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Observation of the radiative decay of the low energy thorium-229 isomer:
En route towards a nuclear clock

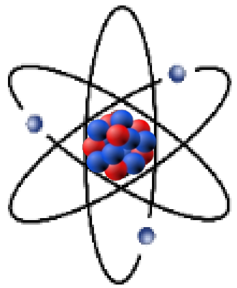
Sandro Kraemer

Outline:
- From atomic to nuclear clocks
- Vacuum-ultraviolet spectroscopy at ISOLDE
- Conclusion and Outlook

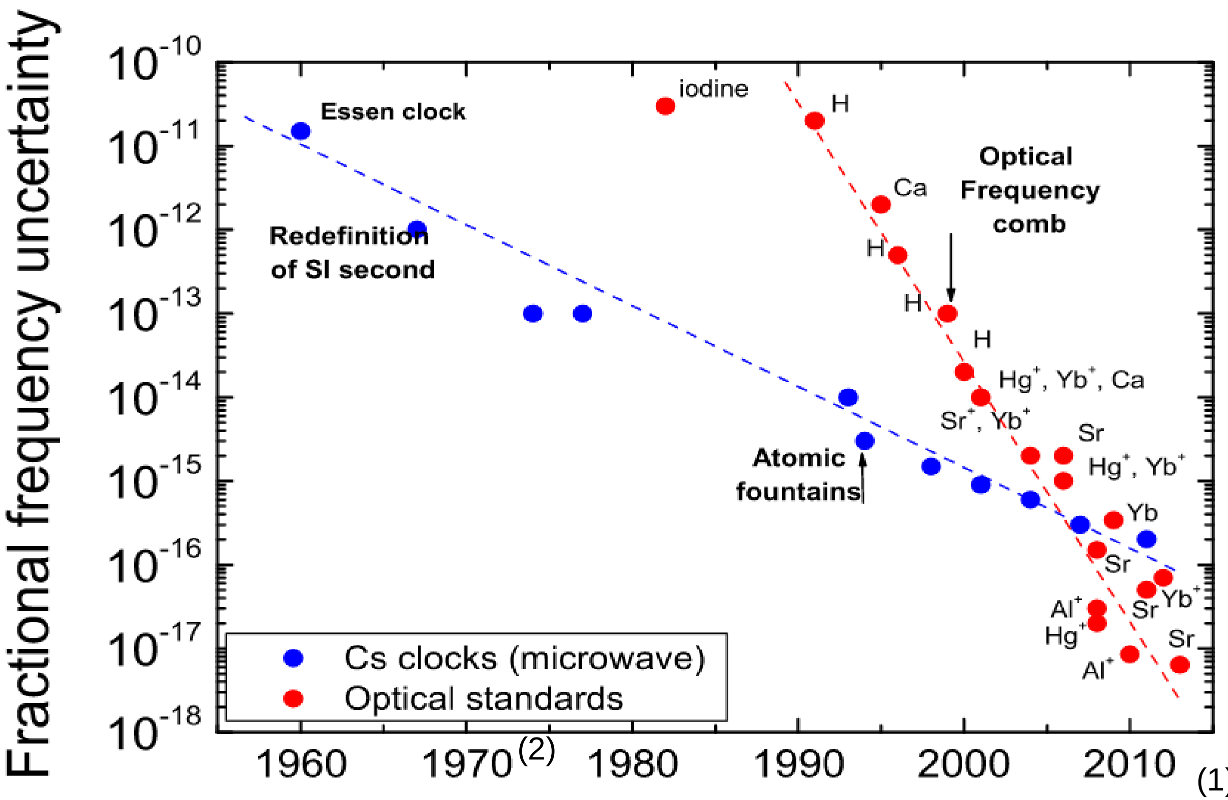
EuNPC
Caen, 26.09.2025

From atomic to nuclear clocks

From atomic to nuclear clocks



(1)



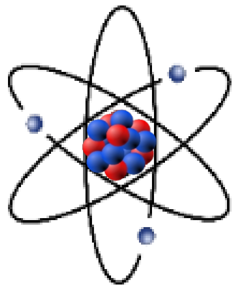
(2)

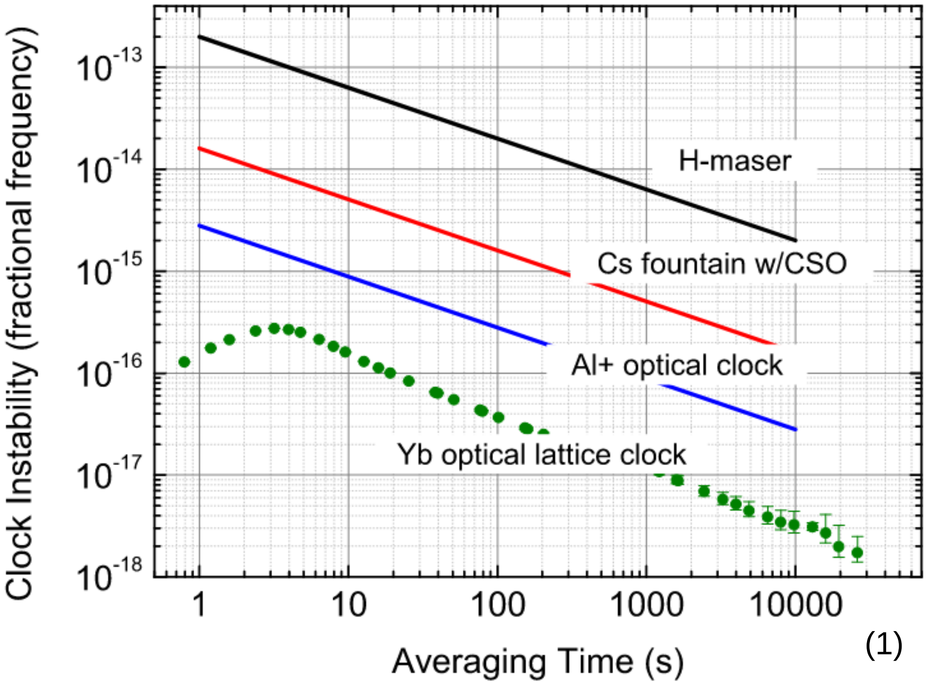
(1)

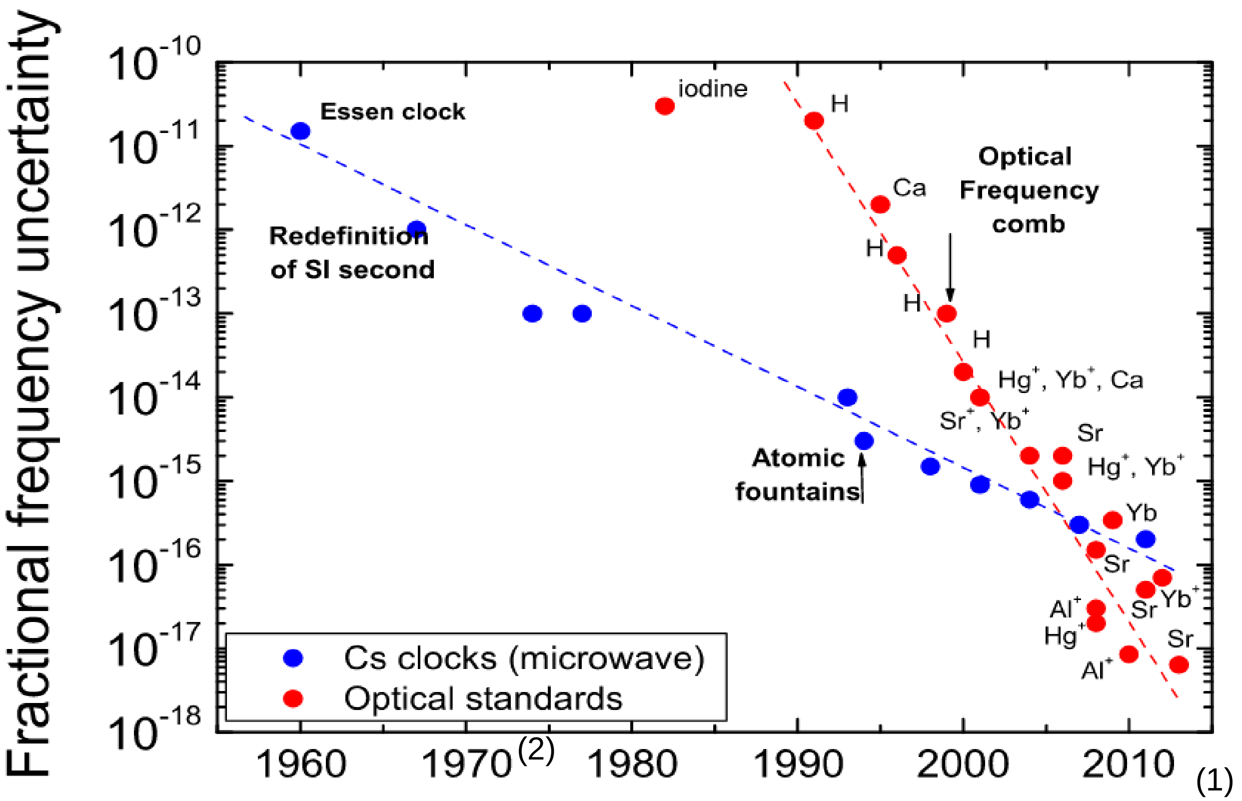
- Accuracy limited by uncertainty on environmental influences

From atomic to nuclear clocks

10^{-10} m



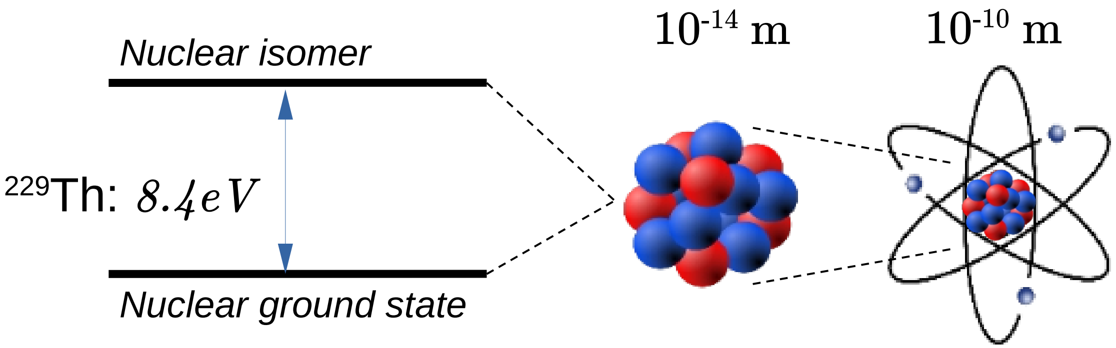


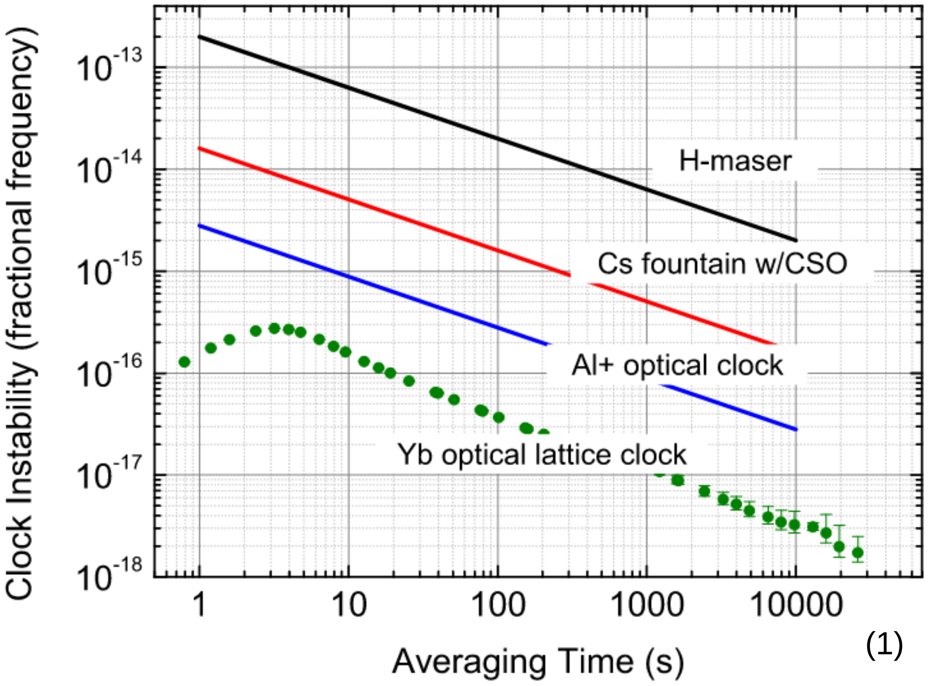


- Accuracy limited by uncertainty on environmental influences
- Stability limited by amount of interrogable two-level systems

