

SOLID-STATE NUCLEAR CLOCK: PROGRESS & ISOTOPE NEEDS



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CHALLENGE INSTITUTE FOR QUANTUM COMPUTATION

THE SOLUTION: CRYSTALS

- TRANSITION MEASUREMENT
- HOST EFFECTS

RUBBER MEETS THE ROAD

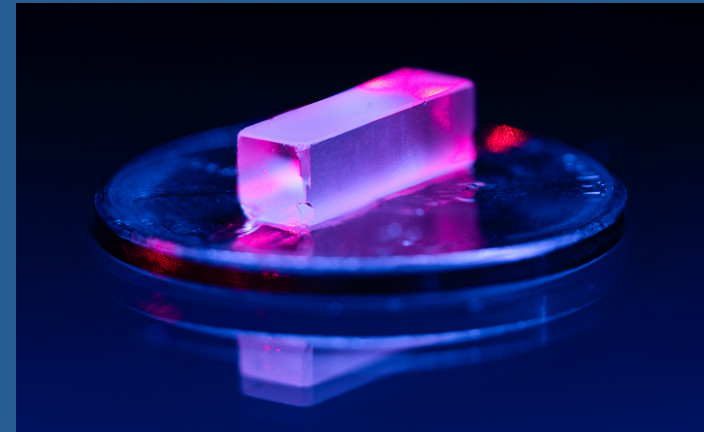
- DATA VS PREDICTIONS

AN EVEN BETTER APPROACH?

- NUCLEAR LASER SPECTROSCOPY IN AN OPAQUE MATERIAL

ISOTOPE NEEDS

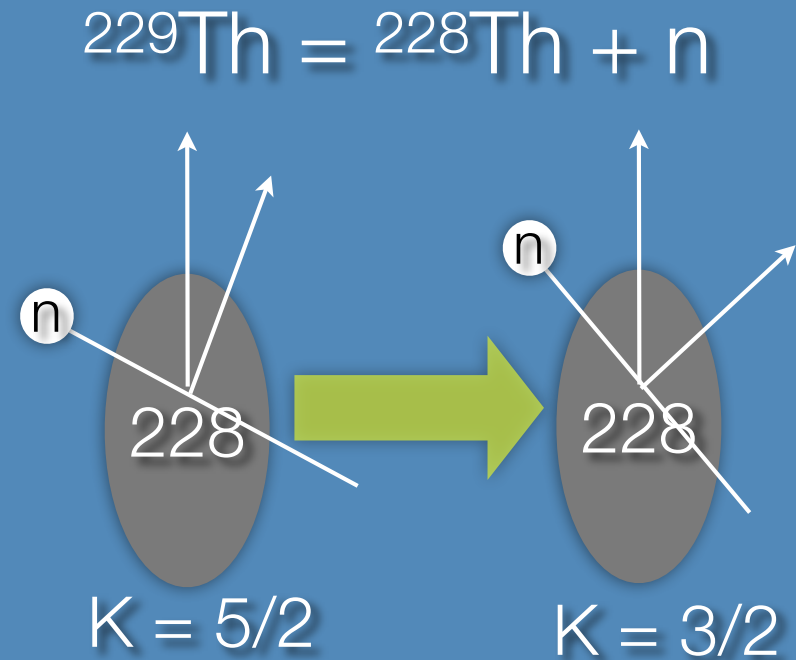
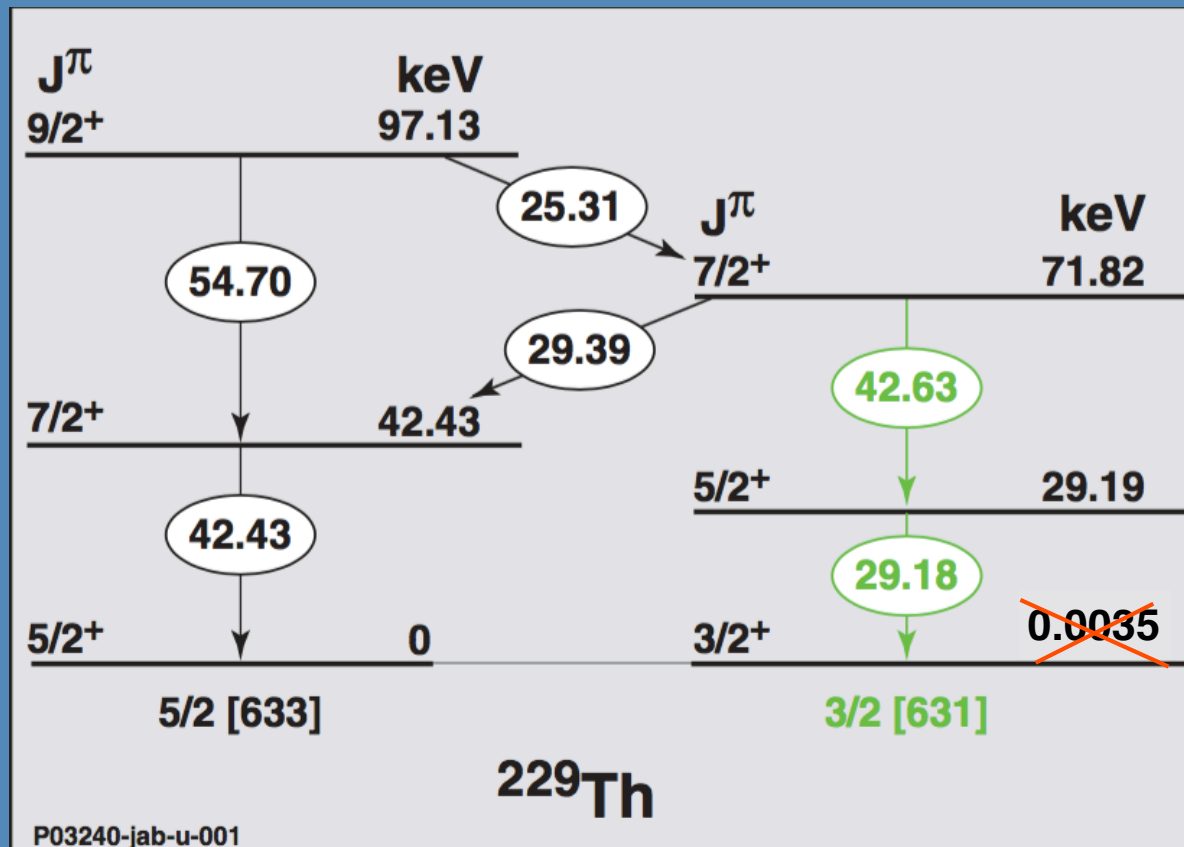
- SCARCITY STIFLES INNOVATION



Th-doped LiSrAlF_6 crystal

- The ^{229}Th nuclear isomeric transition

First on the scene: L. A. Kroger and C. W. Reich, Nucl. Phys. A 259, 29 (1976).



$$\lambda = \begin{matrix} 7.8(5) \text{ eV} \\ 160(10) \text{ nm} \end{matrix} \quad \Gamma = 100 \text{ } \mu\text{Hz}$$

B.R. Beck et al., PRL 98, 142501 (2007); ibid., LLNL-PROC-415170 (2009).

The nuclear clock

$$\lambda = \frac{7.8(5) \text{ eV}}{160(10) \text{ nm}} \quad \Gamma = 100 \text{ } \mu\text{Hz} \quad \longrightarrow \quad Q \sim 10^{19}$$

BBR shift minimal, small differential shifts (nuclear magneton), etc.

PRL **104**, 200802 (2010)

PHYSICAL REVIEW LETTERS

week ending
21 MAY 2010

Constraining the Evolution of the Fundamental Constants with a Solid-State Optical Frequency Reference Based on the ^{229}Th Nucleus

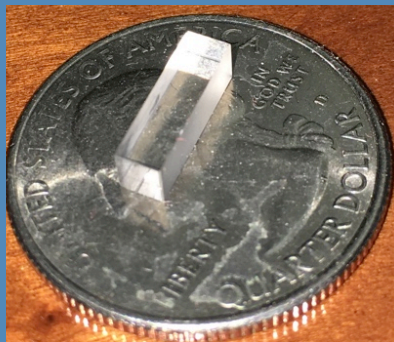
Wade G. Rellergert,¹ D. DeMille,² R. R. Greco,³ M. P. Hehlen,³ J. R. Torgerson,³ and Eric R. Hudson¹

¹*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*

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³*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

(Received 4 June 2009; published 20 May 2010)



NUCLEAR CLOCK @ UCLA



NIST F-1 CLOCK



NUCLEAR CLOCK BASED ON
RARE THORIUM-229
ISOTOPE

PRL 104, 200802 (2010)

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NUCLEAR CLOCK @ UCLA

SPARKED EXCITEMENT
IN
TIMEKEEPING, NAVIGATION,
COMMUNICATION, AND
FUNDAMENTAL SCIENCE (FC
VARIATION, UDM, LV, EPV)
BUT...



NUCLEAR CLOCK BASED ON
RARE THORIUM-229
ISOTOPE

PRL 104, 200802 (2010)

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Finding the isomeric transition

The challenge (~40 yrs):

The needle:

$\gamma \sim 10 \mu\text{Hz} - 100 \mu\text{Hz}$

The haystack:

$140 \text{ nm} < \lambda < 180 \text{ nm}$

The solution:



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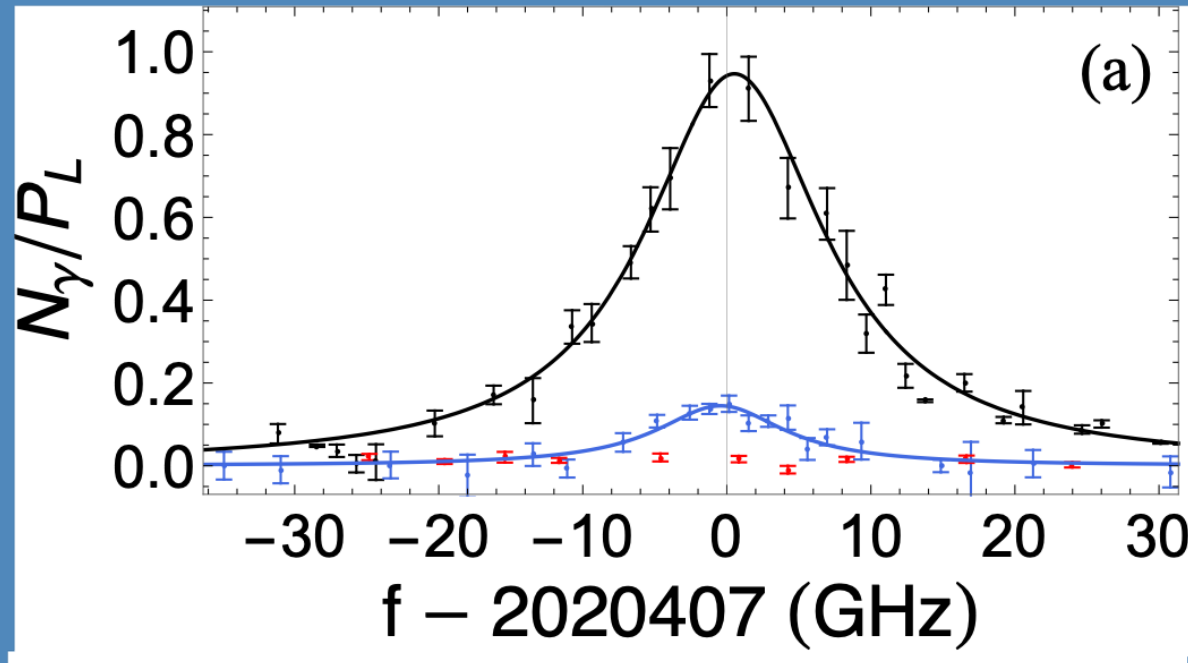
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LASER EXCITATION OF TH-229 NUCLEUS!?

