Towards a nuclear clock: halflife and decay-fraction measurements of the radiative decay of ^{229m}Th

ISOLDE workshop and users meeting 2024

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Context

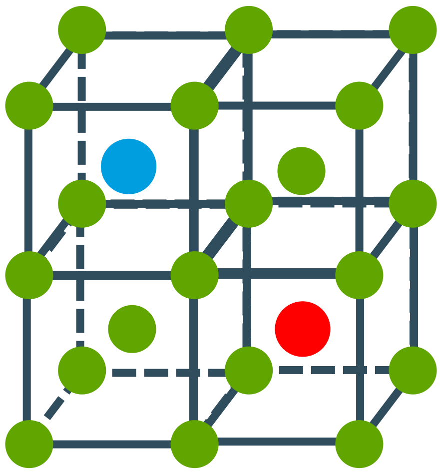
^{229}Th has an isomer that lies low enough to probe with a laser

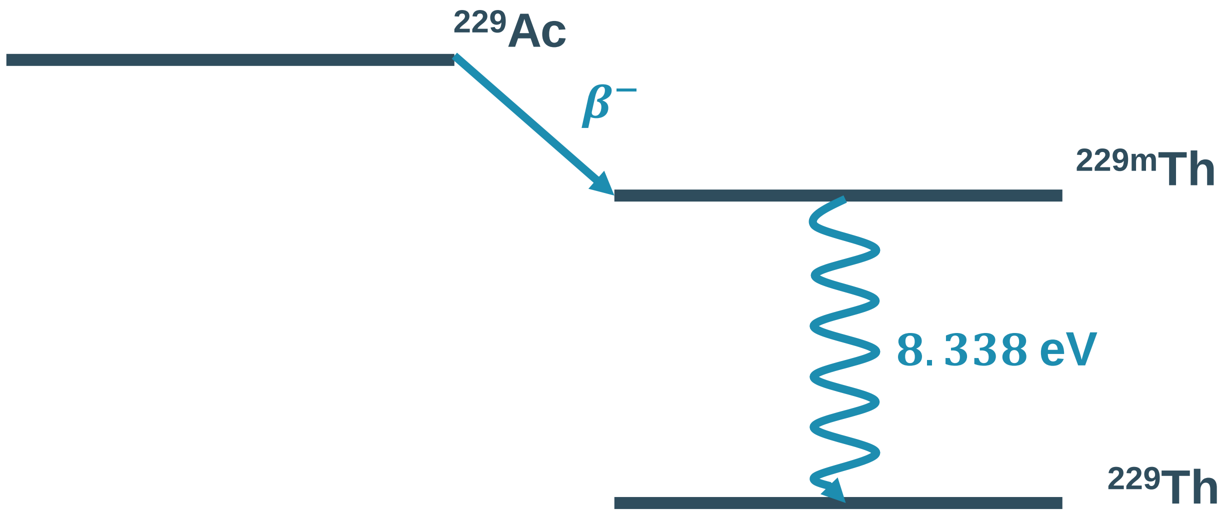
Ideal two-level system for a **nuclear clock**

Challenge: dominating IC decay

Populating the isomer through the **β-decay of ^{229}Ac** within the context of a **large-bandgap crystal**