(1): Poli et al., 2013, *Rivista del Nuovo Cimento* **36** (12)
(2): Peik and Tamm. 2003, *Europhys. Lett.* **61** 2

From atomic to nuclear clocks





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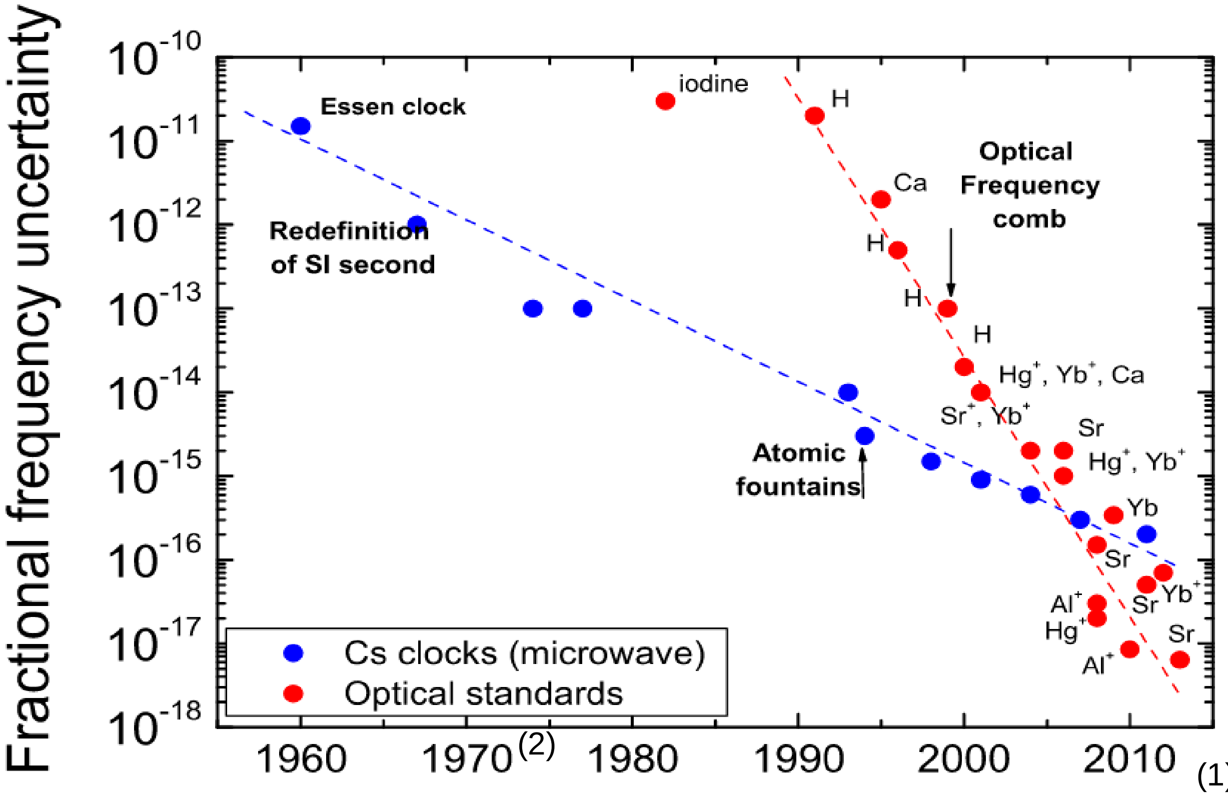

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- Accuracy limited by uncertainty on environmental influences
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→ From electronic to nuclear transition[2]

(1): Poli et al., 2013, *Rivista del Nuovo Cimento* **36** (12)
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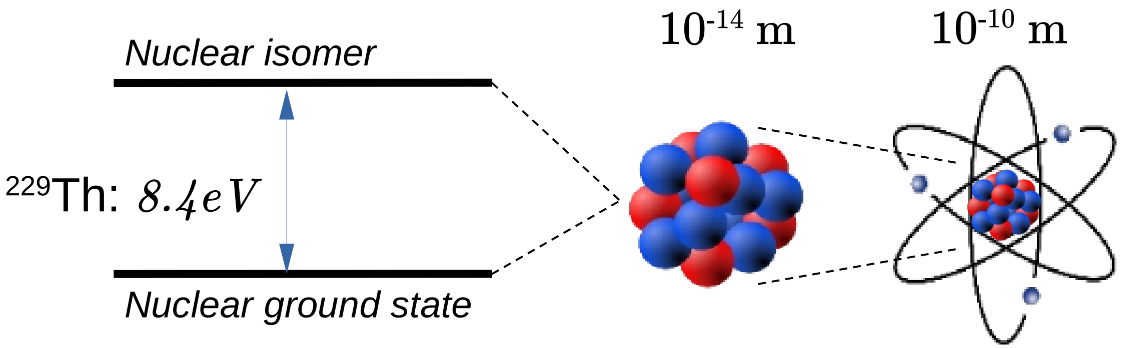
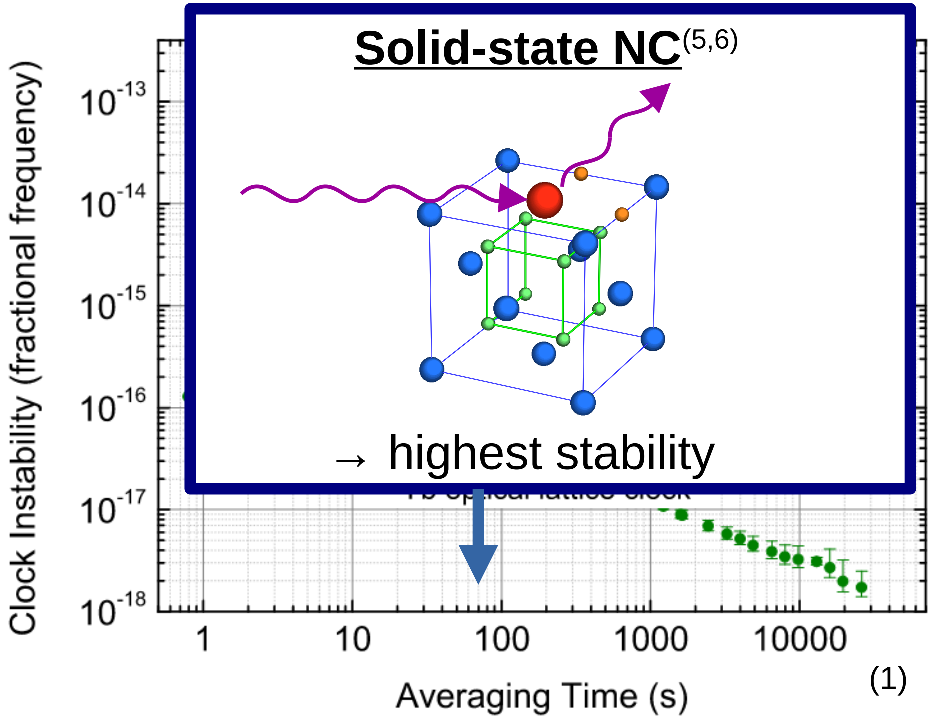
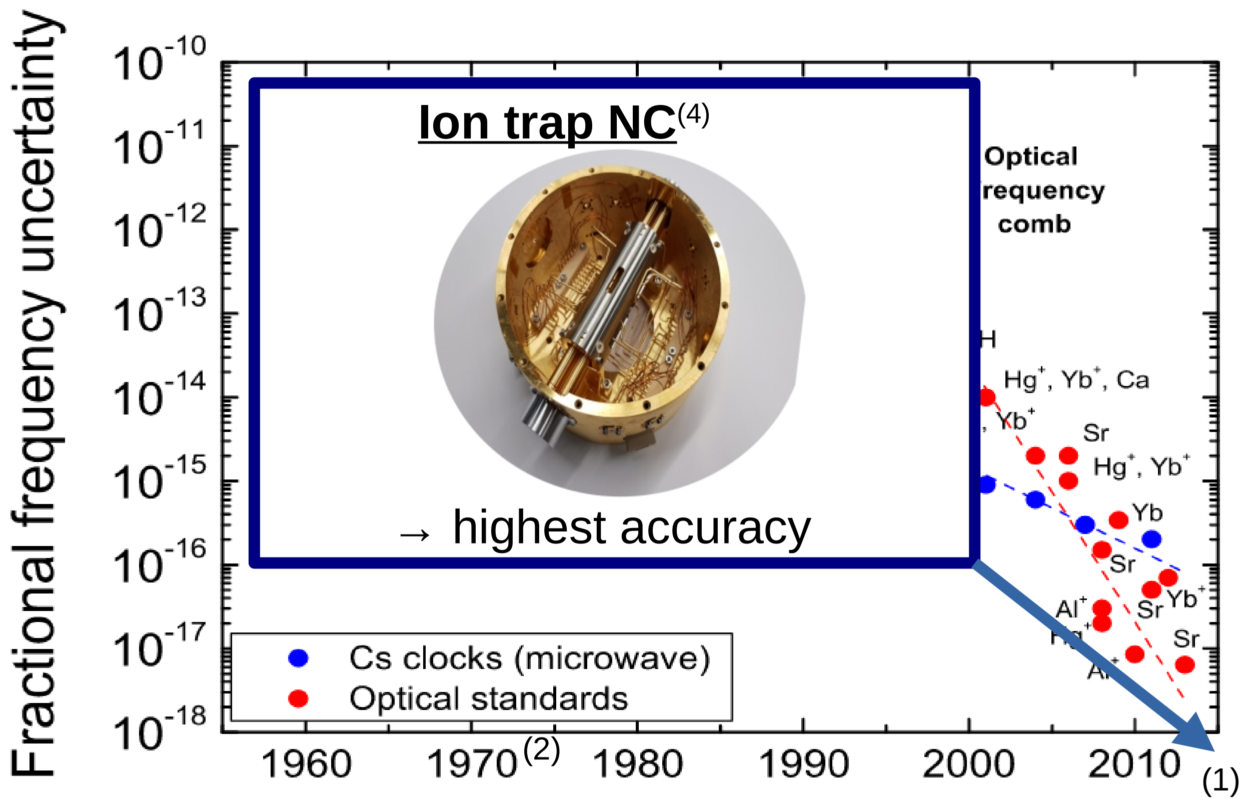
From atomic to nuclear clocks







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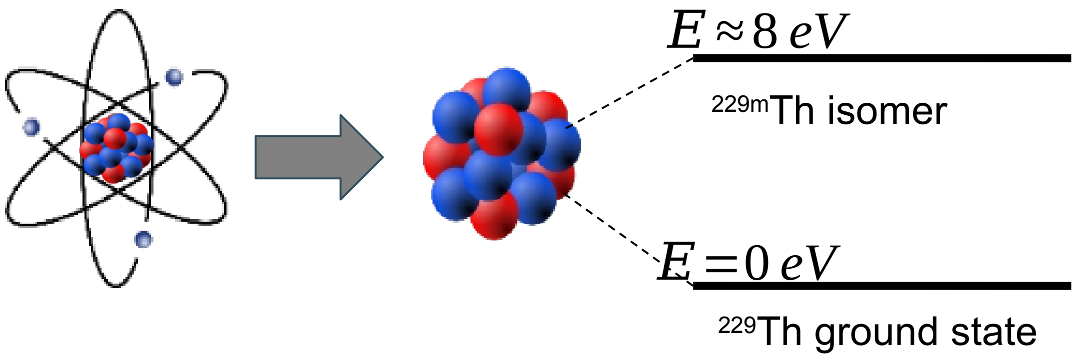
→ From electronic to nuclear transition[2]

