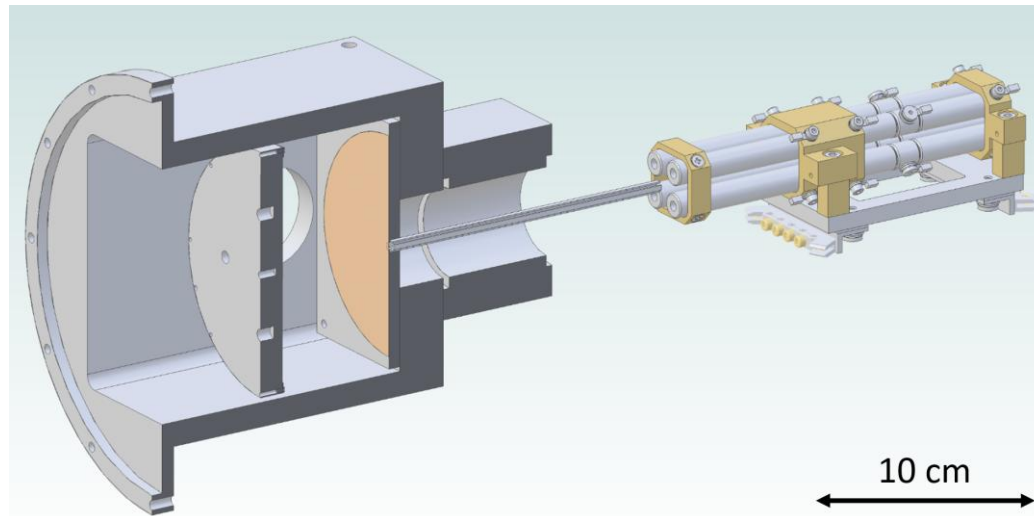


Trapping and laser spectroscopy of triply charged thorium-229 for a nuclear clock



A. Yamaguchi

Space-Time Engineering Research Team, RIKEN

Outline

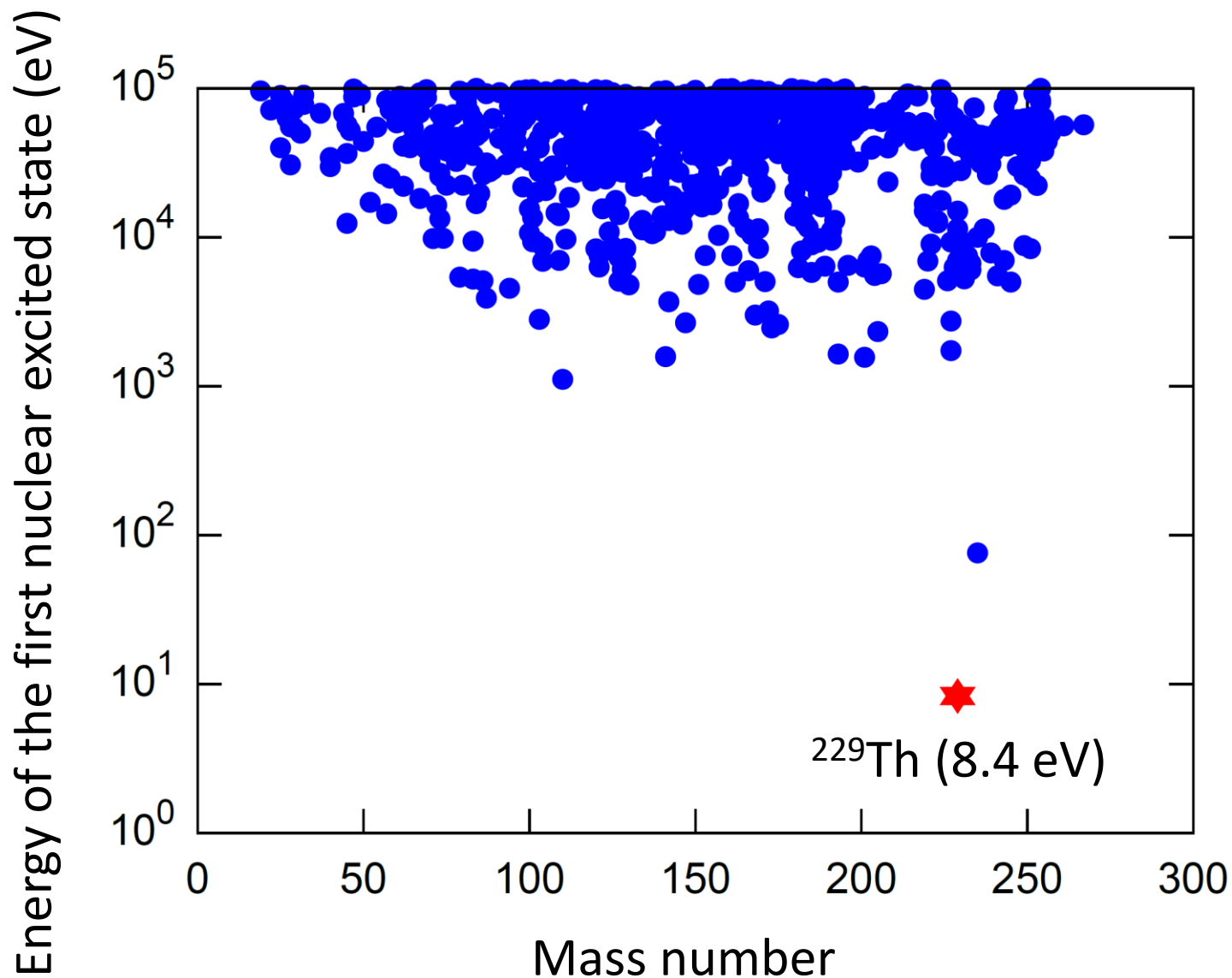
Motivation: Thorium-229 (^{229}Th) nuclear clock

