INPC 2025
May 25-30, 2025
DCC, Daejeon, Korea

The 29th International Nuclear Physics Conference
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The controlling of the Thorium-229 isomer states in CaF_2 crystal

Ming Guan*, Michael Bartokos, Kjeld Beeks, Hiroyuki Fujimoto, Yuta Fukunaga, Hiromitsu Haba, Yoshitaka Kasamatsu, Shinji Kitao, Adrian Leitner, Nobumoto Nagasawa, Martin Pimon, Martin Pressler, Makoto Seto, Yudai Shigekawa, Tomas Sikorsky, Kenji Tamasaku, Tsukasa Watanabe, Atsushi Yamaguchi, Yoshitaka Yoda, Takahiro Hiraki, Takahiko Masuda, Ryoichiro Ogake, Koichi Okai, Noboru Sasao, Fabian Schaden, Thorsten Schumm, Kotaro Shimizu, Sayuri Takatori, Akihiro Yoshimi, and Koji Yoshimura

* On behalf of Okayama Univeristy Th-229 group, guanming-s@s.okayama-u.ac.jp

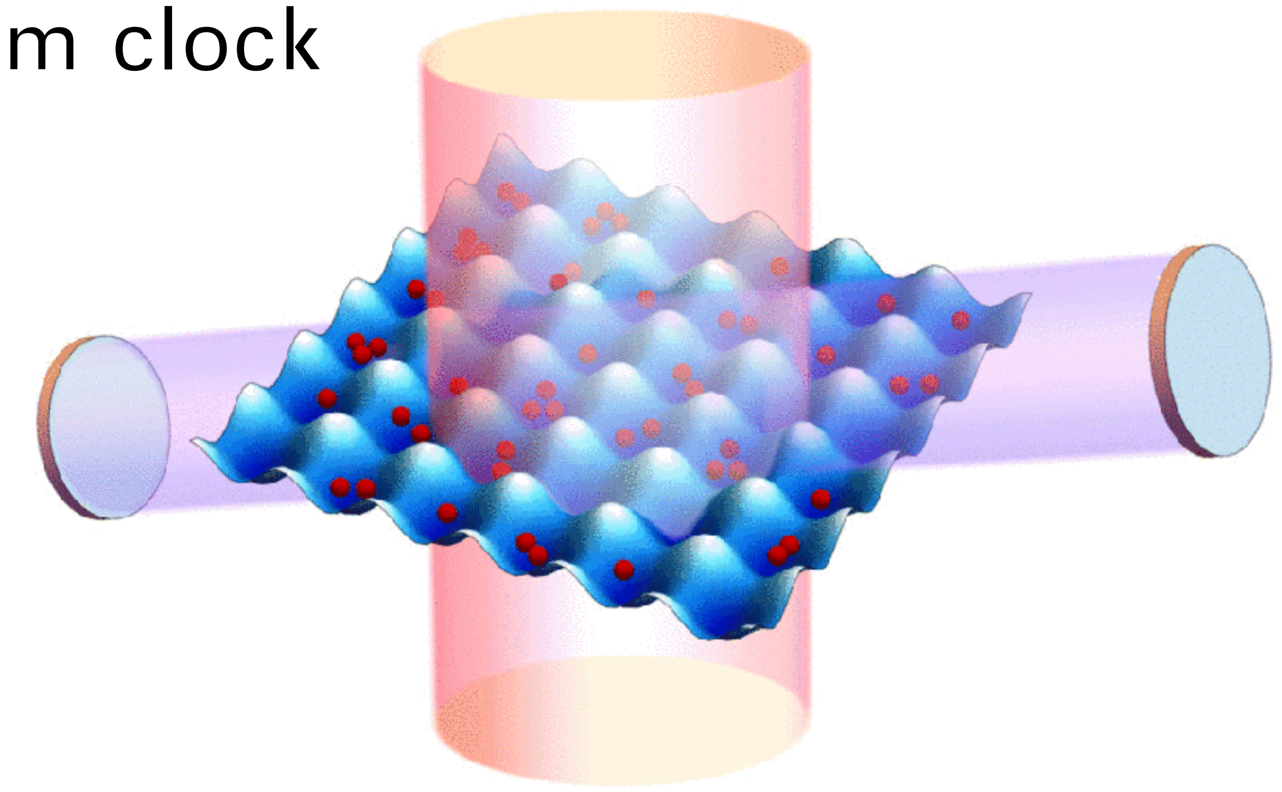
The 29th International Nuclear Physics Conference
Korea Daejeon, 2025 May

Thorium-229 and Nuclear Clock

- ^{229}Th has the lowest nuclear excited state among all nuclei (isomeric state, $^{229m}\mathrm{Th}$)
  - $E = 8.356\,\mathrm{eV}$ corresponds to 148 nm (VUV photons)
  - Application to nuclear clocks (frequency standard using $^{229g}\mathrm{Th} \leftrightarrow {}^{229m}\mathrm{Th}$ transition)

- In contrast to atomic clocks, solid-state nuclear clock can be realized

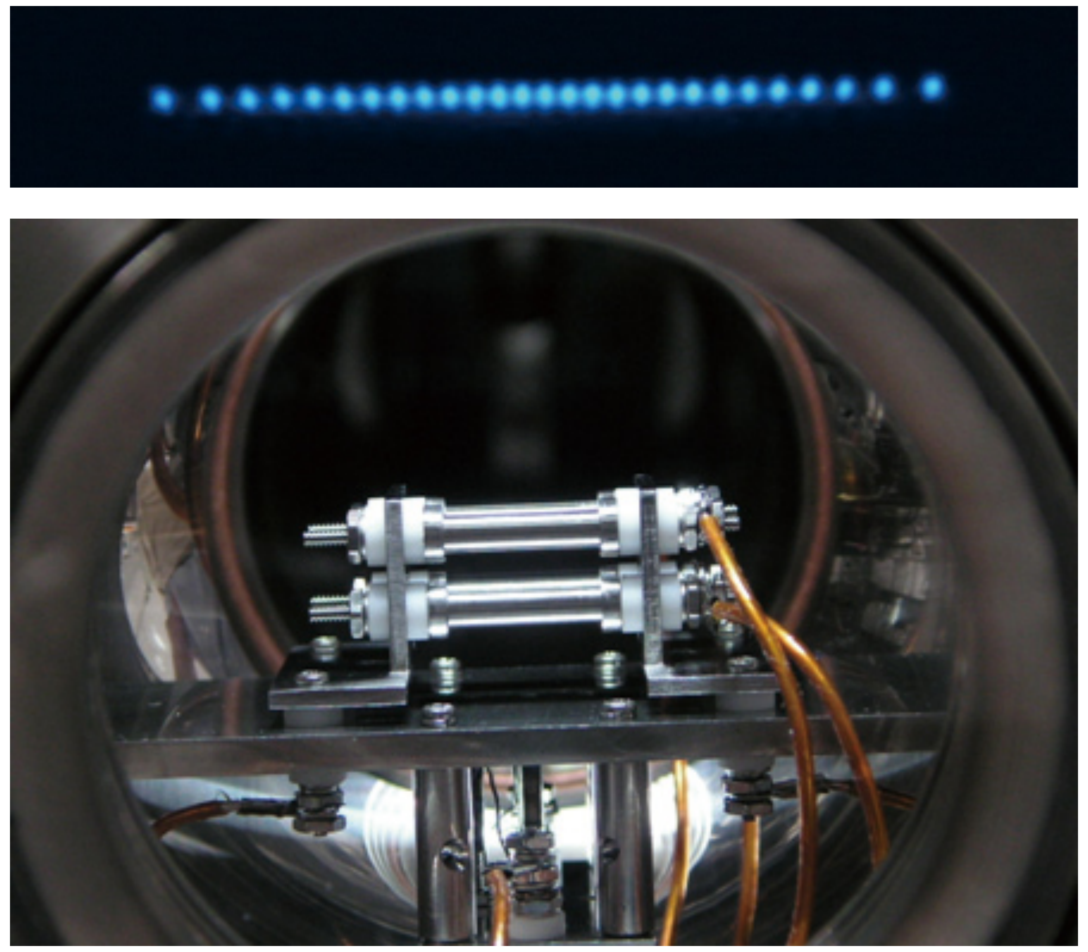
Atom clock



Optical Littice

Nature 455:207 (2008).

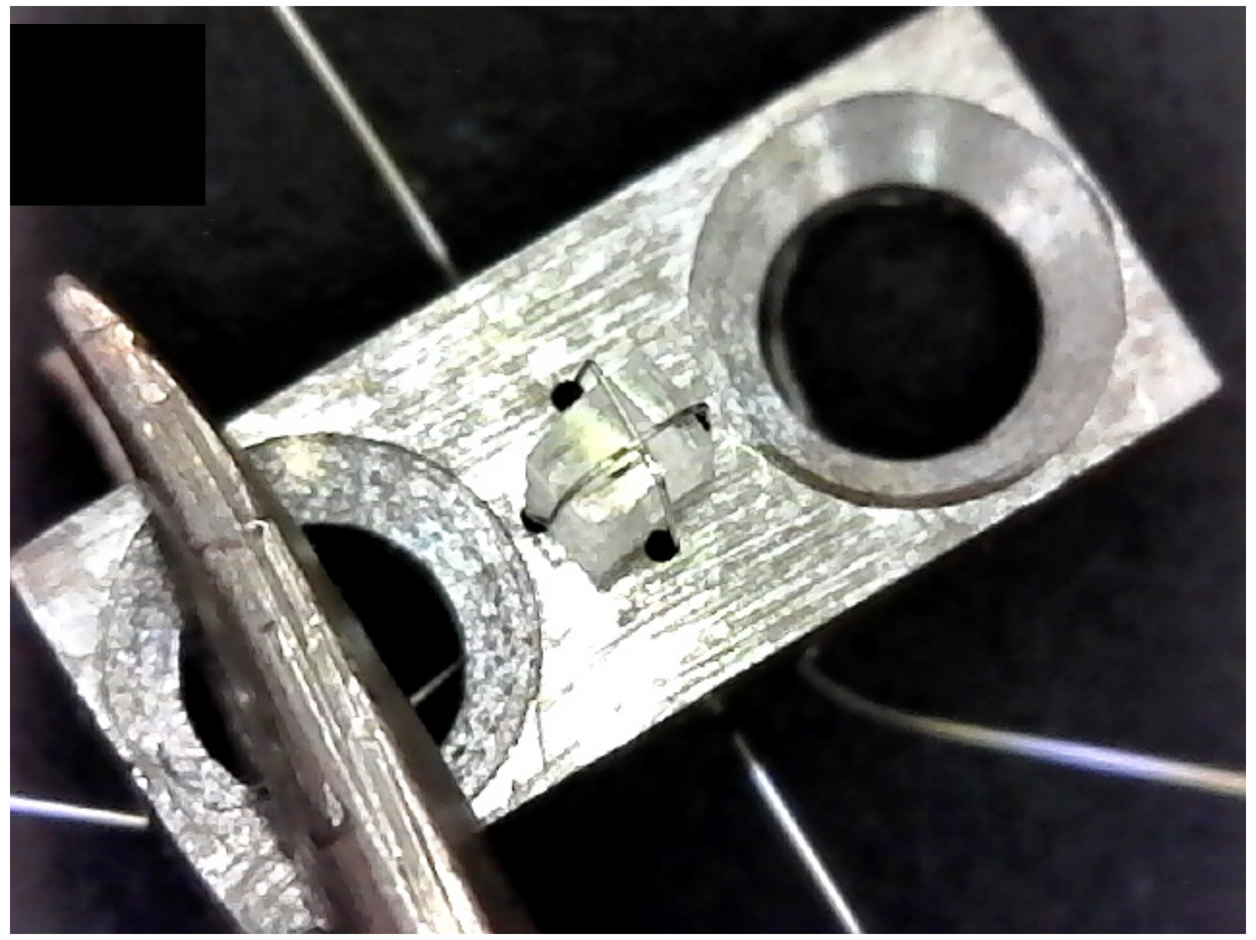
Ion clock



Ion trap

NICT NEWS 2021 No. 2 (Vol. 486)

Solid-state nuclear clock



Crystal Lattice

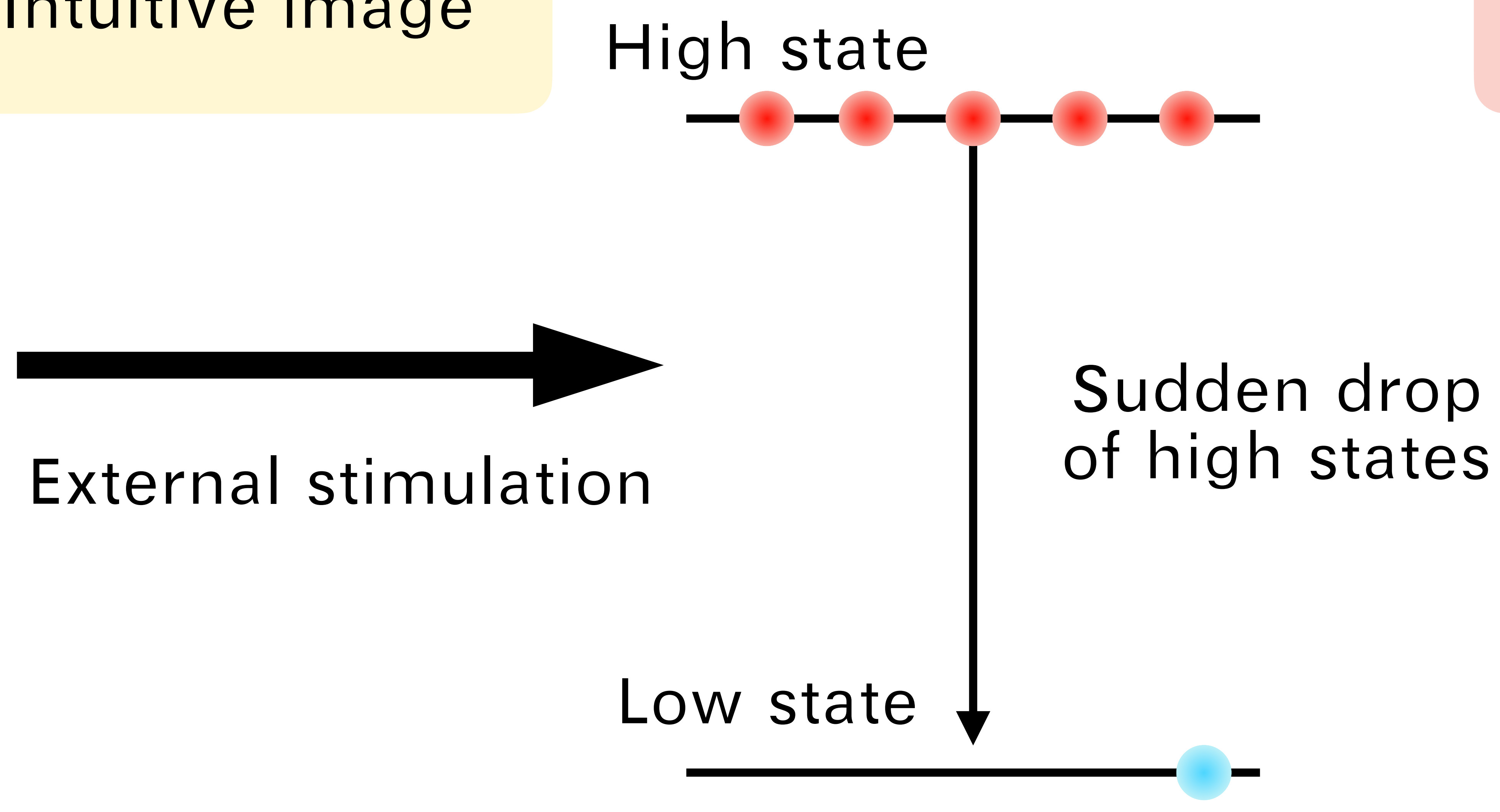
Our group's discovery: XIQ

- 2018, the X-ray pumping of the ^{229m}Th states T. Masuda et al., Nature 573, 238 (2019)
- 2023, we succeeded in observing VUV photons from ^{229m}Th T. Hiraki et al., Nat. Comm. 15, 5536 (2024)