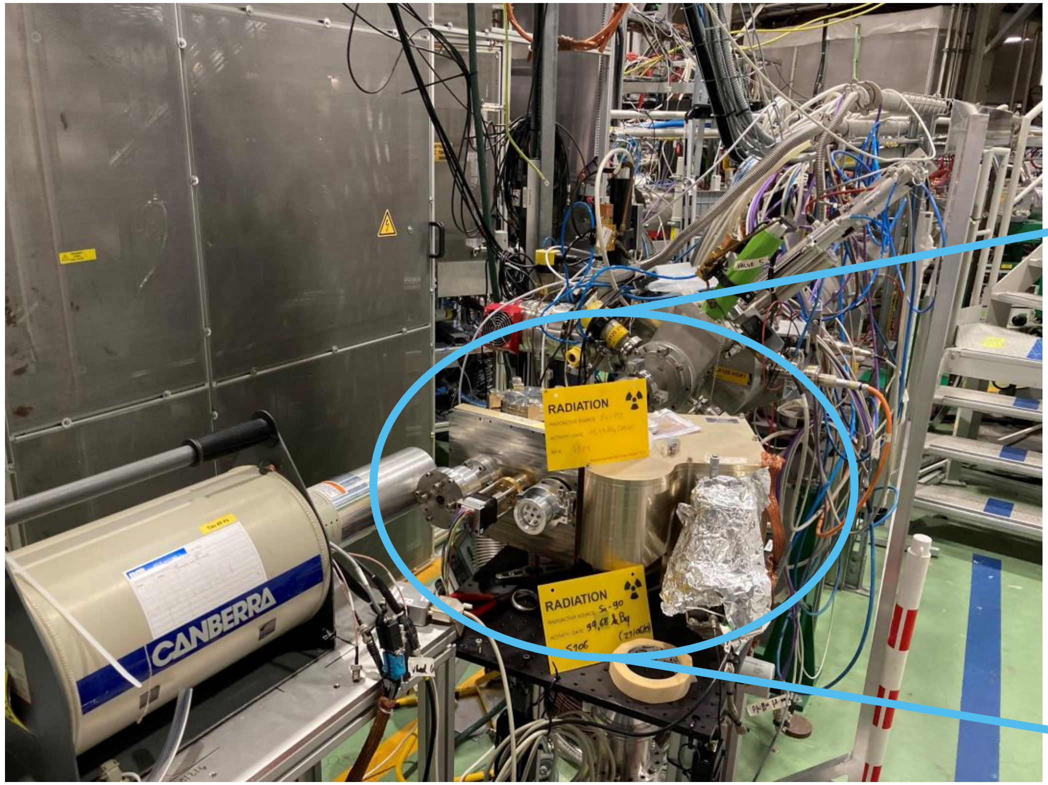
Results from 2021 ISOLDE beam time led to laser excitation in CaF_2 (PTB) and $LiSrAlF_6$ (UCLA), and even excitation with a frequency comb (JILA)