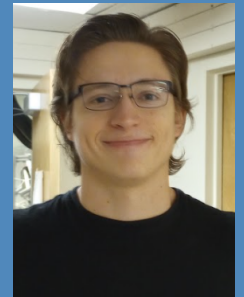


$148.38219(4)_{\text{STAT}}(20)_{\text{SYS}} \text{ nm}$

$2020407.3(5)_{\text{stat}}(30)_{\text{sys}} \text{ GHz}$



Richard Elwell



James Terhune

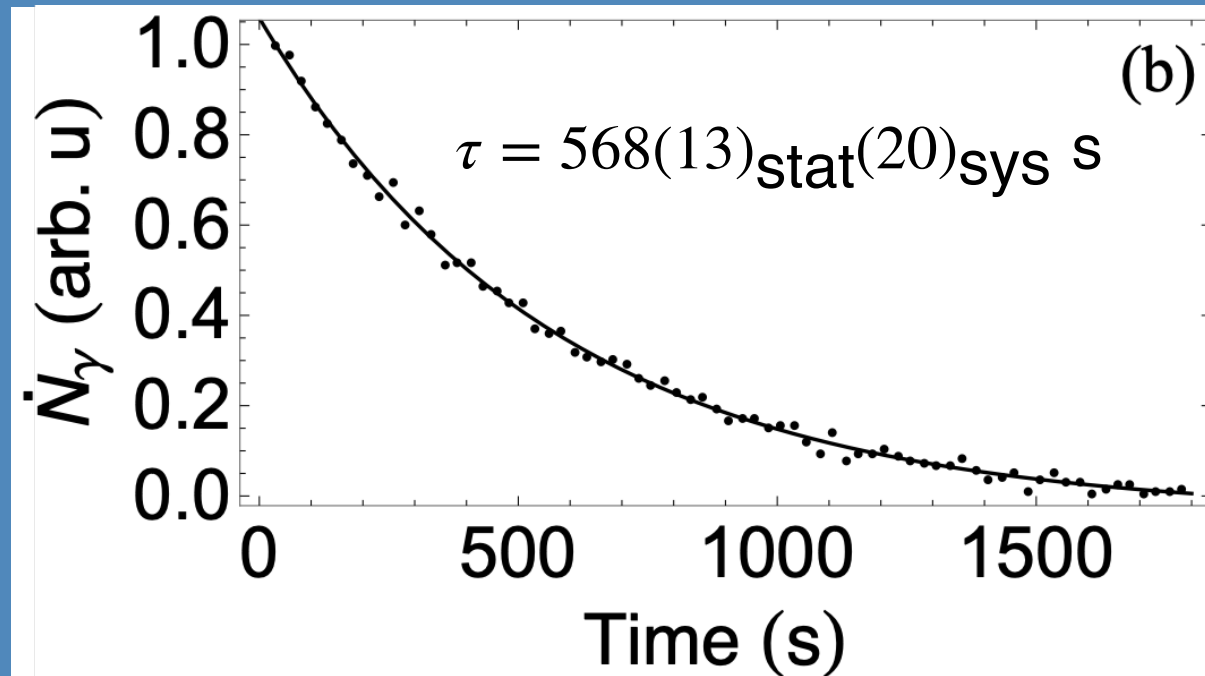
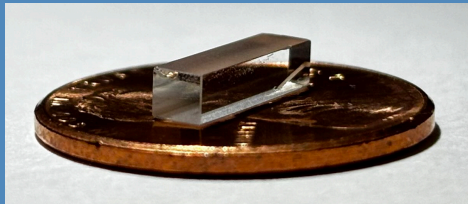
$$\tau_{is} = n^3 \tau$$

$$\approx 1860(43)_{\text{stat}}(66)_{\text{sys}} \text{ s}$$

EXPECTED LIFETIME!

TKALYA ET AL.,

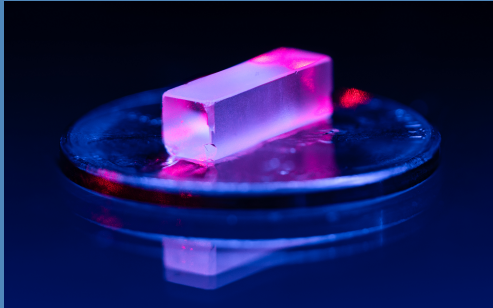
PRC 92 054324 (2015)



2024: THE YEAR OF THORIUM

FREQ. MEASUREMENTS

EXCITATION IN CRYSTALS



CAF₂ PTB/VIENNA: 2020409(7) GHz

LISRALF6 UCLA: 2020407.3(5) GHz

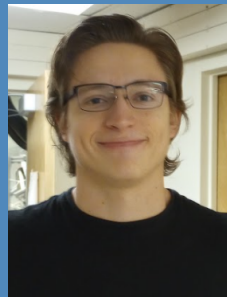
CAF₂ JILA/VIENNA: 2,020,407.29870116 GHz

THF₄ JILA/UCLA: 2,020,407.4(5) GHz

THO₂ UCLA: 2,020,407.5(2) GHz



Richard Elwell



James
Terhune



CHRISTIAN
SCHNEIDER



ANDREI
DEREVIANKO



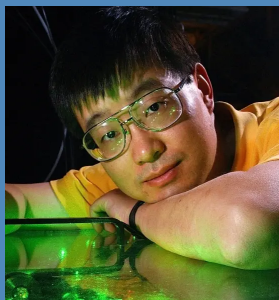
THORSTEN
SCHUMM



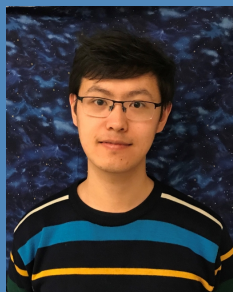
EKKEHARD
PEIK



PIET VAN
DUPPEN



JUN YE



CHUANKUN
ZHANG



KOJI
YOSHIMURA



ATSUSHI
YAMAGUCHI



Peter Thirolf
(LMU Munich)



Lars v.d. Wense
(now: JILA)

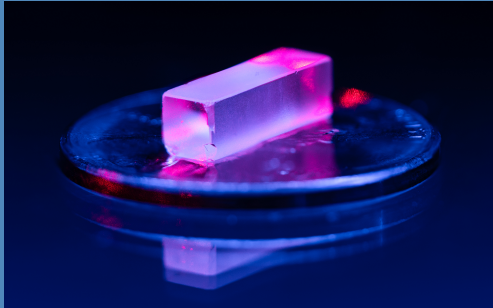


Benedict Seiferle
(LMU Munich)

2024: THE YEAR OF THORIUM

FREQ. MEASUREMENTS

EXCITATION IN CRYSTALS



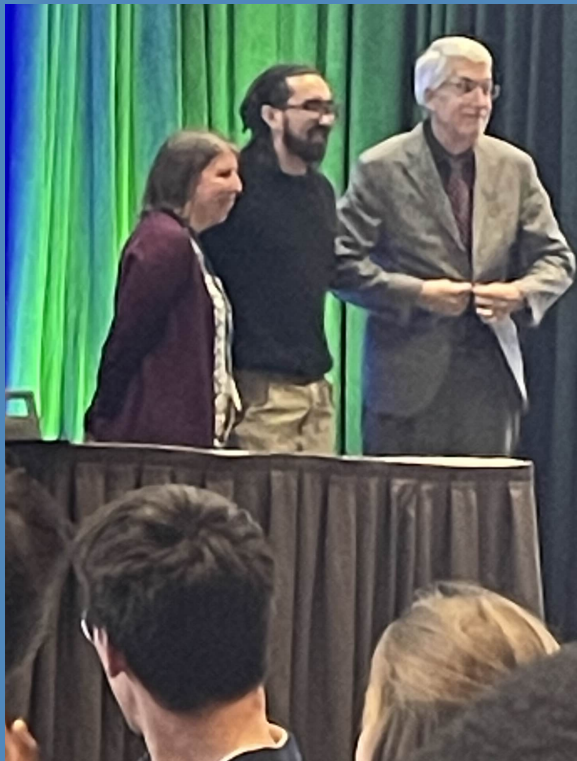
CAF2 PTB/VIENNA: 2020409(7) GHz

LISRALF6 UCLA: 2020407.3(5) GHz

CAF2 JILA/VIENNA: 2,020,407.29870116 GHz

THF4 JILA/UCLA: 2,020,407.5(5) GHz

THO2 UCLA: 2,020,407.5(2) GHz

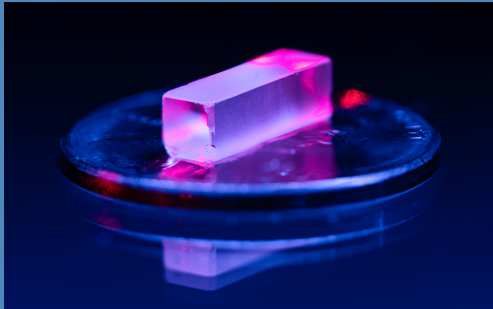


RICKY ELWELL WON THE
2025 DAMOP THESIS PRIZE

THE RUBBER MEETS THE ROAD

FREQ. MEASUREMENTS

EXCITATION IN CRYSTALS



CAF2 PTB/VIENNA: 2020409(7) GHz

LISRALF6 UCLA: 2020407.3(5) GHz

CAF2 JILA/VIENNA: 2,020,407.29870116 GHz

THF4 JILA/UCLA: 2,020,407.5(5) GHz

THO2 UCLA: 2,020,407.5(2) GHz

HOST EFFECTS

SHIFTS AND QUENCHING?

$$\hat{H}_{HFS} = \hat{H}_{E0} + \hat{H}_{M1} + \hat{H}_{E2} + \dots$$

LARGELY VERIFIED BY
EXPERIMENT ALREADY!

QUENCHING & NEXT ORDER
OF ACCURACY?

PRL 104, 200802 (2010)

PHYSICAL REVIEW LETTERS

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Constraining the Evolution of the Fundamental Constants with a Solid-State Optical Frequency Reference Based on the ^{229}Th Nucleus

Wade G. Kellergert,¹ D. DeMille,² R. R. Greco,³ M. P. Hehlen,³ J. R. Torgerson,³ and Eric R. Hudson¹

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TABLE I. Summary of relevant fractional shifts and broadenings for LiCAF. For broadenings, K^{-1} refers to the magnitude of the temperature variation across the sample.

