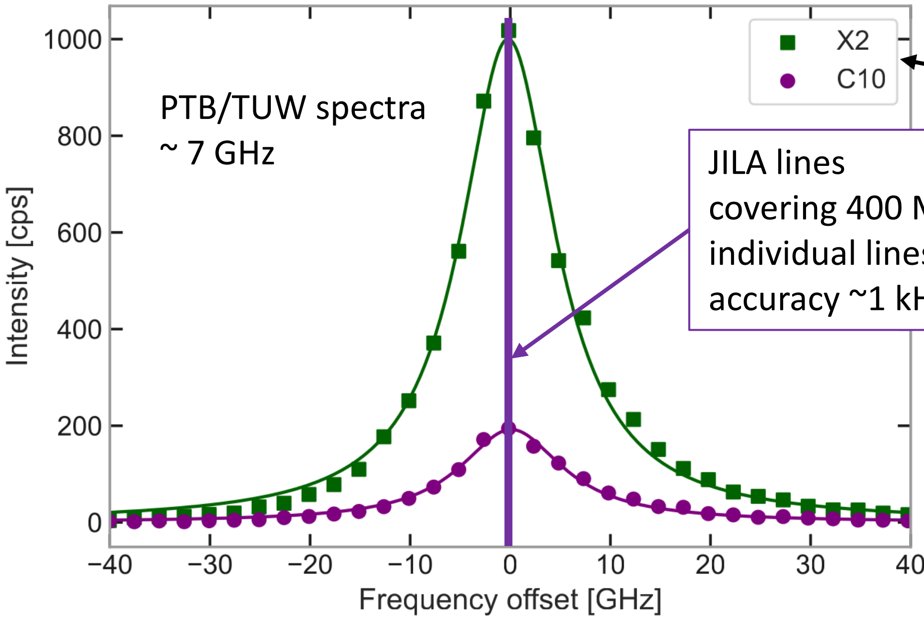
PTB/TUW spectra
~ 7 GHz

JILA lines
covering 400 MHz
individual lines ~ 30 kHz
accuracy ~1 kHz

$$\nu_{isomer} = 2\ 020\ 407\ 384\ 335(2)\ \text{kHz}$$

VUV frequency comb precision spectroscopy

JILA experiment vs. PTB/UCLA

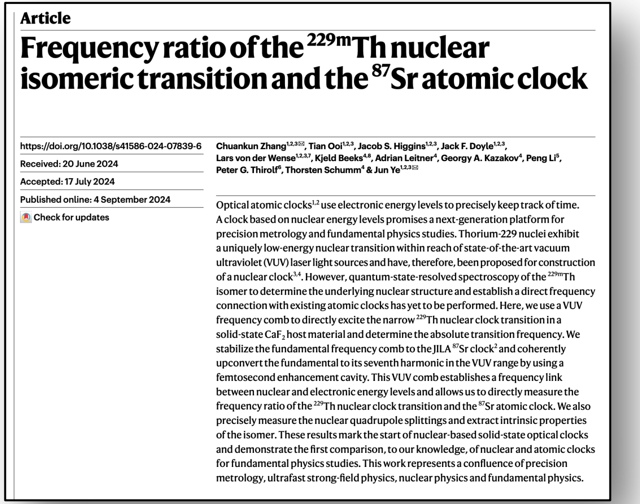


PTB/TUW spectra
~ 7 GHz

JILA lines
covering 400 MHz
individual lines ~ 30 kHz
accuracy ~1 kHz

same crystals X2 and C10 used at PTB and JILA

ν_{isomer}= 2 020 407 384 335(2) kHz



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
Received: 20 June 2024
Accepted: 17 July 2024

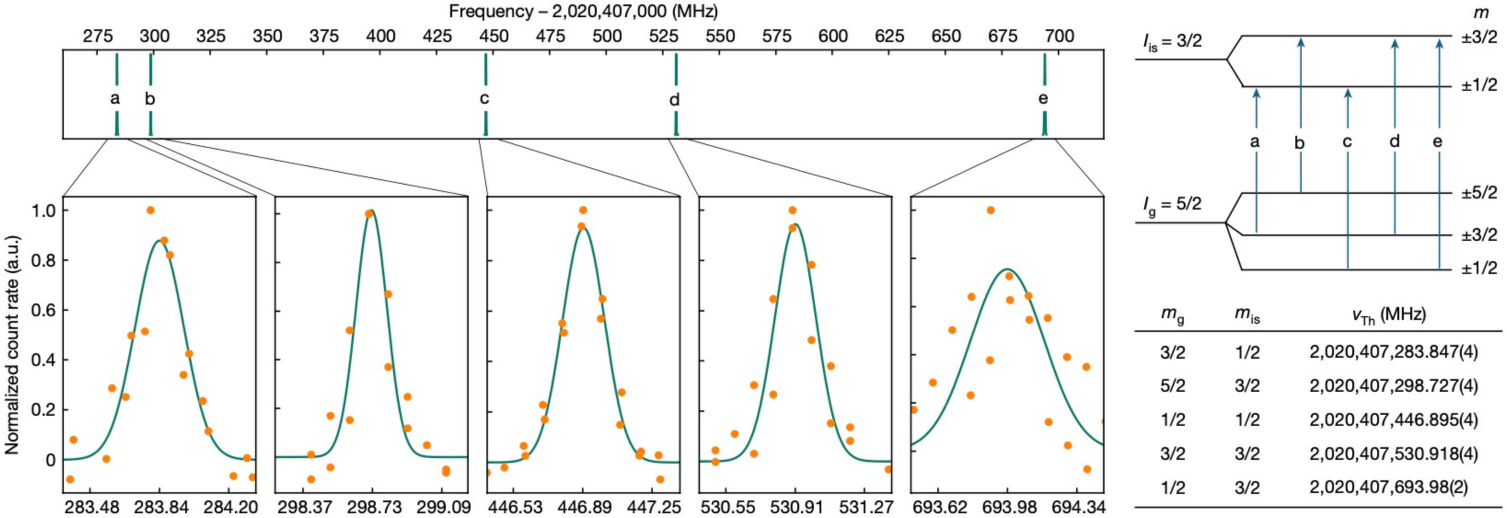
Chuankun Zhang[1,2,3]✉, Tian Ooi[1,2,3], Jacob S. Higgins[1,2,3], Jack F. Doyle[1,2,3], Lars von der Wense[1,2,3,7], Kjeld Beeks[4,8], Adrian Leitner[4], Georgy A. Kazakov[4], Peng Li[5], Peter G. Thirolf[6], Thorsten Schumm[4] & Jun Ye[1,2,3]✉

Optical atomic clocks[1,2] use electronic energy levels to precisely keep track of time. A clock based on nuclear energy levels promises a next-generation platform for precision metrology and fundamental physics studies. Thorium-229 nuclei exhibit a uniquely low-energy nuclear transition within reach of state-of-the-art vacuum ultraviolet (VUV) laser light sources and have, therefore, been proposed for construction of a nuclear clock[3,4]. However, quantum-state-resolved spectroscopy of the ^{229m}Th isomer to determine the underlying nuclear structure and establish a direct frequency connection with existing atomic clocks has yet to be performed. Here, we use a VUV frequency comb to directly excite the narrow ^{229}Th nuclear clock transition in a solid-state CaF_2 host material and determine the absolute transition frequency. We stabilize the fundamental frequency comb to the JILA ^{87}Sr clock[2] and coherently upconvert the fundamental to its seventh harmonic in the VUV range by using a femtosecond enhancement cavity. This VUV comb establishes a frequency link between nuclear and electronic energy levels and allows us to directly measure the frequency ratio of the ^{229}Th nuclear clock transition and the ^{87}Sr atomic clock. We also precisely measure the nuclear quadrupole splittings and extract intrinsic properties of the isomer. These results mark the start of nuclear-based solid-state optical clocks and demonstrate the first comparison, to our knowledge, of nuclear and atomic clocks for fundamental physics studies. This work represents a confluence of precision metrology, ultrafast strong-field physics, nuclear physics and fundamental physics.