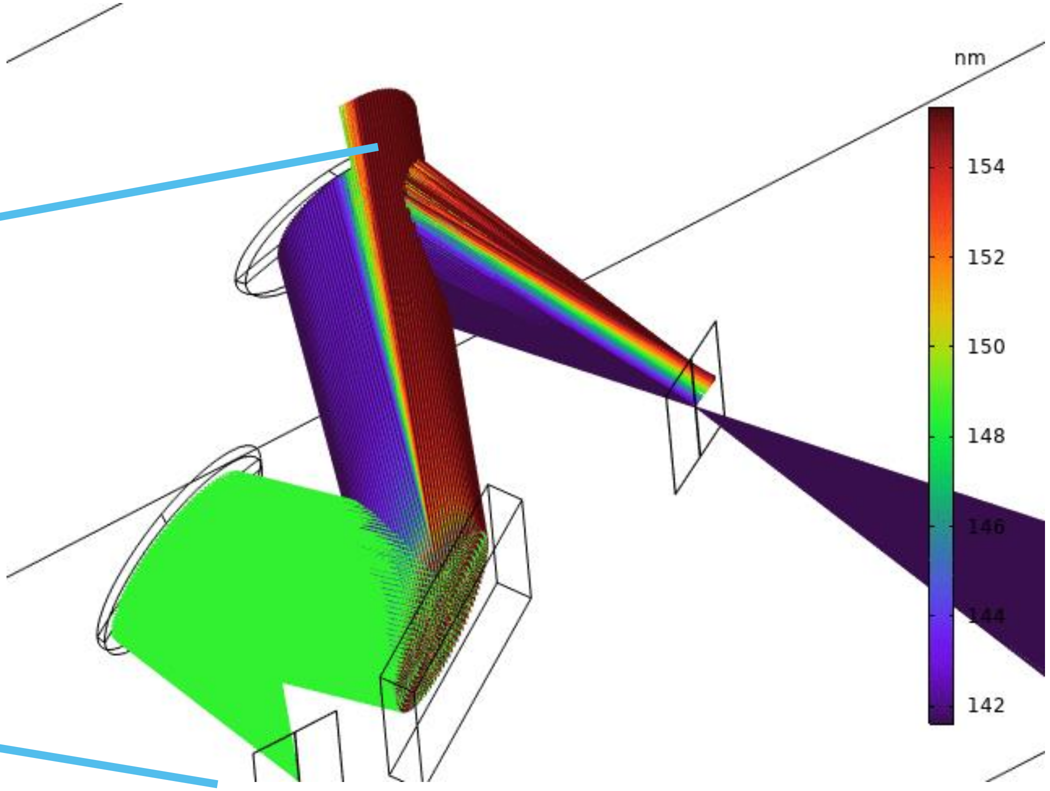




[1] S. Kraemer et al. *Observation of the radiative decay of the ^{229}Th nuclear clock isomer*, 2024
[2] J.Tiedau et al. *Laser excitation of the ^{229}Th nucleus*, 2024
[3] R. Elwell et al. *Laser excitation of the ^{229}Th nuclear isomeric transition in a solid-state host*, 2024
[4] C. Zhang et al. *Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock*, 2024

On-line VUV spectroscopy of the isomer at LA1





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2023 campaign goals

Study the **effect** of the implanted **crystal** on the **radiative decay fraction**

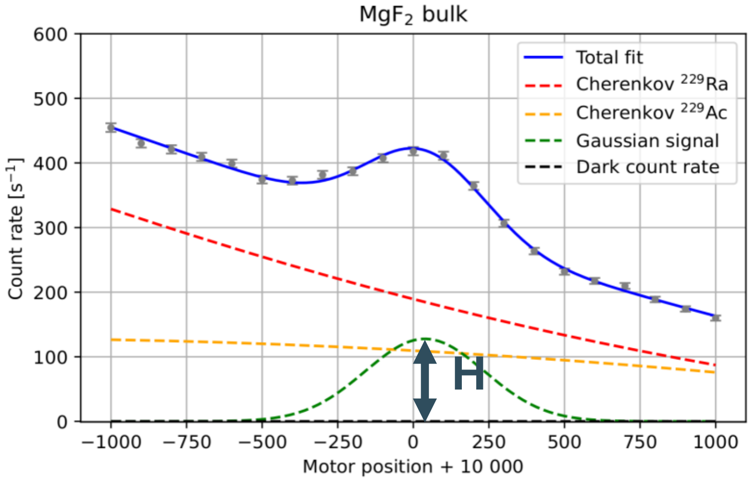
Study the **time behaviour** of the radiative decay in different crystalline environments

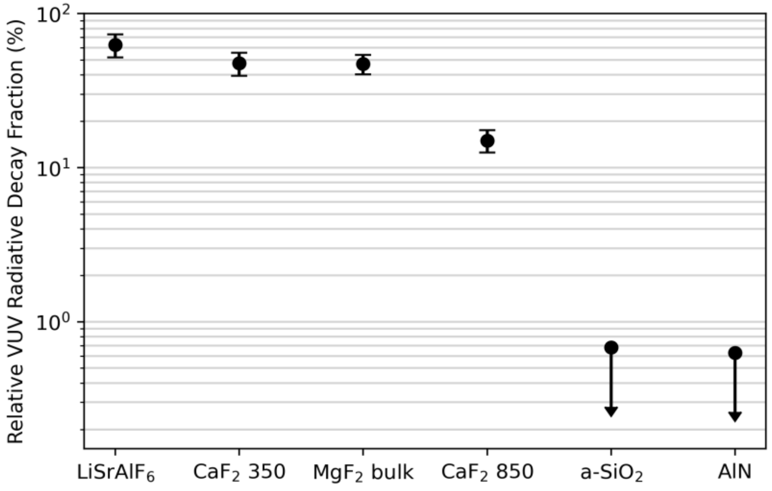
Decay fractions in different crystals

$$\varepsilon_{\mathrm{VUV}} = \frac{H}{A_{\mathrm{iso}}\,\varepsilon_{\mathrm{I}}}$$

Compare the radiative decay fraction of different crystals relative to CaF_2 bulk (highest absolute efficiency)

Determine limits for AlN and SiO_2





[5] S. Pineda et al. *Radiative decay of the ^{229m}Th nuclear clock isomer in different host materials*, 2024