Moreover, we found the X-ray induced quenching (XIQ) of ^{229m}Th

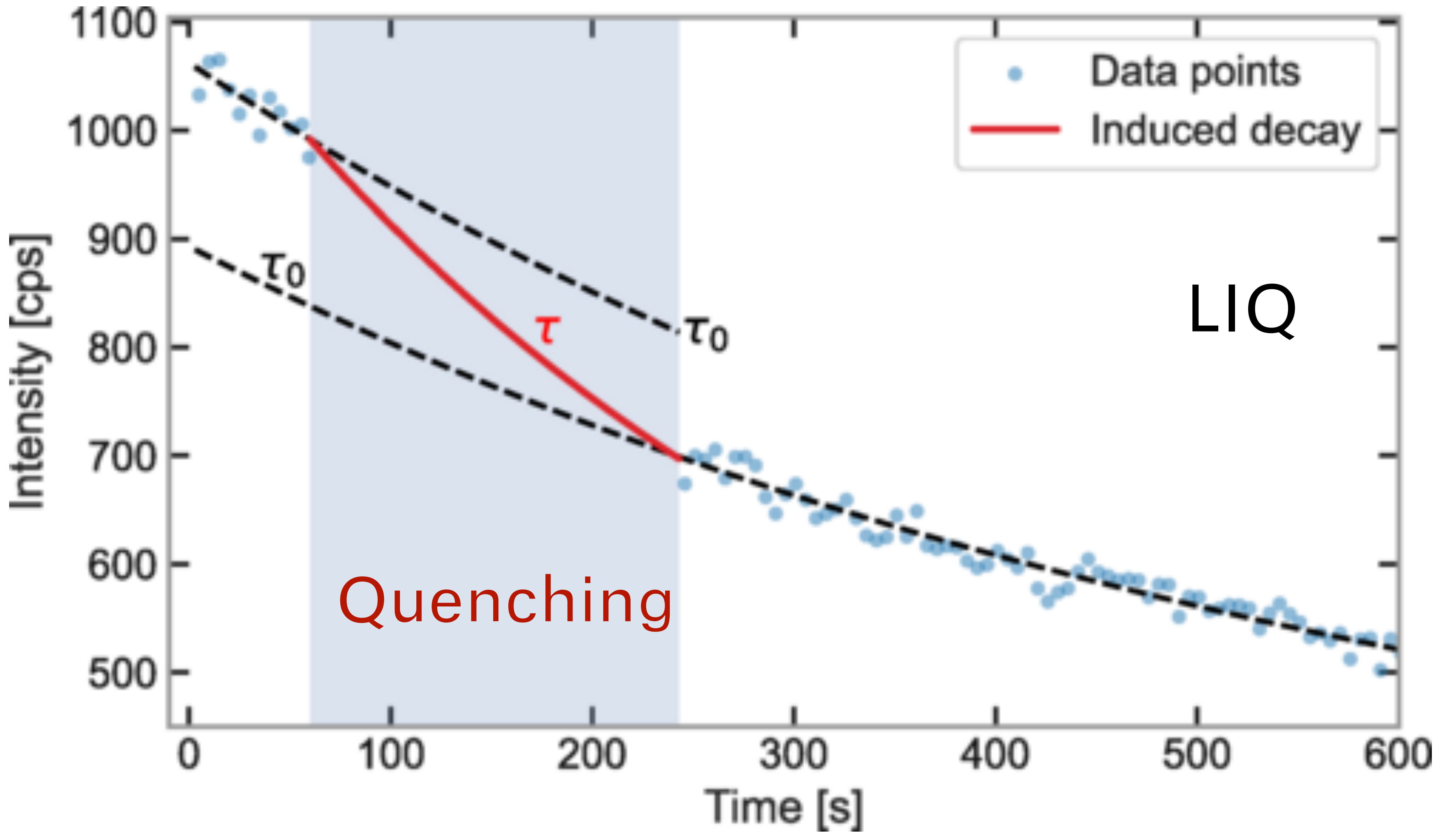
→ Controlling (NRS & XIQ) the ^{229m}Th state can update the performance of nuclear clock

Intuitive image



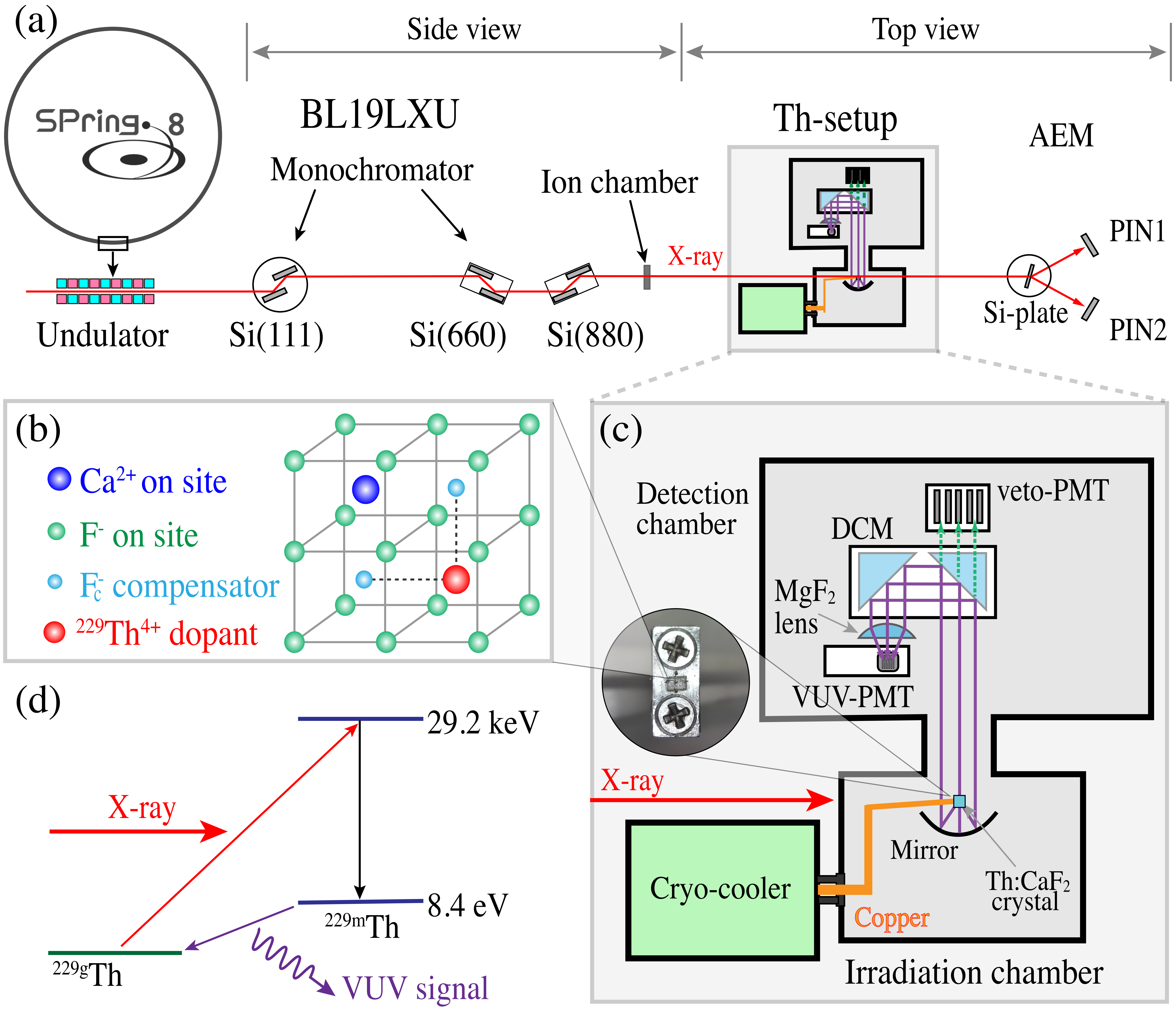
Experiment measurement

Phys. Rev. Research 7, L022036

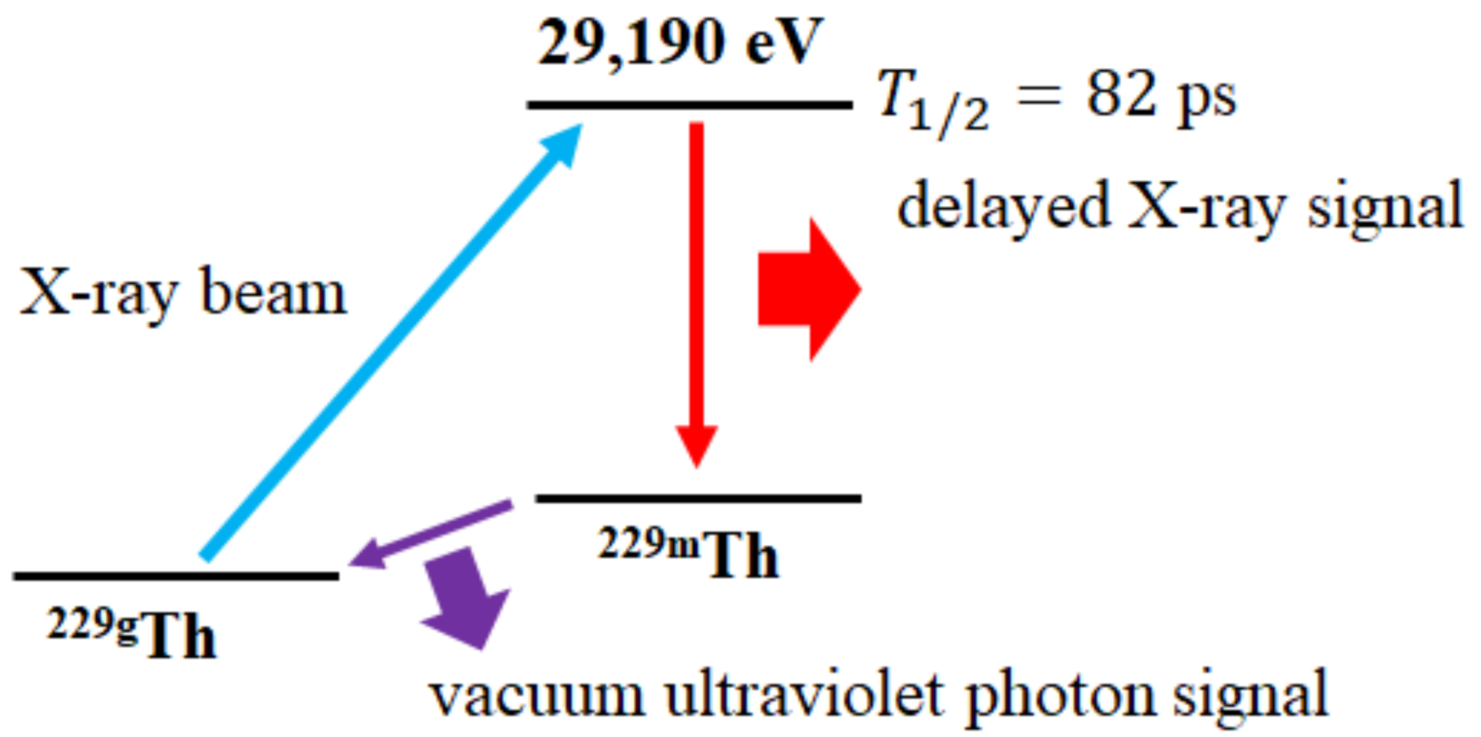


SPring-8, the largest 3rd generation SR in Japan

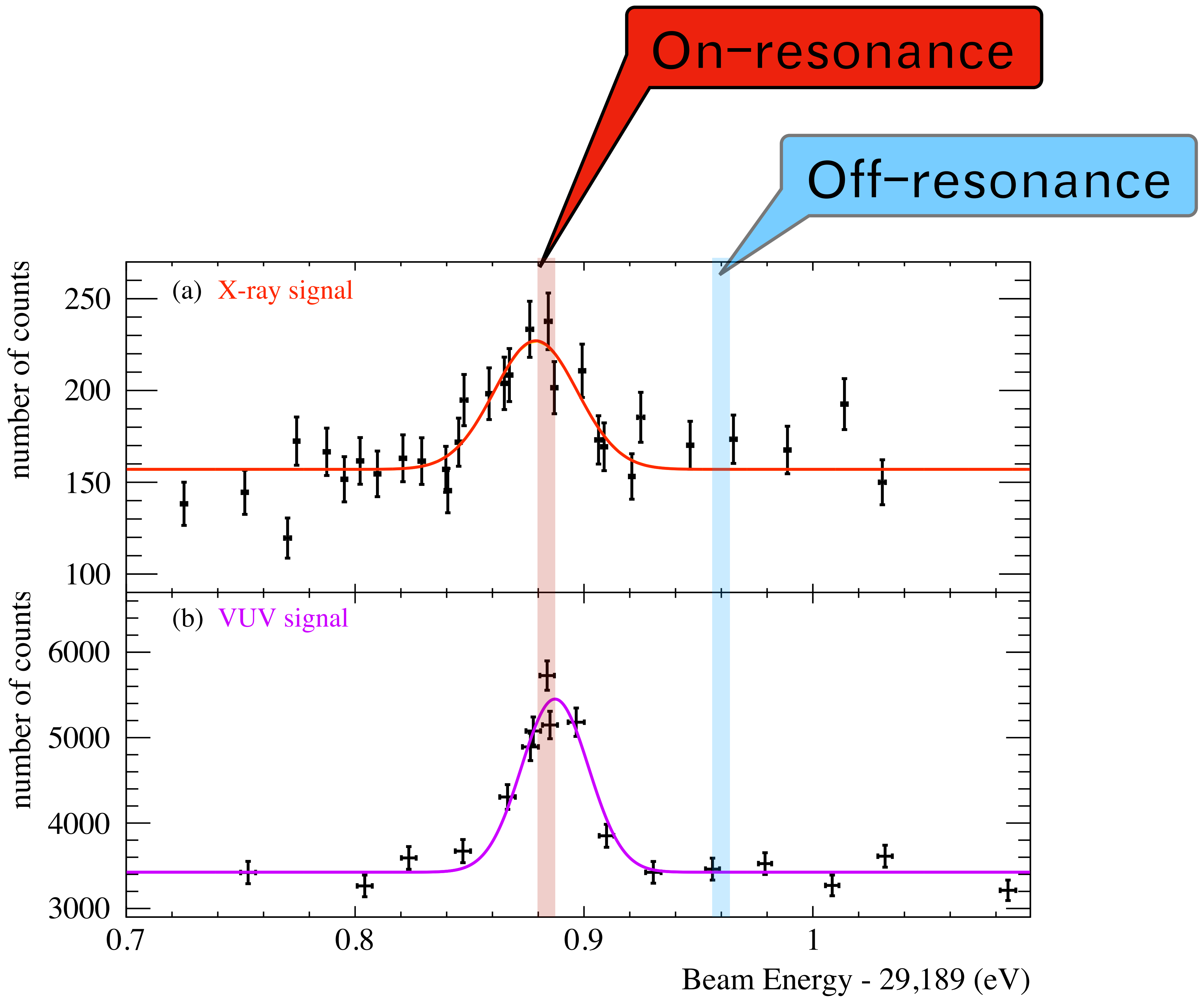
Items	Values
X-ray energy	29189 eV
Bandwidth	~14 meV
Photon flux	~16 x 10^{10} ph./s
Spot size	~1.0 x 0.5 mm^2