(4) Peik et al., 2021, *Quantum. Sci. Technol.* **6** 034003
(5) G A Kazakov et al., 2012 *New J. Phys.* **14** 083019
(6) von der Wense et al., 2019, *Hyperf. Interact.* **240** 2

A novel quantum sensor



Atomic clock: electron
EM force

Nuclear clock: nucleon transition
EM force + nuclear forces

(7) for a review: Thirolf et al., 2019 *Journ. Phys. B: At. Mol. Opt. Phys.* **52** 203001 and references therein
(8) Fuchs et al. *ArXiv* 2407.15924

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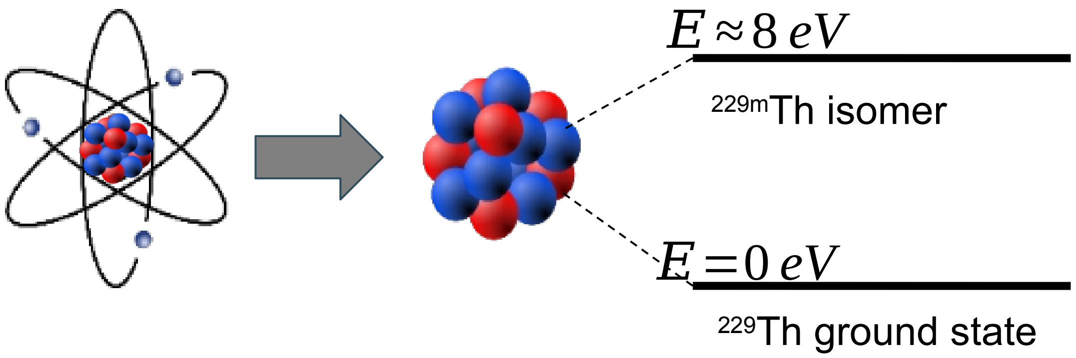

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- **Lineshape analysis**[7]
- **Clock comparisons (-networks)**[8]

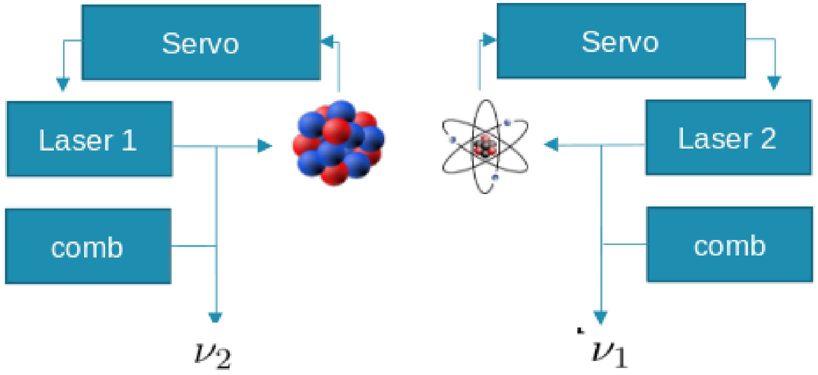
  time variations of fundamental constants

  → up to 10^4 times more sensitive than optical clock comparisons

  oscillatory ultralight dark matter (QCD coupling)

  → up to 10^8 more sensitive than atomic clock comparisons

$$\frac{\partial}{\partial t}\ln\frac{\nu_2}{\nu_1} = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial \alpha}{\partial t}$$



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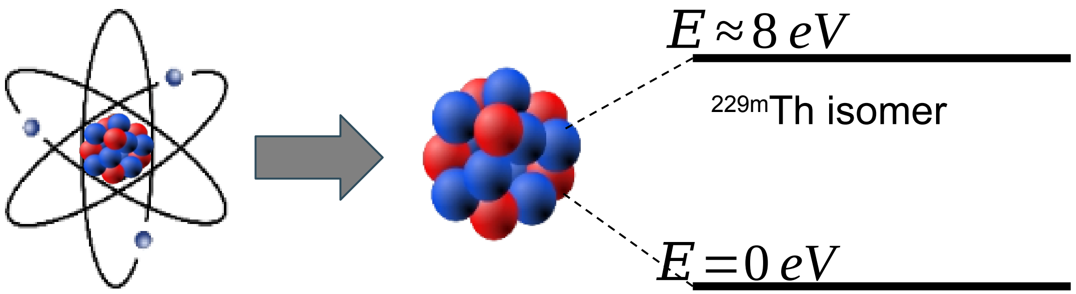

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- **Lineshape analysis**[8]
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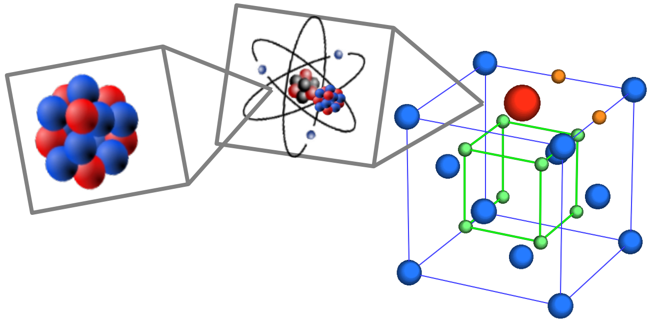

Large number of nuclei in crystalline medium[8]

- **Ultrastable clock (-networks)**
  gravimetry
- **Industrial applications**
  telecom, sattelite-based navigation

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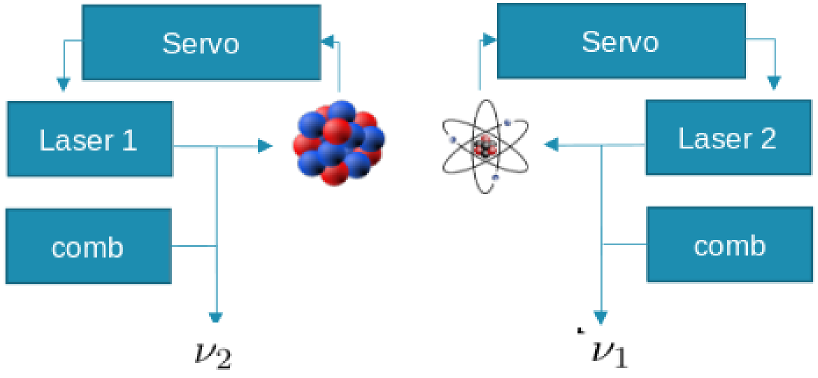

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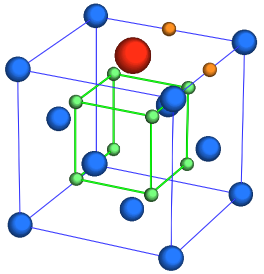
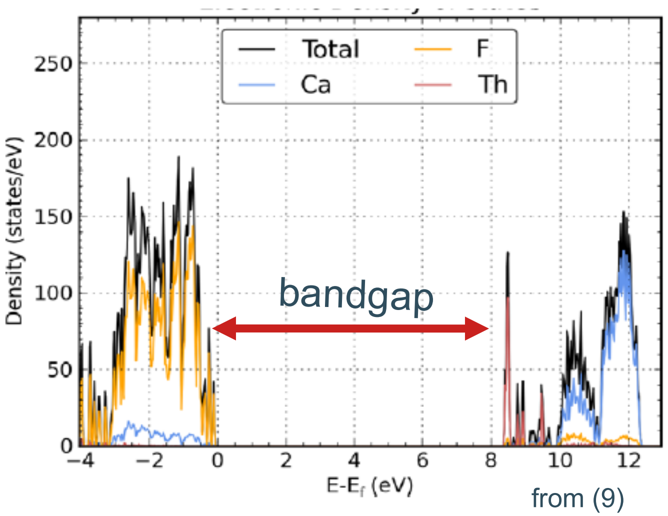
The role of the chemical environment

CaF_2: $^{229}Th^{4+}$ in Ca-substitutional position(1:



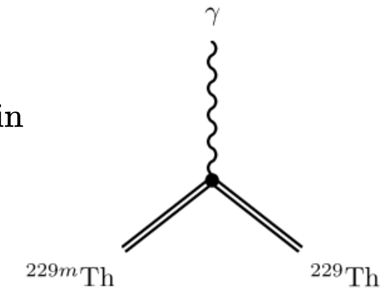


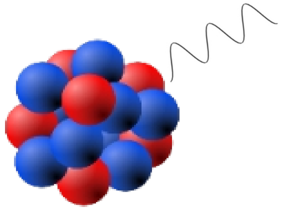
from (9)

Decay mode:

γ-decay

$1/\Gamma_\gamma = T_{1/2} \approx 10\text{min}$





(9) Dessovic. et al., 2014 *J. Phys. Condens. Matter* **26** 10

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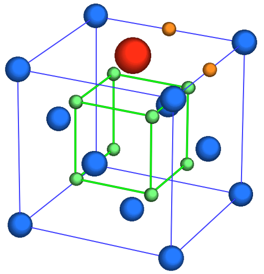
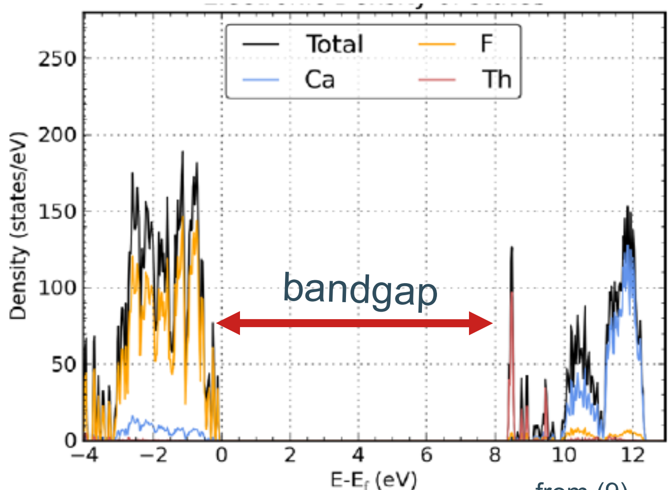
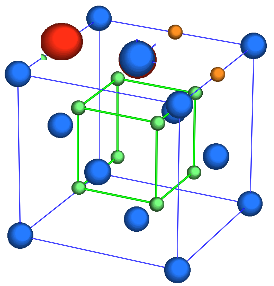
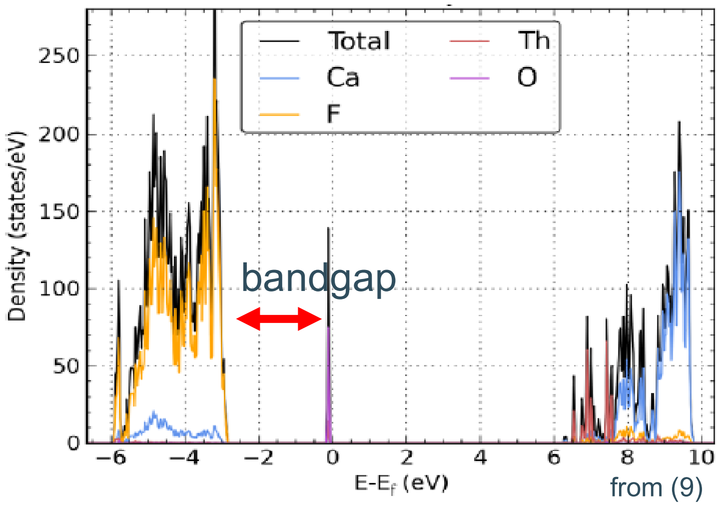




from (9)

CaF_2: $^{229}Th^{4+}$ in interstitial position(12)