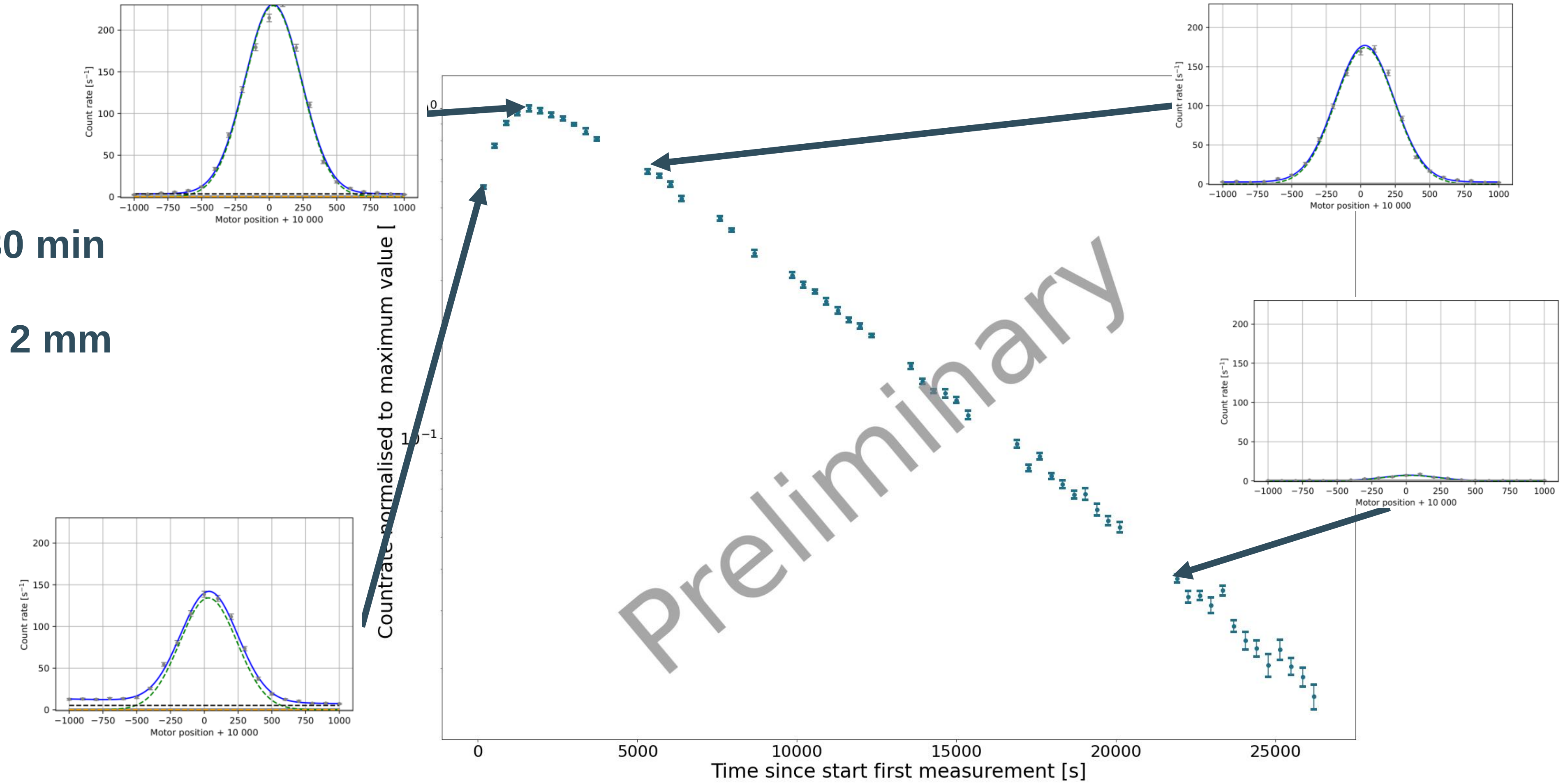
Studying the time behaviour of the VUV signal

General method:
Implant crystal for **15-30 min**

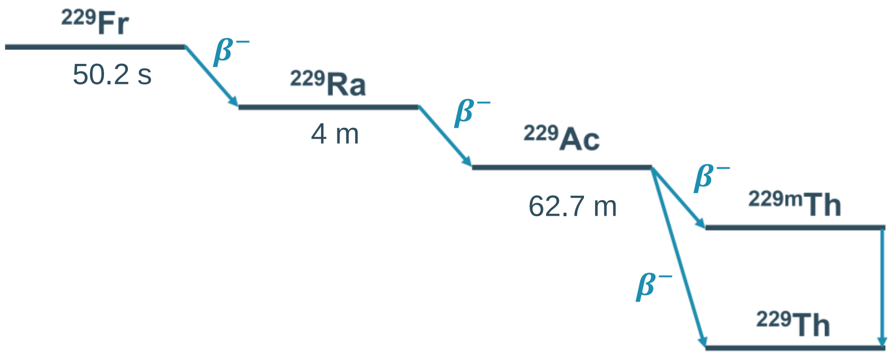
Move crystal in front of **2 mm entrance slit**