September 2024

Nuclear quadrupole structure in ^{229}Th:CaF2

JILA experiment



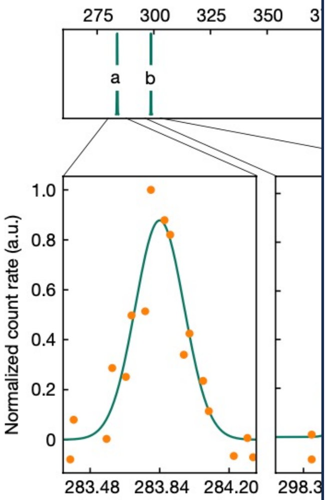
m_g	m_{is}	ν_{Th} (MHz)
3/2	1/2	2,020,407,283.847(4)
5/2	3/2	2,020,407,298.727(4)
1/2	1/2	2,020,407,446.895(4)
3/2	3/2	2,020,407,530.918(4)
1/2	3/2	2,020,407,693.98(2)

- 4 strong + 1 additional line observed → asignement **to nuclear quadrupole structure**
- absolute frequency determination

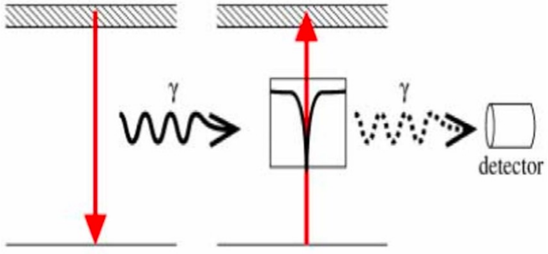
(let‘s not totally forget about the 2 weak lines)

Nuclear quadrupole structure in ^{229}Th:CaF2

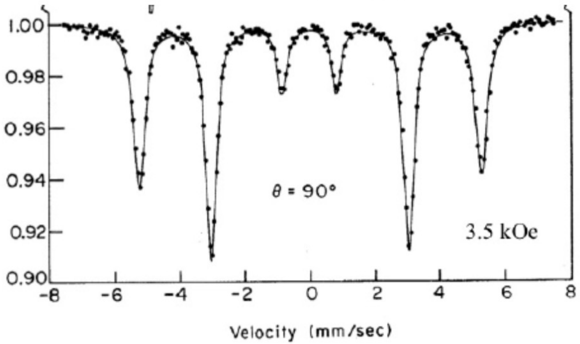
JILA experimen

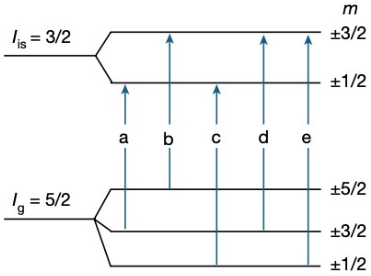


„traditional“ Mössbauer spectroscopy



Example of zeeman splitting spectrum





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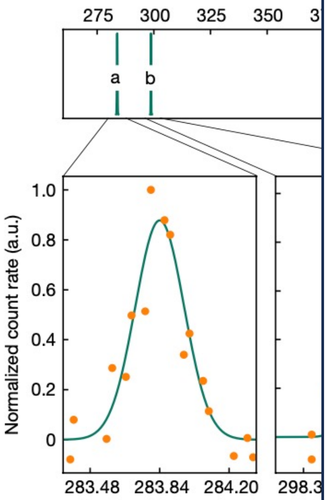
- 4 strong **+ 1 a** **ear quadrupole structure**
- absolute frequ

(let‘s not totally f

Nuclear quadrupole structure in ^{229}Th:CaF2

JILA experimen



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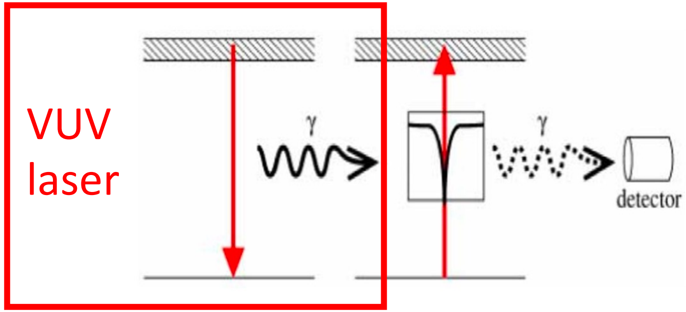

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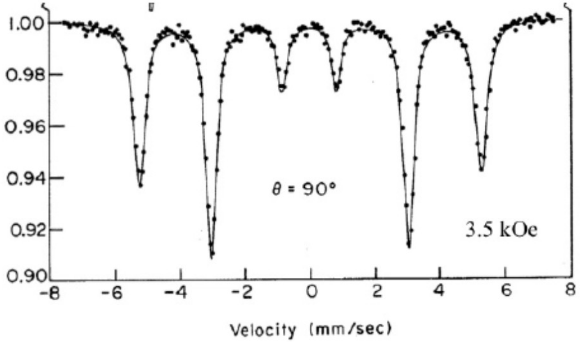

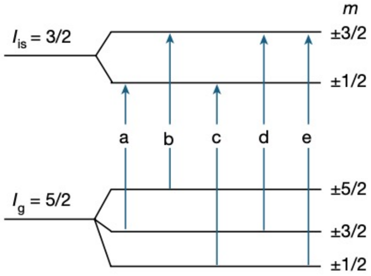

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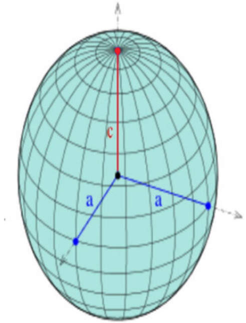
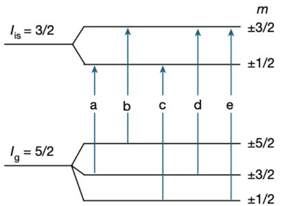
(let‘s not totally f

Nuclear quadrupole structure in ^{229}Th:CaF$_2$

Quadrupole structure determined by nuclear and material parameters



Prolate



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$$H = \frac{QV_{zz}}{4I(2I-1)}\left[3I_z^2 - \mathbf{I}^2 + \eta\left(I_x^2 - I_y^2\right)\right]$$

Q – (intrinsic) quadrupole moment „universal“

V_{zz} – electric field gradient (EFG)

η – anisotropie parameter

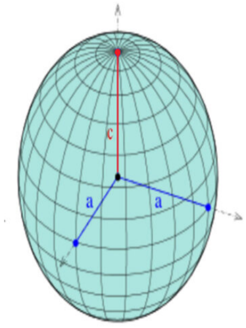
$\Big\}$ host-specific

change in quadrupole moment…

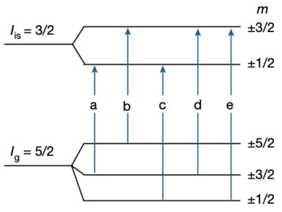
$\Delta Q/Q$ = 1.791(2)%

Nuclear quadrupole structure in ^{229}Th:CaF$_2$

Quadrupole structure determined by **nuclear** and **material parameters**



Prolate



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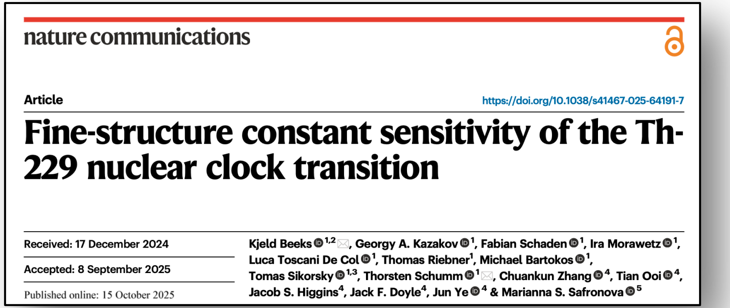


nature communications

Article

https://doi.org/10.1038/s41467-025-64191-7

Fine-structure constant sensitivity of the Th-229 nuclear clock transition

Received: 17 December 2024

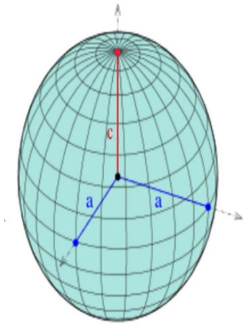
Accepted: 8 September 2025

Published online: 15 October 2025

Kjeld Beeks[1,2], Georgy A. Kazakov[1], Fabian Schaden[1], Ira Morawetz[1], Luca Toscani De Col[1], Thomas Riebner[1], Michael Bartokos[1], Tomas Sikorsky[1,3], Thorsten Schumm[1], Chuankun Zhang[4], Tian Ooi[4], Jacob S. Higgins[4], Jack F. Doyle[4], Jun Ye[4] & Marianna S. Safronova[5]