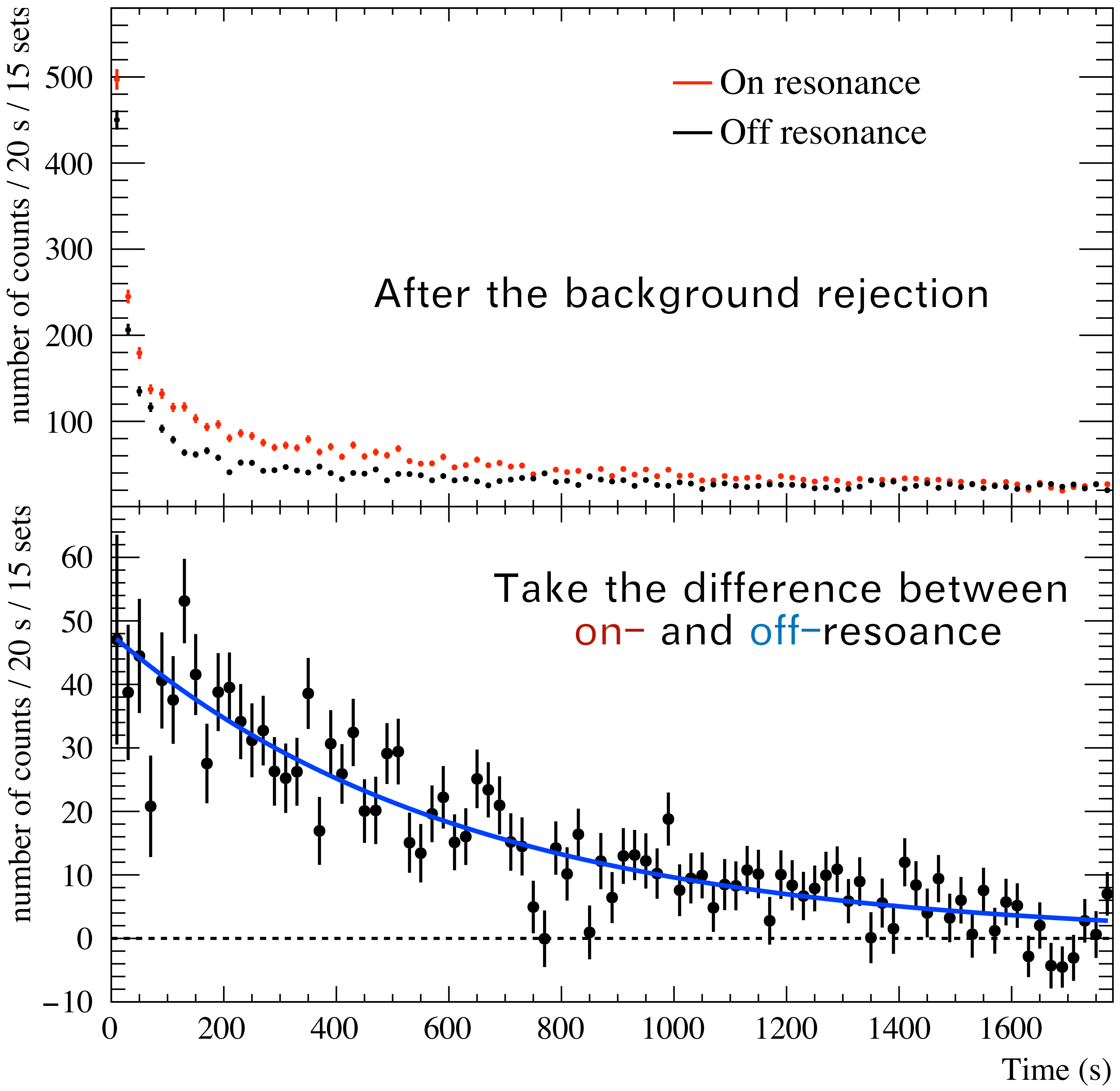
The Nuclear Resonance Scattering method



T. Masuda et al., Natture 573, 238 (2019)

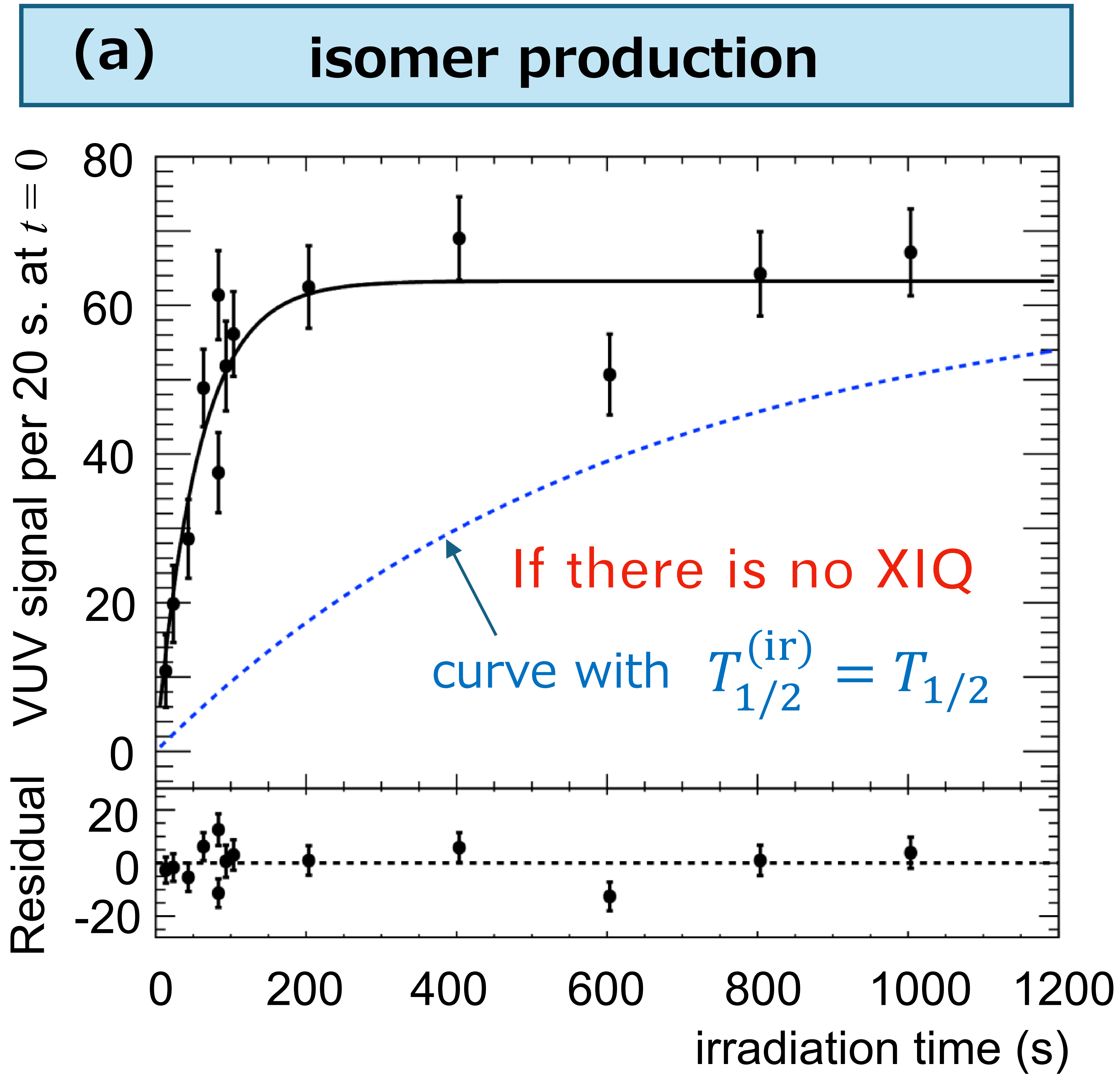


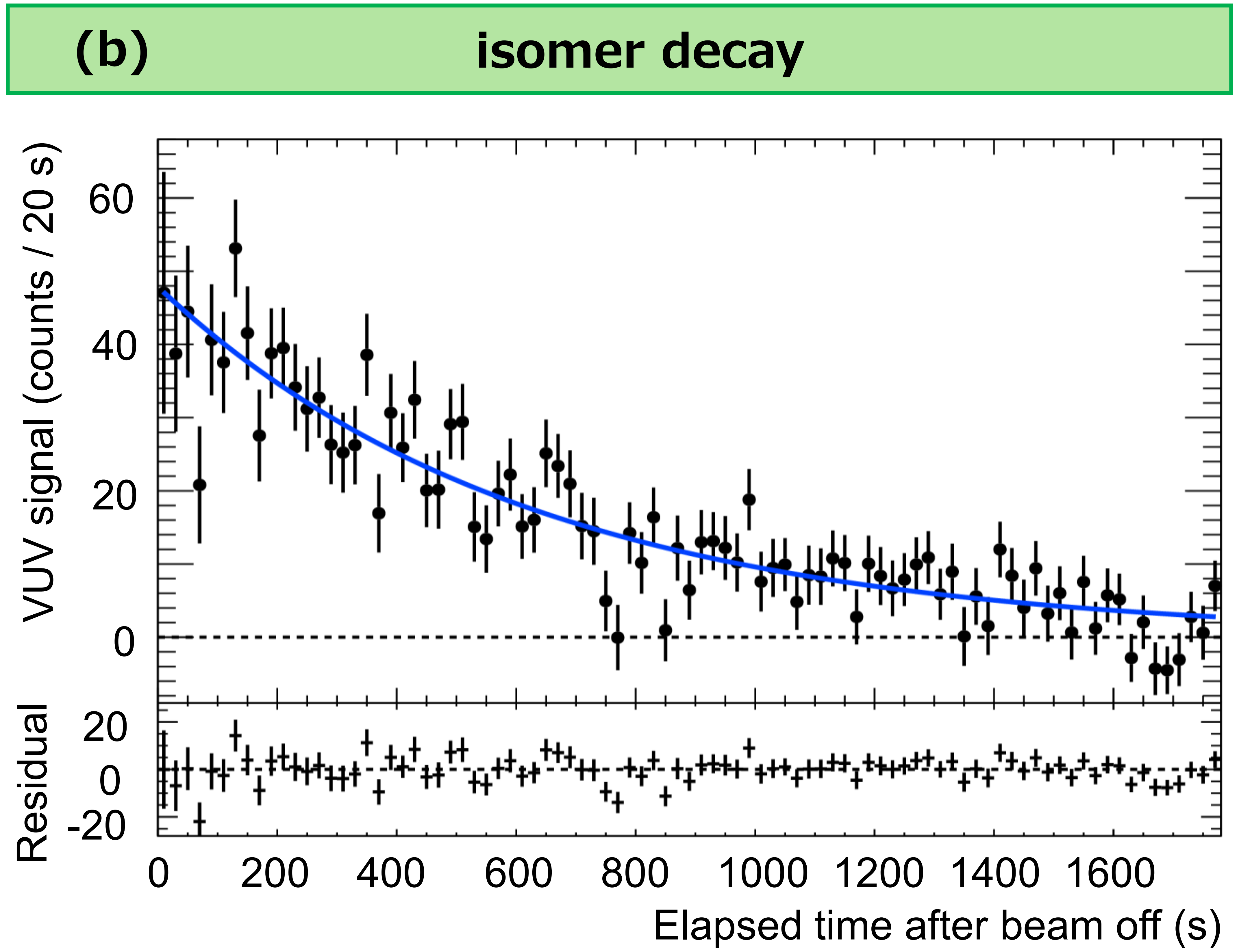
T. Hiraki et al., Nat. Comm. 15, 5536 (2024)