Repeatedly scan ROI

Determine height as a function of time

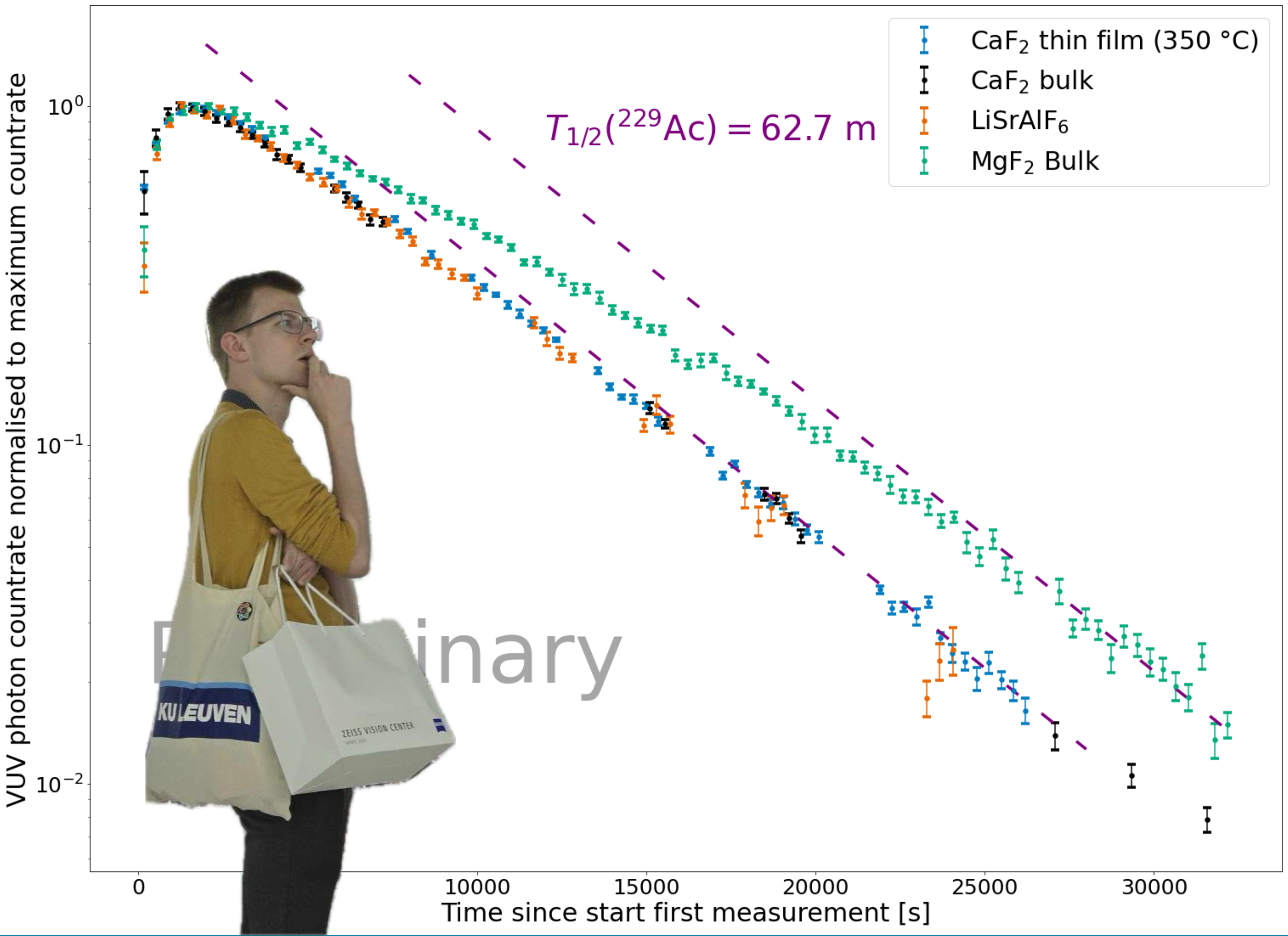


Studying the isomer’s time behaviour



The isomer’s radiative decay does not reach transient equilibrium with ^{229}Ac when expected