Effect	T -dependent Shift	Broadening
Monopole	$5 \times 10^{-12} \text{ K}^{-1}$	$5 \times 10^{-12} \text{ K}^{-1}$
Magnetic Dipole	0	$\leq 5 \times 10^{-12}$
Electric Quadrupole	$\leq 1 \times 10^{-12} \text{ K}^{-1}$	$\leq 1 \times 10^{-12} \text{ K}^{-1}$
Second Order Doppler	$\leq 1 \times 10^{-15} \text{ K}^{-1}$	$\leq 1 \times 10^{-15} \text{ K}^{-1}$

$$\hat{H}_{HFS} = \hat{H}_{E0} + \hat{H}_{M1} + \hat{H}_{E2} + \dots$$

LARGELY VERIFIED BY EXPERIMENT

QUENCHING & NEXT ORDER OF ACCURACY?

PHYSICAL REVIEW LETTERS 135, 123001 (2025)

Editors' Suggestion

Host-Dependent Frequency Offsets in ^{229}Th Nuclear Clockwork

U. C. Perera,¹ H. W. T. Morgan^{2,3}, Eric R. Hudson^{4,5,6} and Andrei Derevianko¹

PHYSICAL REVIEW LETTERS 134, 253801 (2025)

Editors' Suggestion

Theory of Internal Conversion of the ^{229}Th Nuclear Isomer in Solid-State Hosts

H. W. T. Morgan^{1,2}, H. B. Tran Tan^{3,4}, R. Elwell,⁵ A. N. Alexandrova,¹ Eric R. Hudson^{5,6,7} and Andrei Derevianko^{3,*}

PHYSICAL REVIEW RESEARCH 7, L022062 (2025)

Letter



ANDREI
DEREVIANKO



HARRY
MORGAN

of the ^{229}Th isomer in a solid-state host

Tan,^{2,3} U. C. Perera,² H. W. T. Morgan,^{4,5} A. N. Alexandrova,¹ and Eric R. Hudson^{1,6,7}

Th:CaF_2

Science

Laser Mössbauer spectroscopy of ^{229}Th in CaF_2

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Authors Info & Affiliations

+16 authors

K. Hudson

TAKAHIRO HIRAKI ID, TAKAHIKO MASUDA ID, SAYURI TAKATORI ID, FABIAN SCHADEN ID, MICHAEL BARTOKOS ID, KJELD BECKS ID, YUTA FUKUNAGA, MING GUAN ID, I.-I. AND KOJI YOSHIMURA ID

THE NEXT STEPS

MATERIAL OPTIMIZATION:

- TH:CAF2 LIMIT = UNCONTROLLED STRAIN
- HOST QUENCHING
- DOPING SEGREGATION
- VACUUM AND VUV LASERS ADD COMPLEXITY & SWAP

THE NEXT STEPS

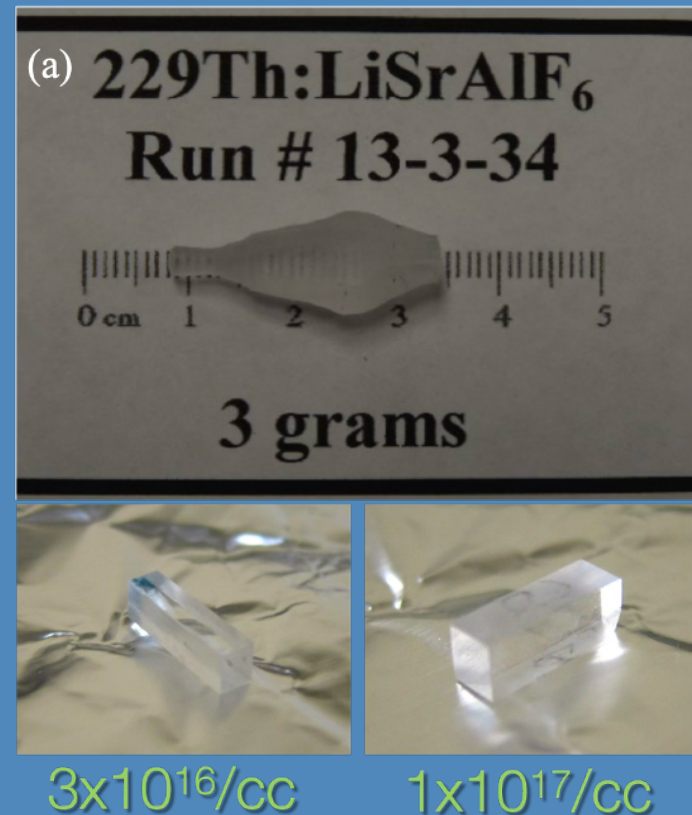
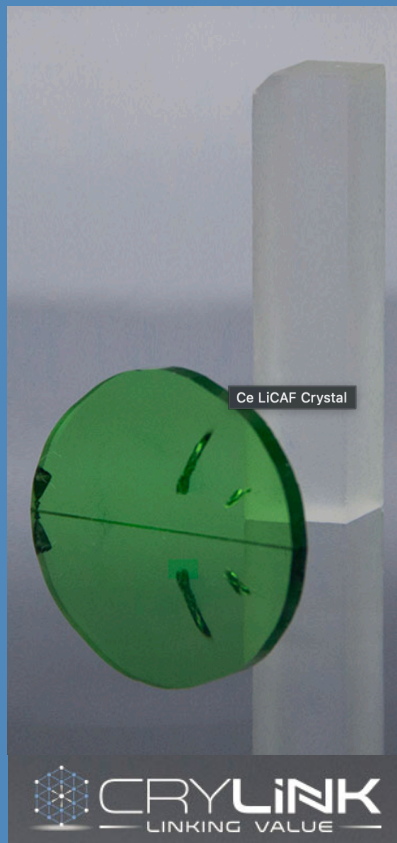
MATERIAL OPTIMIZATION:

- TH:CAF2 LIMIT = UNCONTROLLED STRAIN
- HOST QUENCHING
- DOPING SEGREGATION
- VACUUM AND VUV LASERS ADD COMPLEXITY & SWAP

CR:LISAF AND CE:LISAF



TH:LISAF



THE NEXT STEPS

MATERIAL OPTIMIZATION:

- TH:CAF₂ LIMIT = UNCONTROLLED STRAIN
- HOST QUENCHING
- DOPING SEGREGATION
- VACUUM AND VUV LASERS ADD COMPLEXITY & SWAP

THE NEXT STEPS

MATERIAL OPTIMIZATION:

- TH:CAF₂ LIMIT = UNCONTROLLED STRAIN
- HOST QUENCHING
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- VACUUM AND VUV LASERS ADD COMPLEXITY & SWAP

STOICHIOMETRIC MATERIAL



²²⁹ThF₄ thin films for solid-state nuclear clocks

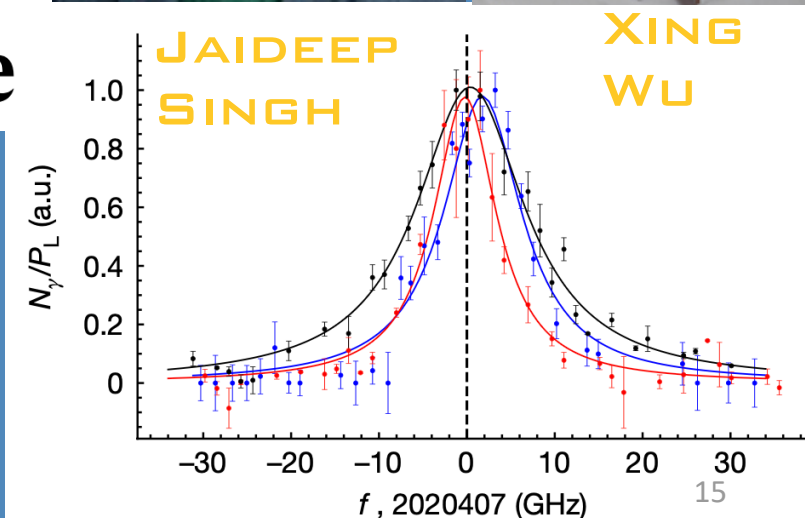
[Chuangkun Zhang](#), [Lars von der Wense](#), [Jack F. Doyle](#), [Jacob S. Higgins](#), [Tian Ooi](#), [Hans U. Friebe](#), [Jun Ye](#) , [R. Elwell](#), [J. E. S. Terhune](#), [H. W. T. Morgan](#), [A. N. Alexandrova](#), [H. B. Tran Tan](#), [Andrei Derevianko](#) & [Eric R. Hudson](#) 

[Nature](#) **636**, 603–608 (2024) | [Cite this article](#)



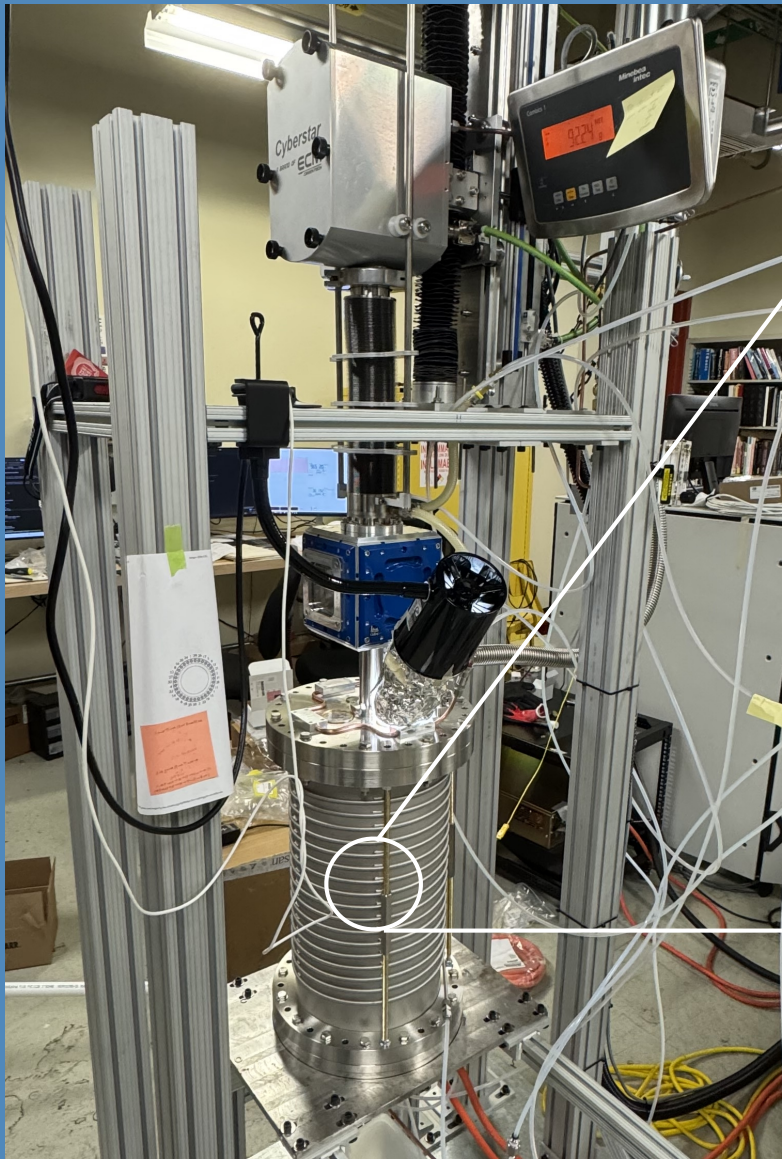
nature

- THIN FILMS: NUCLEAR INTEGRATED PHOTONICS
- BULK STOIC. MAT.: OPTIMUM PERFORMANCE



THE NEXT STEPS

THESE STOICHIOMETRIC MATERIALS REQUIRE A MORE FLEXIBLE FURNACE



THE NEXT STEPS

MATERIAL OPTIMIZATION:

- TH:CAF2 LIMIT = UNCONTROLLED STRAIN
- HOST QUENCHING
- DOPING SEGREGATION
- VACUUM AND VUV LASERS ADD COMPLEXITY & SWAP

THE NEXT STEPS

MATERIAL OPTIMIZATION:

- VACUUM AND VUV LASERS ADD COMPLEXITY & SWAP

Applied Physics Letters

ARTICLE

pubs.aip.org/aip/apl

Proposal and theoretical investigation of ^{229}Th -doped nonlinear optical crystals for compact solid-state clocks ^{EP}

H. W. T. Morgan,^{1,2}  R. Elwell,³  J. E. S. Terhune,³  H. B. Tran Tan,^{4,5}  U. C. Perera,⁴  A. Derevianko,⁴ 
A. N. Alexandrova,¹  and E. R. Hudson^{3,6,7,a)} 

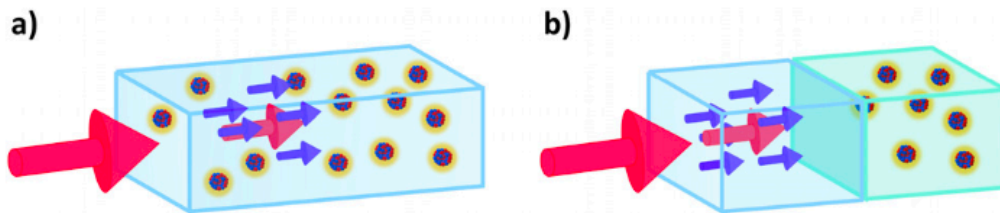
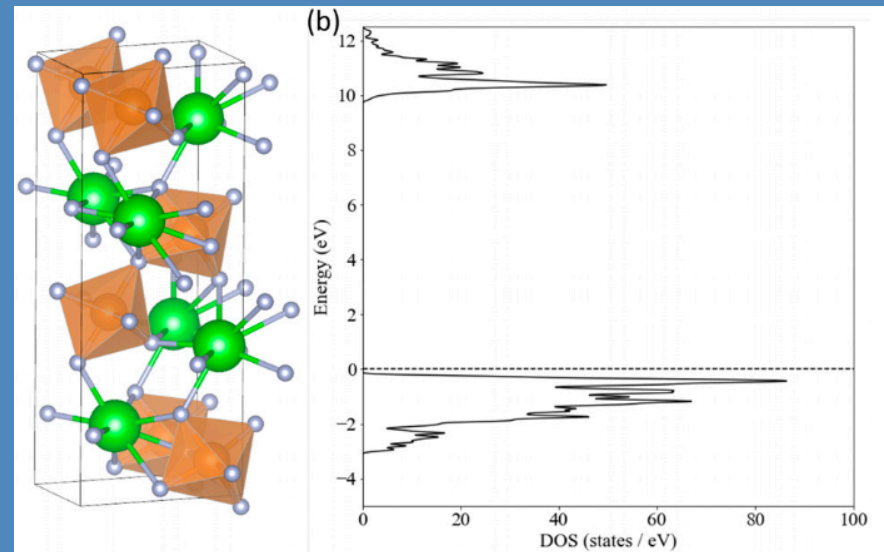


FIG. 3. A solid-state ^{229}Th nuclear clock can be constructed without requiring vacuum operation by (a) doping ^{229}Th directly into a nonlinear optical medium or (b) joining a ^{229}Th -doped material directly to a nonlinear optical medium. This would allow, for example, the use of $\sim 296.8\text{ nm}$ light to excite the nuclear transition at $\sim 148.4\text{ nm}$.

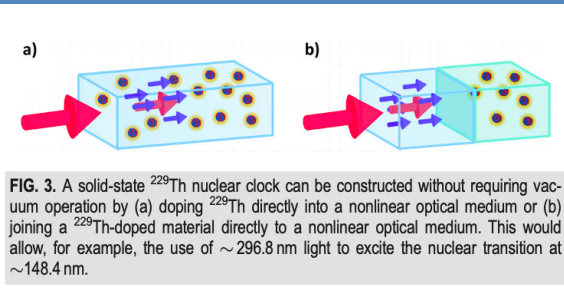


“VERIFIED”

297 NM AND DOES NOT REQUIRE VACUUM

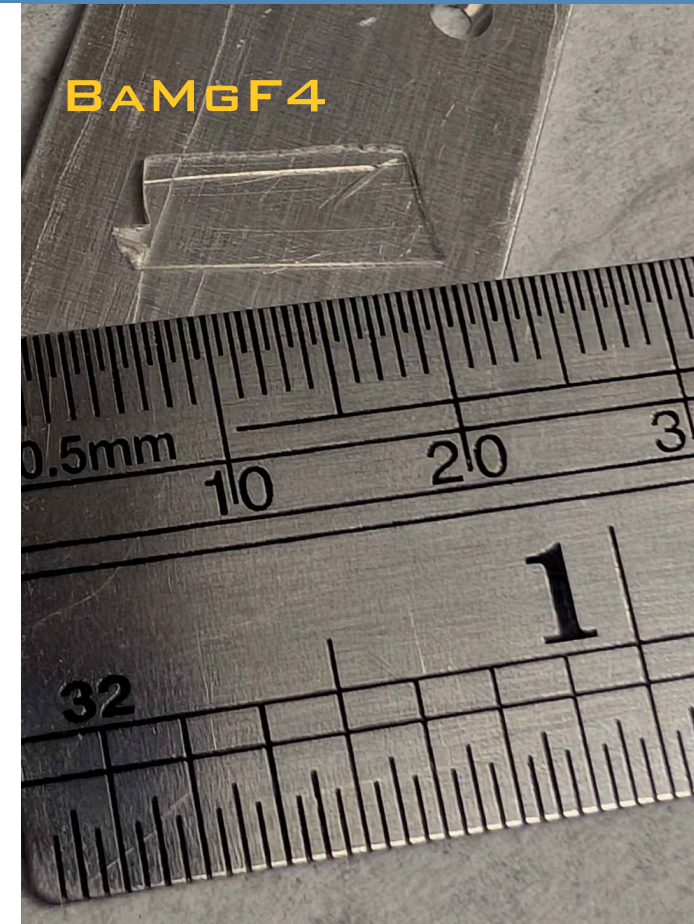
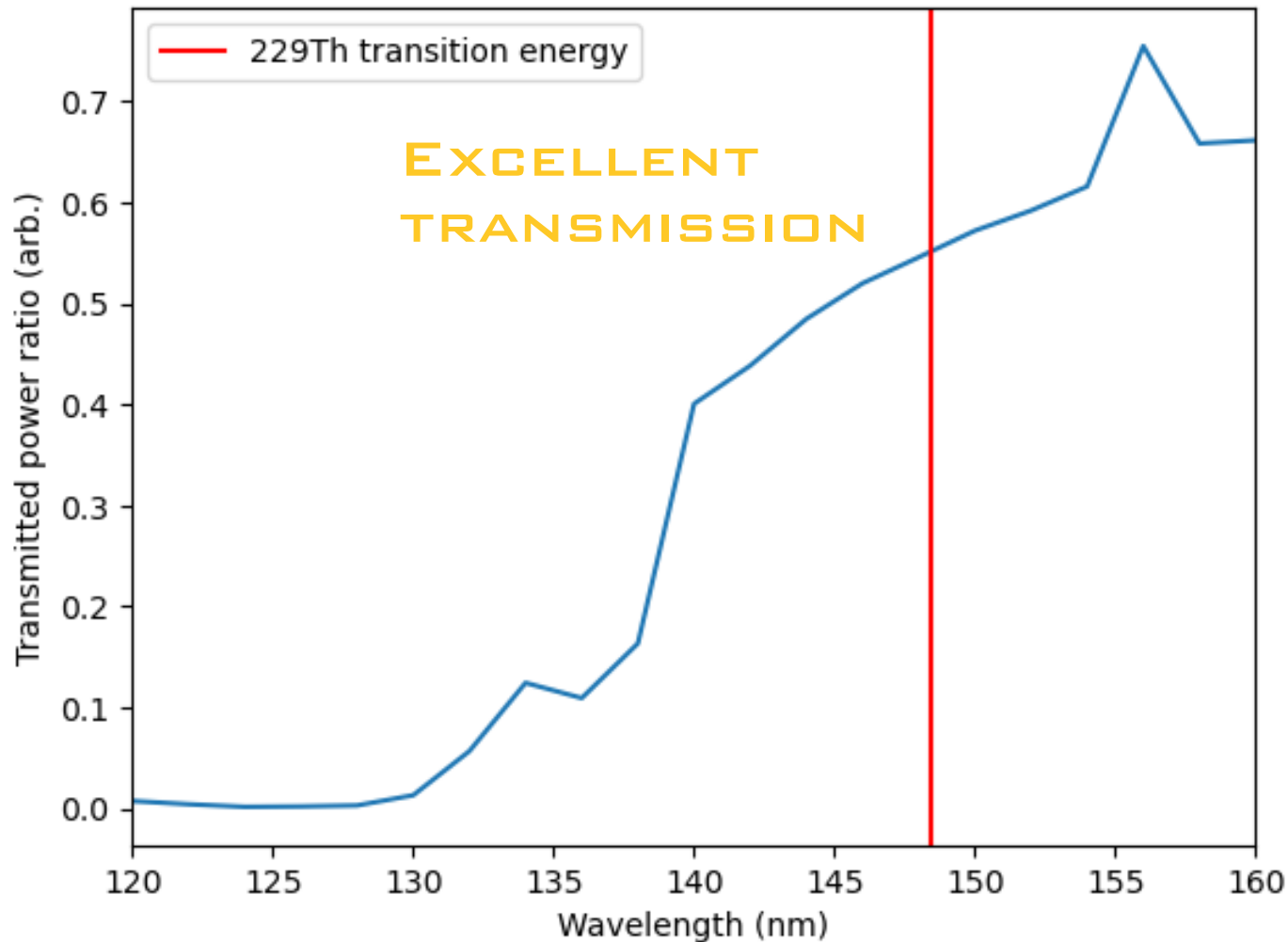
TH:BAMGF4, TH:BAZNF4, TH:SRB4O7, TH:BPO4, TH:SRMGF4