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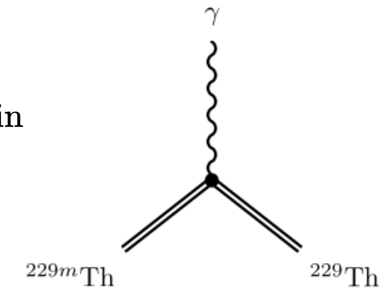
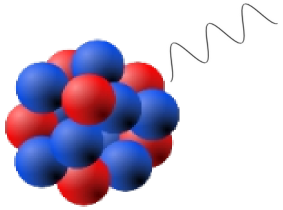
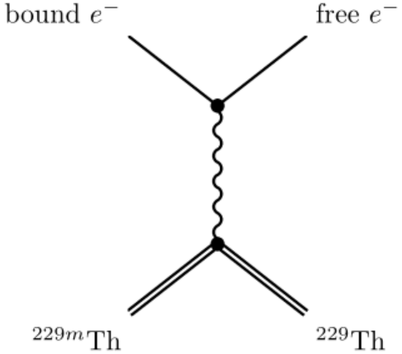
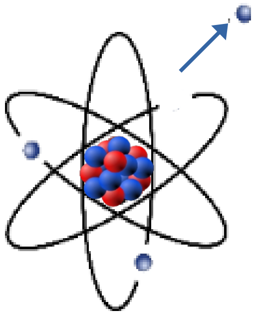




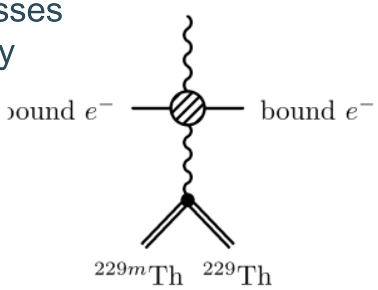
Internal conversion (IC) decay

$1/\Gamma_{IC} = T_{1/2} \approx 7\mu s$

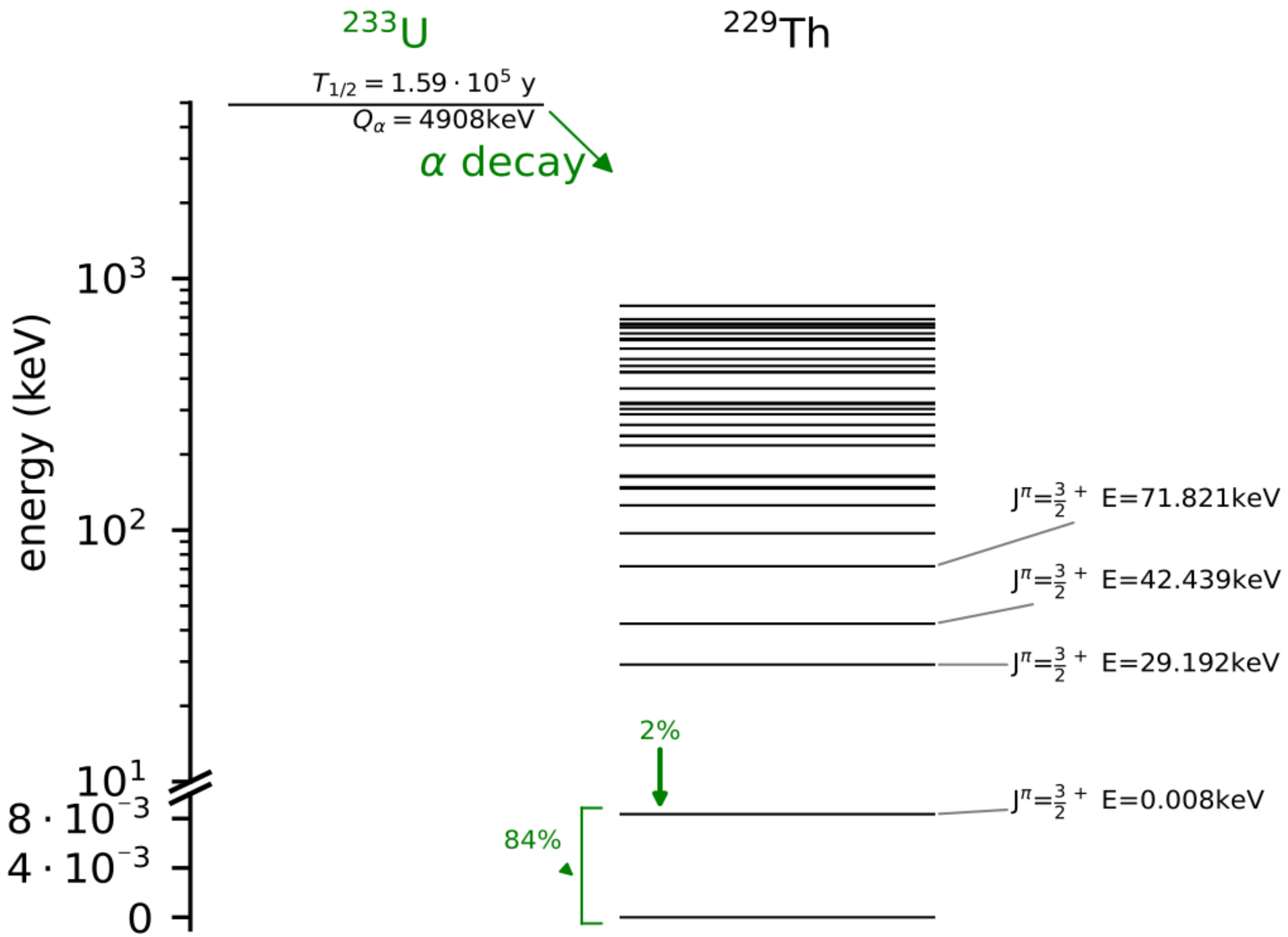




Higher order processes
e.g. bound IC-decay



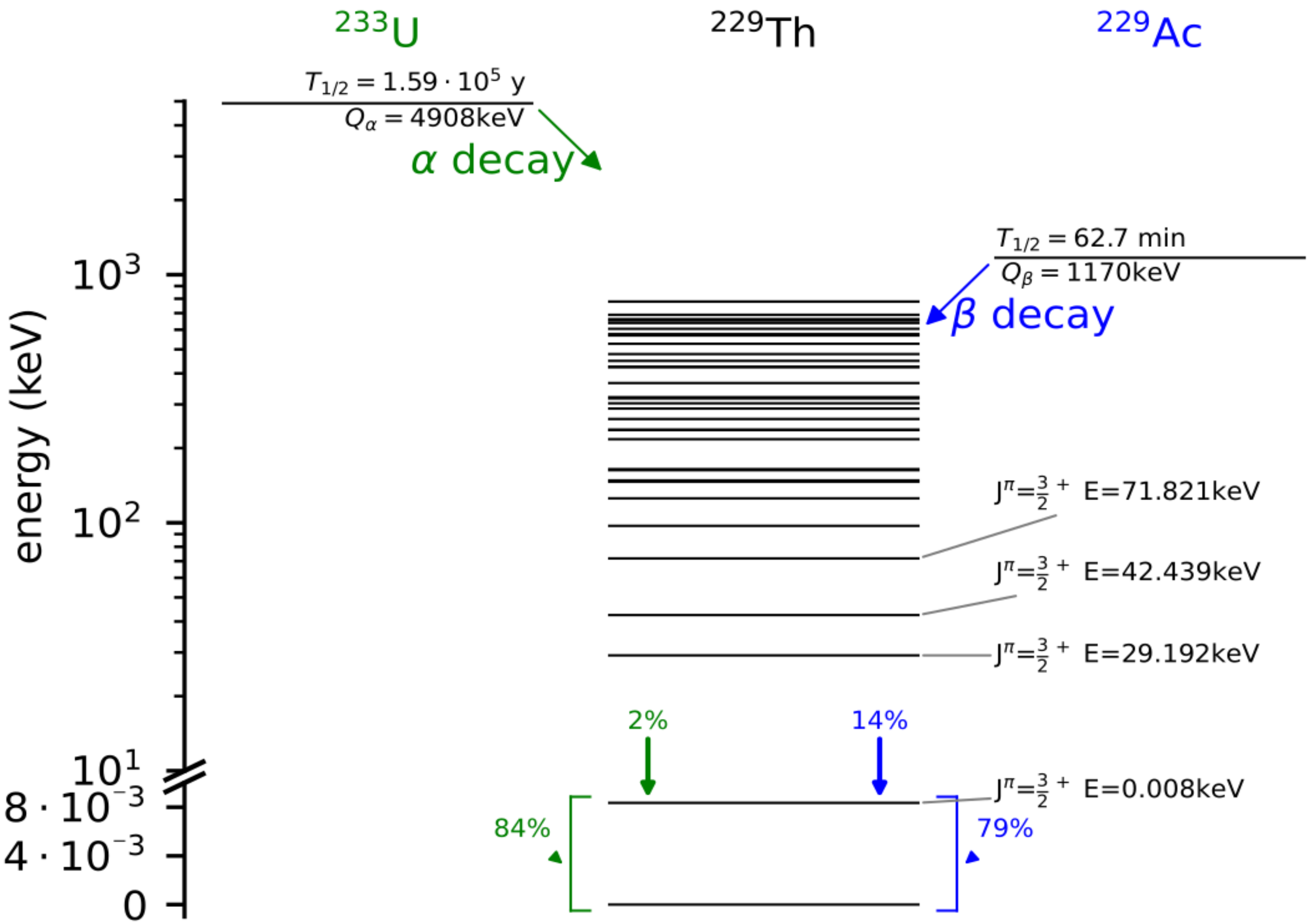
Populating the isomer



What about the radiative decay?

(10) Verlinde, M. et al. *Phys. Rev. C* **100**, 024315 (2019).

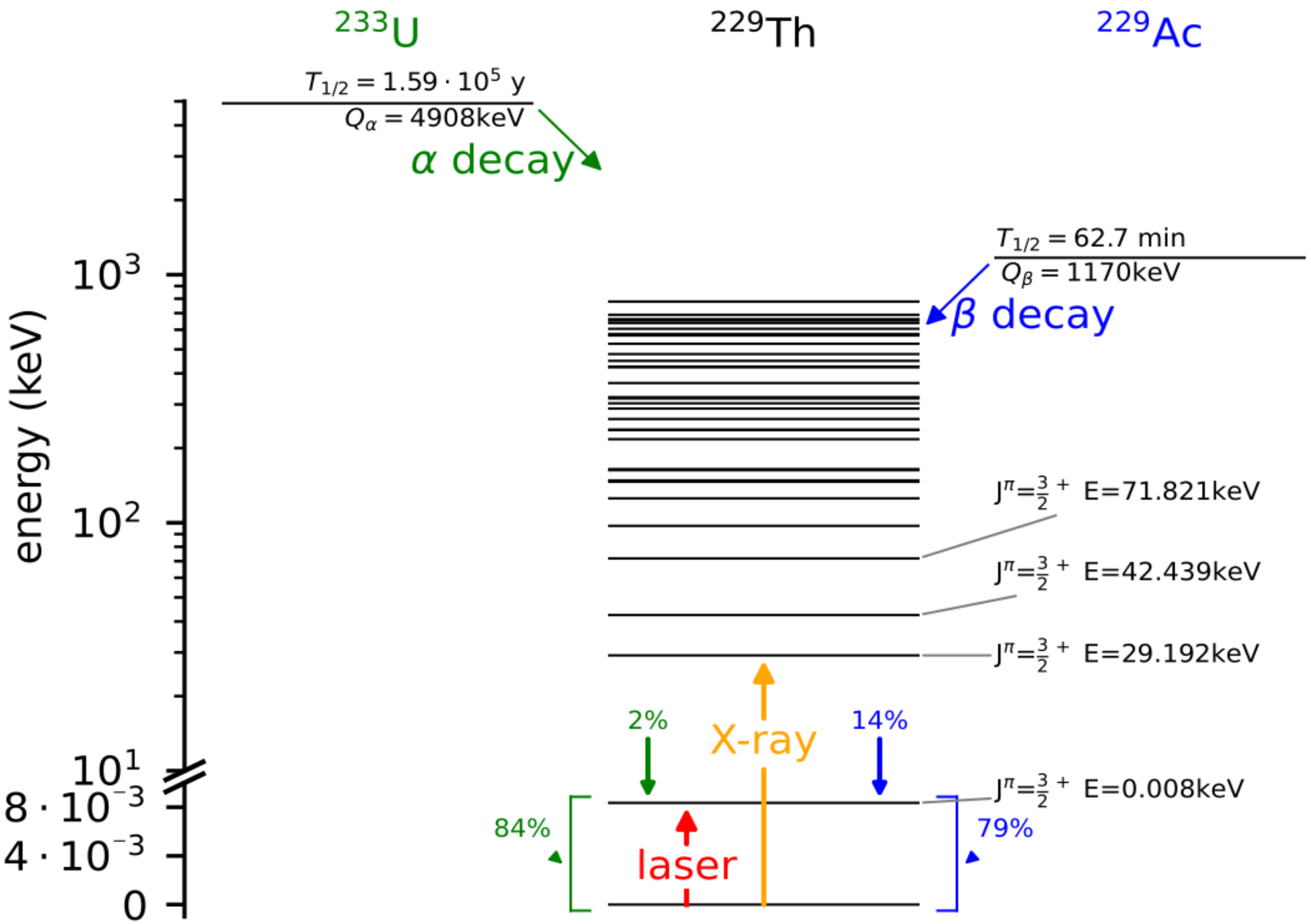
Populating the isomer



What about the radiative decay?
→ *^{229}Ac β-decay + solid-state host*(10)

(10) Verlinde, M. et al. *Phys. Rev. C* **100**, 024315 (2019).