When it reaches equilibrium depends on the crystal



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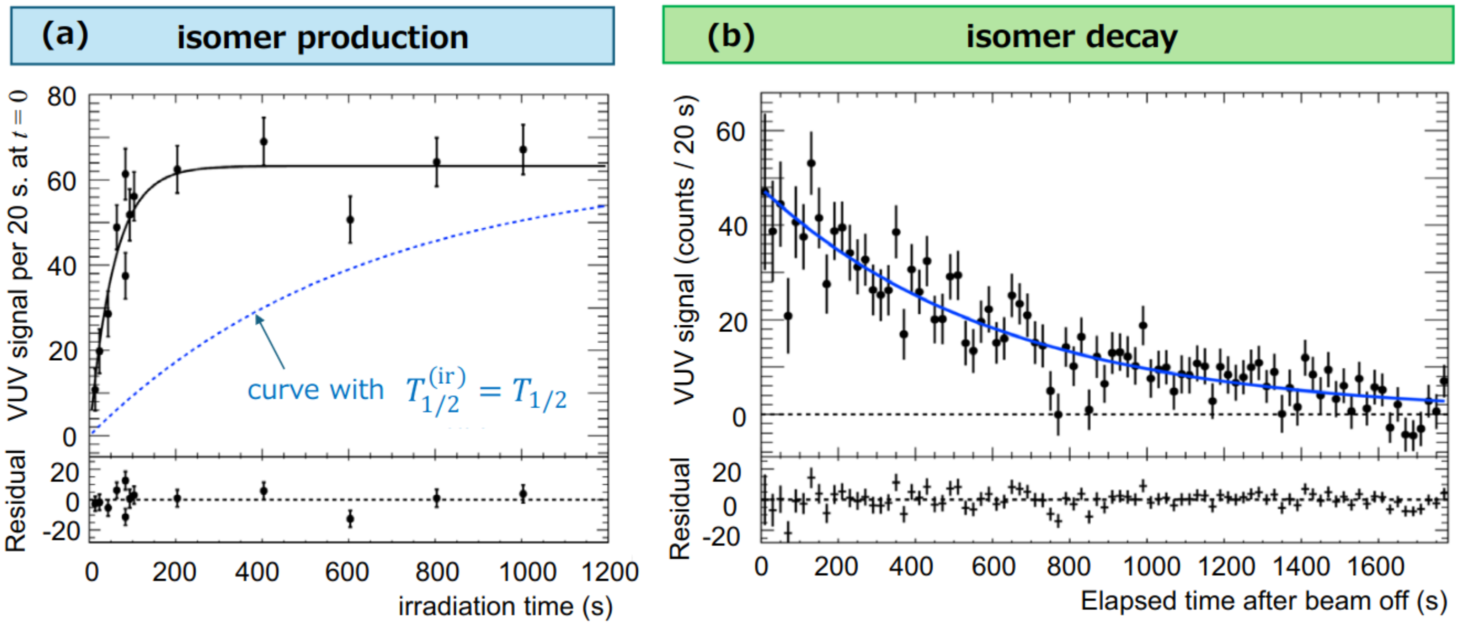
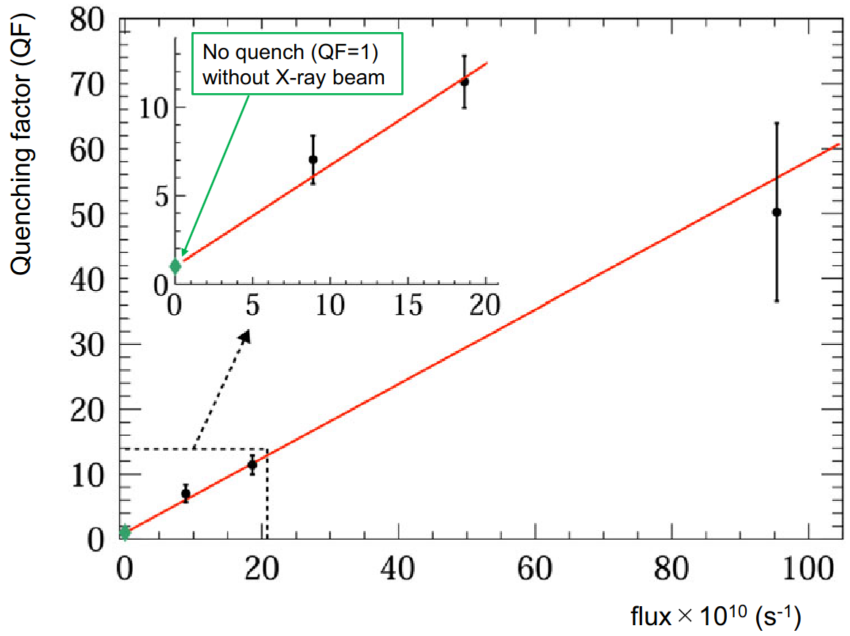
‘Quenching’ of the halflife