Nuclear quadrupole structure in ^{229}Th:CaF$_2$

Quadrupole structure determined by **nuclear** and **material parameters**



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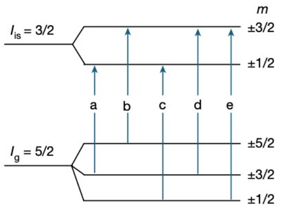

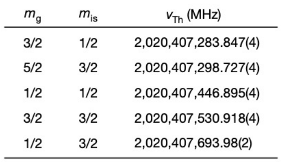

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$$H = \frac{QV_{zz}}{4I(2I-1)}\left[3I_z^2 - \mathbf{I}^2 + \eta\left(I_x^2 - I_y^2\right)\right]$$

Q – (intrinsic) quadrupole moment „universal“

V_{zz} – electric field gradient (EFG)

η – anisotropie parameter

host-specific

change in quadrupole moment…

$$\Delta Q/Q = 1.791(2)\%$$

Extracted electrical field gradient (EFG)

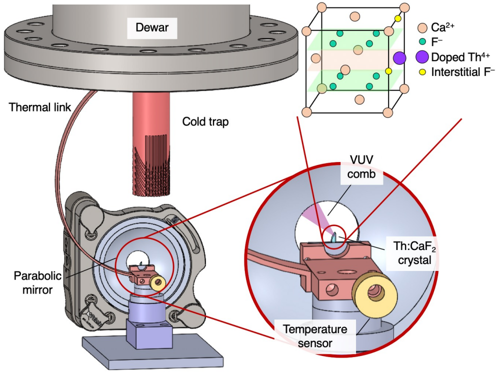
$$V_{zz} = 109.1(7)\ \mathrm{V/Å^2}$$

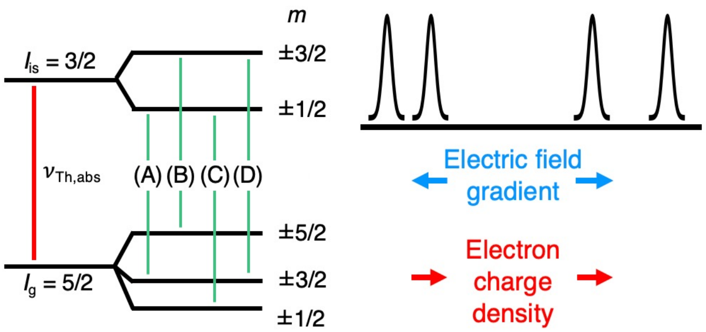
$$\eta = 0.59163(5)$$

extremely well reproduced over 3 different crystals

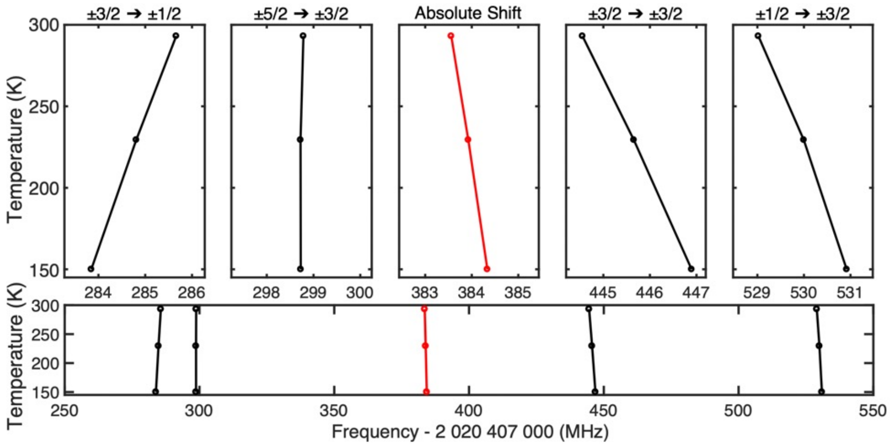
Temperature dependence of spectroscopy lines

JILA experiment





tracing 4 strongest lines over temperature

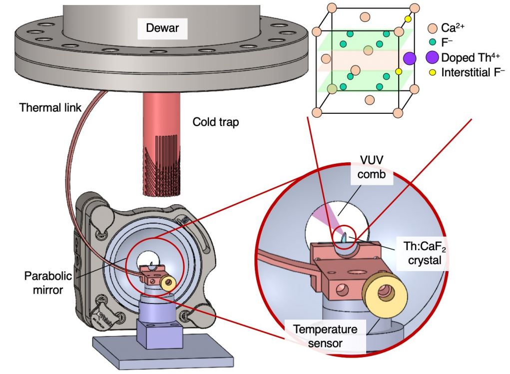


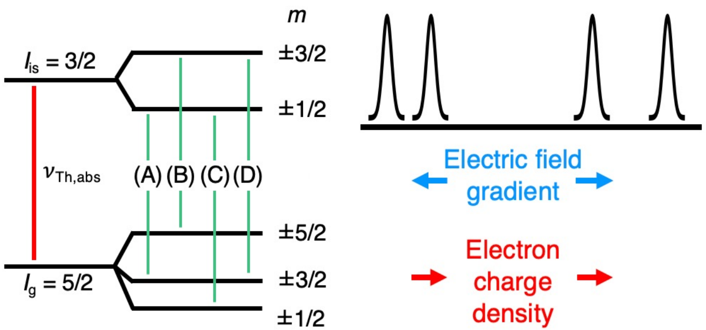
- EFG and eta parameter „well behaved“
- compatible with thermal expansion
- interesting cancellellation in (B) transition (clock?)
- strong eta indicates breaking of lattice symmetry

transitions now clearly depend on host material and temperature (CaF_2, $LiSaF_6$…)

Temperature dependence of spectroscopy lines

JILA experiment





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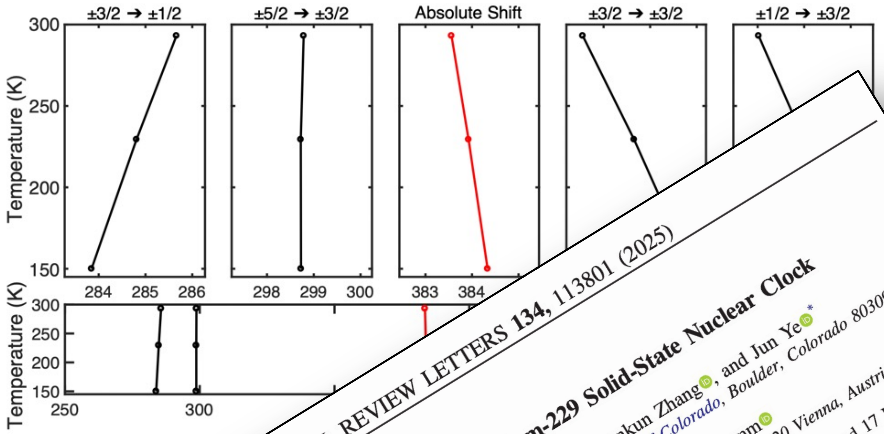
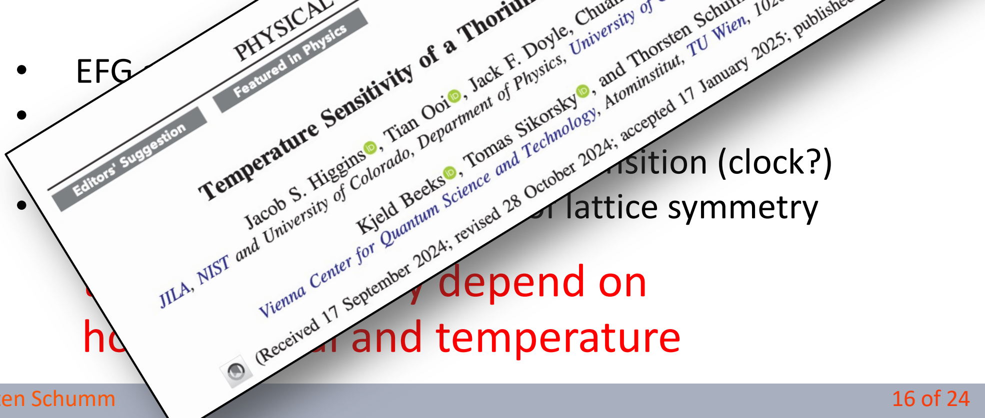