Populating the isomer



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Vacuum-ultraviolet spectroscopy at ISOLDE

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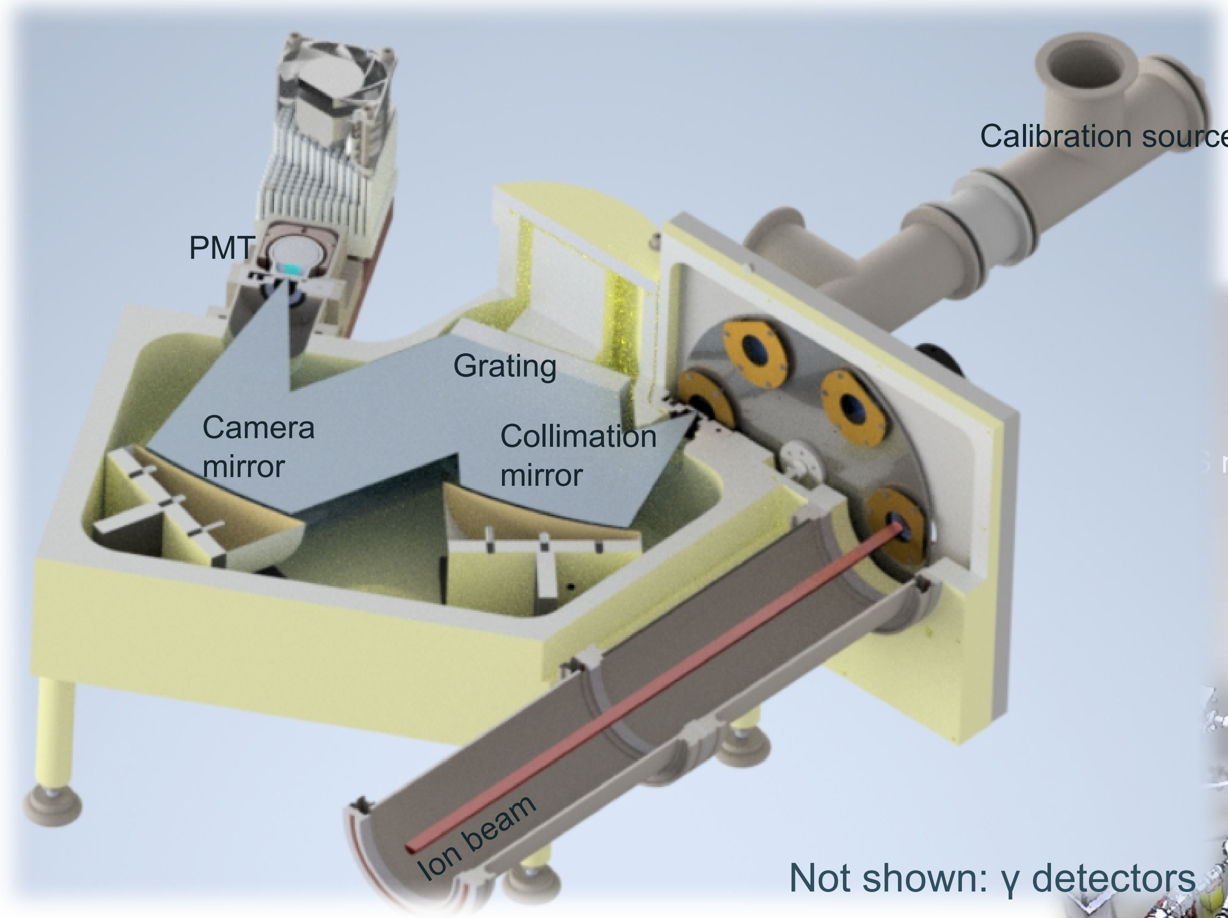
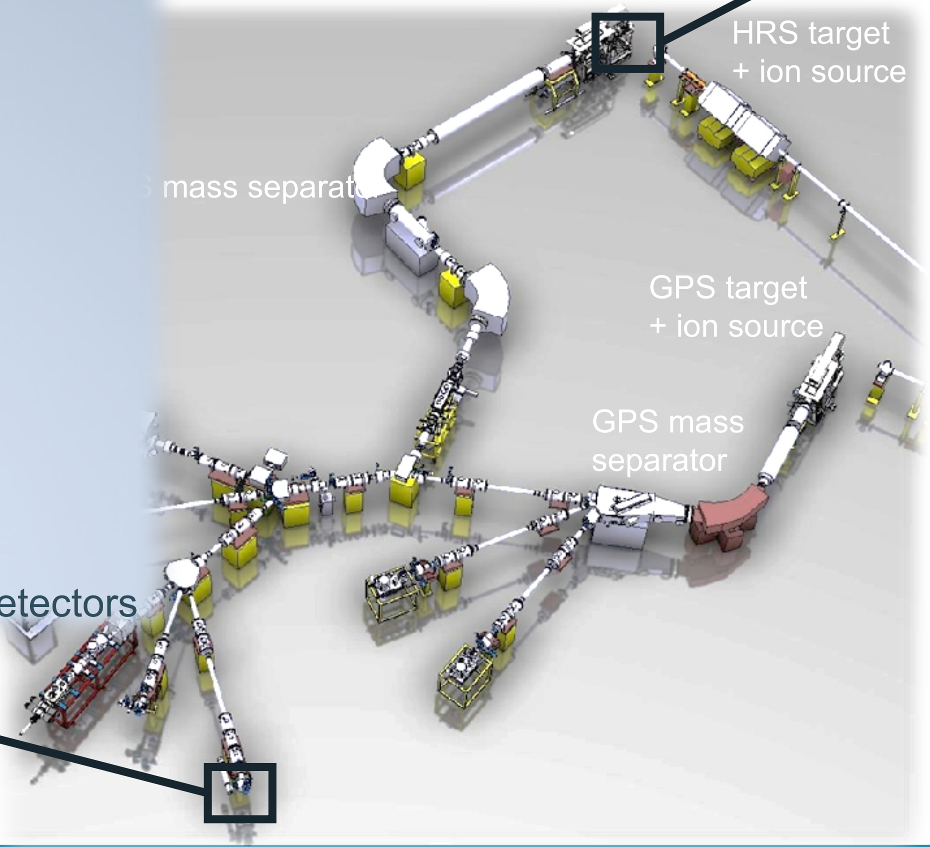
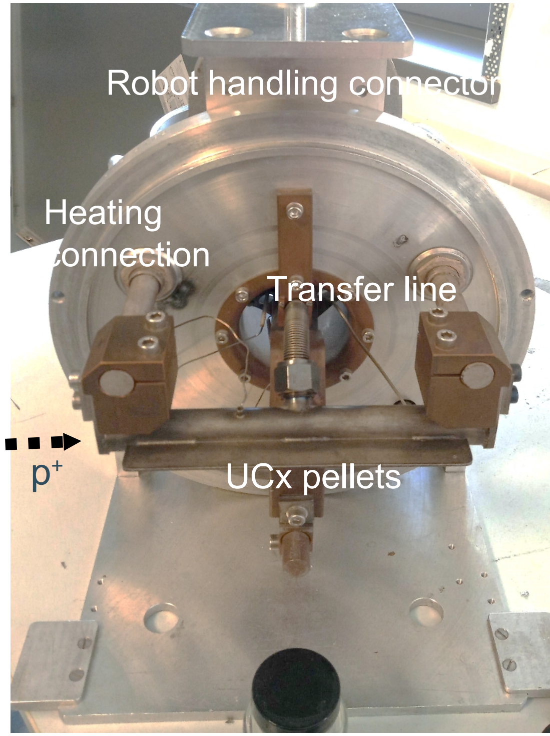