The discovery of XIQ

T. Hiraki et al., Nat. Comm. 15, 5536 (2024)



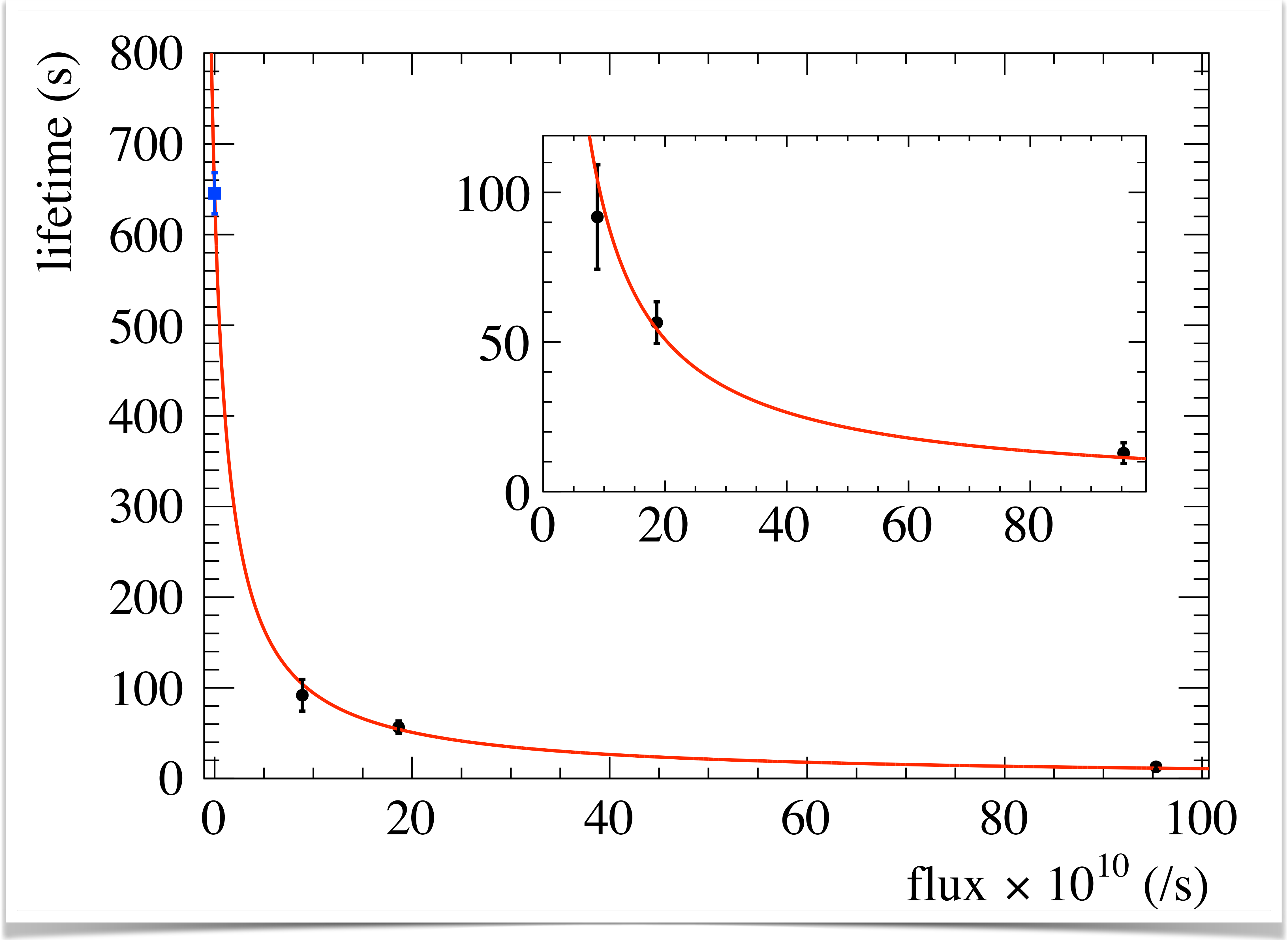


$$\text{Quench factor (QF)} = \frac{{}^{229m}\text{Th natural radiative decay lifetime}}{{}^{229m}\text{Th X-ray irradiation induced quench lifetime}} = \frac{640\ \text{s}}{60\ \text{s}} \sim 11$$

XIQ dependence on X-ray flux

T. Hiraki et al., Nat. Comm. 15, 5536 (2024)

The lifetime of ^{229m}Th during XIQ



Stronger X-ray intensity, stronger quenching.

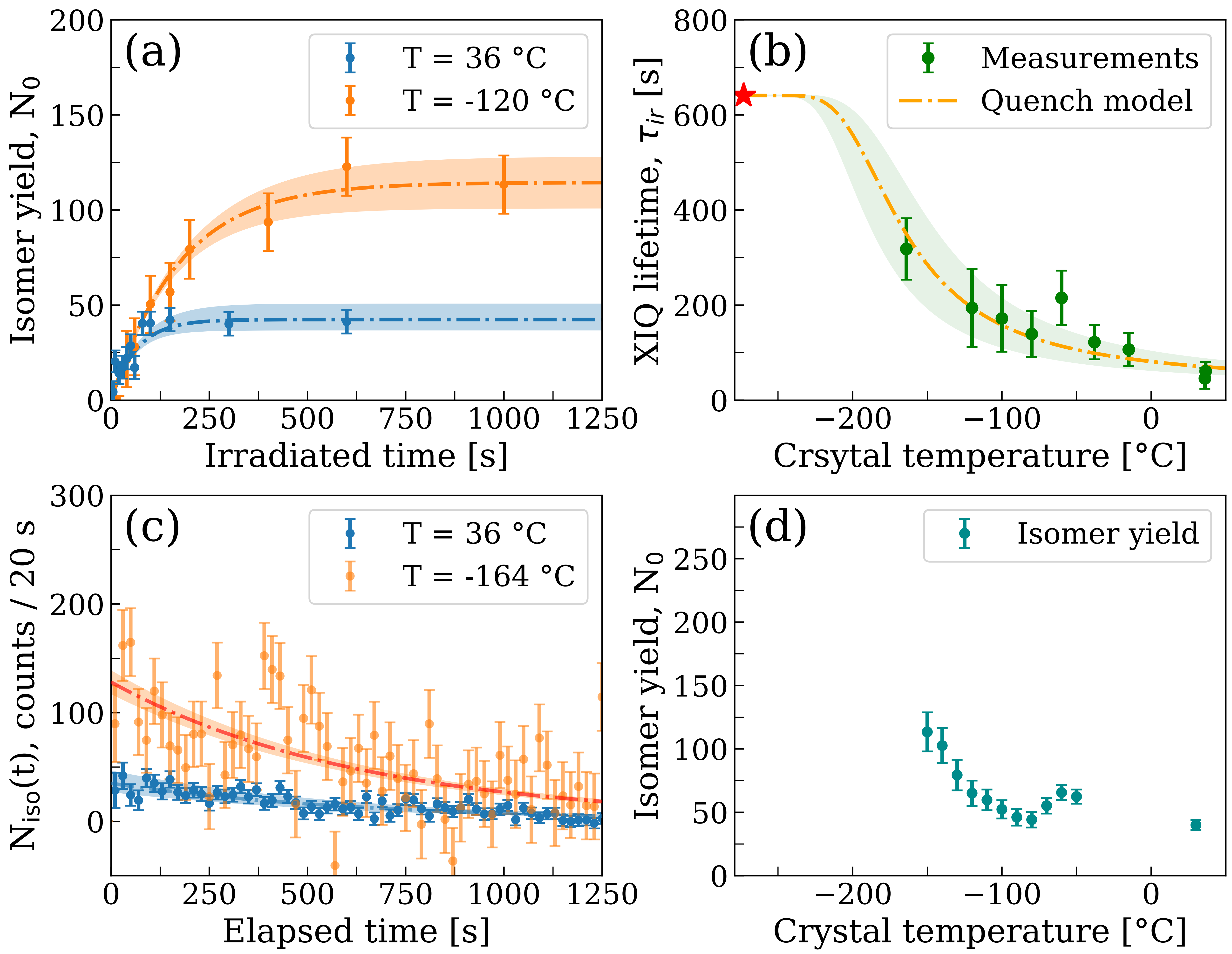
The quenching rate proportional to X-ray flux.

$$\tau_{ir} = \frac{1}{\Gamma_0 + \Gamma_q}$$

$$\Gamma_q = k \cdot f_{\text{X-ray}}$$

XIQ dependence on crystal temperature

arXiv:2505.03852v1



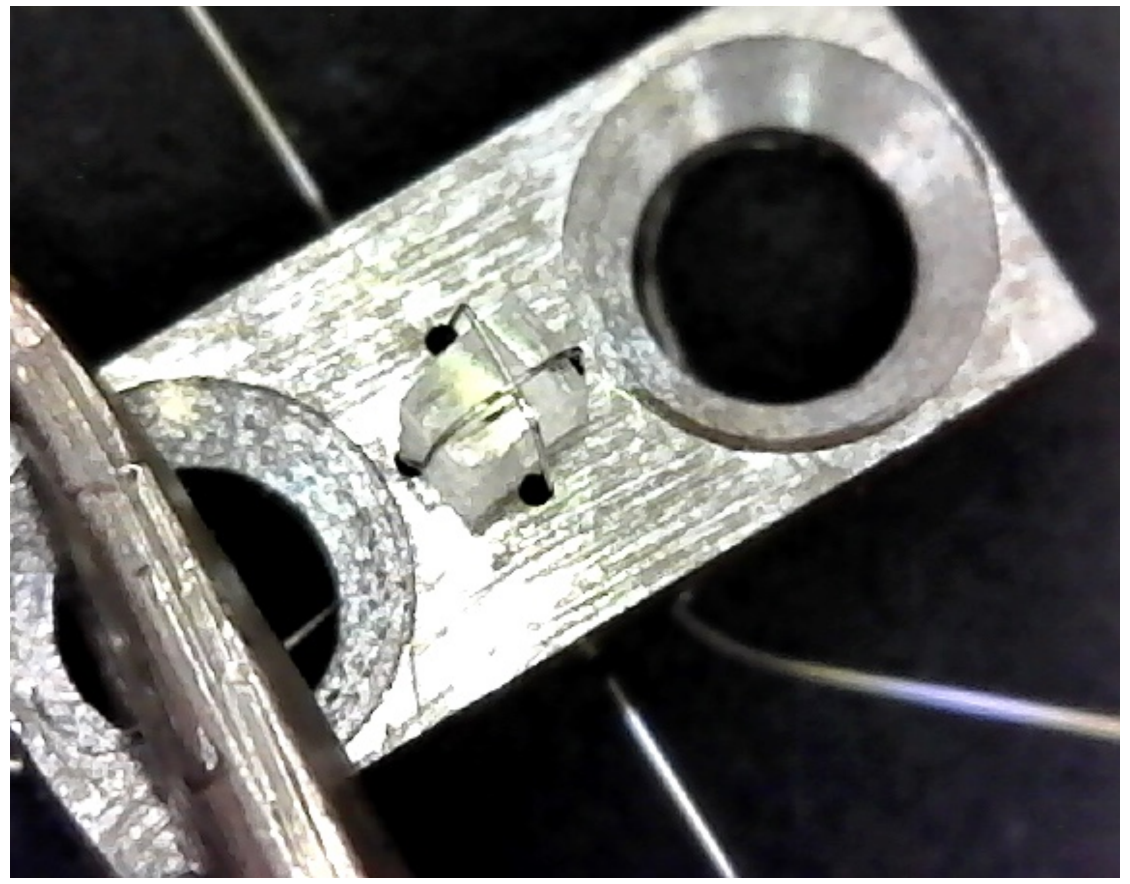
- The lower temperature
- The smaller XIQ amplitude
- The longer τ_{ir}
- The more ^{229m}Th yield

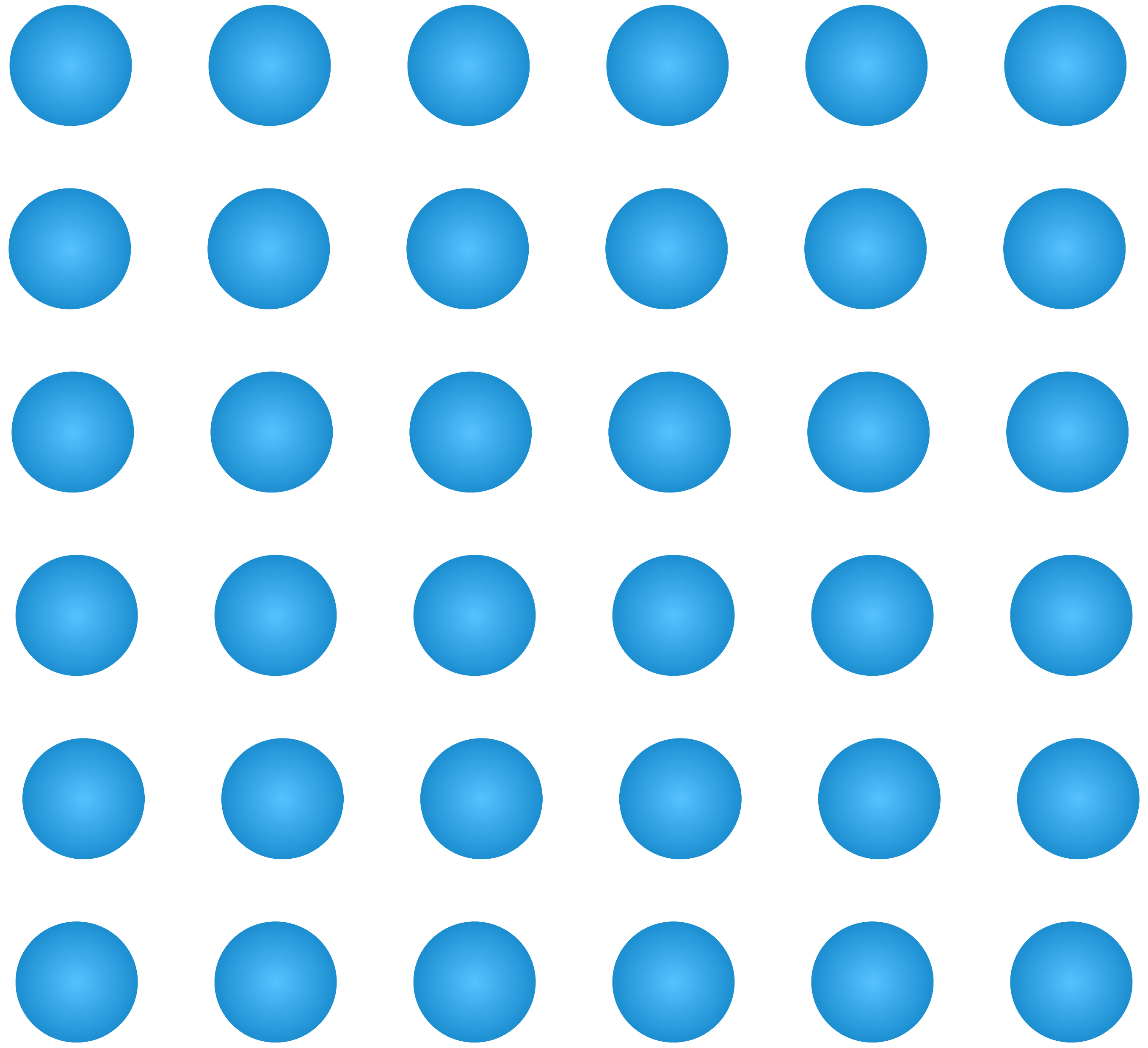
Conclusion:

Cooling the crystal can mitigate the XIQ process.