- EFG
-
- nsition (clock?)
- lattice symmetry

depend on

ho and temperature



PHYSICAL REVIEW LETTERS 134, 113801 (2025)

Editors' Suggestion Featured in Physics

Temperature Sensitivity of a Thorium-229 Solid-State Nuclear Clock

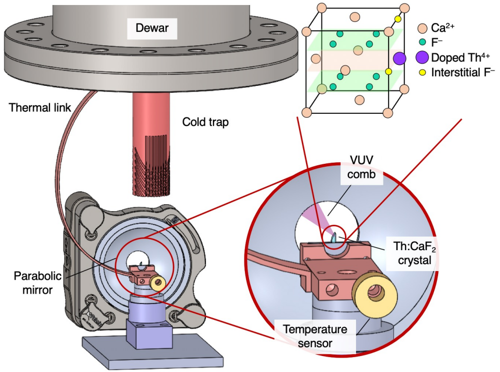
Jacob S. Higgins, Tian Ooi, Jack F. Doyle, Chuankun Zhang, and Jun Ye*
JILA, NIST and University of Colorado, Department of Physics, University of Colorado, Boulder, Colorado 80309, USA

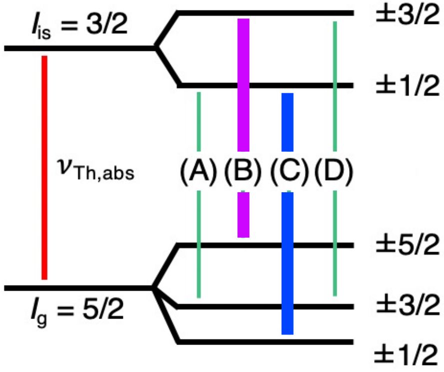
Kjeld Beeks, Tomas Sikorsky, and Thorsten Schumm
Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria

(Received 17 September 2024; revised 28 October 2024; accepted 17 January 2025; published 17 March 2025)

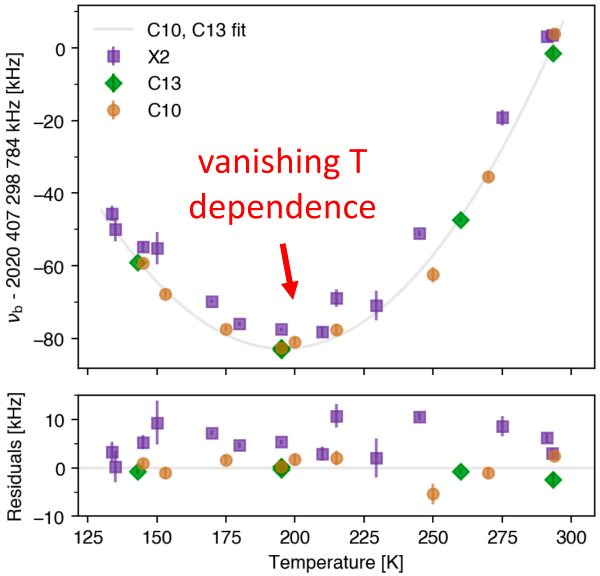
Towards a ^{229}Th:CaF$_2$ solid-state nuclear clock

JILA experiment

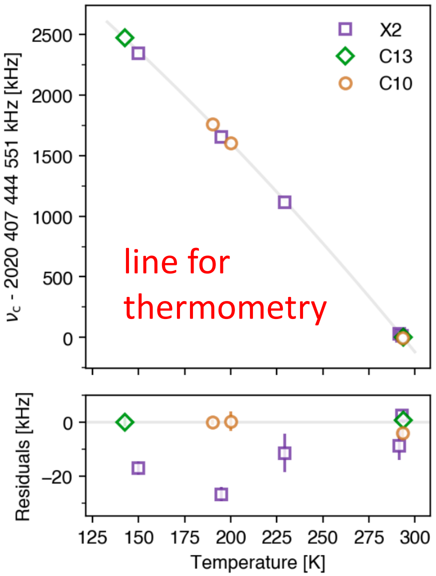




(B) transition



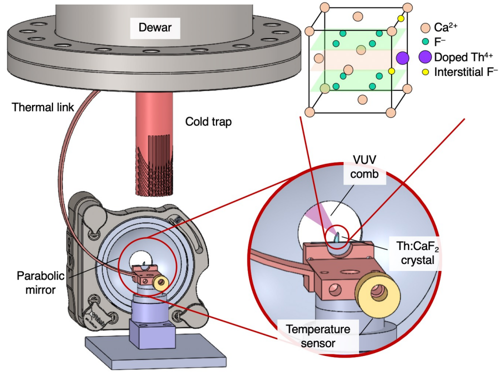
(C) transition

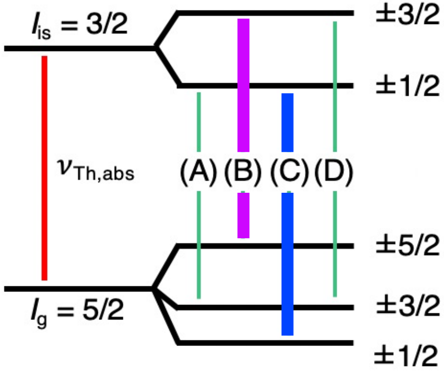


- transition frequencies consistent within ~kHz over different crystals
- linewidth 10-100 kHz, scaling with concentration („micro-strain“)
- Continuous interrogation at fixed T (over 1 year) within 1 kHz