Not shown: γ detectors





ISOLDE beamline and accelerator complex sketches: CERN

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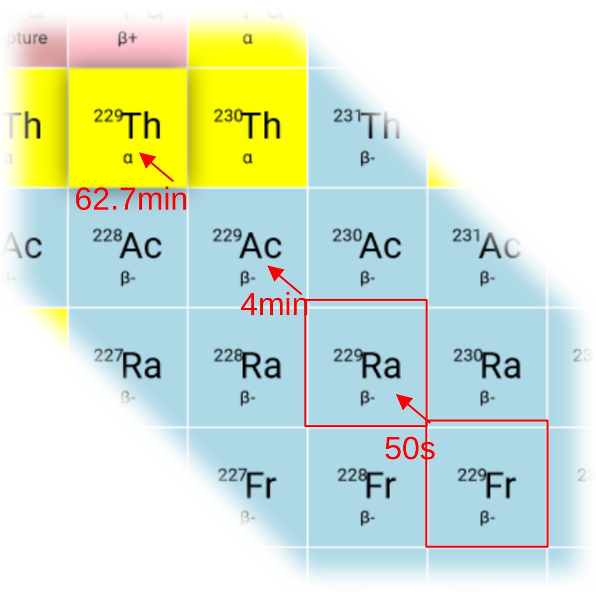
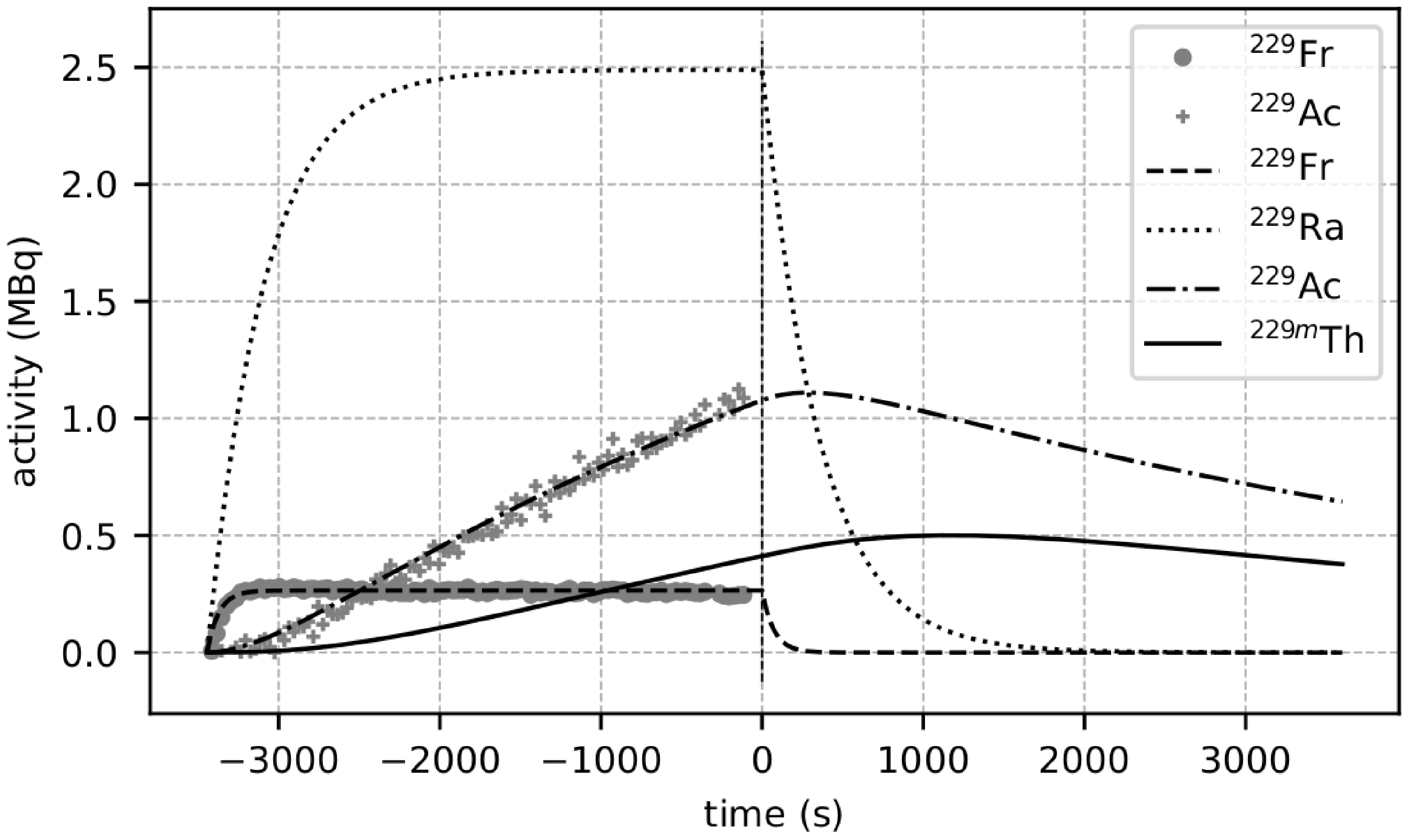
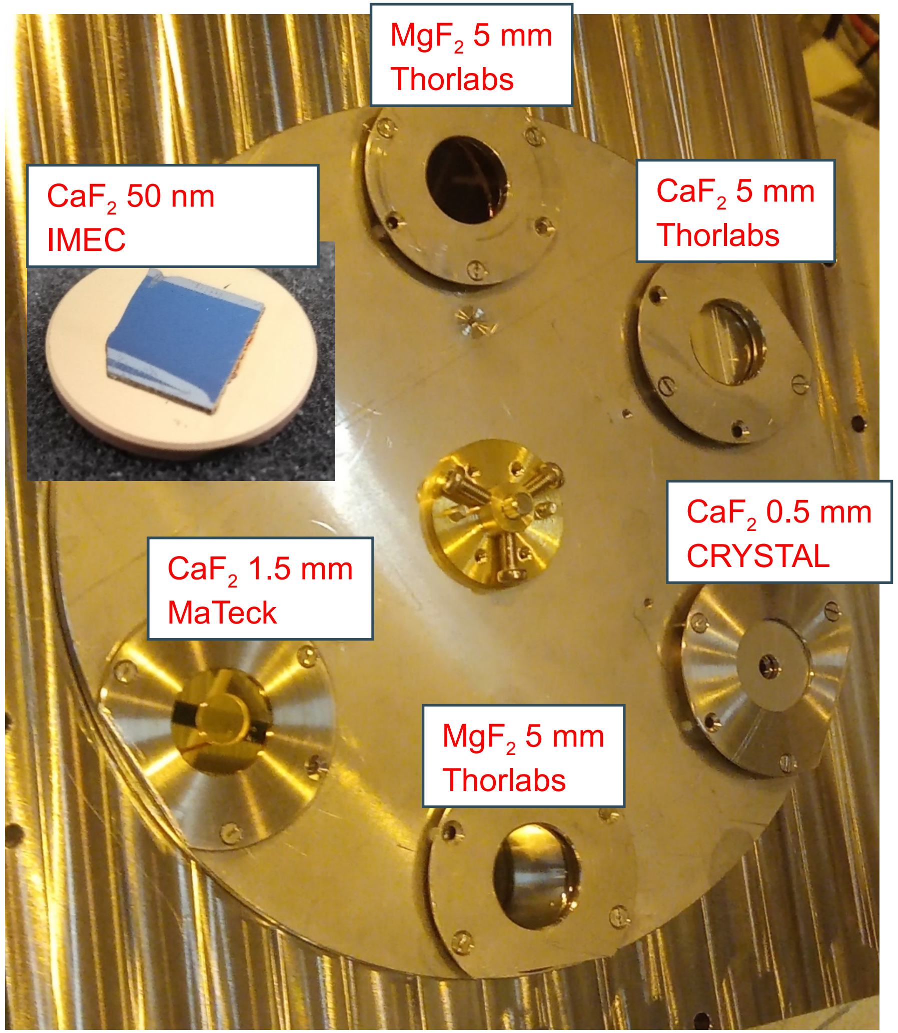
Vacuum-ultraviolet spectroscopy at ISOLDE





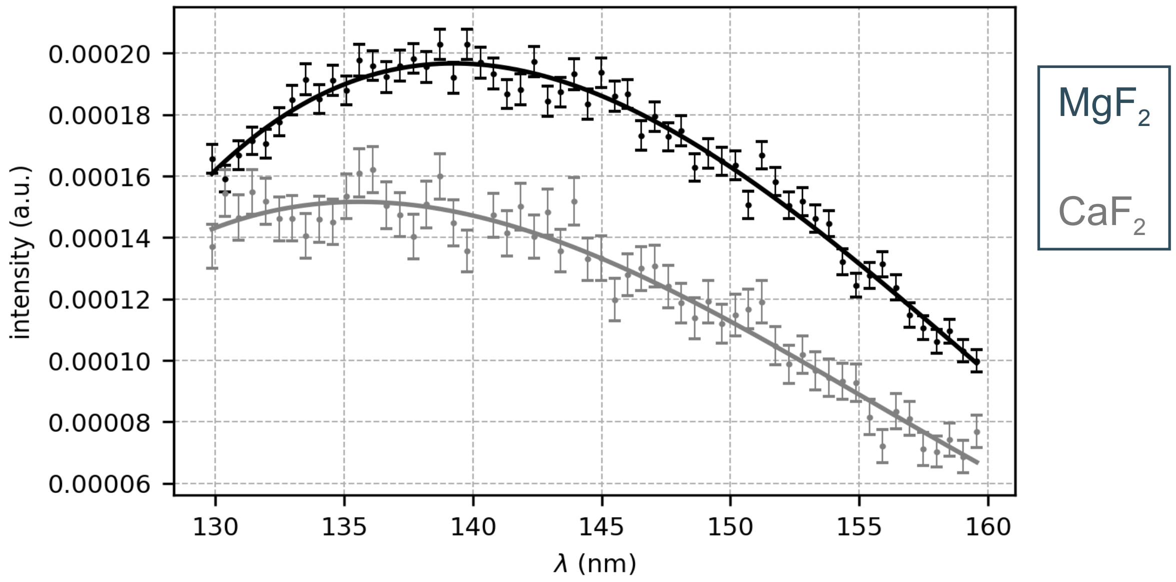
Vacuum-ultraviolet spectroscopy at ISOLDE



Background induced by radiation:

Cherenkov photon emission
→ *Continuous spectrum*

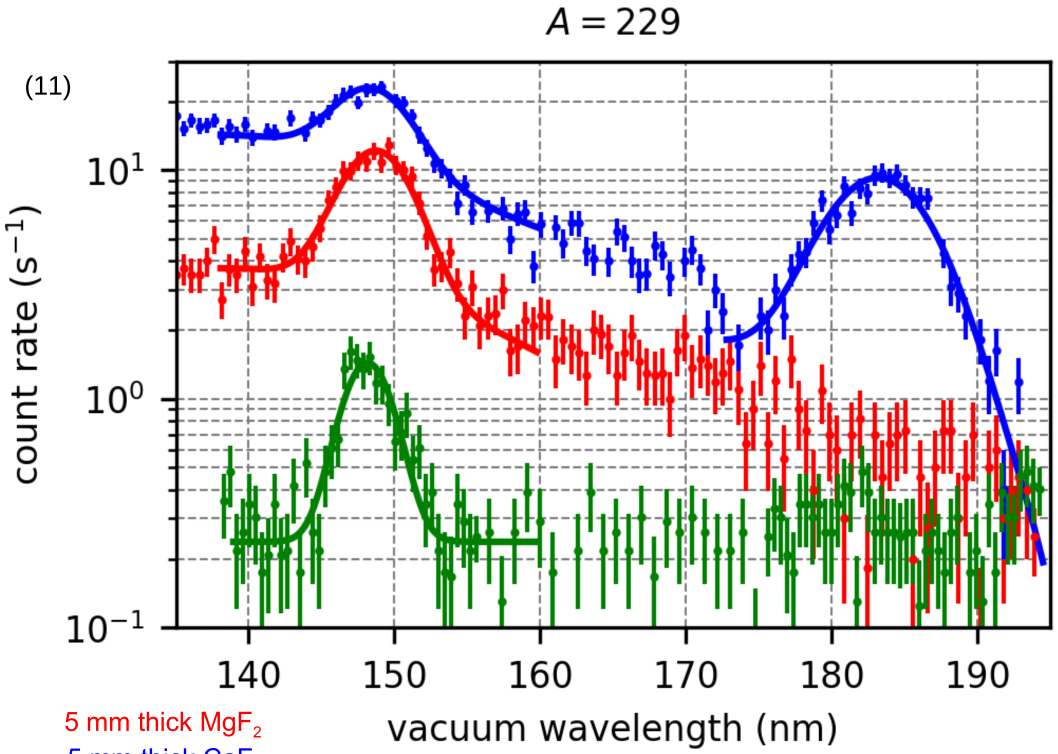
Observed spectral shape:
Cherenkov spectrum + instruments and crystal bandpass



Radioluminescence of crystal defects
→ *Limited spectral width*

Identification

(11)



5 mm thick MgF_2
5 mm thick CaF_2
50 nm thick CaF_2

(11) Kraemer et al., *Nature* **617** 7962

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Identification

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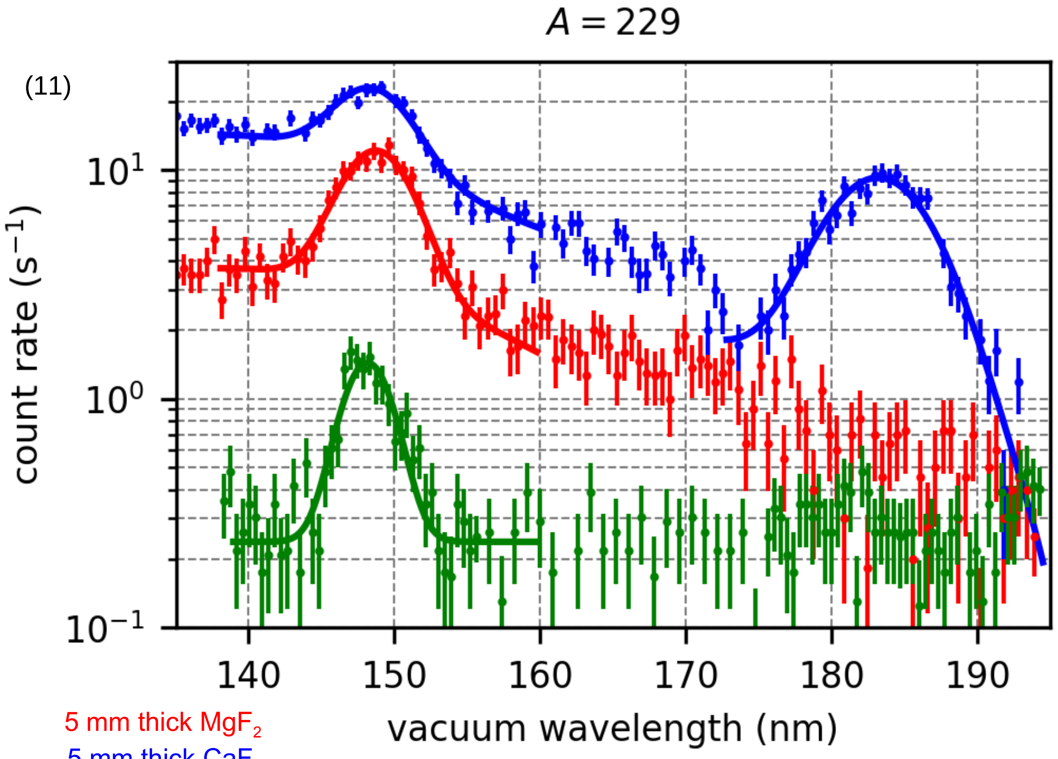