Experiment: Trapping of $^{229}\text{Th}^{3+}$ ions

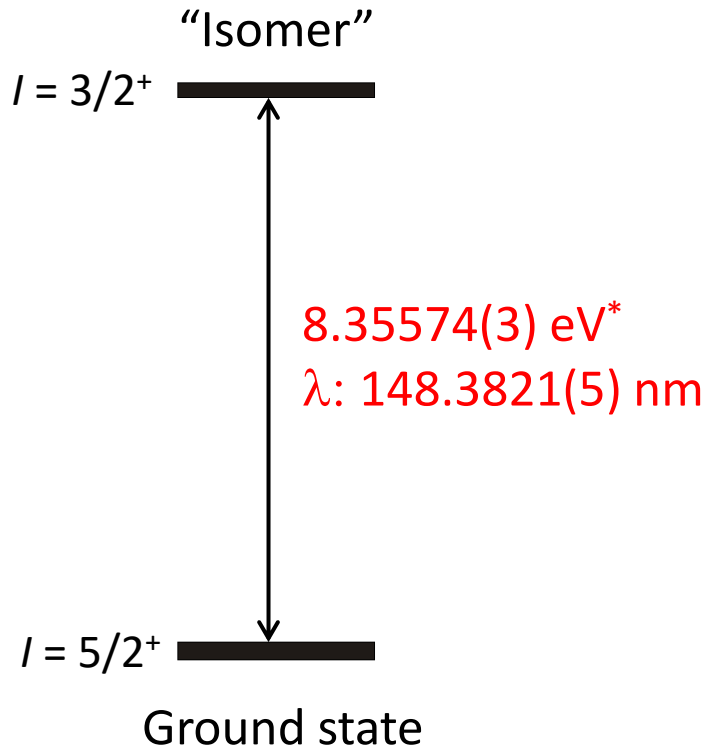
Laser spectroscopy of $^{229}\text{Th}^{3+}$ isomer

Summary & prospects

Low-energy nuclear state in ^{229}Th



Low-energy nuclear state in Th-229



*[In crystal]
J. Tiedau *et al.*, Phys. Rev. Lett. **132**, 182501 (2024).

Transition energy is in VUV.
→ **Laser spectroscopy of atomic nuclei**

Long lifetime of isomer
($\sim 10^3$ seconds)
→ **Narrow natural linewidth**



"Nuclear clock"

E. Peik and Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

Highly accurate frequency standard

C. J. Campbell *et al.*, Phys. Rev. Lett. **108** 120802 (2012)

K. Beloy *et al.*, Phys. Rev. Lett. **130**, 103201 (2024).

Highly sensitive for variations of α

V. Flambaum, Phys. Rev. Lett. **97**, 092502 (2006)

M. S. Safronova *et al.*, Rev. Mod. Phys. **90**, 025008 (2018)

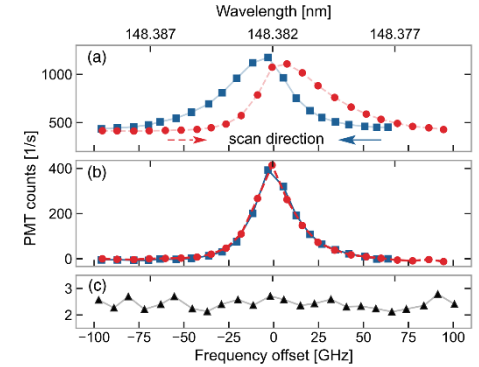
Laser excitation of Th-229 nuclear transition in crystal (2024)

PTB(GER), TU Wien J. Tiedau *et al.*, Phys. Rev. Lett. **132**, 182501 (2024).