Towards a ^{229}Th:CaF$_2$ solid-state nuclear clock

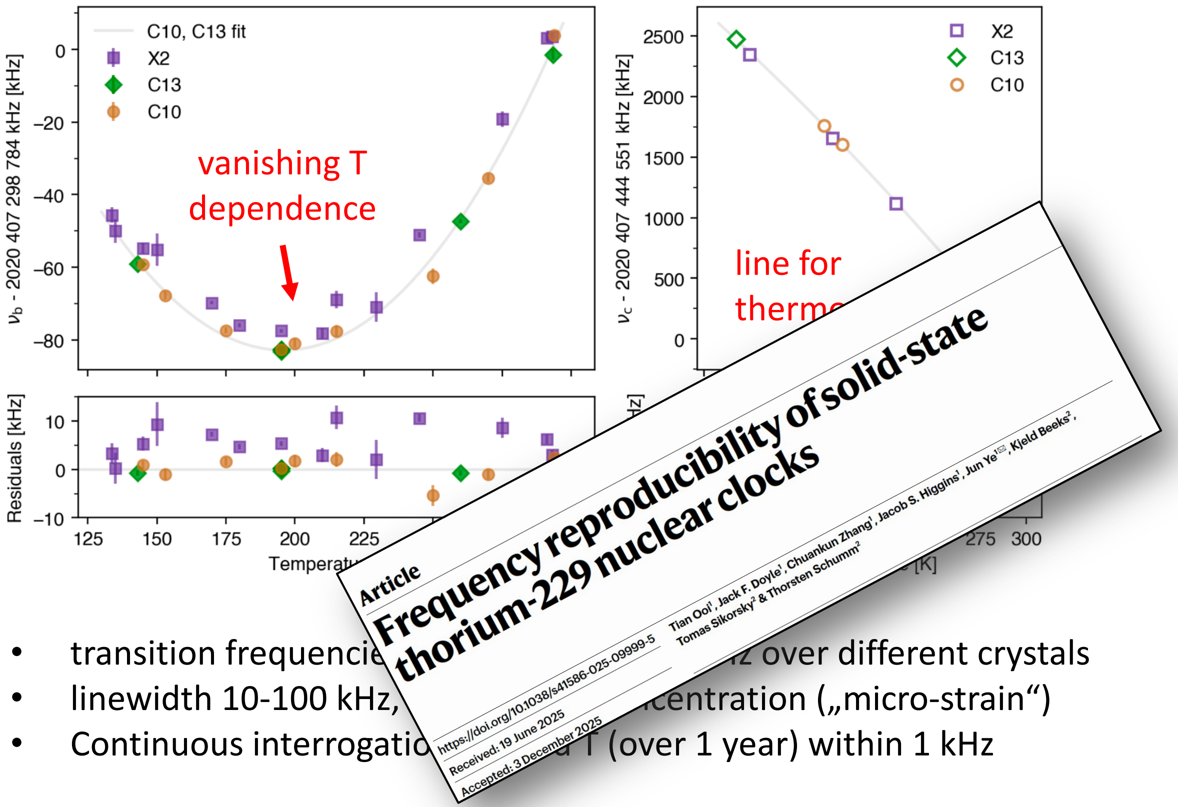
JILA experiment





(B) transition

(C) transition



vanishing T dependence

line for therm

Article

Frequency reproducibility of solid-state thorium-229 nuclear clocks

Tian Ooi[1], Jack F. Doyle[1], Chuankun Zhang[1], Jacob S. Higgins[1], Jun Ye[1]✉, Kjeld Beeks[2], Tomas Sikorsky[2] & Thorsten Schumm[2]

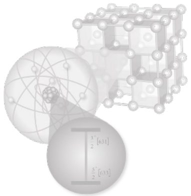
https://doi.org/10.1038/s41586-025-09999-5
Received: 19 June 2025
Accepted: 3 December 2025

- transition frequencie z over different crystals
- linewidth 10-100 kHz, centration („micro-strain“)
- Continuous interrogatio d T (over 1 year) within 1 kHz

...any **questions?**...any **time!**

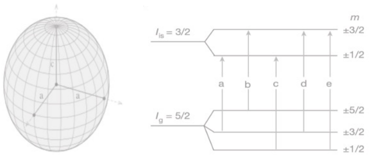
or contact:
thorsten.schumm@tuwien.ac.at

OUTLINE



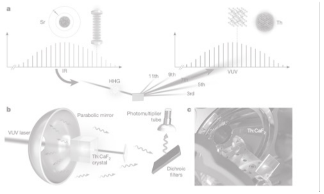
The „solid state approach“ to a Th-229 nuclear clock

- Basic concept and implementation



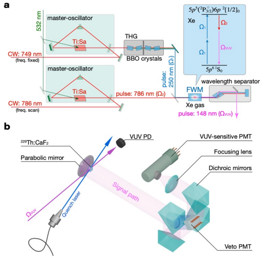
Nuclear quadrupole structure

- Nuclear – solid coupling
- Separating nuclear properties and material parameters



JILA experiment

- Absolute Mössbauer spectroscopy
- Temperature depencence
- Towards a solid-state nuclear clock

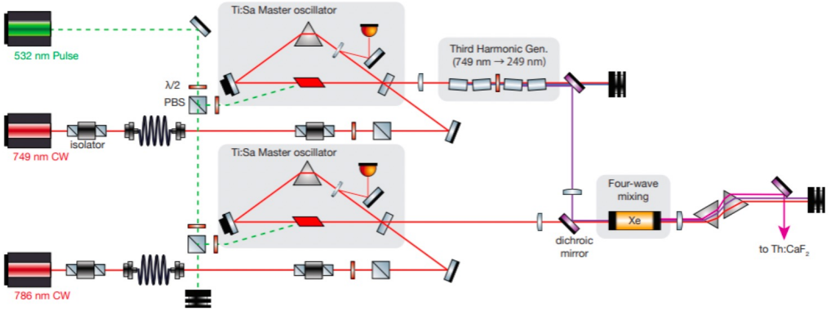


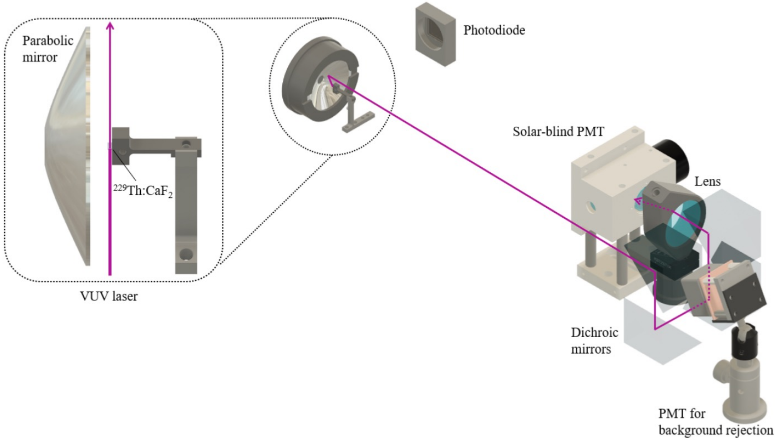
OKAYAMA experiment

- Multiple defect centers
- Site-dependent properties

Multiple doping sites in a single crystal

Okayama experiment





- 4-wave mixing laser similar to PTB/UCLA
- **linewidth 30 MHz** → resolve Q-structure
- factor 50 higher excitation rate than JILA

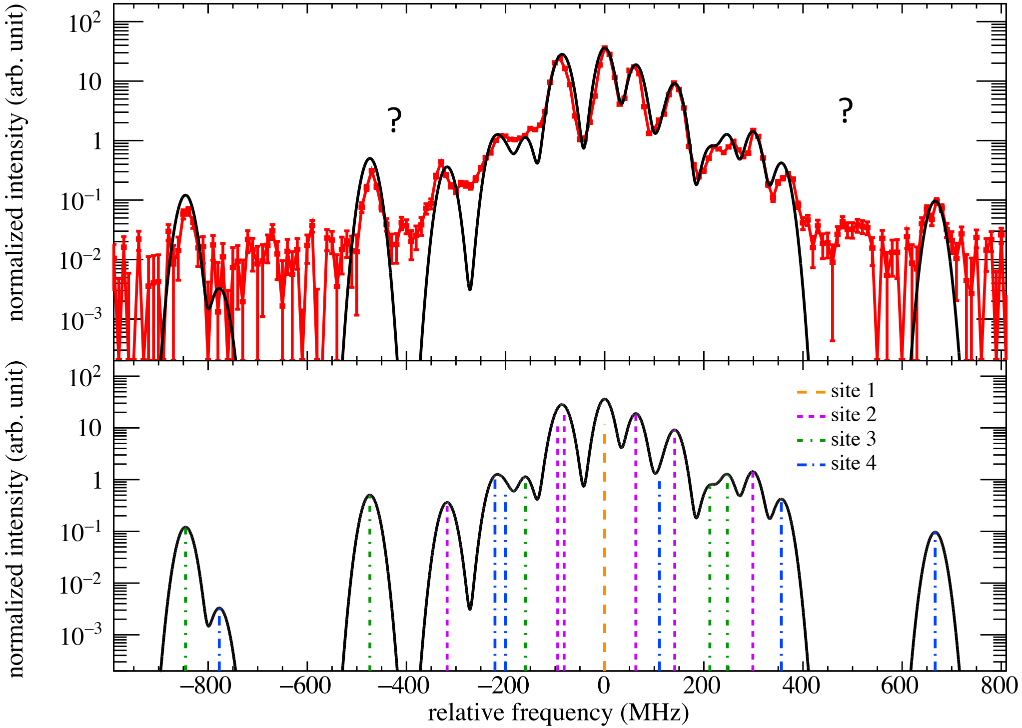
- detection system taken from SPring-8
- 3 crystals from Vienna (always the same)