The color–centers in crystals

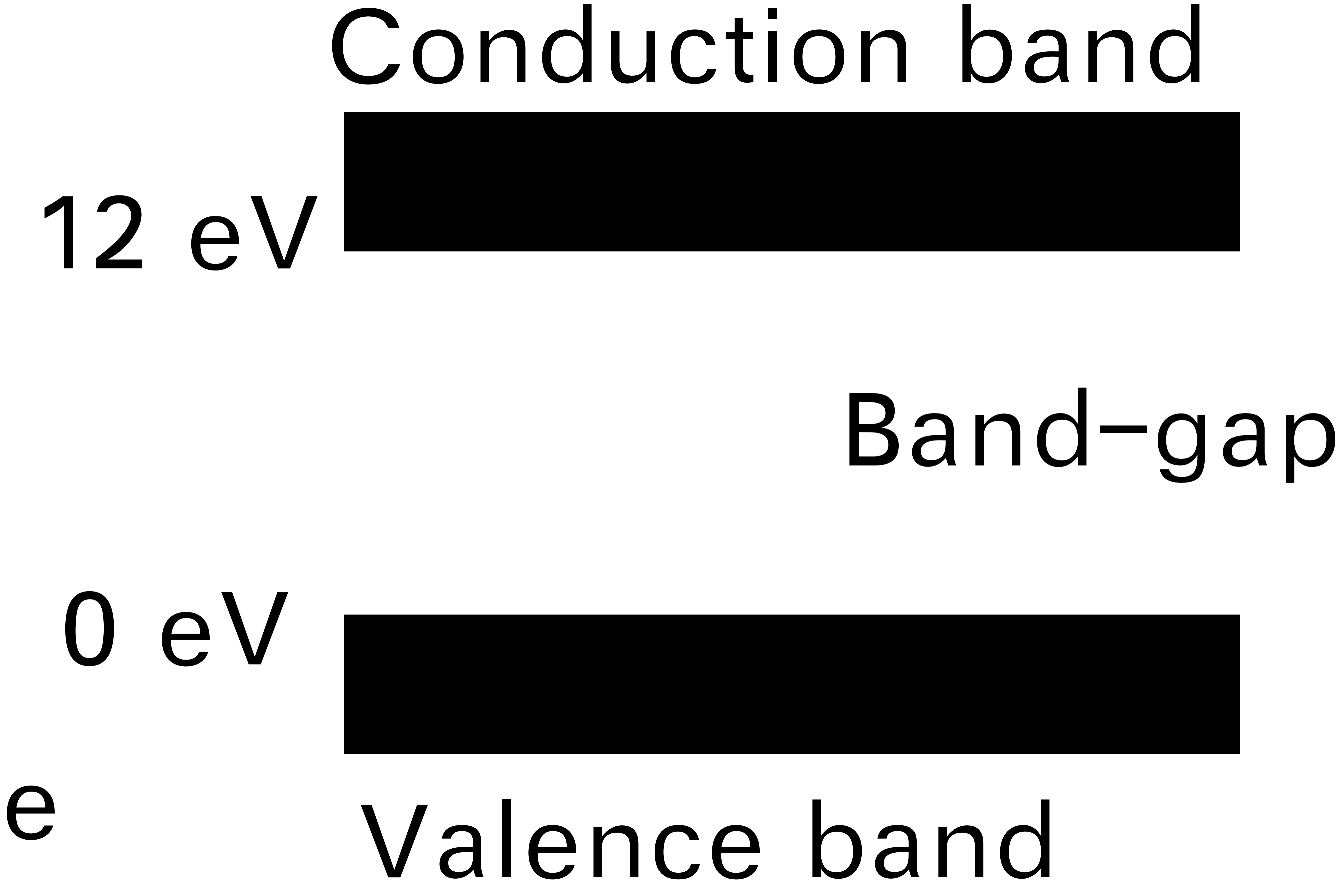
- A mini–review about color–centers in solid–state physics