Crystal : CaF₂

Laser : Pulse, Xe four-wave-mixing

Isomer energy: 8.355 74(3) eV



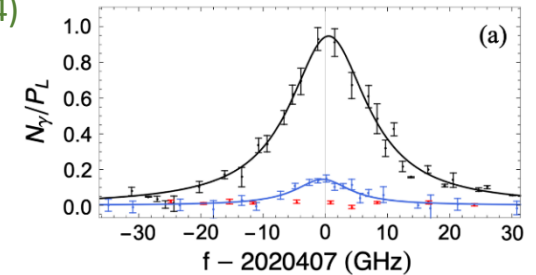
UCLA(USA)

R. Elwell *et al.*, Phys. Rev. Lett. **133**, 013201 (2024)

Crystal : LiSrAlF₆

Laser : Pulse, Xe four-wave-mixing

Isomer energy: 8.355 733(10) eV



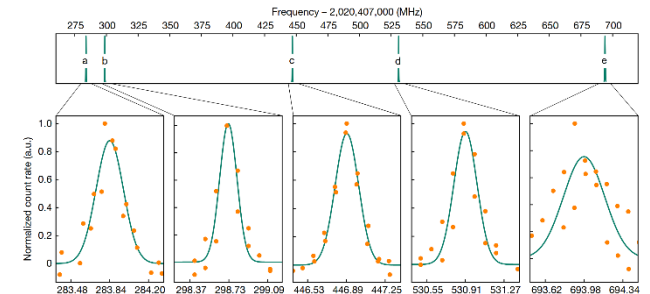
JILA (USA)

C. Zhang *et al.*, Nature **633**, 63 (2024).

Crystal : CaF₂

Laser: Comb, HHG

Isomer energy: 8.355 733 554 029 (8) eV



Okayama (Japan)

T. Hiraki *et al.*, arXiv:2509.00041 (2025).

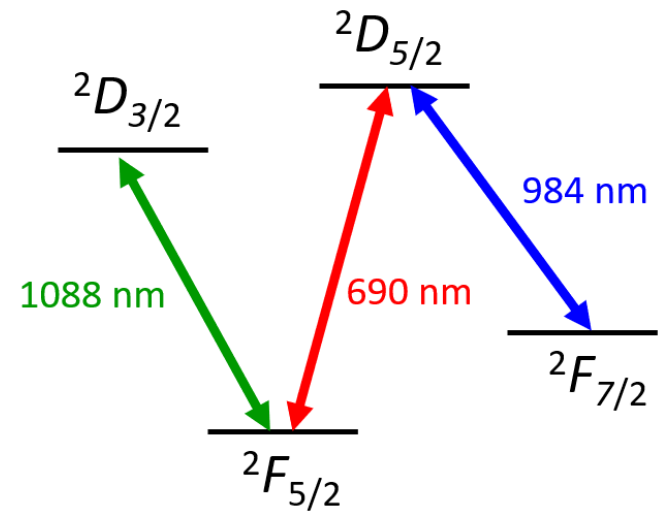
Crystal : CaF₂

Laser : Pulse, Xe four-wave-mixing

Nuclear clock based on $^{229}\text{Th}^{3+}$ in a trap

Why 3+ ?

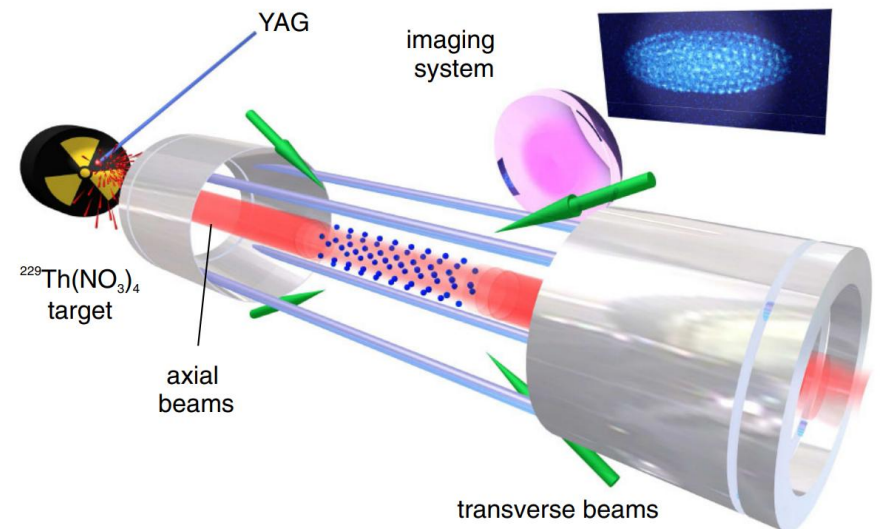
Availability of closed electronic transitions
→ Laser cooling, fluorescence detection,
state preparation...



[Previous study]

- Direct laser cooling of $^{229}\text{Th}^{3+}$ ions (nuclear ground state)
- $^{229}\text{Th}^{3+}$ ions were prepared by laser ablation

↑ We cannot use laser ablation in Japan.