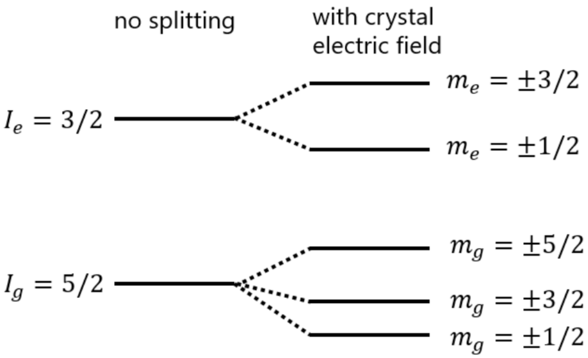
Table 1: **Parameters of ^{229}Th:CaF$_2$ crystals.**

crystal name	C10	C13	X2
concentration (/mm^3)	4×10^{14}	8×10^{14}	5×10^{15}
^{229}Th activity (kBq)	1.1	2.7	17.2

Multiple doping sites in a single crystal

Okayama experiment





- at least 4 different Th sites identified in all 3 crystals
- one of them is „JILA site“ (site 2)
- missing 6th line of „JILA site“ observed
- Relative occurences of sites changes with concentration

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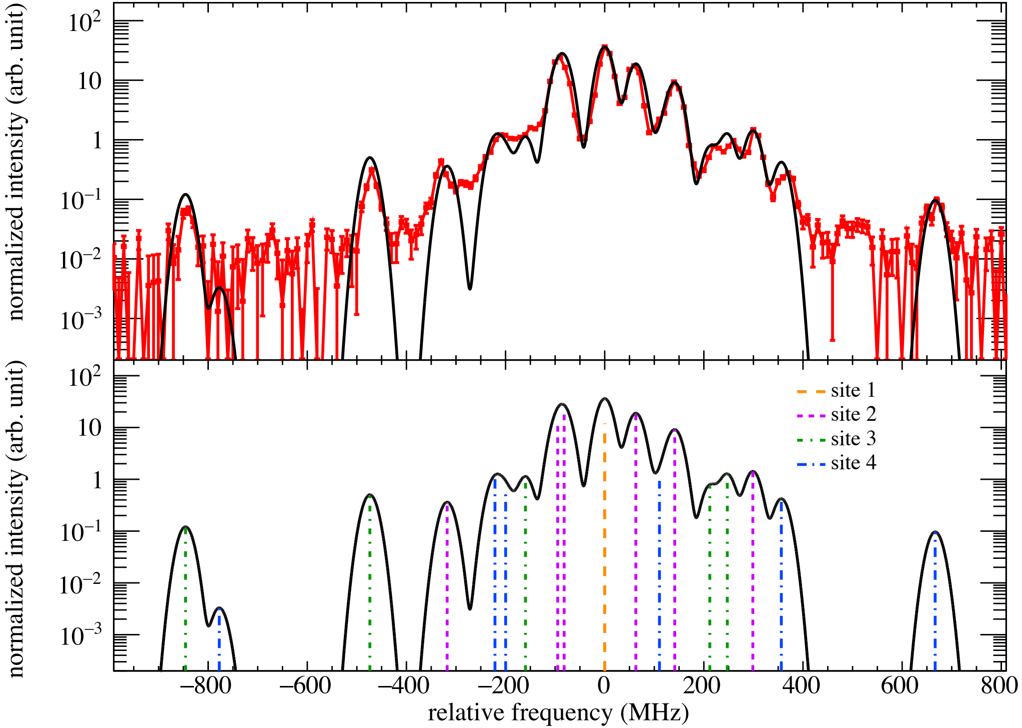


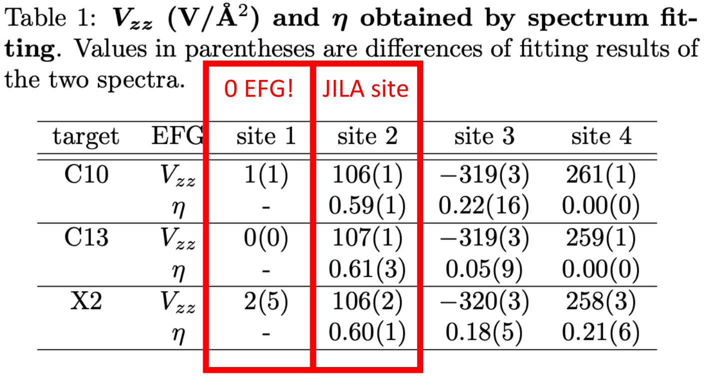
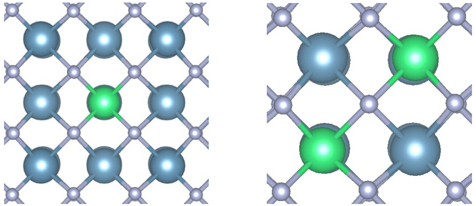


Table 1: $\boldsymbol{V_{zz}}$ **(V/Å^2) and $\boldsymbol{\eta}$ obtained by spectrum fitting**. Values in parentheses are differences of fitting results of the two spectra.

		0 EFG!	JILA site		
target	EFG	site 1	site 2	site 3	site 4
C10	V_{zz}	1(1)	106(1)	−319(3)	261(1)
	η	-	0.59(1)	0.22(16)	0.00(0)
C13	V_{zz}	0(0)	107(1)	−319(3)	259(1)
	η	-	0.61(3)	0.05(9)	0.00(0)
X2	V_{zz}	2(5)	106(2)	−320(3)	258(3)
	η	-	0.60(1)	0.18(5)	0.21(6)



tentative assignment: single Th and 2Th cluster **without local charge compensation**

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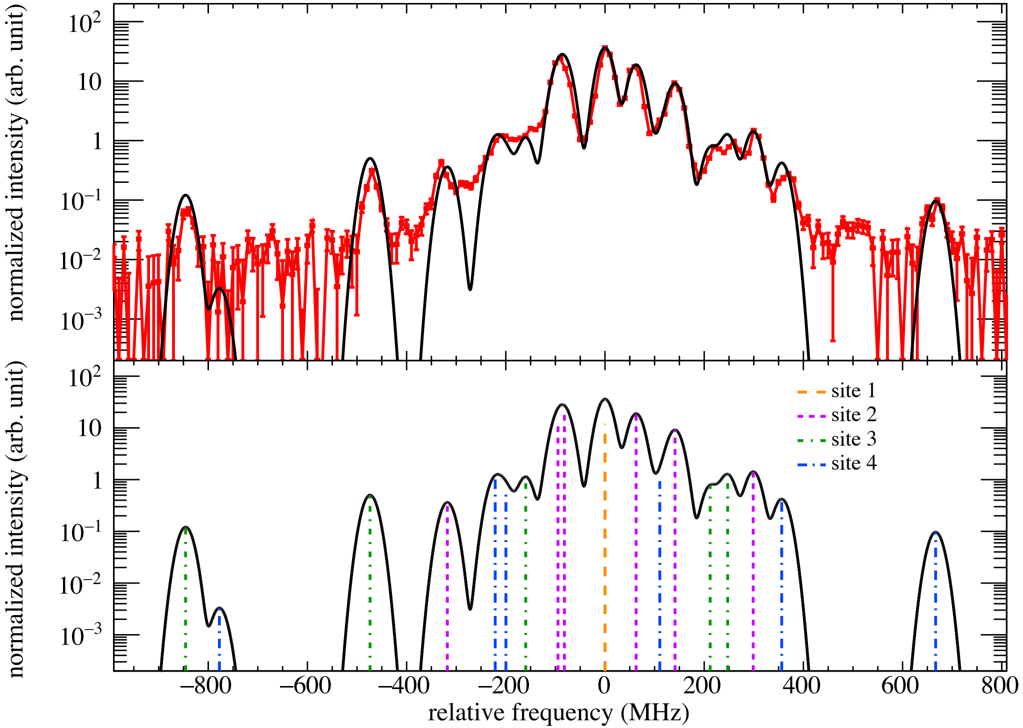