THE NEXT STEPS

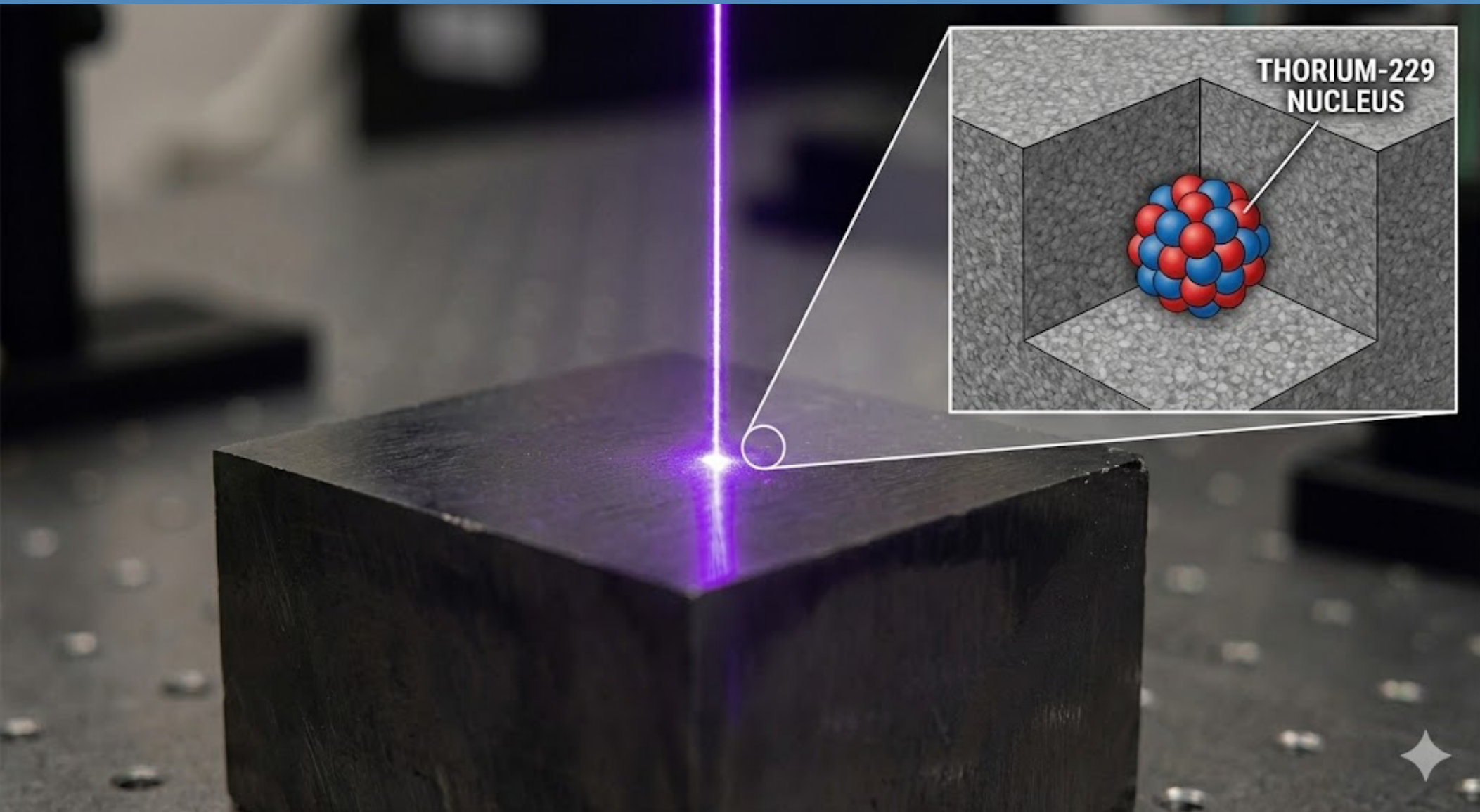


Th:BaMgF₄,
Th:BaZnF₄,
Th:SRB4O₇, ...

BMF transmission measurement - 0.55 mm thick



DISRUPTIVE NEW PATH: NUCLEAR SPECTROSCOPY IN AN OPAQUE MATERIAL?

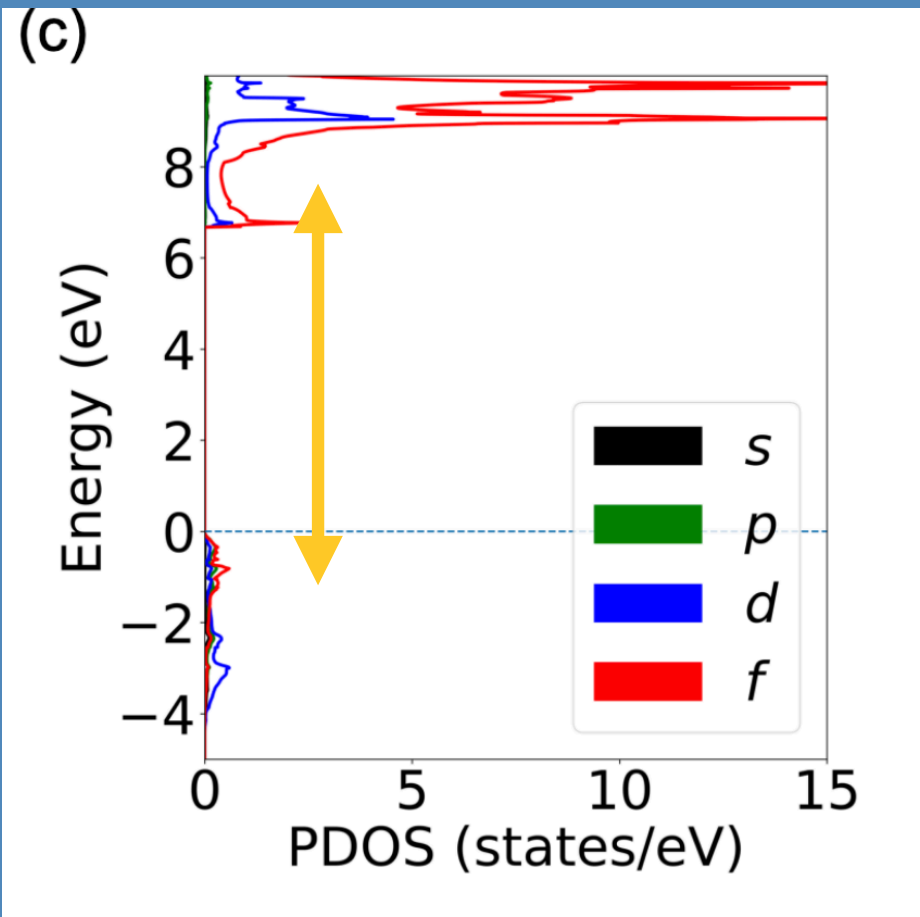


SMALL BAND GAP MATERIALS?

EXCITATION IN NON-TRANSPARENT MATERIAL



SS ELECTROPLATED
WITH TiO_2

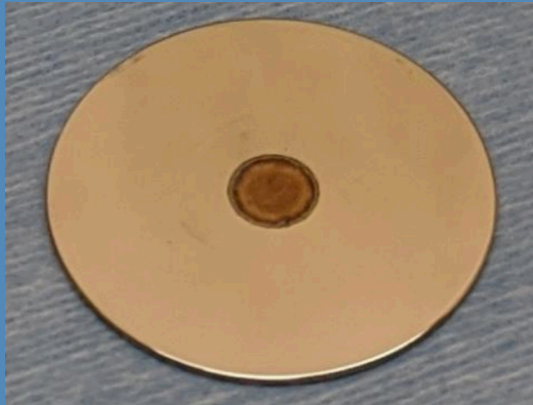


CHALLENGES:

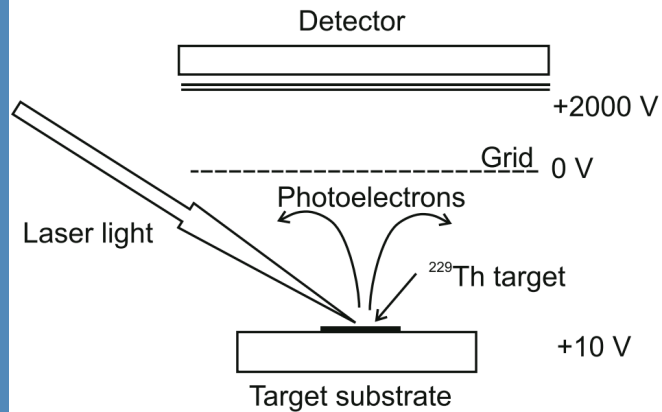
1. LASER ABSORBED
2. INTERNAL CONVERSION

SMALL BAND GAP MATERIALS?

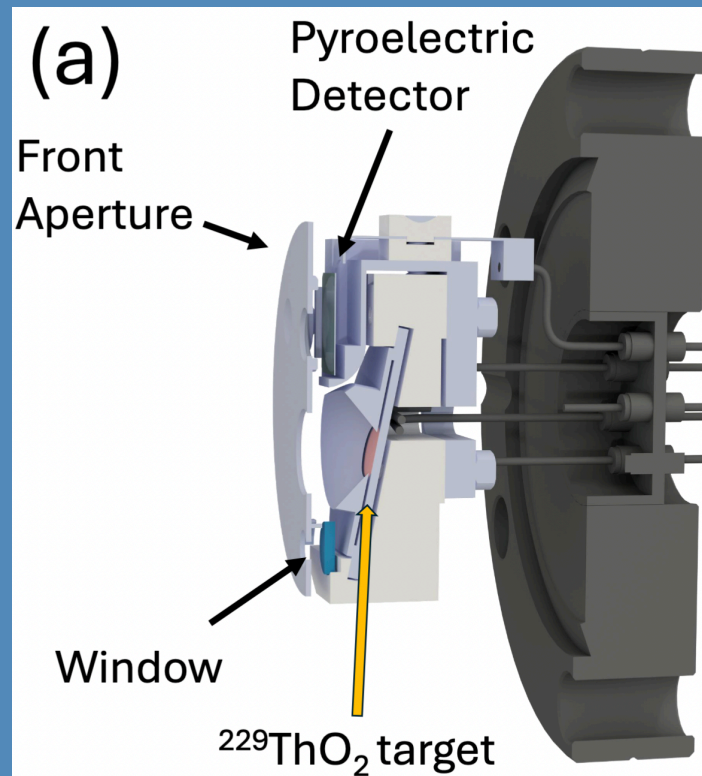
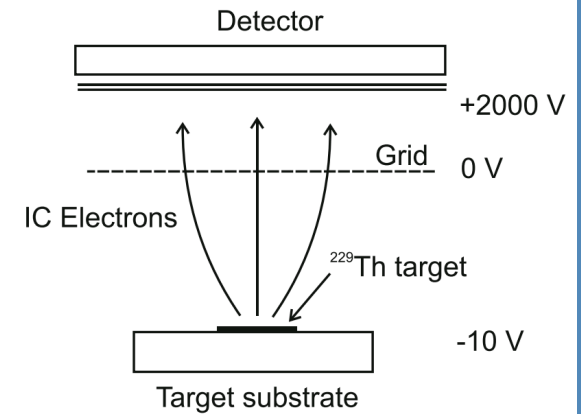
THORIUM METAL TARGET