^{233}U as a source of $^{229\text{m}}\text{Th}$ (Isomer) ions



[Previous studies]

First direct detection of $^{229\text{m}}\text{Th}$

L. van der Wense *et al.*, Nature **533**, 47 (2016).

Laser spectroscopy of $^{229\text{m}}\text{Th}^{2+}$

J. Thielking *et al.*, Nature **556**, 321 (2018).

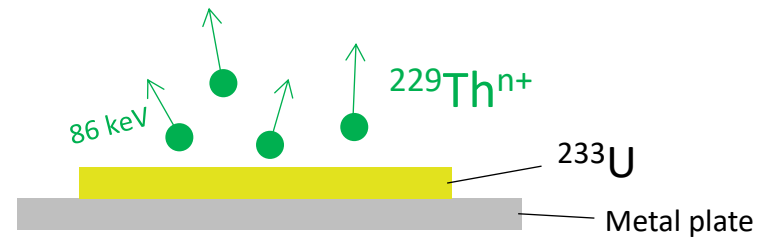
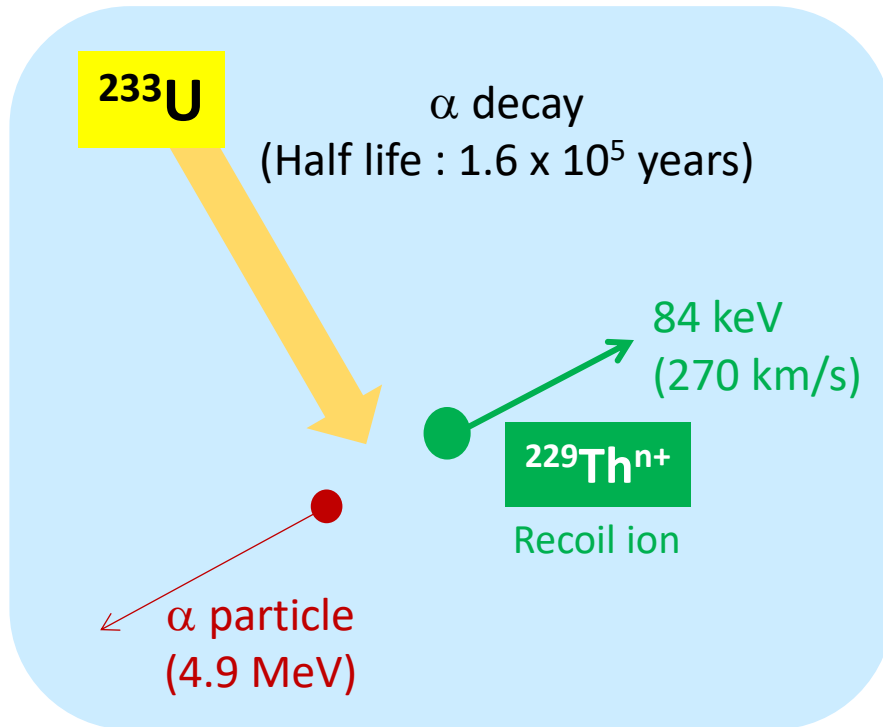
Precise determination of isomer energy

B. Seiferle *et al.*, Nature **573**, 243 (2019).

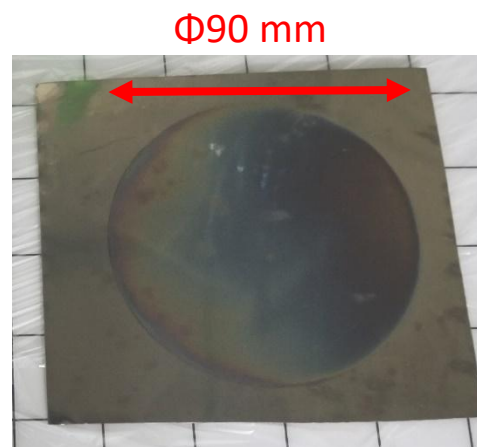
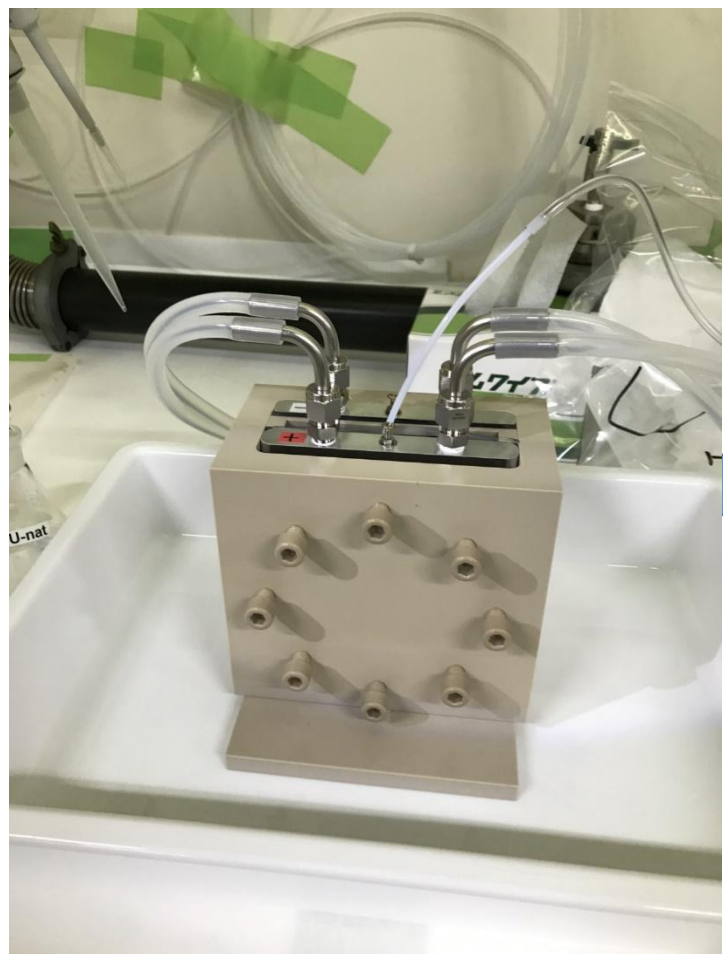
This study