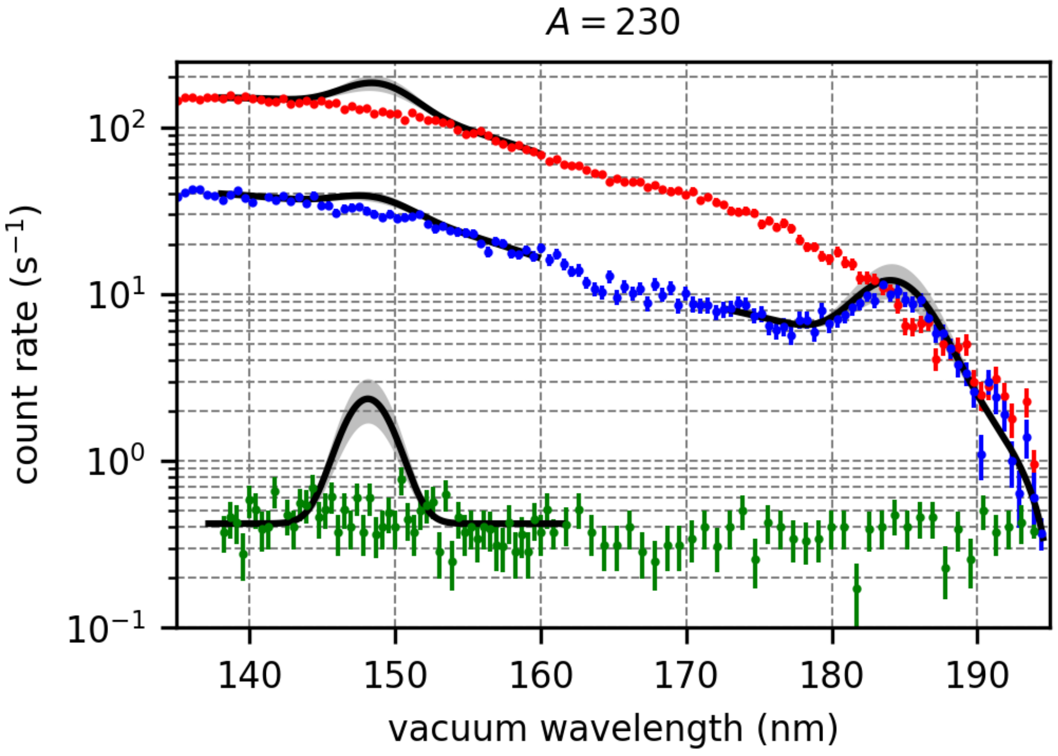

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^{229m}Th radiative decay

CaF_2 defect radioluminescence

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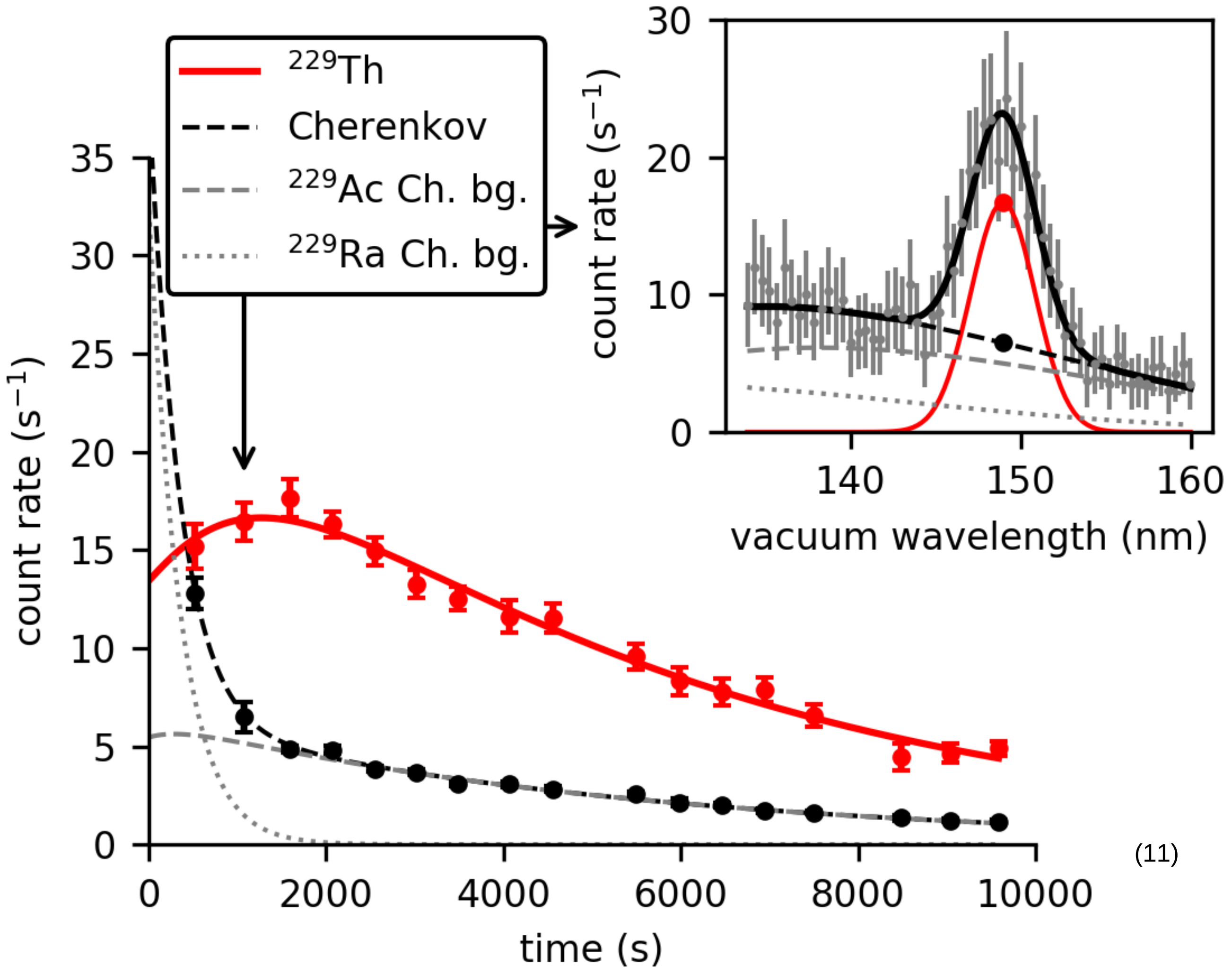
Half-life

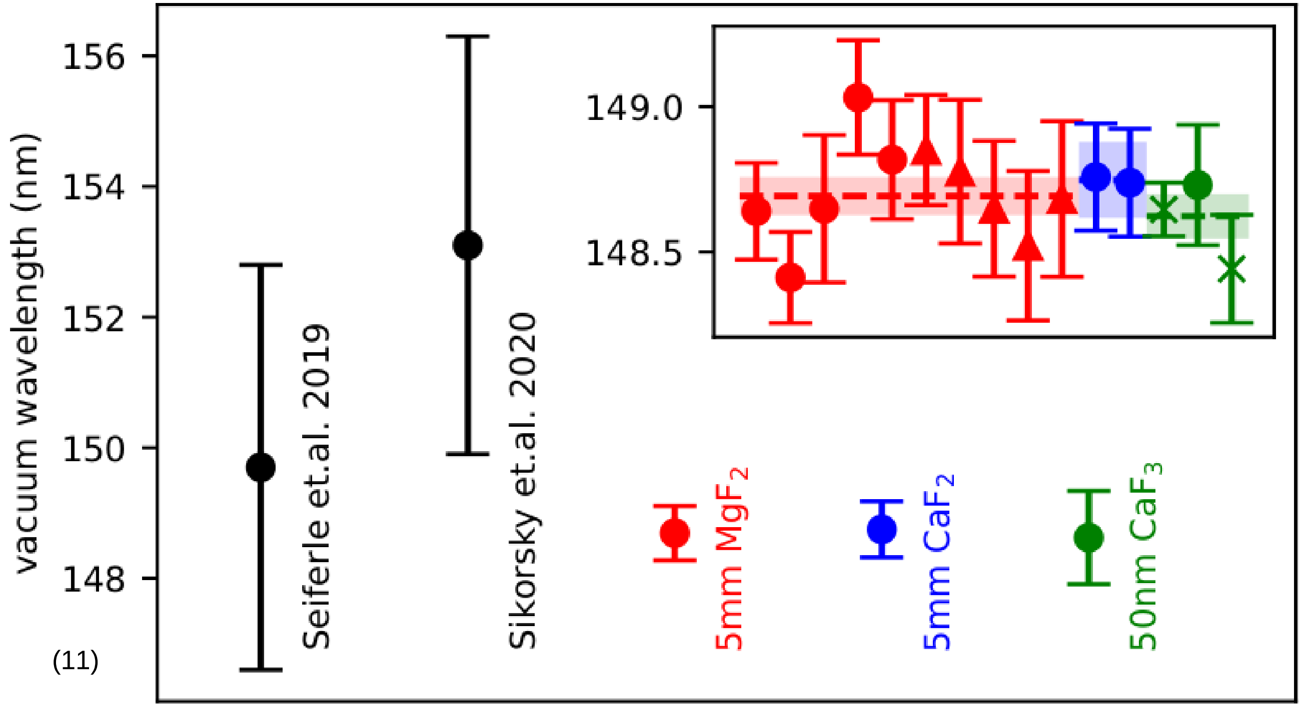


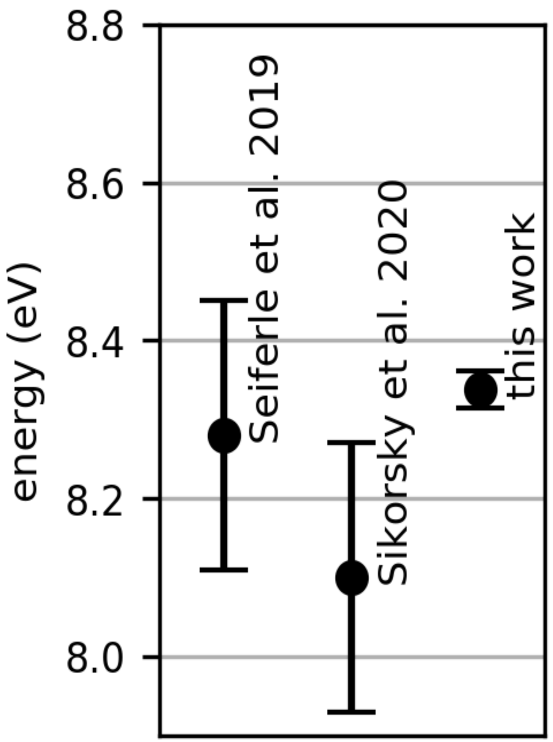
(11)