Step 1: Nuclear laser excitation



Step 2: IC electron detection



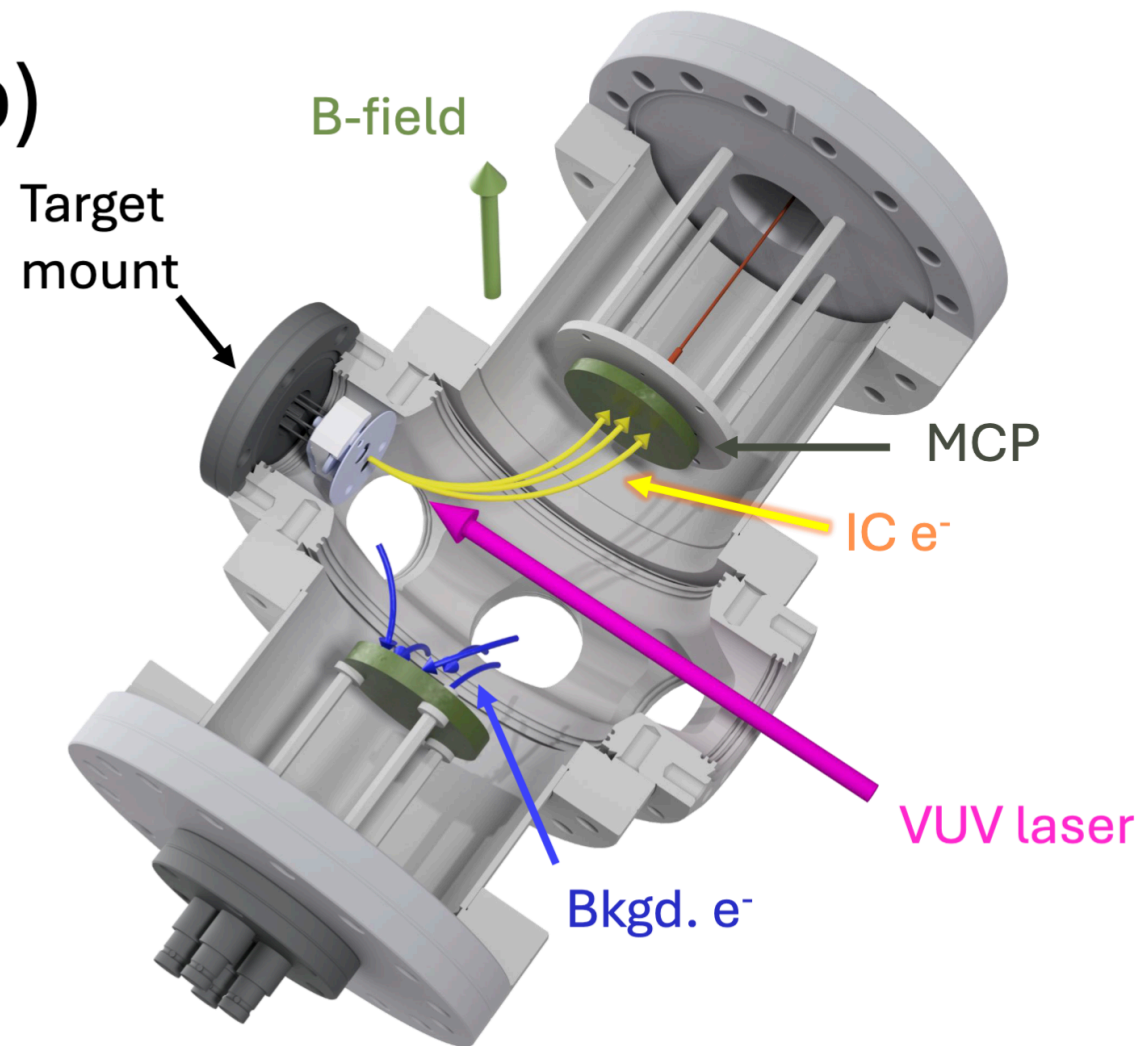
LOOK MOM, NO CRYSTALS!

EXCITATION IN NON-TRANSPARENT MATERIAL



SS ELECTROPLATED
WITH ThO_2

(b)



CHALLENGES:

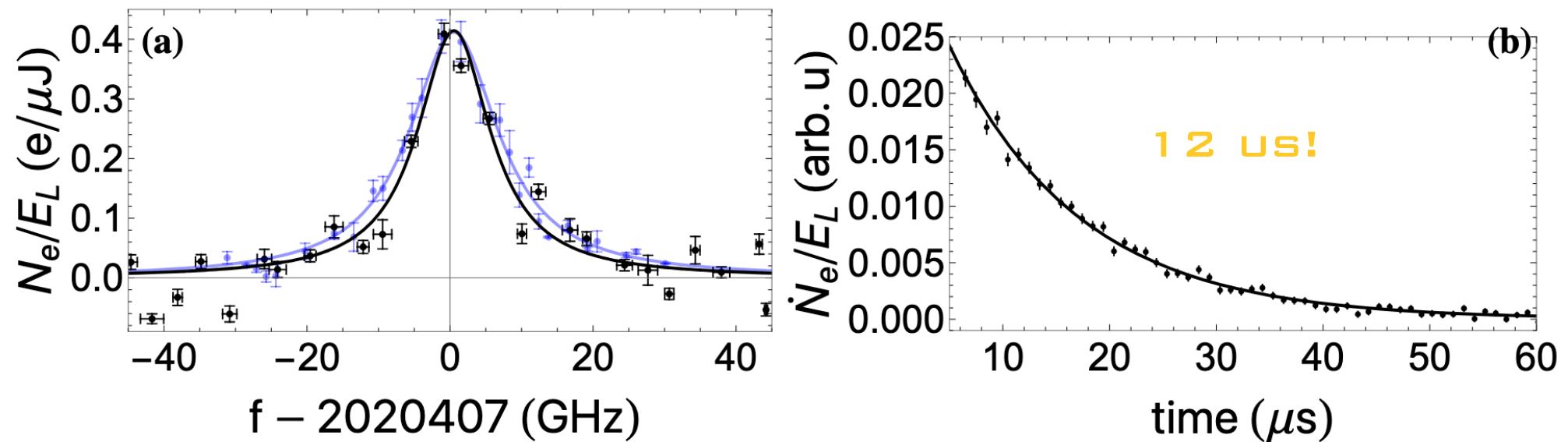
1. LASER ABSORBED
2. INTERNAL CONVERSION

LOOK MOM, NO CRYSTALS!

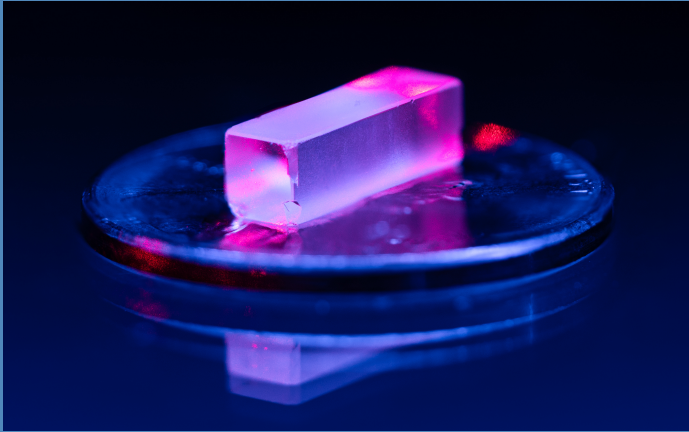
Laser-based conversion electron Mössbauer spectroscopy of $^{229}\text{ThO}_2$

[Ricky Elwell](#), [James E. S. Terhune](#), [Christian Schneider](#), [Harry W. T. Morgan](#), [Hoang Bao Tran Tan](#),
[Udeshika C. Perera](#), [Daniel A. Rehn](#), [Marisa C. Alfonso](#), [Lars von der Wense](#), [Benedict Seiferle](#), [Kevin Scharl](#),
[Peter G. Thirolf](#), [Andrei Derevianko](#) & [Eric R. Hudson](#) ✉

[Nature](#) **648**, 300–305 (2025) | [Cite this article](#)



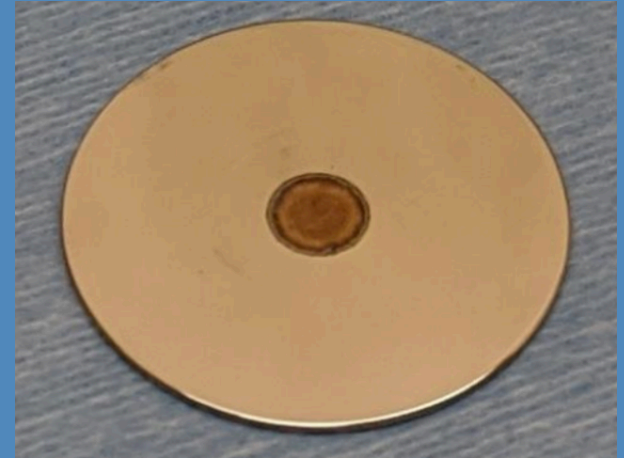
AN IC CLOCK?



TH:CAF₂ LINEWIDTHS
20-100 KHZ

IN FLUORIDE CRYSTALS I
EXPECT ~5 KHZ IS
POSSIBLE (M1 LIMIT)

Vs



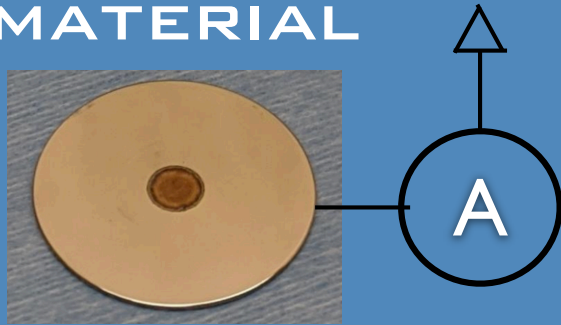
THO₂ NUCLEAR SPIN
FREE (NO M1 LIMIT)

LIFETIME BROADENING

THO₂: NUCLEAR SPIN FREE
 $\tau_{IC} \gtrsim 30 \mu\text{s}$: SIMILAR LINEWIDTH

LOOK MOM, NO CRYSTALS!