Trapping and laser spectroscopy of $^{229\text{m}}\text{Th}^{3+}$

Preparation of $^{229}\text{Th}^{3+}$



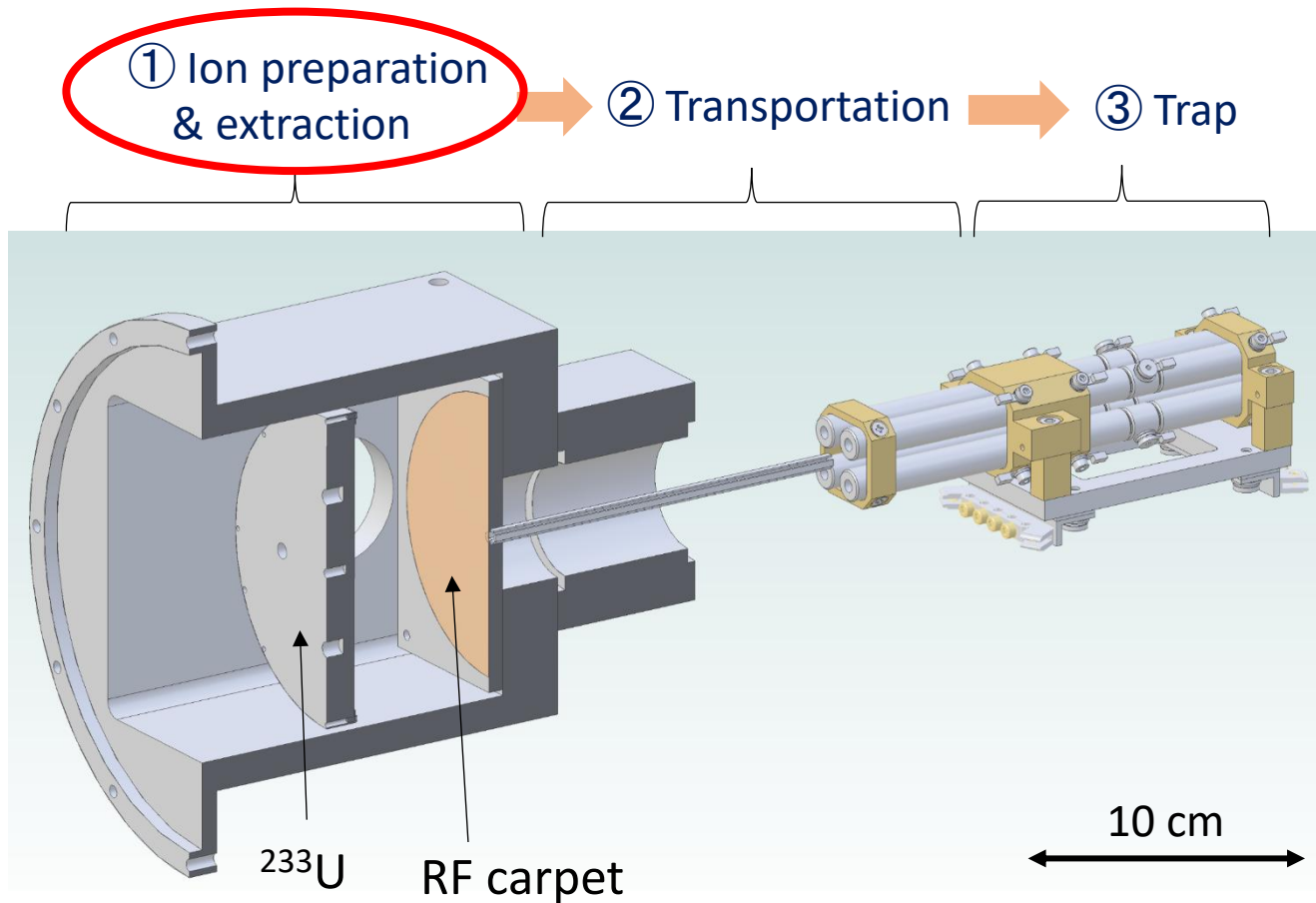
Electrodeposition of ^{233}U



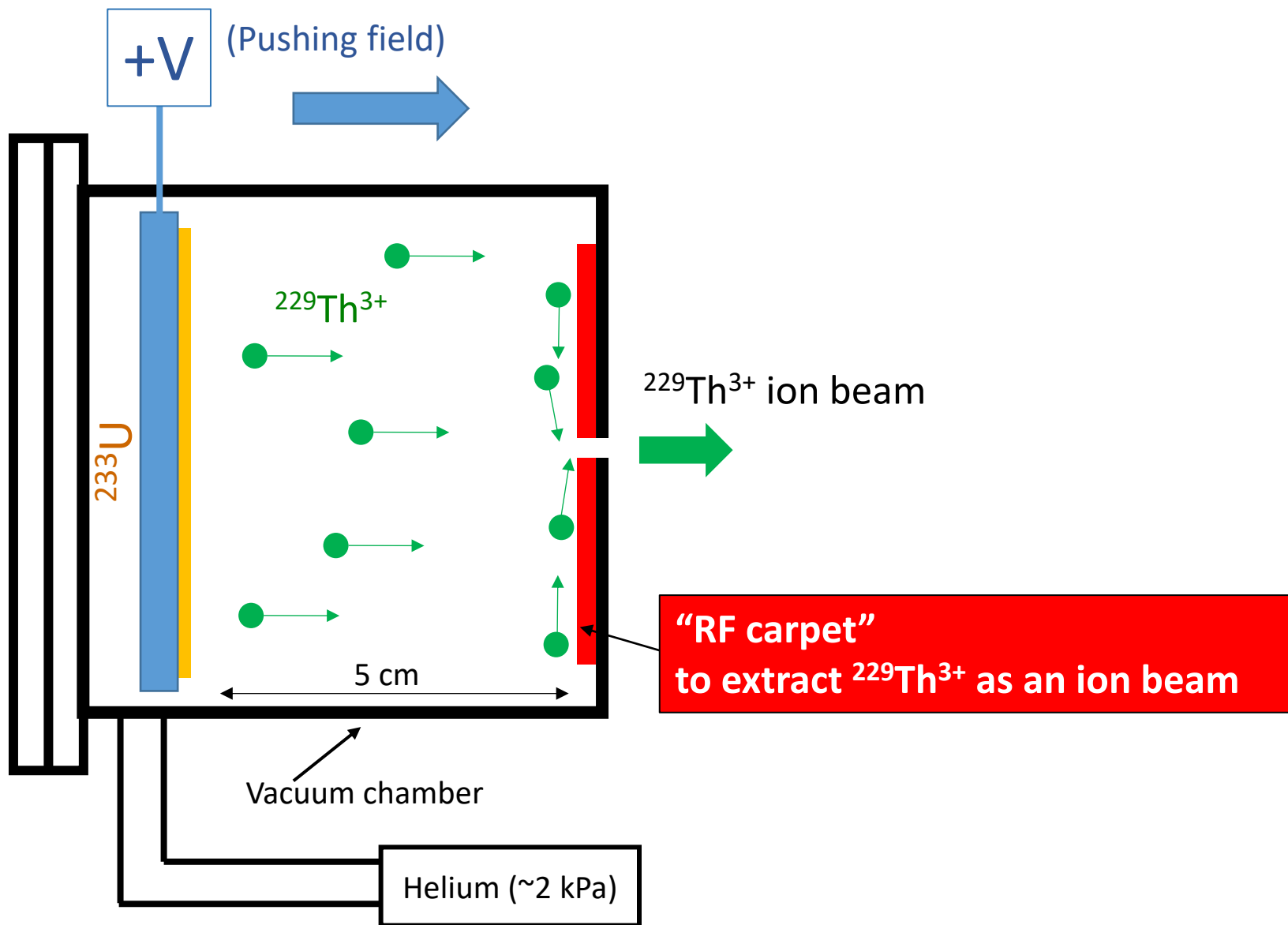
600 kBq of U-233 is electrodeposited.

Y. Shigekawa and H. Haba
Nuclear Chemistry Lab (RIKEN)

Experimental apparatus



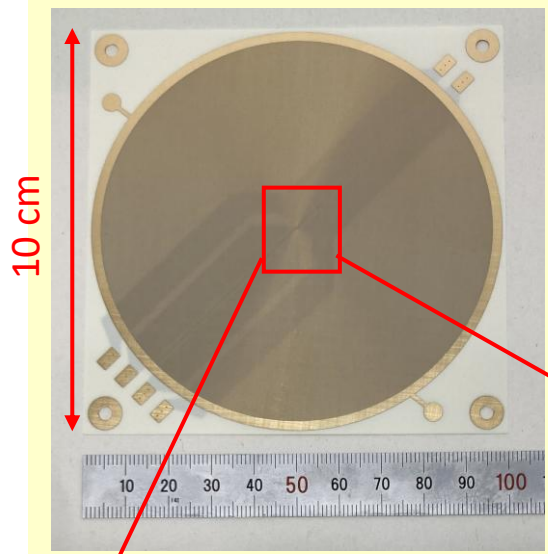
Extraction of $^{229}\text{Th}^{3+}$ ions