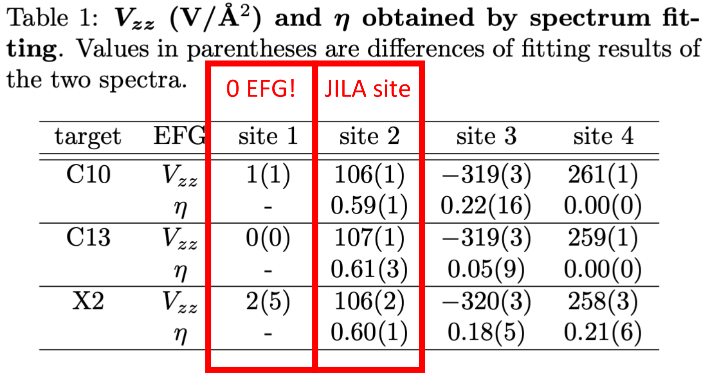

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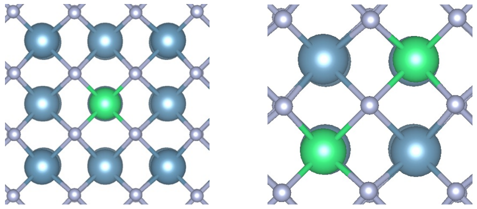


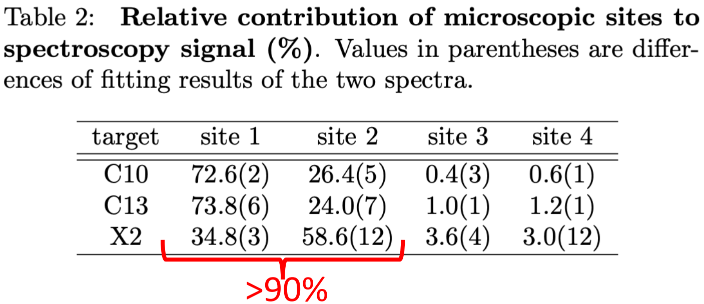


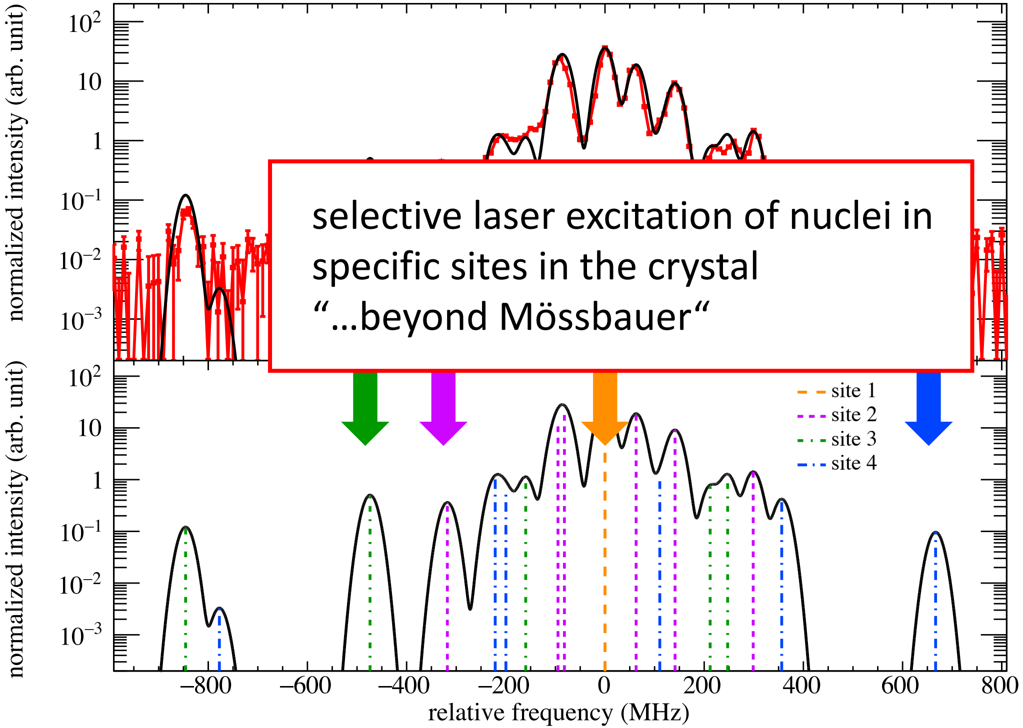
Table 2: **Relative contribution of microscopic sites to spectroscopy signal (%)**. Values in parentheses are differences of fitting results of the two spectra.

target	site 1	site 2	site 3	site 4
C10	72.6(2)	26.4(5)	0.4(3)	0.6(1)
C13	73.8(6)	24.0(7)	1.0(1)	1.2(1)
X2	34.8(3)	58.6(12)	3.6(4)	3.0(12)

$\underbrace{34.8(3)\quad 58.6(12)}_{>90\%}$

Multiple doping sites in a single crystal

Okayama experiment



selective laser excitation of nuclei in specific sites in the crystal
“…beyond Mössbauer“

Table 1: **V_{zz} (V/Å^2) and η obtained by spectrum fitting**. Values in parentheses are differences of fitting results of the two spectra.

0 EFG!

JILA site

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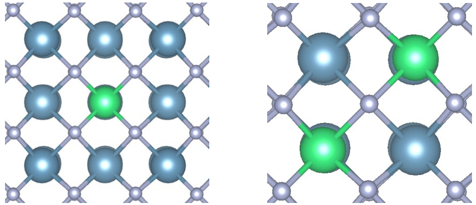

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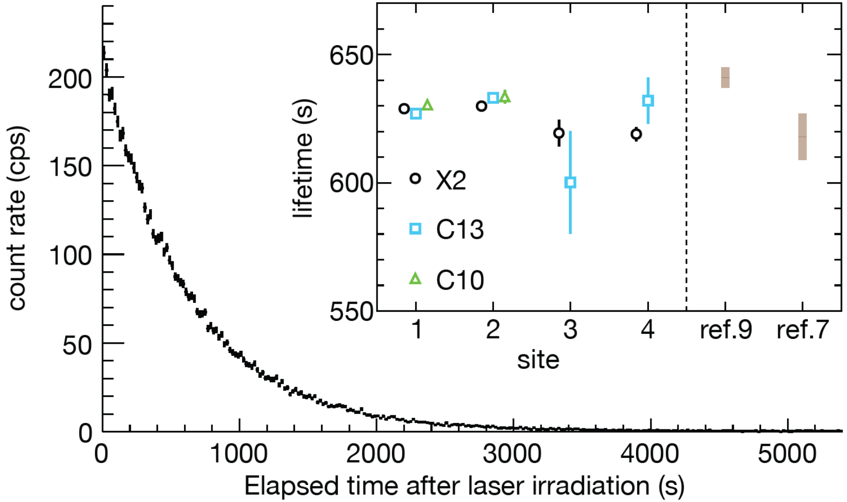
Multiple doping sites in a single crystal

Okayama experiment

isomer lifetime **DOES NOT** seem to depend (much) on Th doping site

(all measurements at room temperature)