EXCITATION IN NON-TRANSPARENT MATERIAL



SS ELECTROPLATED
WITH THO2

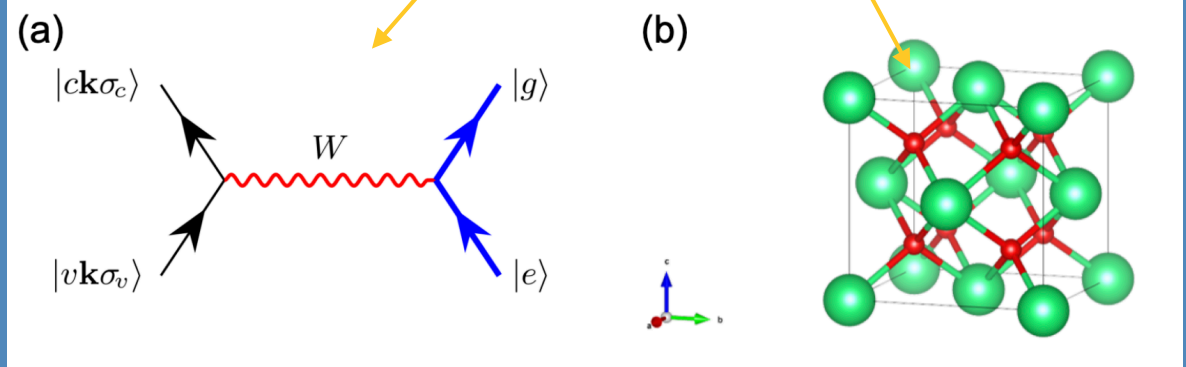
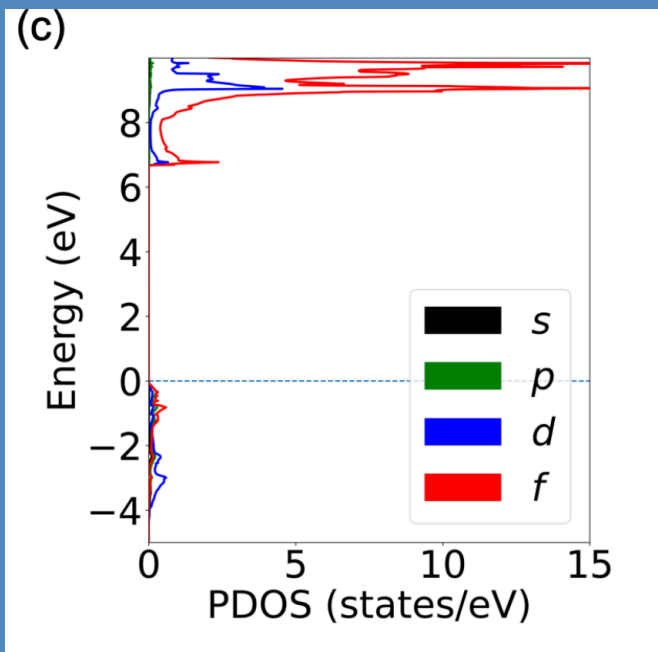
THO2 UCLA: 2020407.3(5) GHz

BIG ADVANTAGE FOR A CLOCK?

CURRENT READOUT!

CHEMICAL TUNING OF LIFETIME

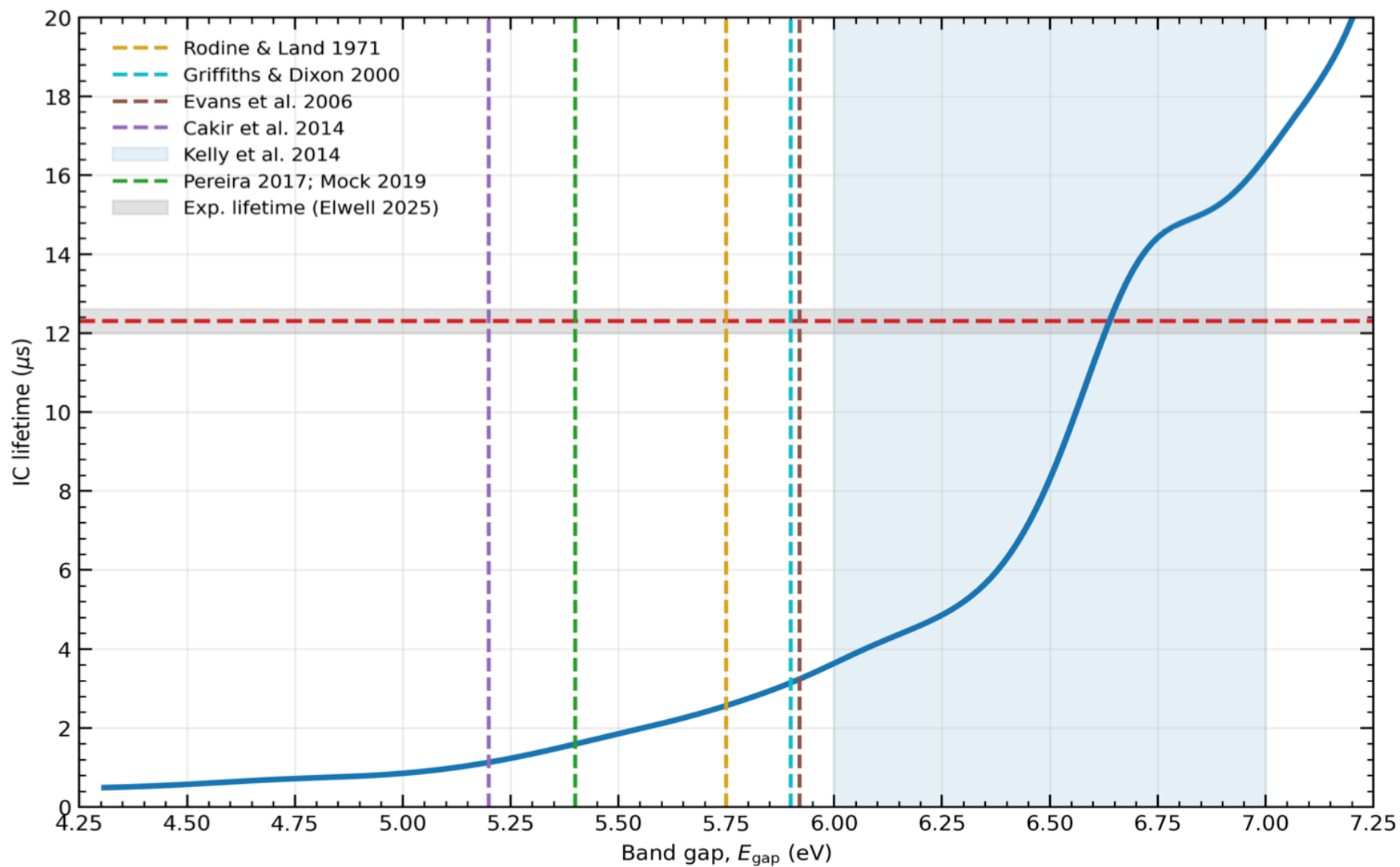
$$1/\tau_{IC} = \frac{2\pi}{\hbar} |W|^2 \rho(E)$$



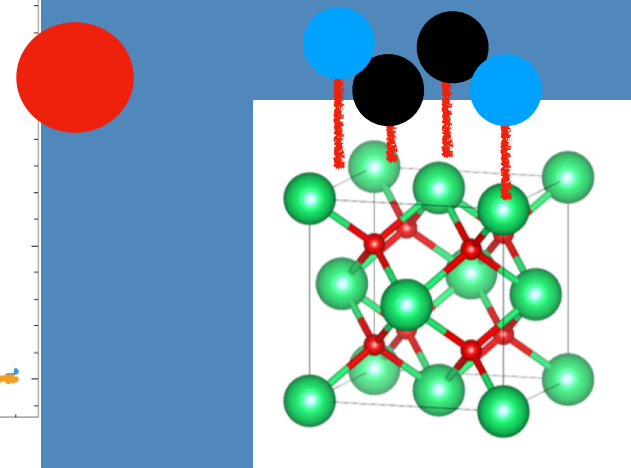
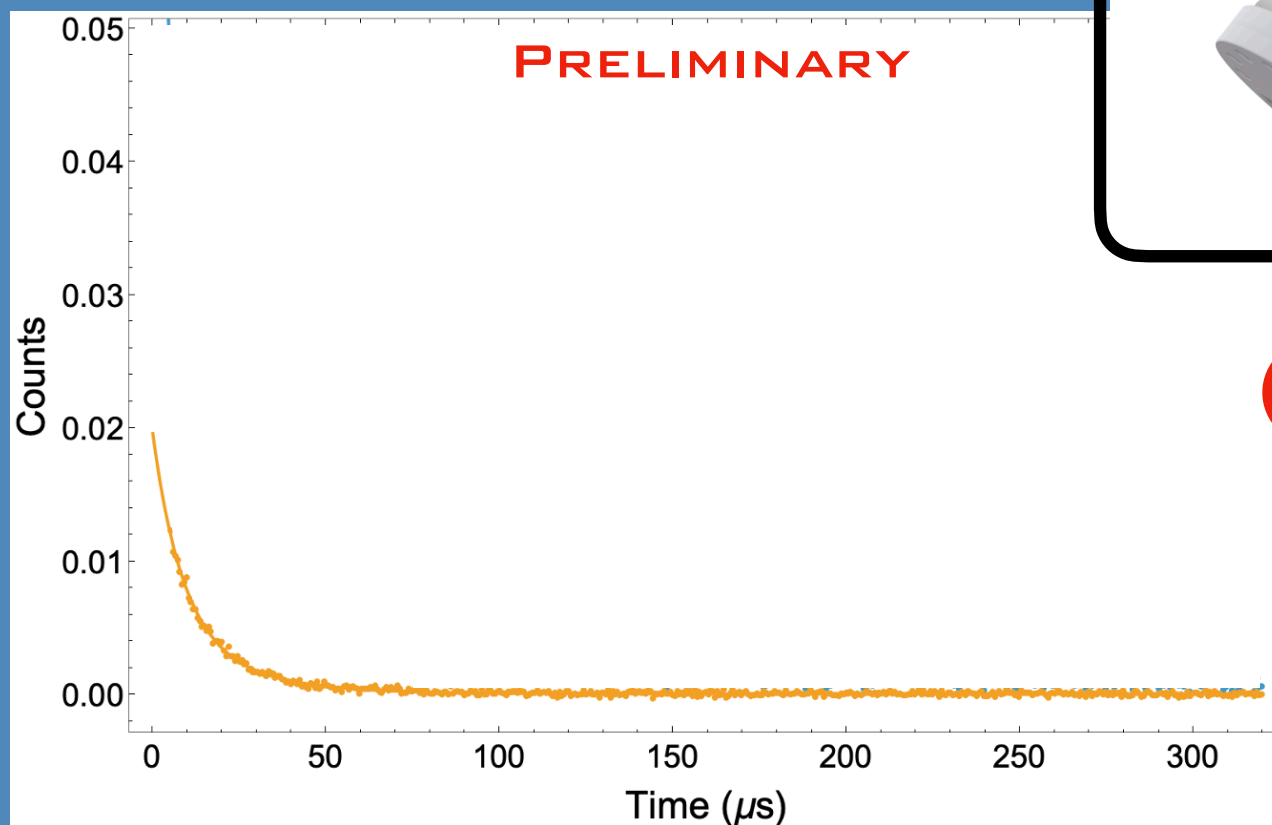
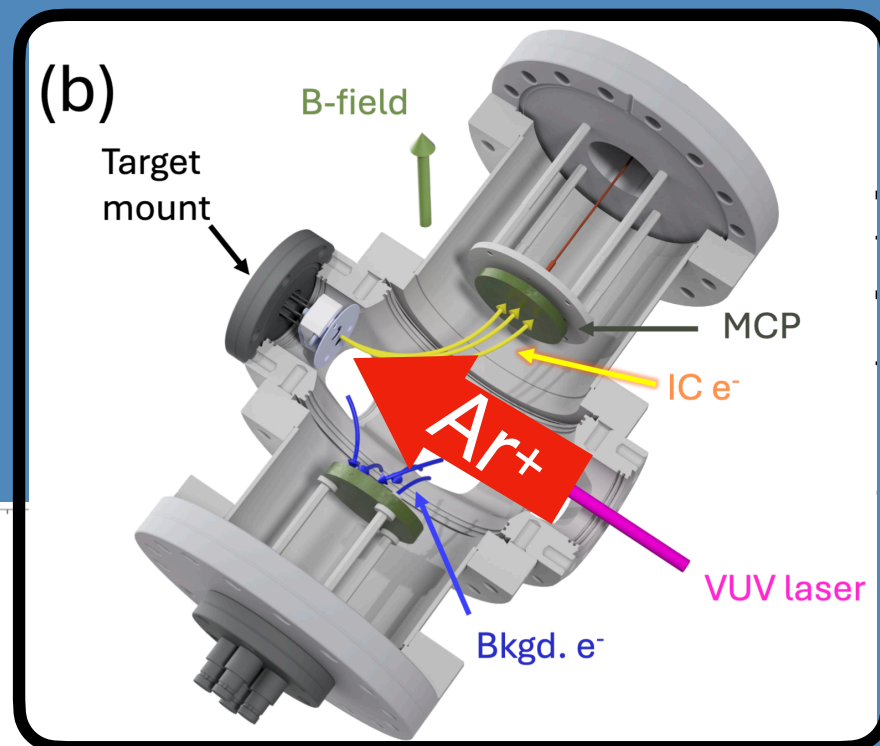
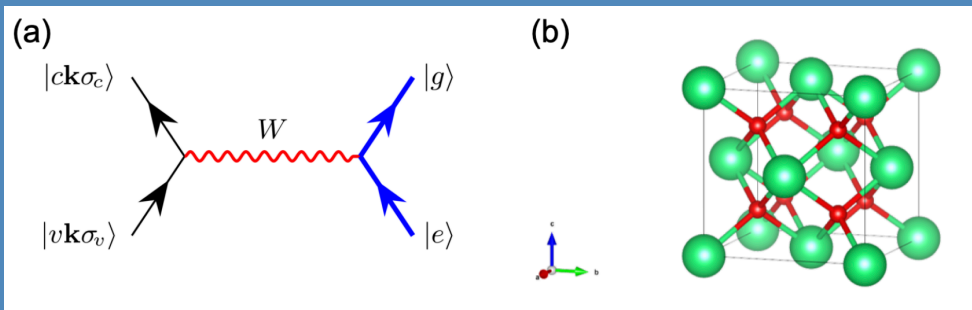
Ab initio calculations of ^{229}Th band-to-band internal conversion rate in $^{229}\text{ThO}_2$