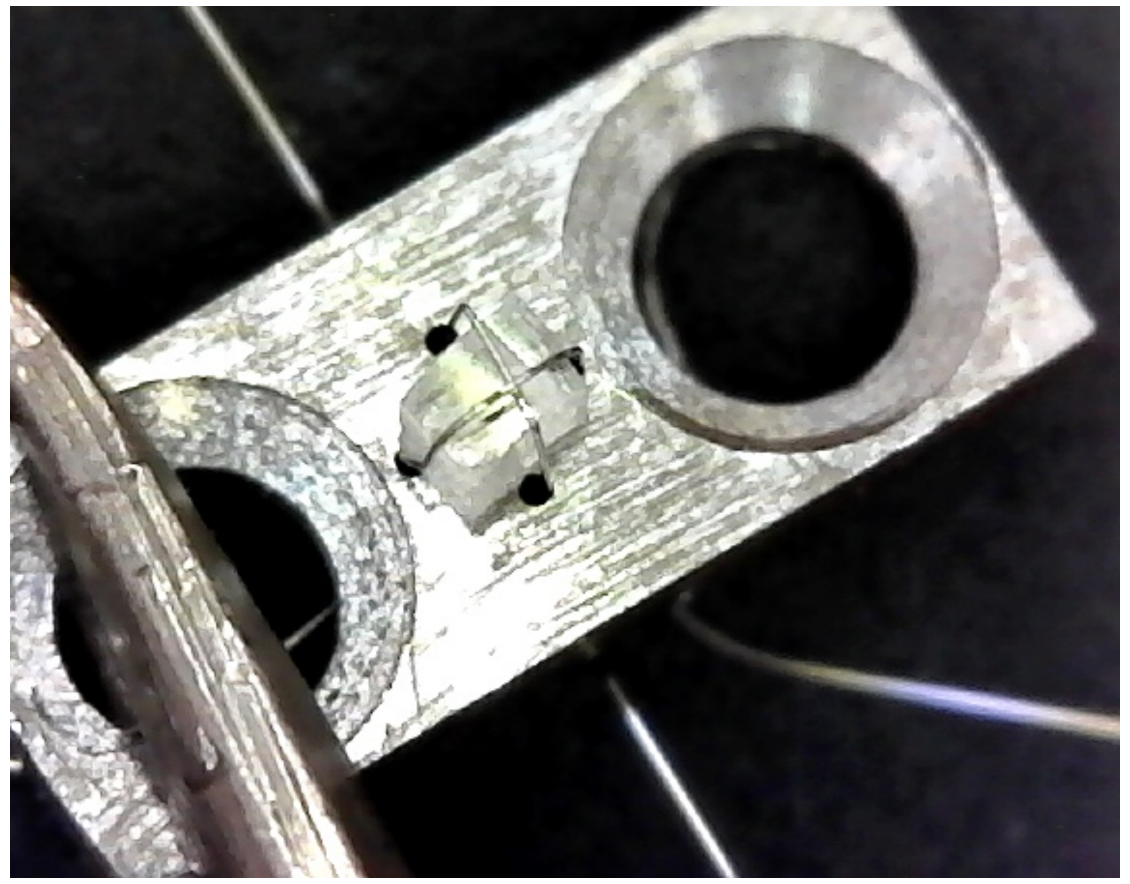
Perfect crystal lattice structure

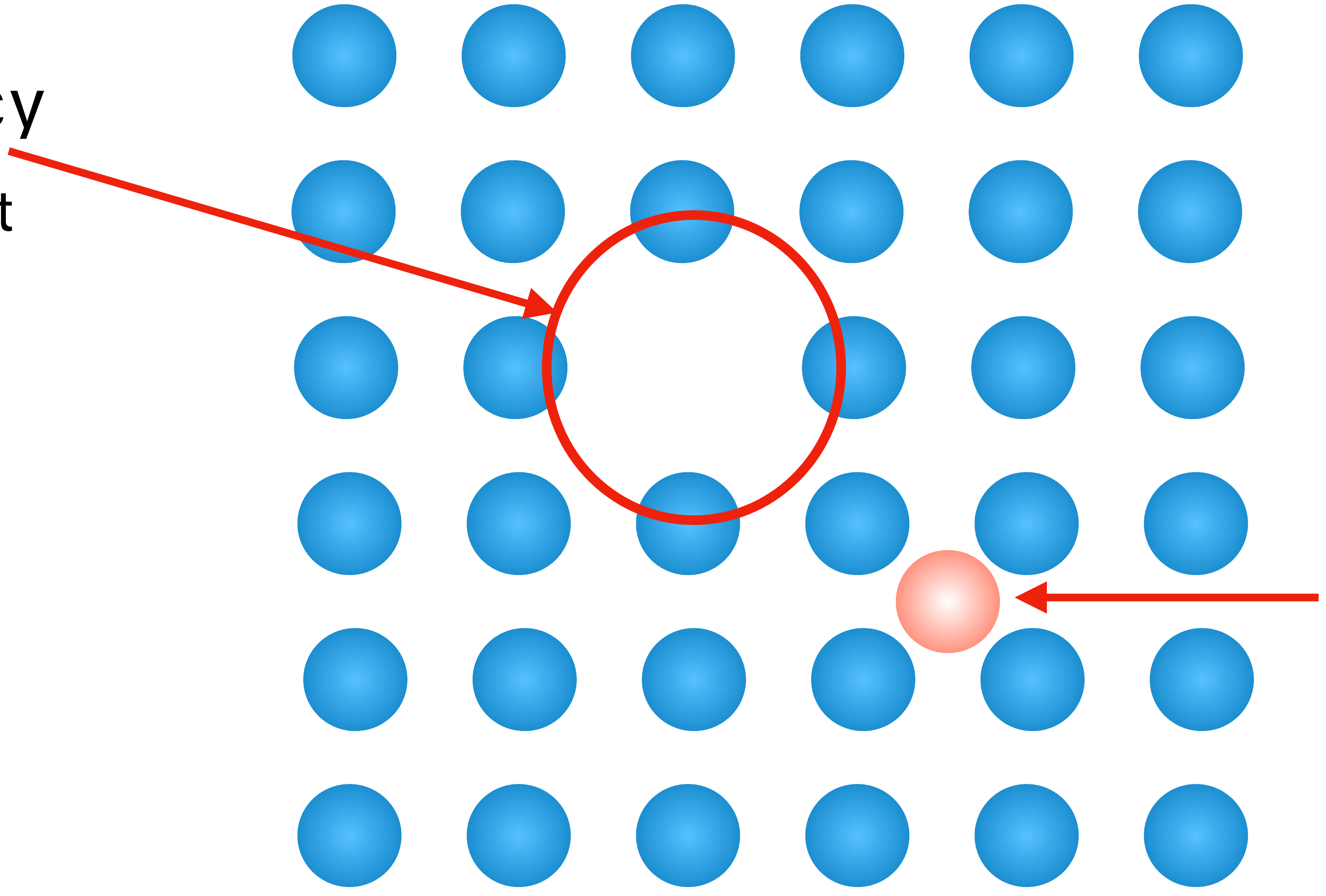
F^-



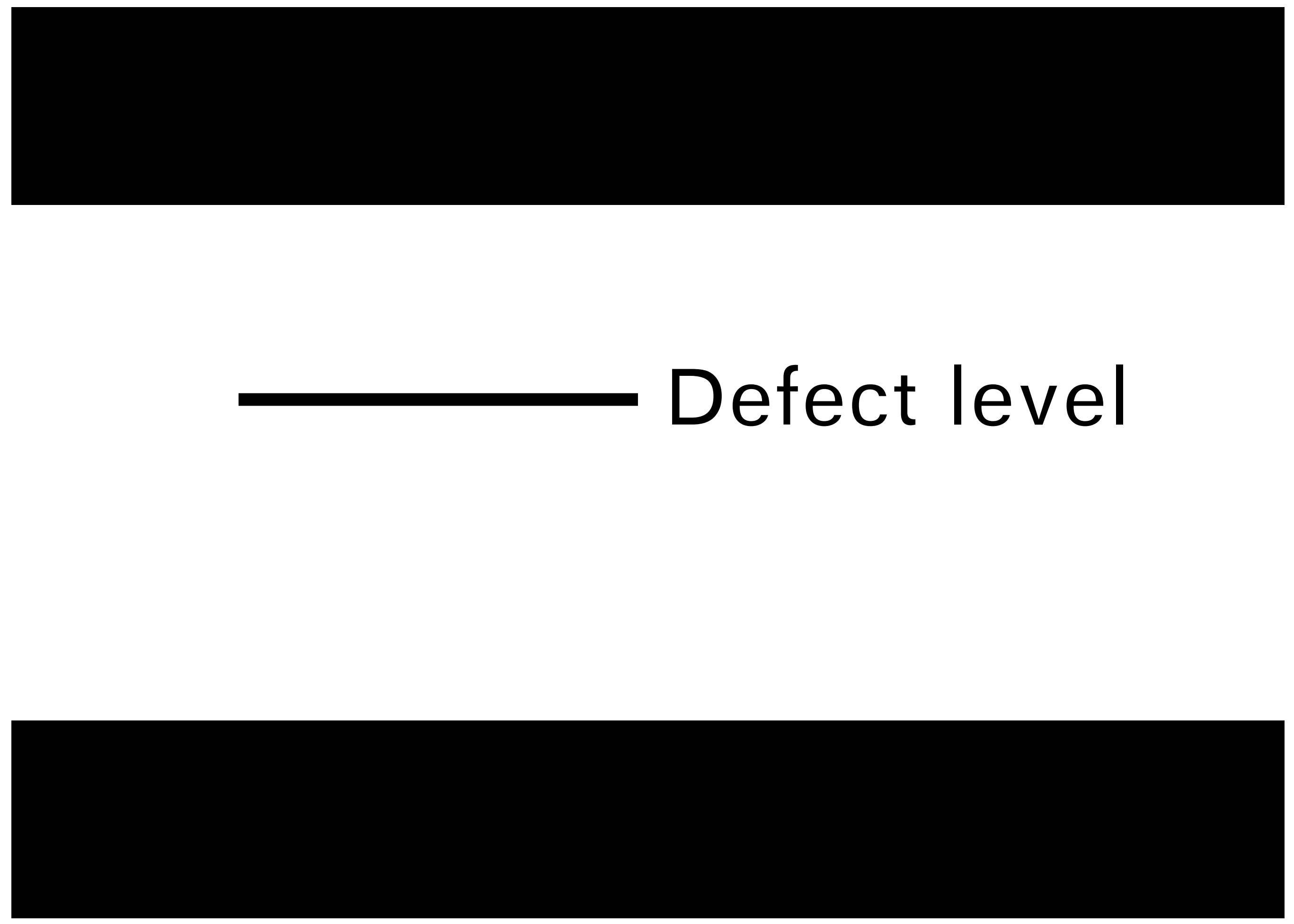
The color-centers in crystals

- A mini-review about color-centers in solid-state physics



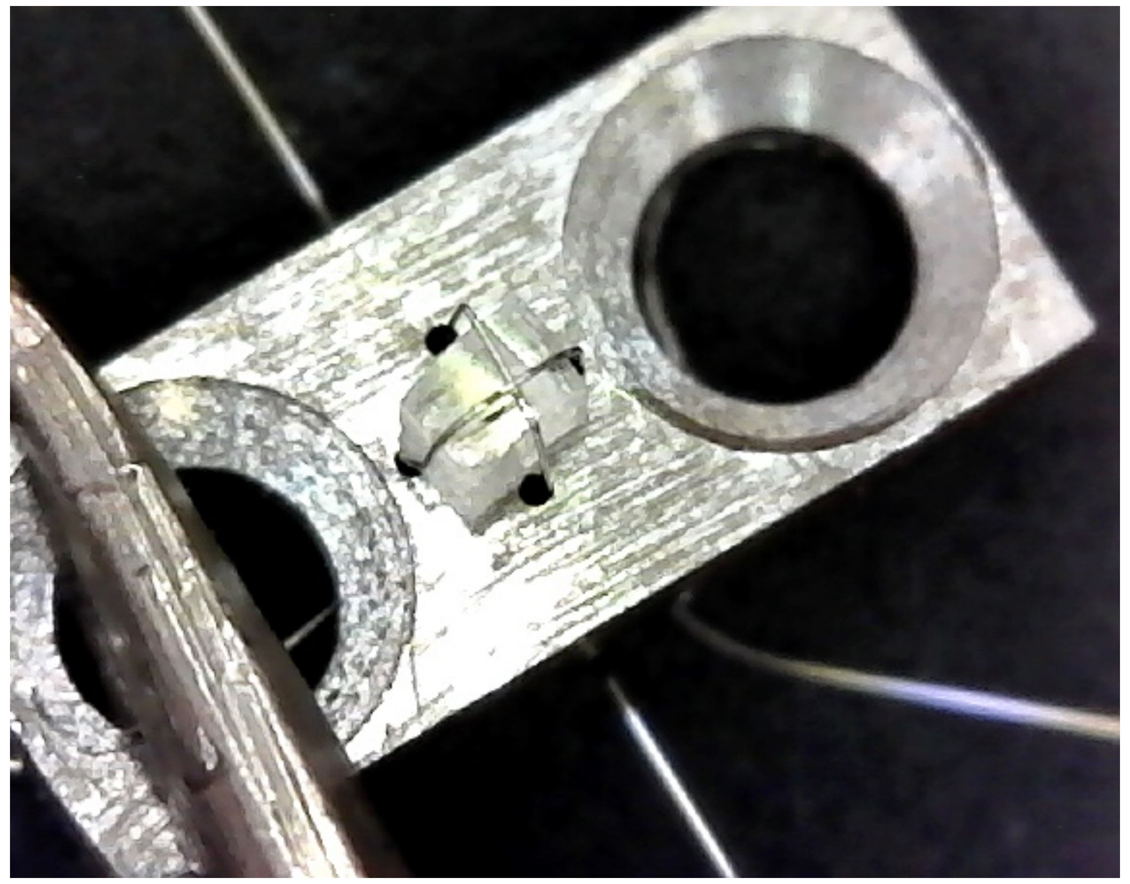


Perfect crystal lattice structure



The color-centers in crystals

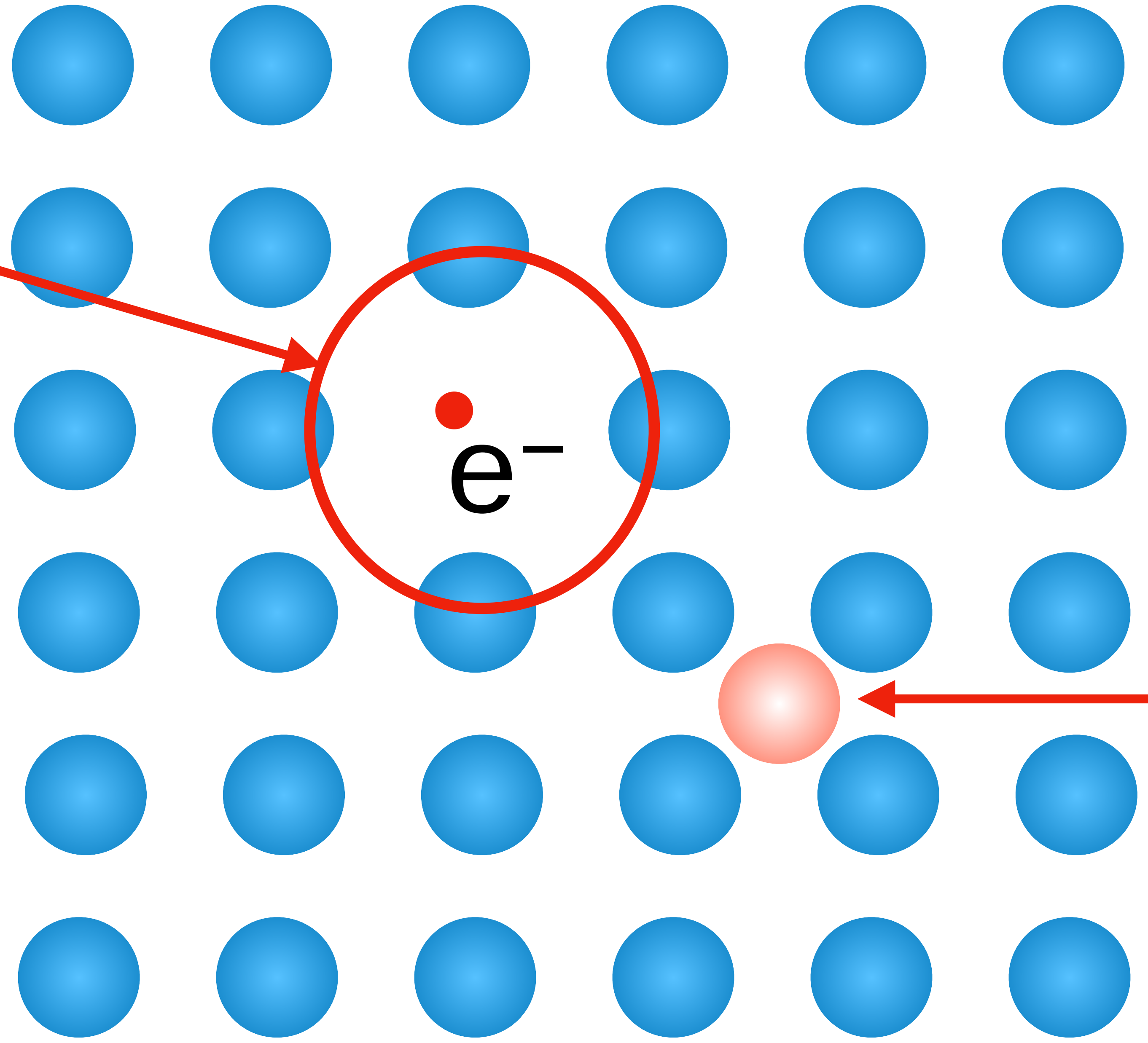
- A mini-review about color-centers in solid-state physics