VUV spectroscopy at Spring-8 by X-ray pumping the isomer

Flux-dependent ‘quenching’ of the observed halflife

$$Q = \frac{t_{1/2}}{t_{1/2}^{(\mathrm{irr})}}$$





[6] T. Hiraki et al. *Controlling ^{229}Th isomeric state population in a VUV transparent crystal,* 2024

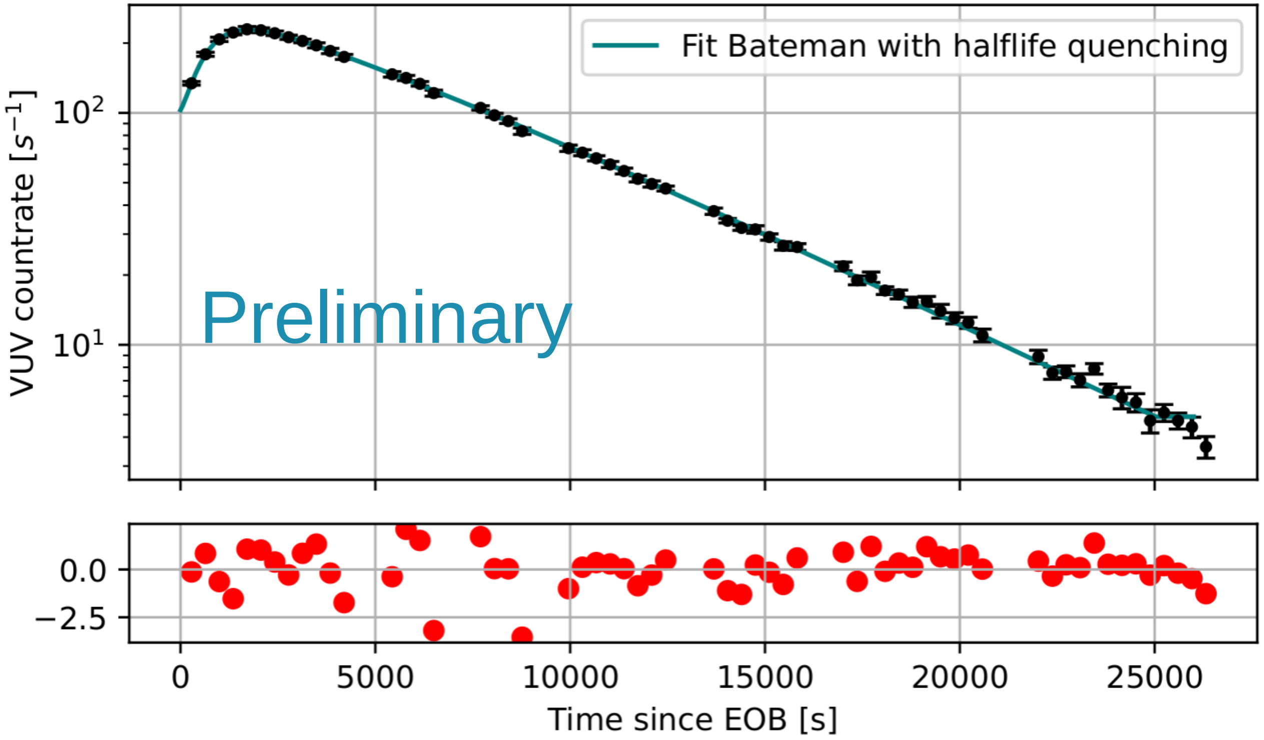
Quenching of the halflife: CaF_2 thin film