Udeshika C. Perera,¹ H. B. Tran Tan,² H. W. T. Morgan,³ Eric Hudson,^{4, 5, 6} Daniel A. Rehn,² and Andrei Derevianko¹

arXiv:2607.08941 (2026)



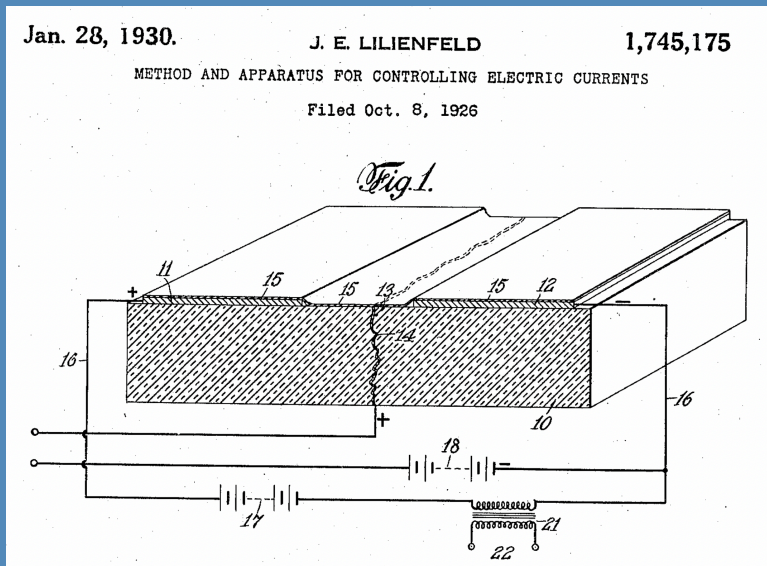
CHEMICAL TUNING OF LIFETIME?



ISOTOPE NEEDS

SCARCITY STIFLES INNOVATION

LESSONS FROM HISTORY

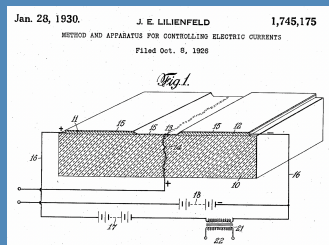


SEMICONDUCTOR MATERIAL:
FIELD-EFFECT TRANSISTOR
PATENT 1930

ISOTOPE NEEDS

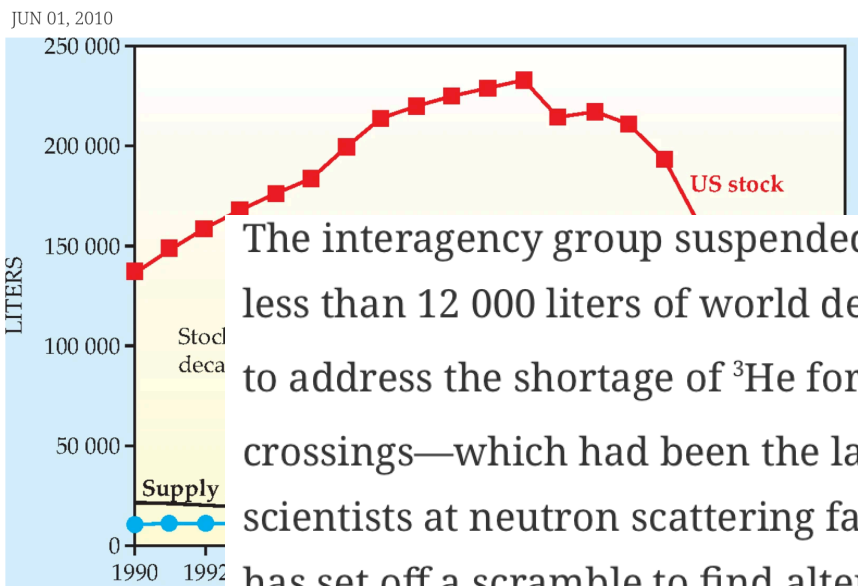
SCARCITY STIFLES INNOVATION

LESSONS FROM HISTORY



SEMICONDUCTOR MATERIAL: FIELD-EFFECT TRANSISTOR PATENT 1930

DOE begins rationing helium-3



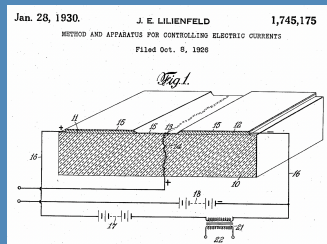
The interagency group suspended all distributions in 2009 and curtailed releases this year to less than 12 000 liters of world demand, estimated at 70 000 to 76 000 liters, while it seeks ways to address the shortage of ^3He for use in radiation monitors at ports, airports, and border crossings—which had been the largest ^3He consumer by far. A warning by DOE officials that scientists at neutron scattering facilities abroad need to look elsewhere for their requirements has set off a scramble to find alternative neutron-detection technologies.

^3He SHORTAGE: NEUTRON DETECTION, LOW T PHYSICS

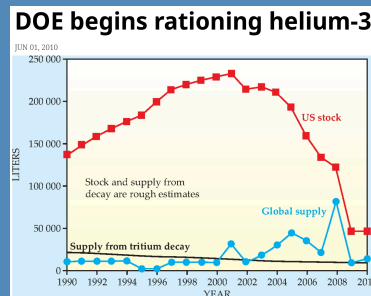
ISOTOPE NEEDS

SCARCITY STIFLES INNOVATION

LESSONS FROM HISTORY



SEMICONDUCTOR MATERIAL:
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PATENT 1930

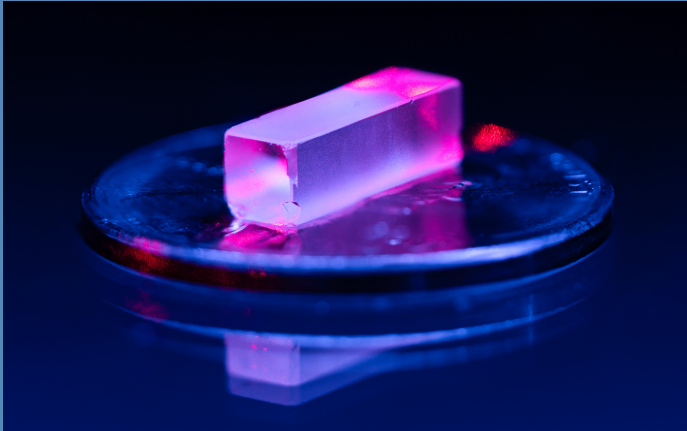


^3He SHORTAGE:
NEUTRON DETECTION, LOW T
PHYSICS

^{28}Si SHORTAGE:
QUANTUM COMPUTING

ISOTOPE NEEDS

SCARCITY STIFLES INNOVATION



GROWTH RUN 0(1 MG)

~20 RUNS/YR

20 MG/YR (MY GROUP)

PURITY NEEDS

SPECIFIC ACTIVITY:

TH-229: 0.2 CI/G

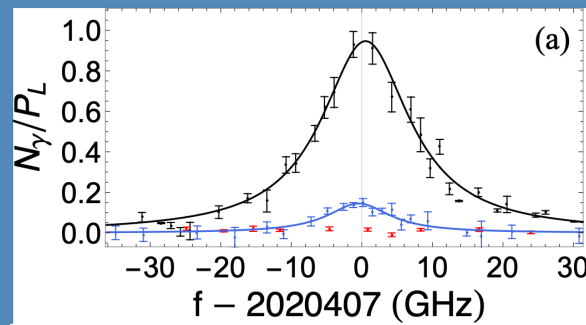
TH-228: 820 CI/G

99.98% PURE FOR SIMILAR ACTIVITY

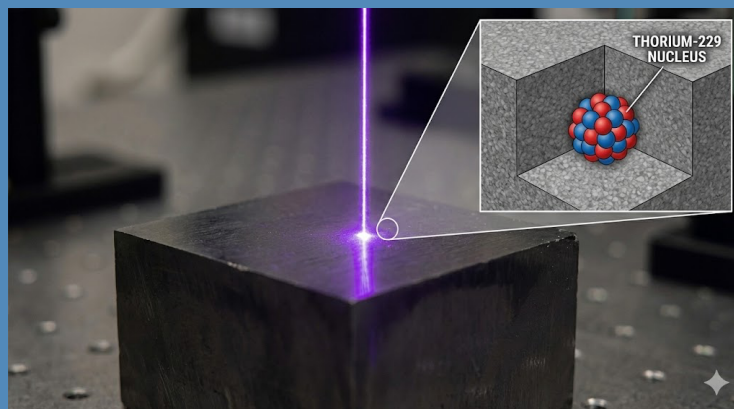
ALL THORIUM CAN BE RECAPTURED IN
“FAILED” SAMPLES

SUMMARY

SOLID-STATE CLOCK AND THE SEARCH



NEW PATHS!



RMP ARTICLE:

COLLOQUIA: NUCLEAR CLOCKS
ARXIV:2606.11048