Anion vacancy

Potential well in quantum mechanics

F-center



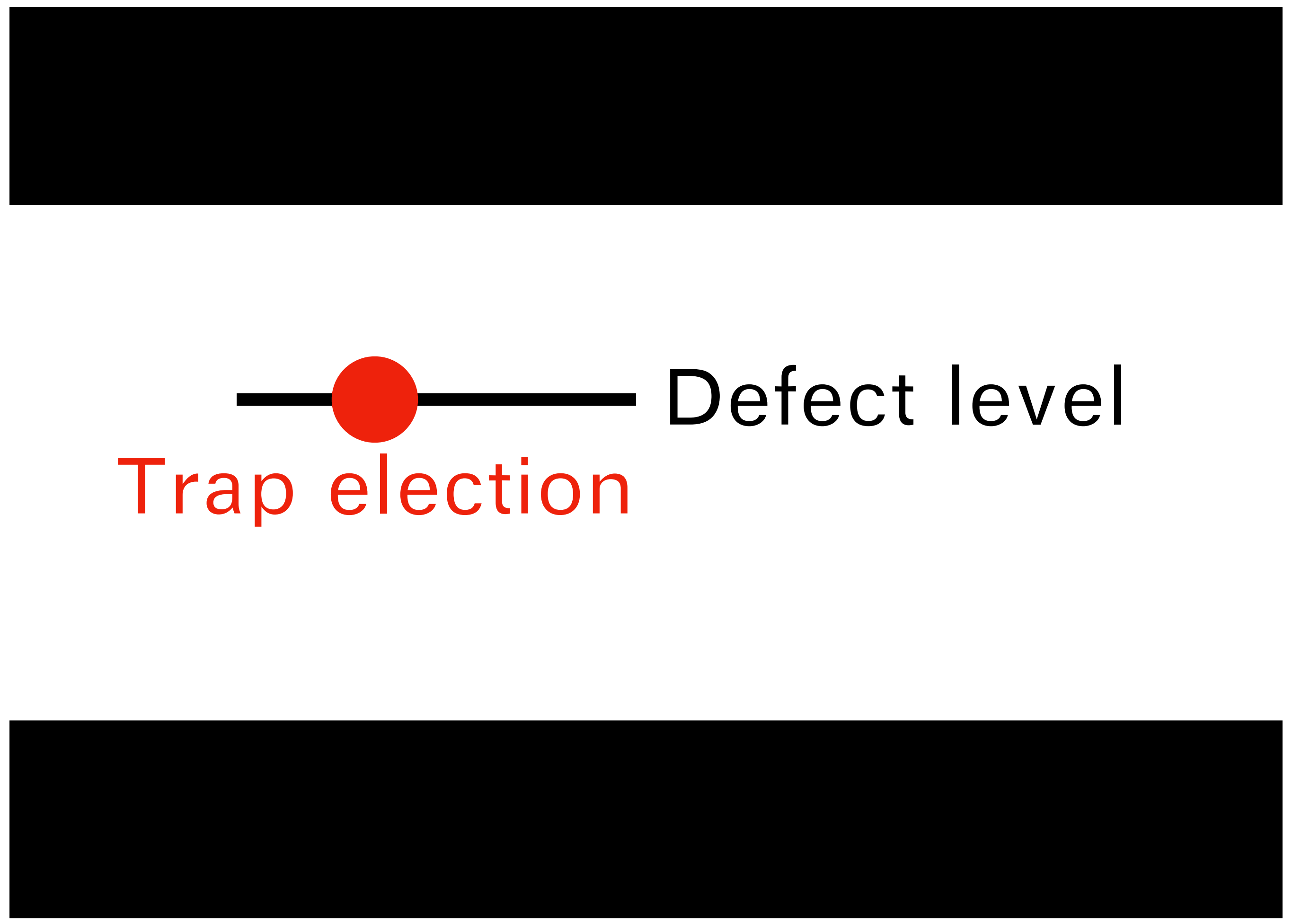
Interstitial atom

Perfect crystal lattice structure

F⁻

Conduction band

12 eV



Defect level

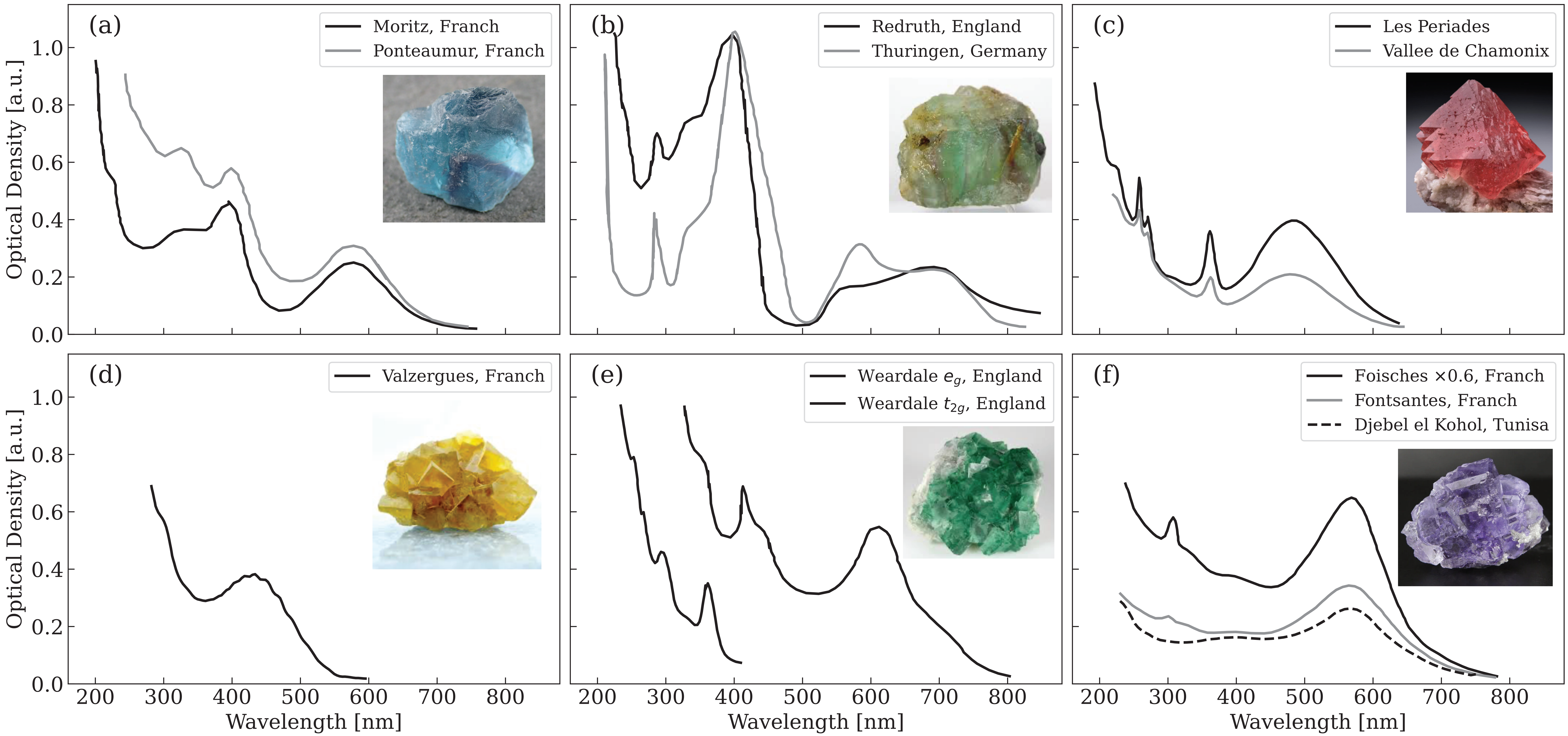
Trap election

0 eV

Valence band

Mineral CaF_2 crystals with different color-centers

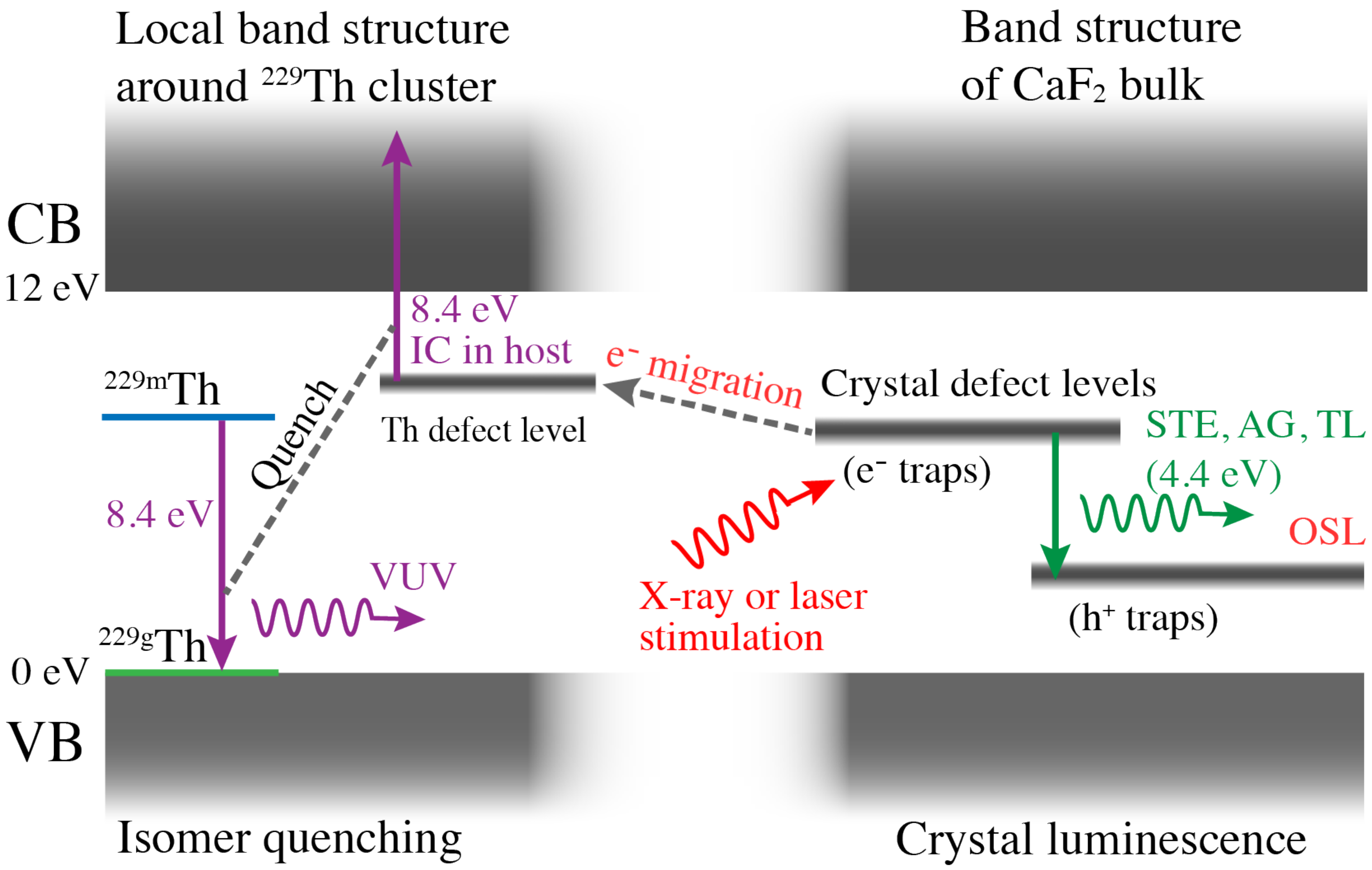
H. Bill et al., Physics and Chemistry of Minerals 3, 117–131 1978



^{229m}Th Quenching model

arXiv:2505.03852v1

Very Preliminary!



Summaries

- We used the 29.2-keV X-ray to pump the ^{229}Th nucleus to the isomer state
- The VUV signal was detected by the our setup
- The spontaneous lifetime of ^{229m}Th is measured as 646(37) s in CaF_2 crystal
- X-ray can induce the quenching of ^{229m}Th in CaF_2
- Quench can be used for nuclear clock initialization
- Cooling the crystal can mitigate the XIQ magnitude, resulting in
  - Longer lifetime during X-ray irradiation
  - Larger ^{229m}Th yields during X-ray irradiation
- A quenching model based on e^- migration in the crystal is proposed

More details could be found at here!

arXiv:2505.03852 [pdf, other] cond-mat.mtrl-sci nucl-ex

X-ray induced quenching of the 229Th clock isomer in CaF_2

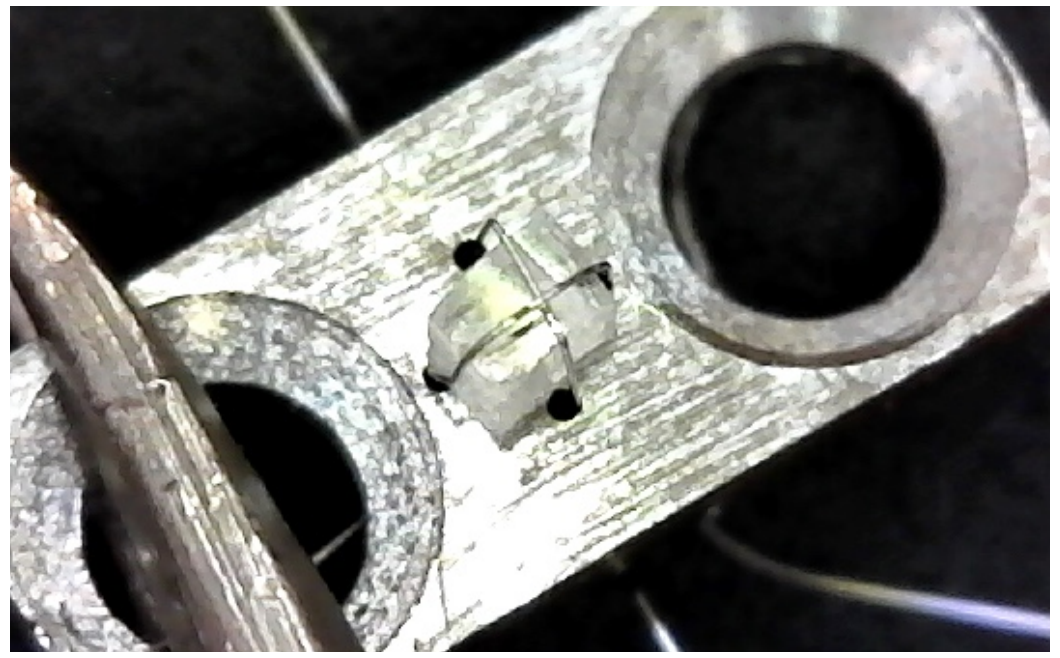
Authors: Ming Guan, Michael Bartokos, Kjeld Beeks, Hiroyuki Fujimoto, Yuta Fukunaga, Hiromitsu Haba, Takahiro Hiraki,

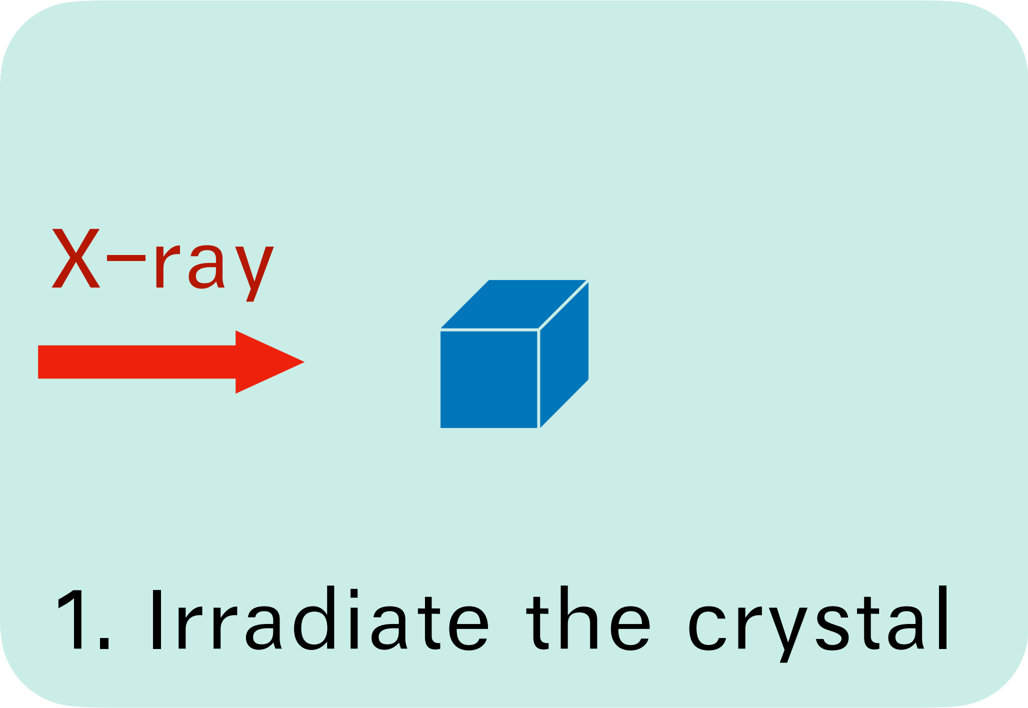
Acknowledgement

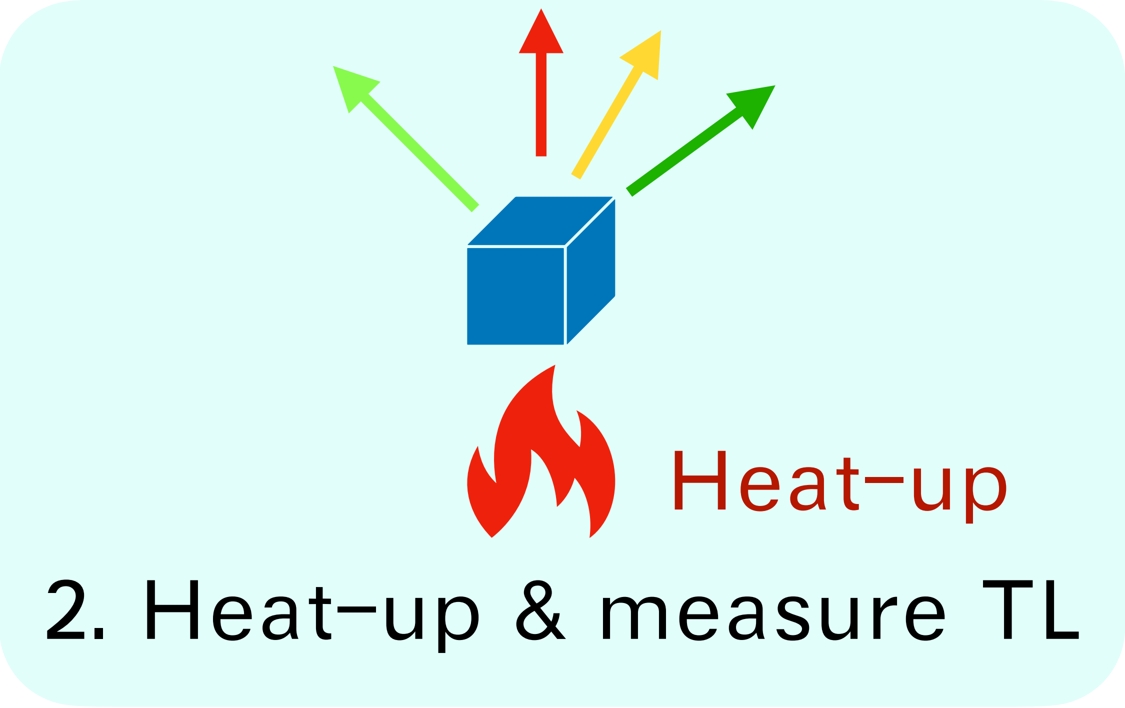
Thanks for your attention!

Any comments will be appreciated.

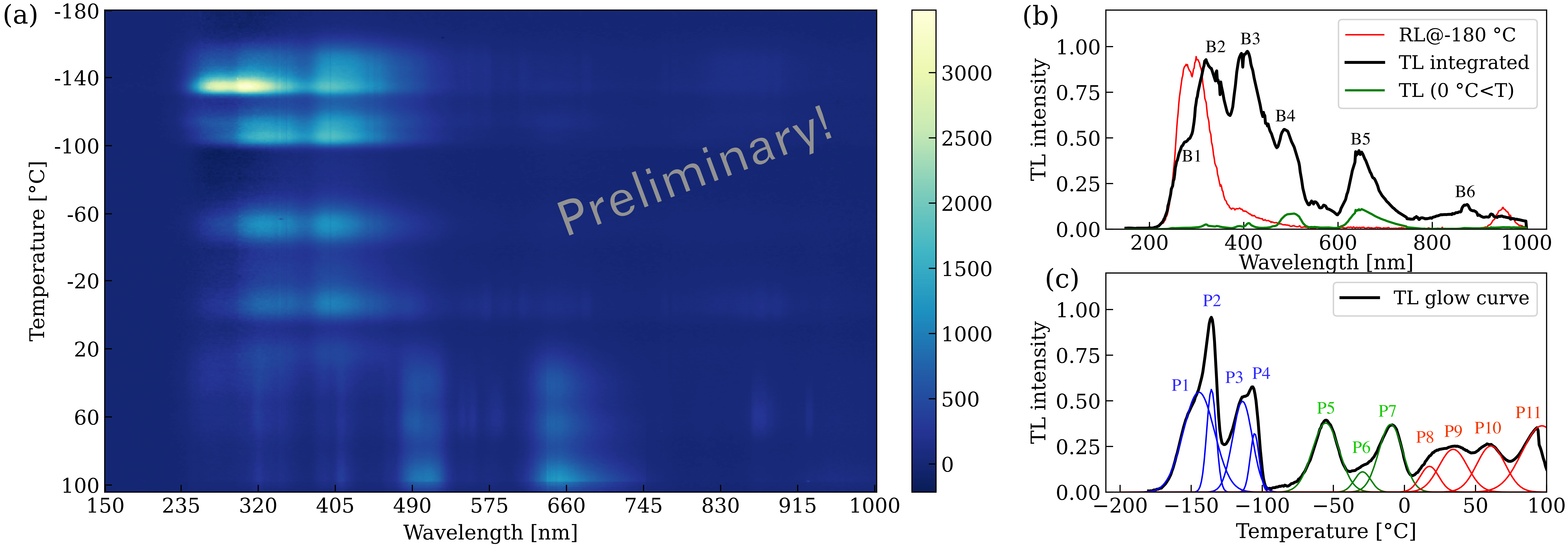
The thermoluminescence of the Th:CaF_2 crystal