V. Sonnenschein *et al.*, Eur. Phys. J. A **48**, 52 (2012).

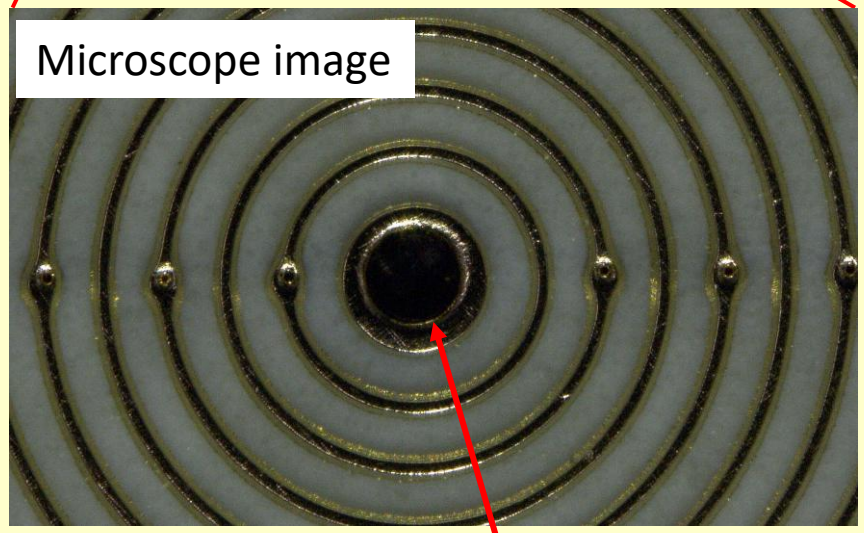
L. van der Wense *et al.*, Nucl. Instrum. Methods Phys. Res. B **376**, 260 (2016).

"RF carpet"



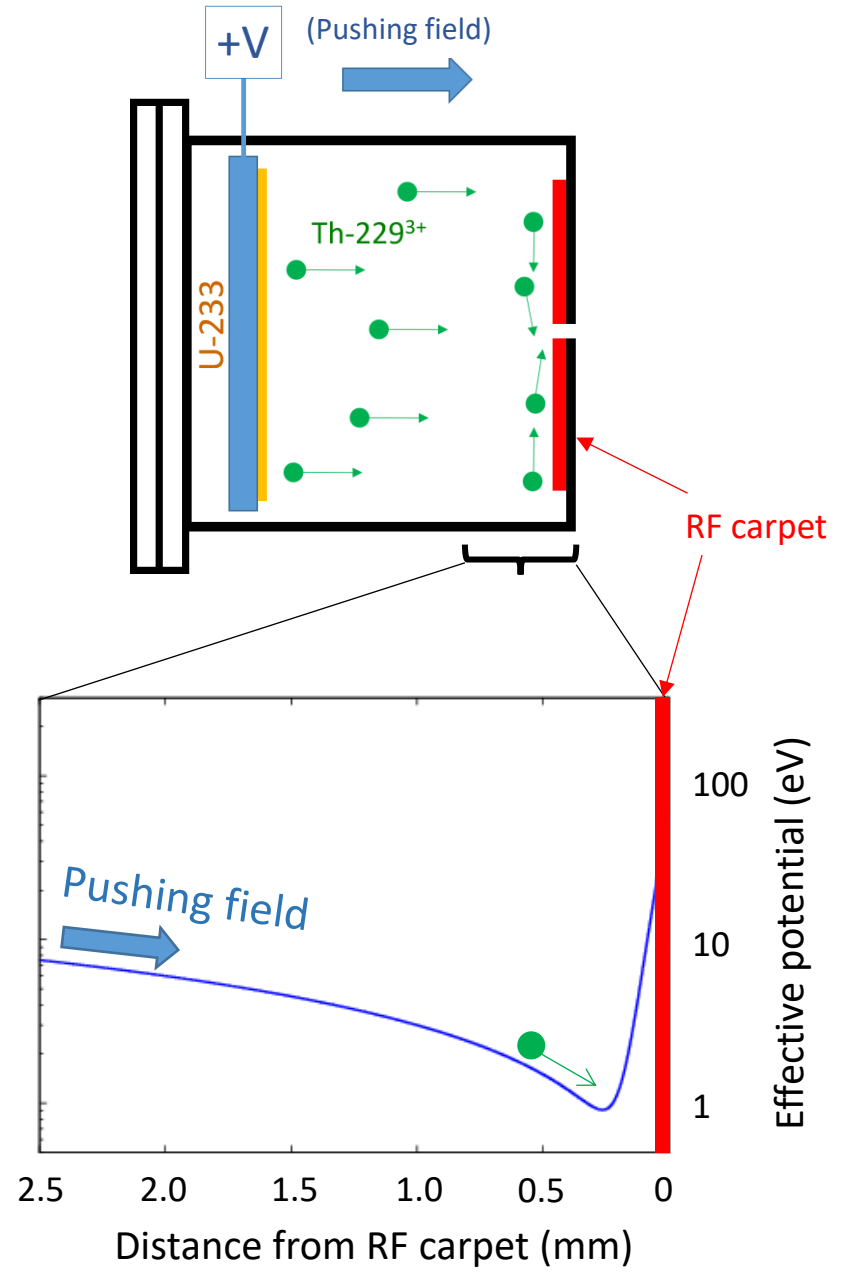
Developed by
M. Wada (KEK)