Make quenching depend linearly on activities of Ra and Ac

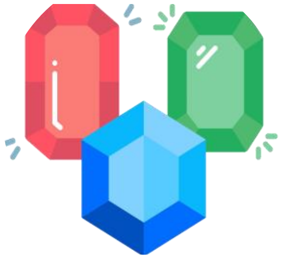
$$\frac{\mathrm{d}N_{\mathrm{rad}}}{\mathrm{d}t} = \lambda_{\mathrm{Ac}} N_{\mathrm{Ac}} - \underbrace{\left(1 + \alpha\lambda_{\mathrm{Ra}} N_{\mathrm{Ra}} + \beta\lambda_{\mathrm{Ac}} N_{\mathrm{Ac}}\right)}_{Q^{-1}} \lambda_{\mathrm{rad}} N_{\mathrm{rad}}$$

Halflife of **488 ± 48 (stat.) s** (very preliminary) seems to correspond with results from PTB (436 ± 10 s), Spring-8 (447 ± 25 s) and JILA (444 ± 3 s)

Doesn't describe MgF_2 well. Probably needs a **'population quenching'** on top of the halflife quenching.



Conclusions and outlook



Determined relative radiative decay fractions in different crystals

CaF_2, MgF_2, $LiSrAlF_6$, AlN, SiO_2

Environmental-dependent ‘quenching’ mechanism observed.

Describes time behaviour in CaF_2, not in MgF_2

Beam time 2025

More crystals: $LiCaAlF_6$, SrF_2, ThF_4, Al_2O_3, BaLiF …

Understanding ‘quenching’: Φ- and T-dependence

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The IS715 collaboration

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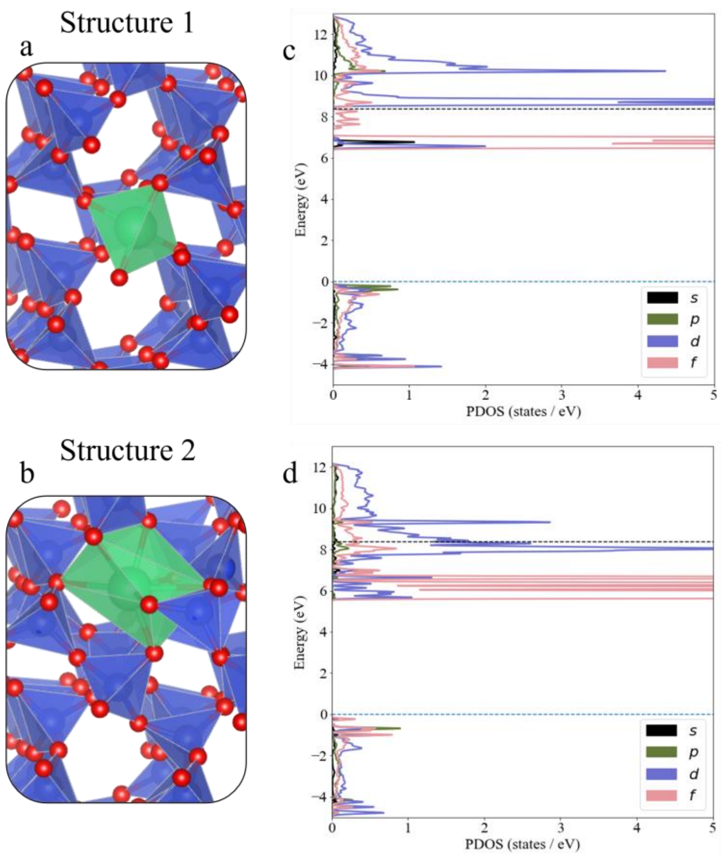
Back up

DFT calculations for SiO_2 by UCLA



DFT calculations for crystalline SiO_2 (experiment = amorphous)

2 structures modeled:

1. Th substitutes Si
2. Th and two O's are added as interstitial defect

Empty Th states emerge within the band gap for both structures

[5] S. V. Pineda *et al*. Radiative decay of the 229mTh nuclear clock isomer in different host materials, 2024.

Q: Is the 'quenching' actually a dead-time issue?

A: No