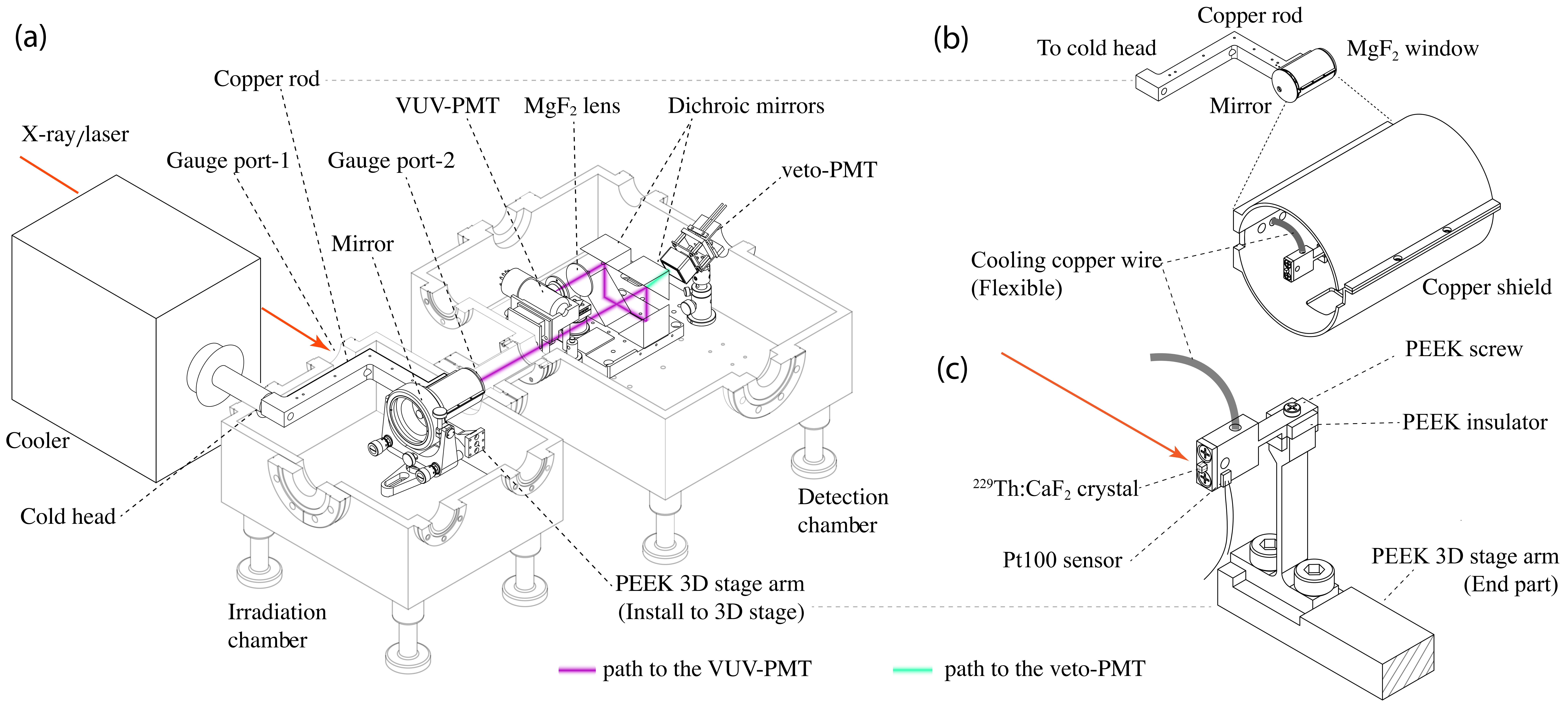


Dosimeter based on TL



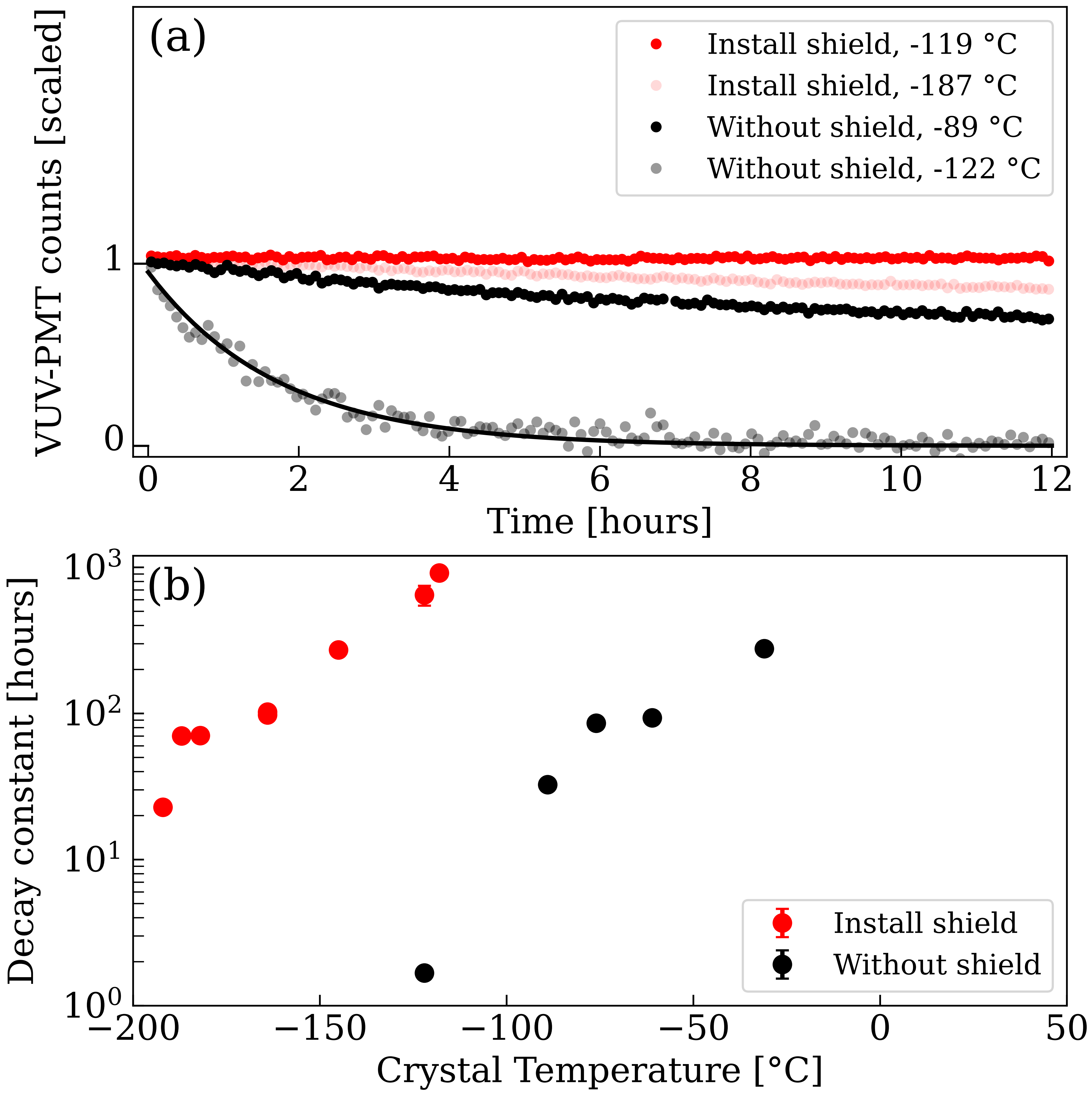
The cooling setup

M. Guan et al., NIMB 562, 165647 (2025)



Cooling, ice-layer and the copper shield

M. Guan et al., NIMB 562, 165647 (2025)



J. Tiedau et al., Phys. Rev.Lett. 132, 182501 (2024)
(Supplement Material)

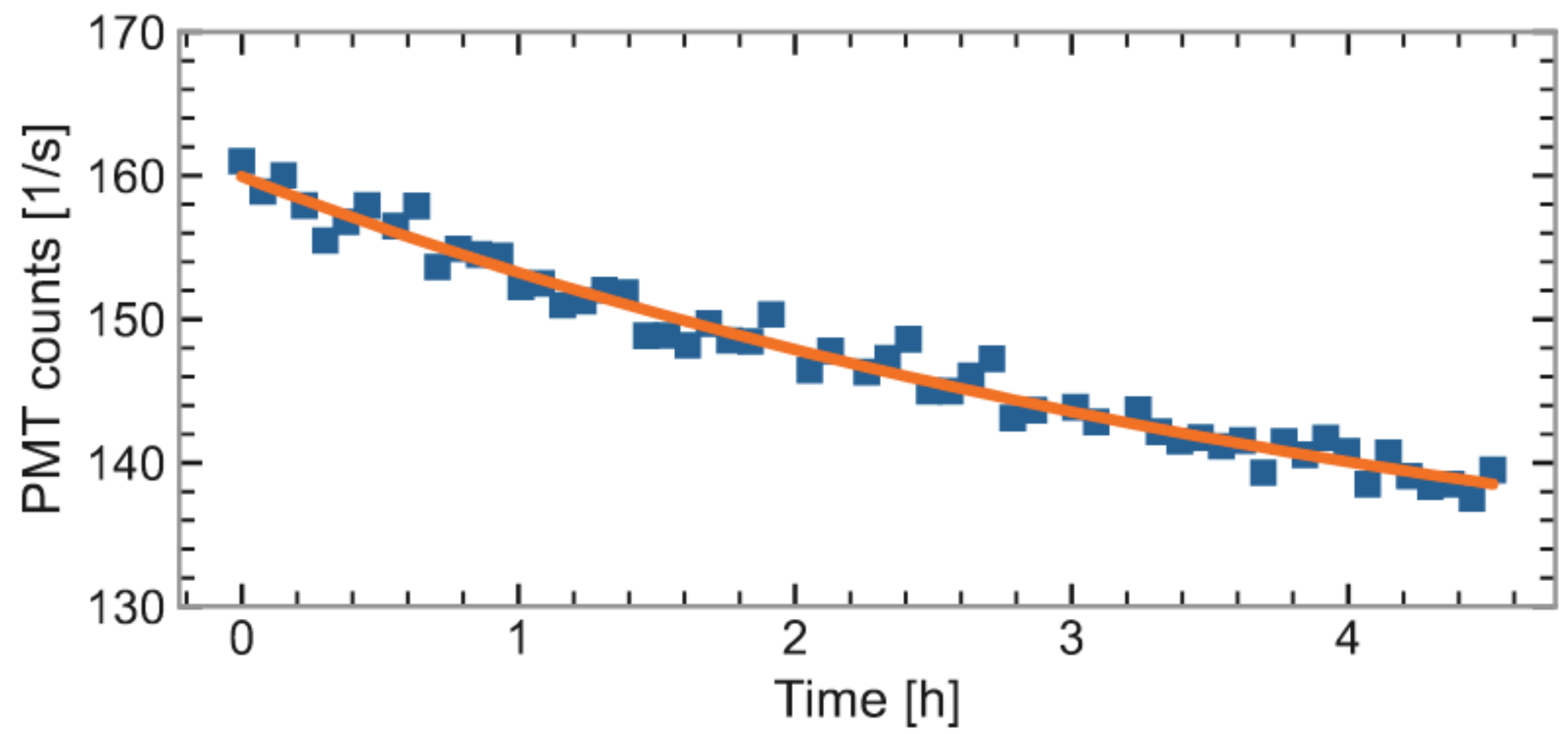
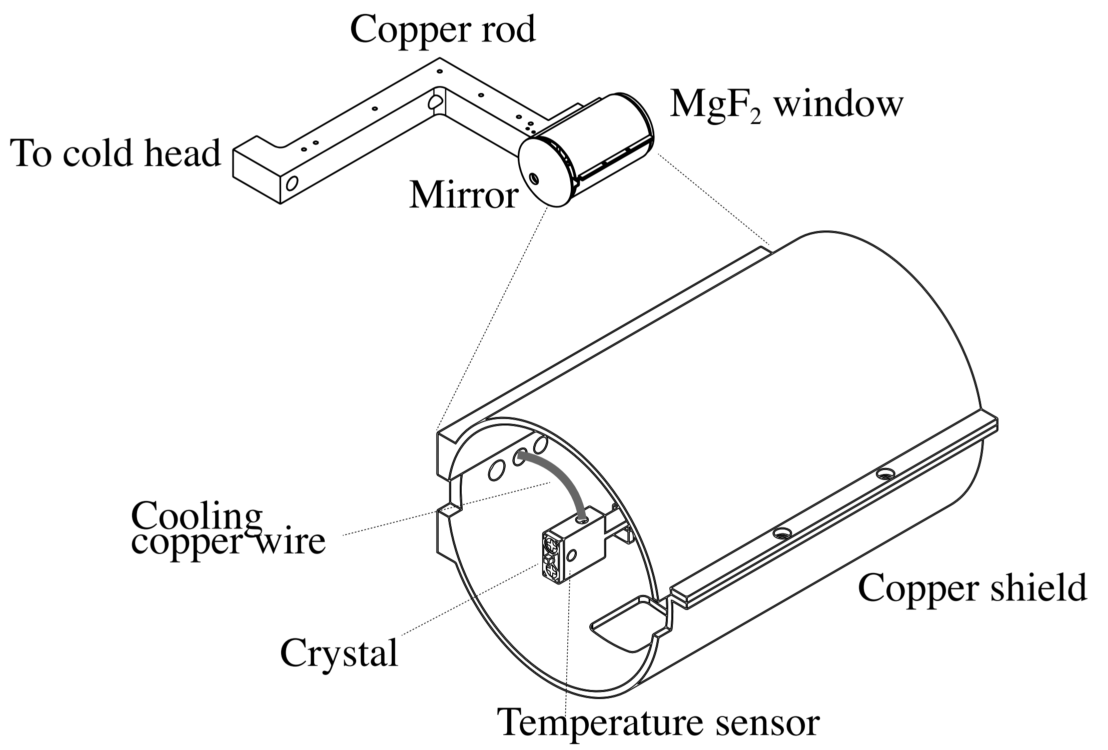
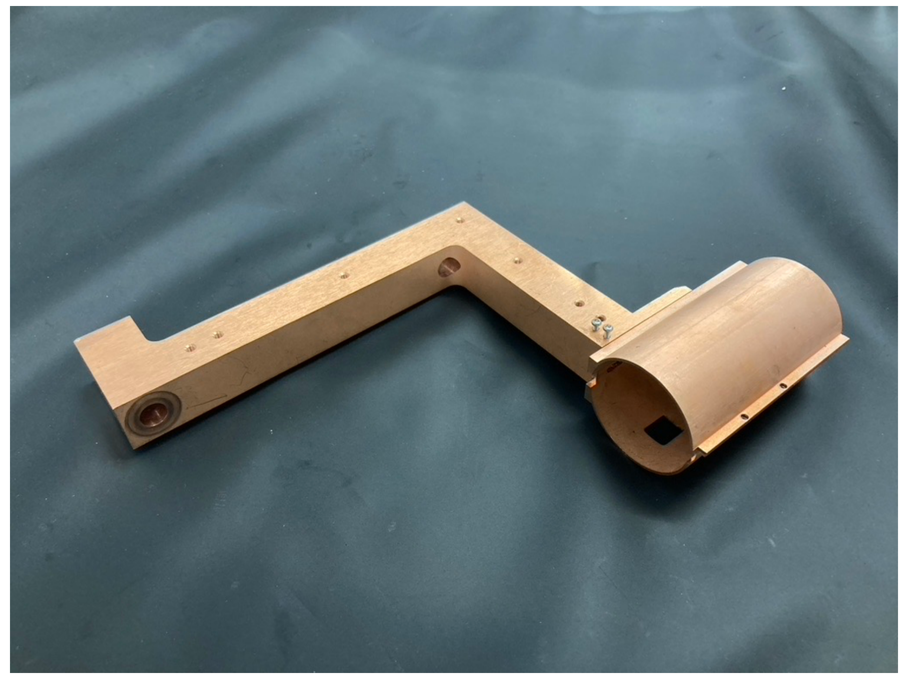


FIG. 6. Decreasing radioluminescence counts caused by an ice-layer formation on the cold crystal at 150 K. Each data point, averaged over 150 s, corresponds to one frequency scan during the search for the nuclear transitions. All points are $\geq$ 3 THz apart from the nuclear resonance. Note the $\approx 10\times$ longer time scale of this effect in comparison to the isomer decay curves.





The quench and afterglow

arXiv:2505.03852v1