Multiple doping sites in a single crystal

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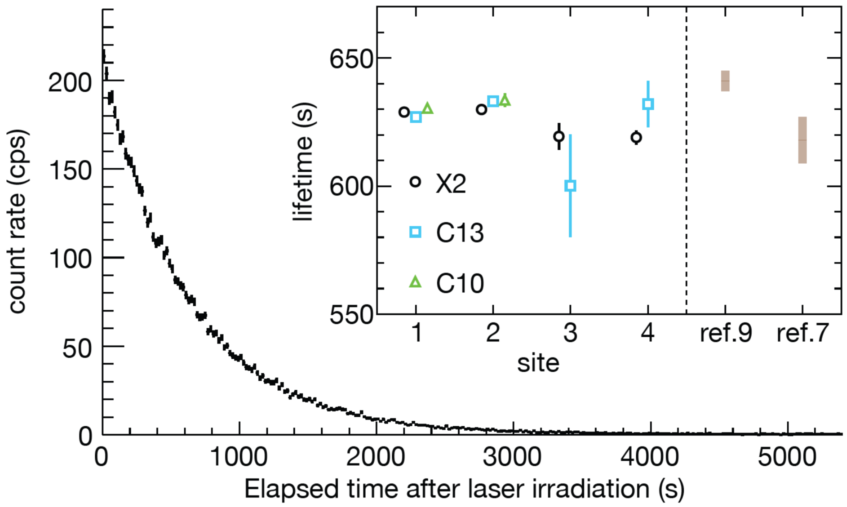
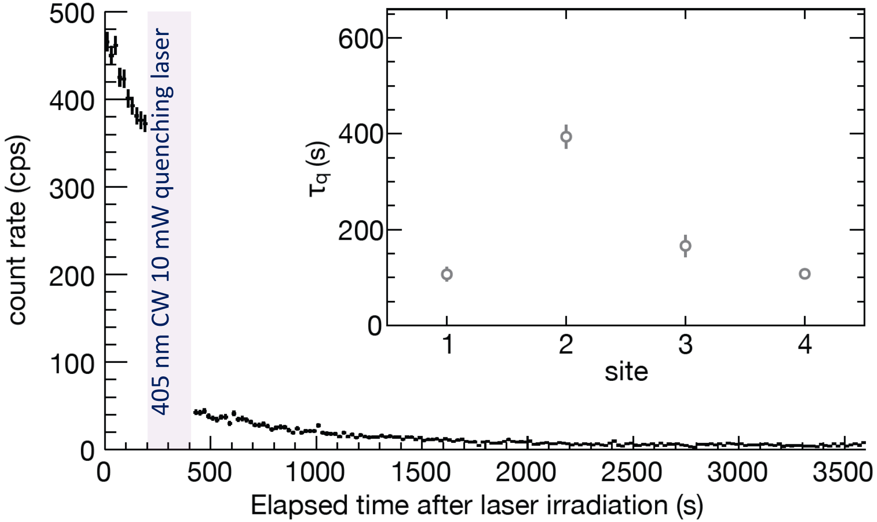


isomer laser quenching **DOES** depend on Th doping site
(all measurements at room temperature)



Multiple doping sites in a single crystal

Okayama experiment

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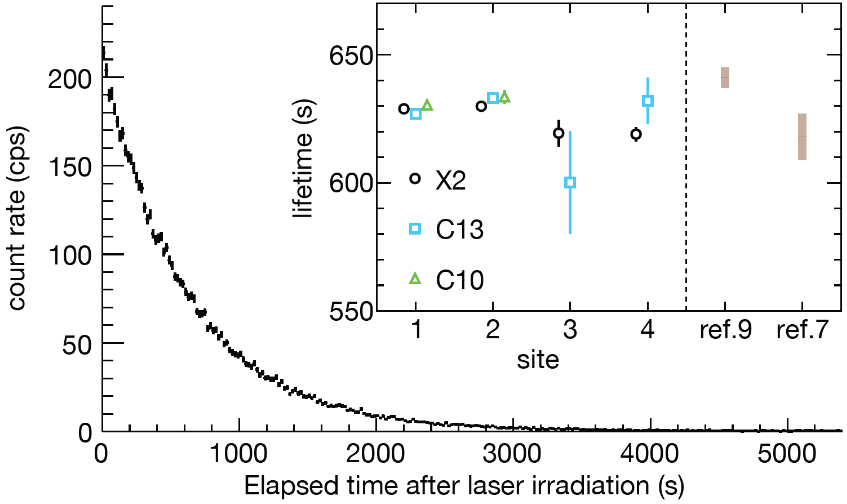

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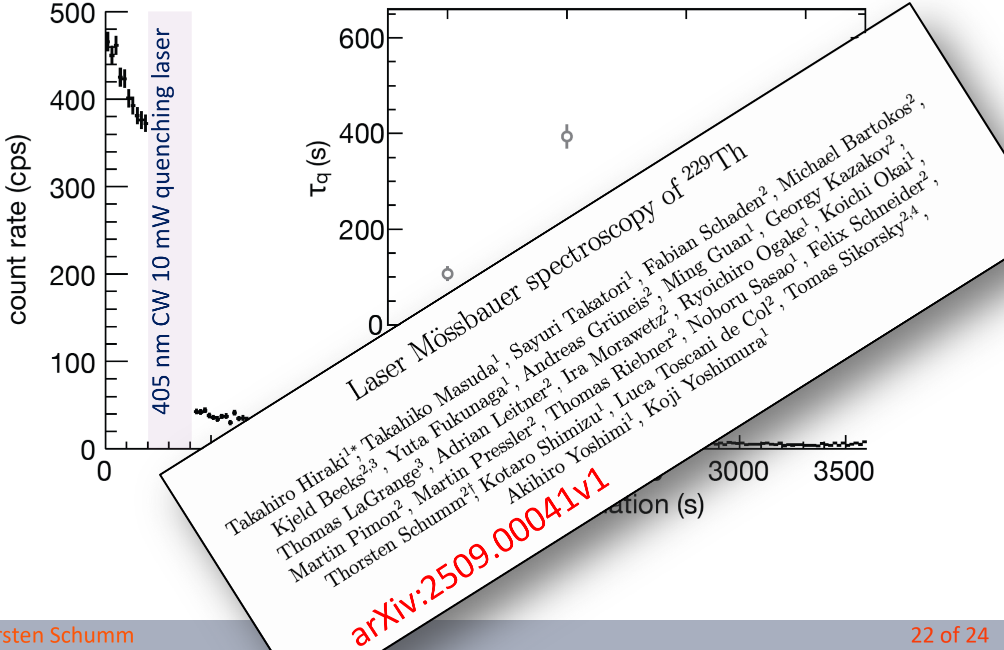

Laser Mössbauer spectroscopy of ^{229}Th

Takahiro Hiraki[1*], Takahiko Masuda[1], Sayuri Takatori[1], Fabian Schaden[2], Michael Bartokos[2], Kjeld Beeks[2,3], Yuta Fukunaga[1], Andreas Grüneis[2], Ming Guan[1], Georgy Kazakov[2], Thomas LaGrange[3], Adrian Leitner[2], Ira Morawetz[2], Ryoichiro Ogake[1], Koichi Okai[1], Martin Pimon[2], Martin Pressler[2], Thomas Riebner[2], Noboru Sasao[1], Felix Schneider[2], Thorsten Schumm[2†], Kotaro Shimizu[1], Luca Toscani de Col[2], Tomas Sikorsky[2,4], Akihiro Yoshimi[1], Koji Yoshimura[1]

arXiv:2509.00041v1

…any **questions?**…last Chance!

or contact:
thorsten.schumm@tuwien.ac.at

Credits (most probably incomplete, I apologize!)

ISOLDE-CERN measurements

S. Kraemer, J. Moens, S. Bara, P. Chhetri, A. Claessens, T. Cocolios,	KU Leuven
S. Geldhof, L. Pareire, S. Sels, A. Vantomme, M. Verlinde, **P.v. Duppen**	
M. Athanasakis-Kaklamanakis, K. Chrysalidis, R. Henke	CERN
K. Beeks, N. Hosseini, T. S.	TU Wien

PTB measurements

J. Tidau, J. Thielking, G. Zitzer K. Zhang, M. Okhapkin, **E. Peik**	PTB Braunschweig
F. Schaden, K. Beeks, T. Pronebner, I. Morawetz, T. Sikorsky, T. S.	TU Wien

SPring-8/Okayama measurements

T. Masuda, A. Yoshimi, A. Fujieda, H. Hara, T. Hiraki, H. Kaino, Y. Miyamoto,	Okayama University
K. Okai, S. Okubo, N. Sasao, S. Uetake, M. Yoshimura, **K. Yoshimura**, K. Suzuki	
H. Fujimoto, T. Watanabe	AIST Tsukuba
H. Haba, A. Yamaguchi, T. Yokokita, K. Tamasaku	RIKEN
Y Kasamatsu, Y. Yasuda, Y. Shigekawa	Osaka University
S. Kitao, M. Seto	Kyoto University
K. Konashi, M. Watanabe	Institute f. Material res. Tohoku
S. Stellmer, K. Beeks, F. Schaden, T. Sikorsky, T. S.	TU Wien

JILA measurements

C. Zhang, T. Ooi, J. Doyle, J. Higgins, **J. Ye**	JILA
K. Beeks, F. Schaden, A. Leitner, T. Sikorsky, G. Kazakov, T. S.	TU Wien

THE END