670(102) s in MgF_2

Crystal: 5 mm MgF_2
Entrance slit: 2 mm

Excitation energy





New energy value:
8.338(24) eV

→ Uncertainty reduced from 41 THz to 5.8 THz

(11) Kraemer et al., *Nature* **617** 7962

Conclusion and Outlook

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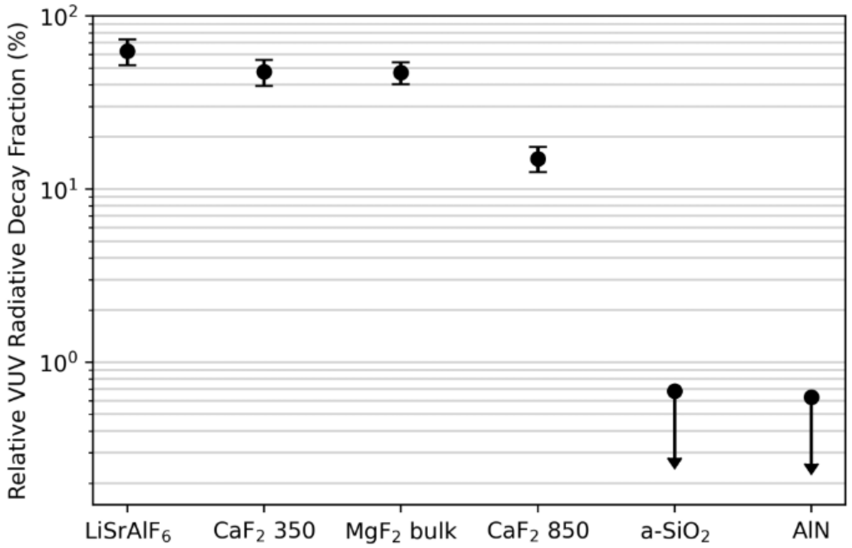
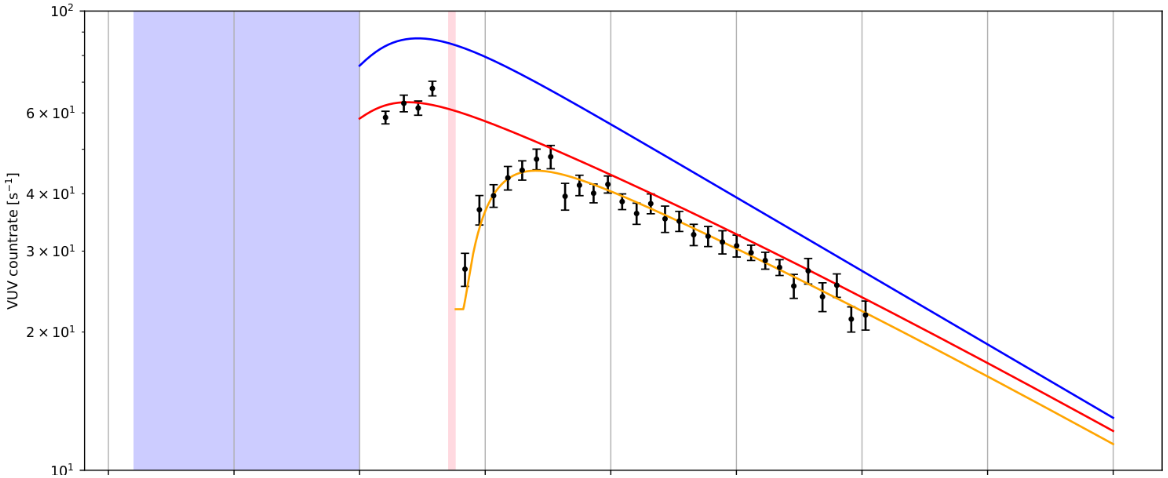
Conclusion

This work[11]:
- Demonstration of the feasability of the solid-state approach
- New energy value to facilitate laser excitation
- Establishing a robust system for material testing using implanted radioactive ion beams

New measurement campaigns[12,13]
- Testing of the radiative decay fraction in candidate materials
- Better understanding of quenching effects



Radioactive quenching (c.f. contribution by Y.Elskens)



(11) Kraemer et al., *Nature* **617** 7962
(12) Pineda, S. V. et al. Phys. Rev. Res. 7, 013052 (2025).
(13) Y.Elskens et al., in preparation

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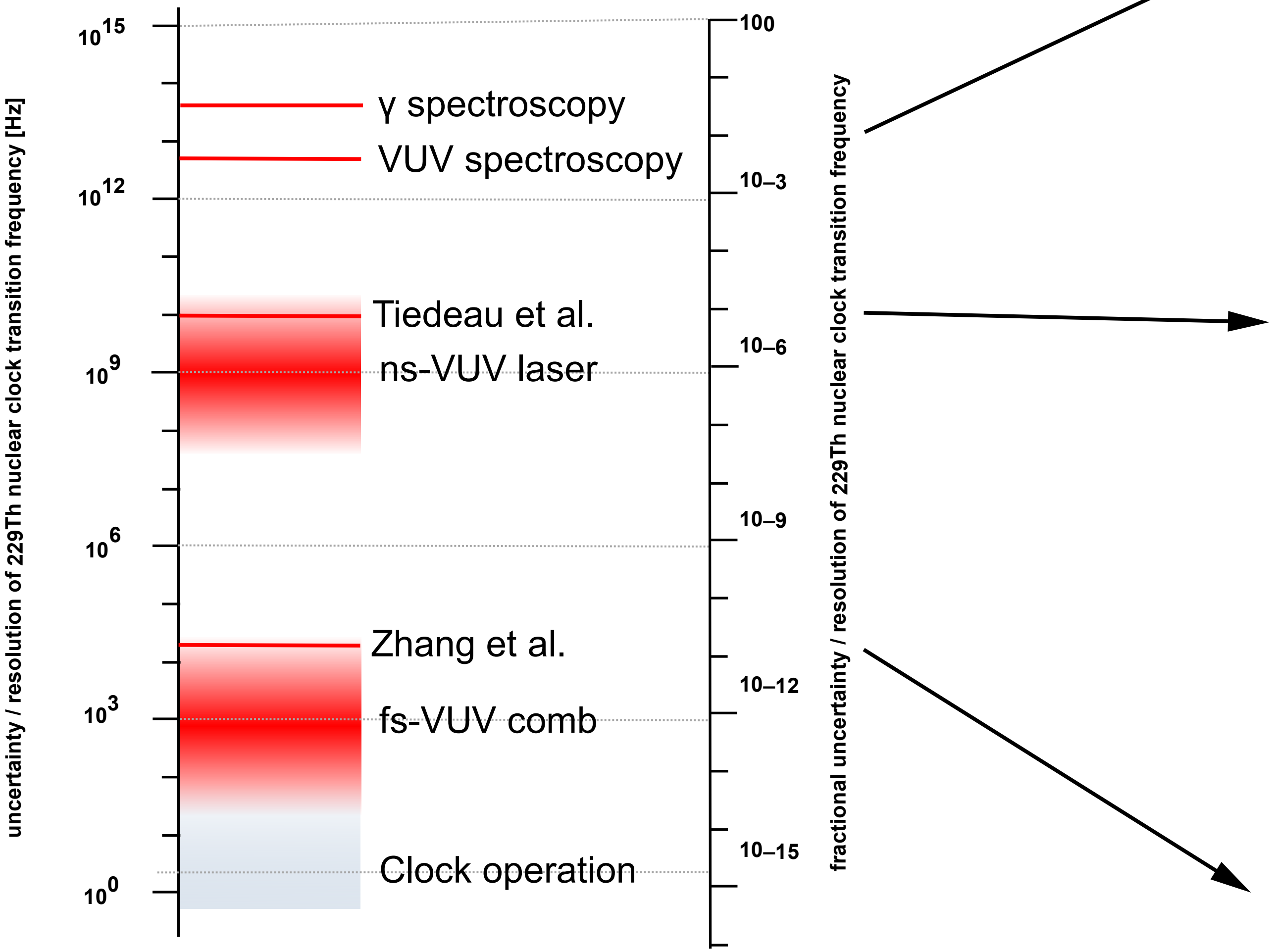
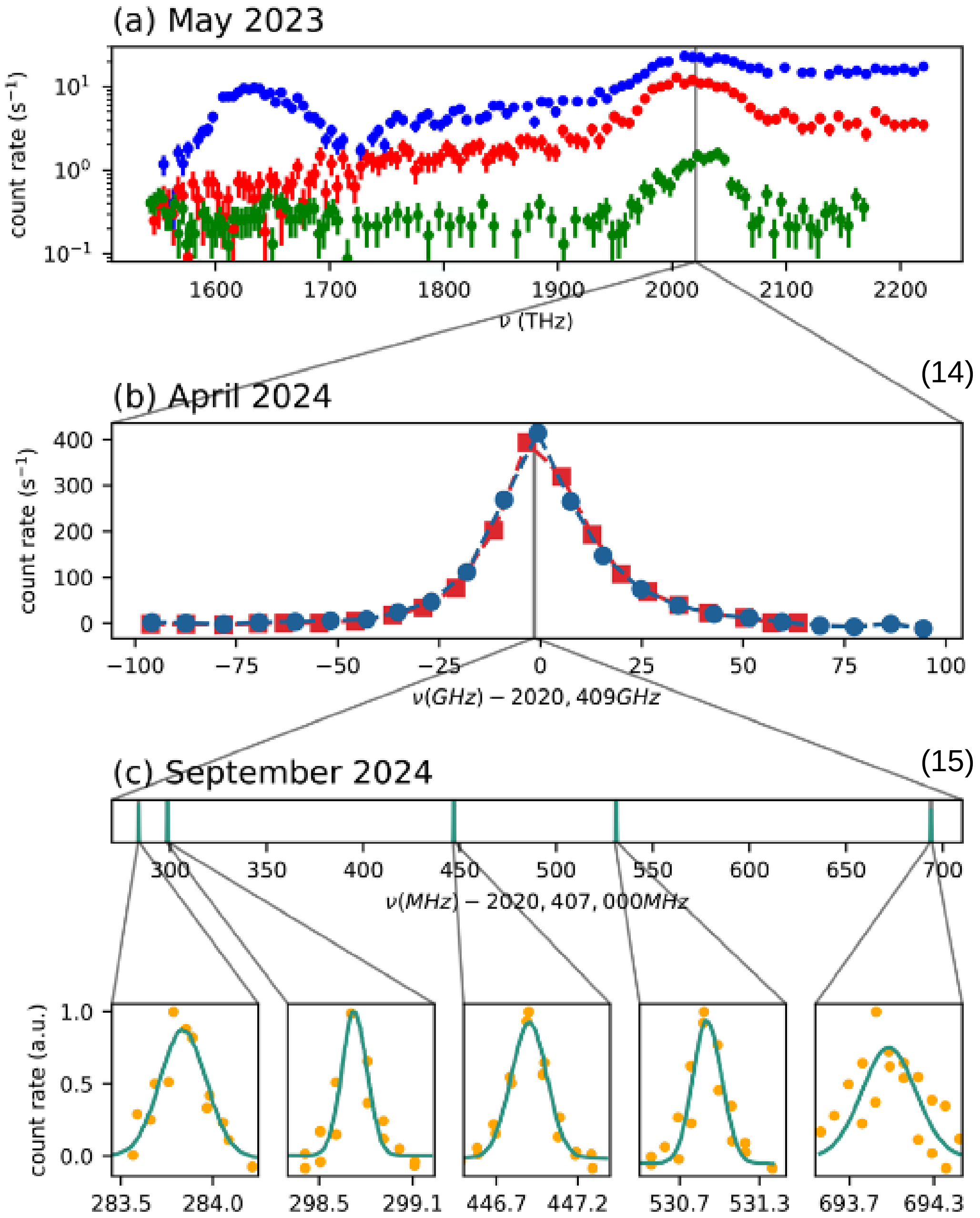
Outlook:Recent developments





(14) Tiedau et al. *Phys. Rev. Lett.* **132**, 182501 (2024).
(15) Zhang, C. et al. *Nature* **633**, 63–70 (2024).

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Thank you very much!

ISOLDE-IS658 collaboration:

M. Athanasakis, S. Bara, K. Beeks, P. Chhetri, A. Claessens, T. Cocolios, J.G. Correia, H. De Witte, R. Ferrer, S. Geldhof, N. Hosseini, U Köster, S. Kraemer, Y. Kudryavtsev, M. Laatiaoui, R. Lica, G. Magchiels, V. Manea, J. Moens, L. M. Pereira, S. Raeder, T. Schumm, S. Sels, P.G. Thirolf, S.M. Tunhuma, P. Van Den Bergh, P. Van Duppen, A. Vantomme, R. Villareal, M. Verlinde, U. Wahl

Funding acknowledgements (IS658):

Fonds Wetenschappelijk Onderzoek: GOA/2015/010 BOF KU Leuven
Fonds Wetenschappelijk Onderzoek and Fonds de la Recherche Scientifique – FNRS Excellence of Science nr. 40007501,
Fundação para a Ciência e Tecnologia CERN/FIS-TEC/0003/2019),
Fonds zur Förderung der wissenschaftlichen Forschung I5971 (REThorIC),
European Union’s Horizon 2020 ENSAR2 nr. 654002, MSCA nr. 101026762
European Research Council Thorium Nuclear Clock nr. 856415, LRC nr. 819957