M. Wada *et al.*,
Nucl. Instr. And Meth. B **70**, 309 (1992).

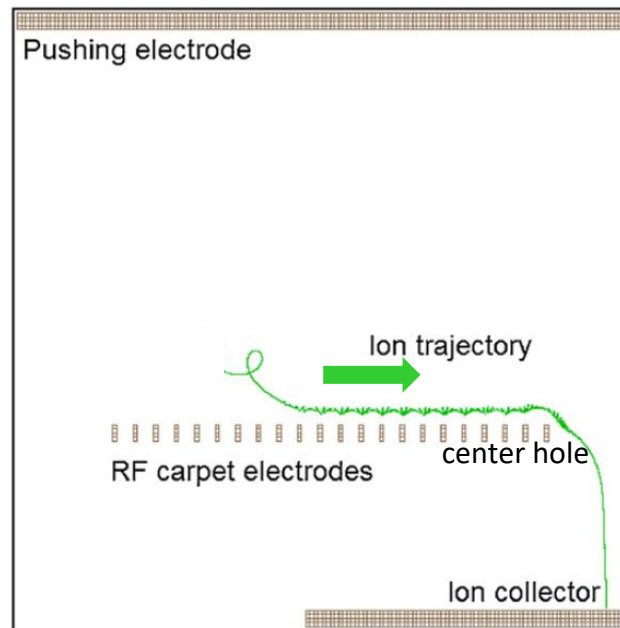
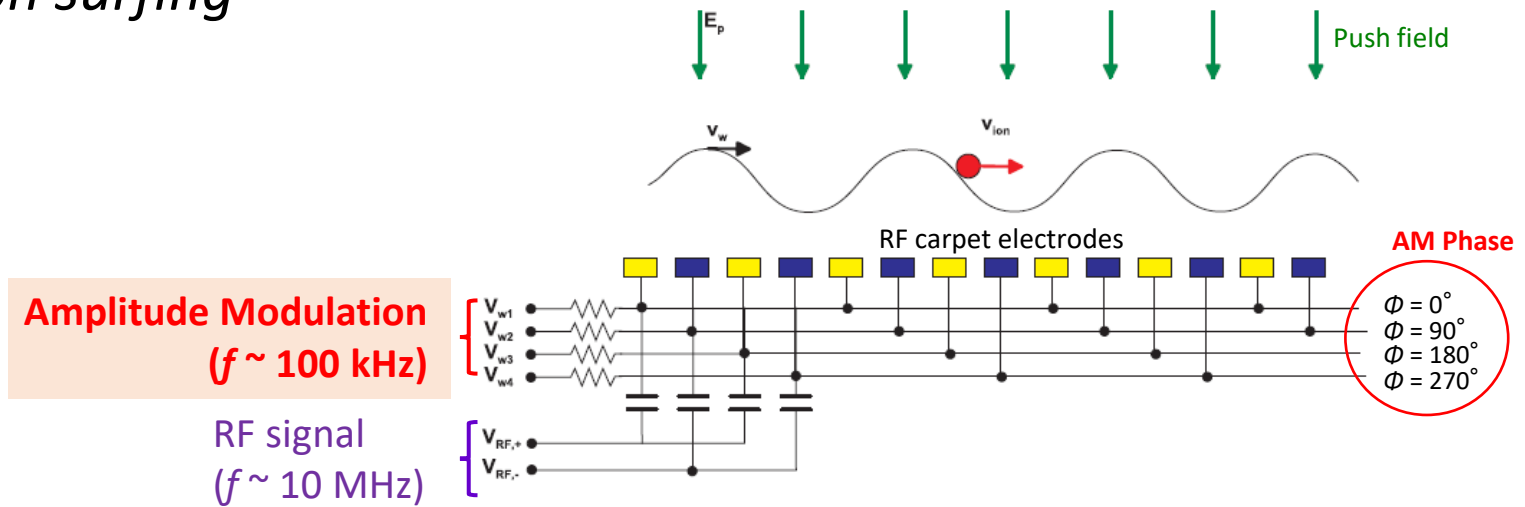


Microscope image

Hole ($\Phi 0.32$ mm) for ion extraction



“Ion surfing”



Ion extraction by “ion surfing” technique (simulation)

Experimental apparatus

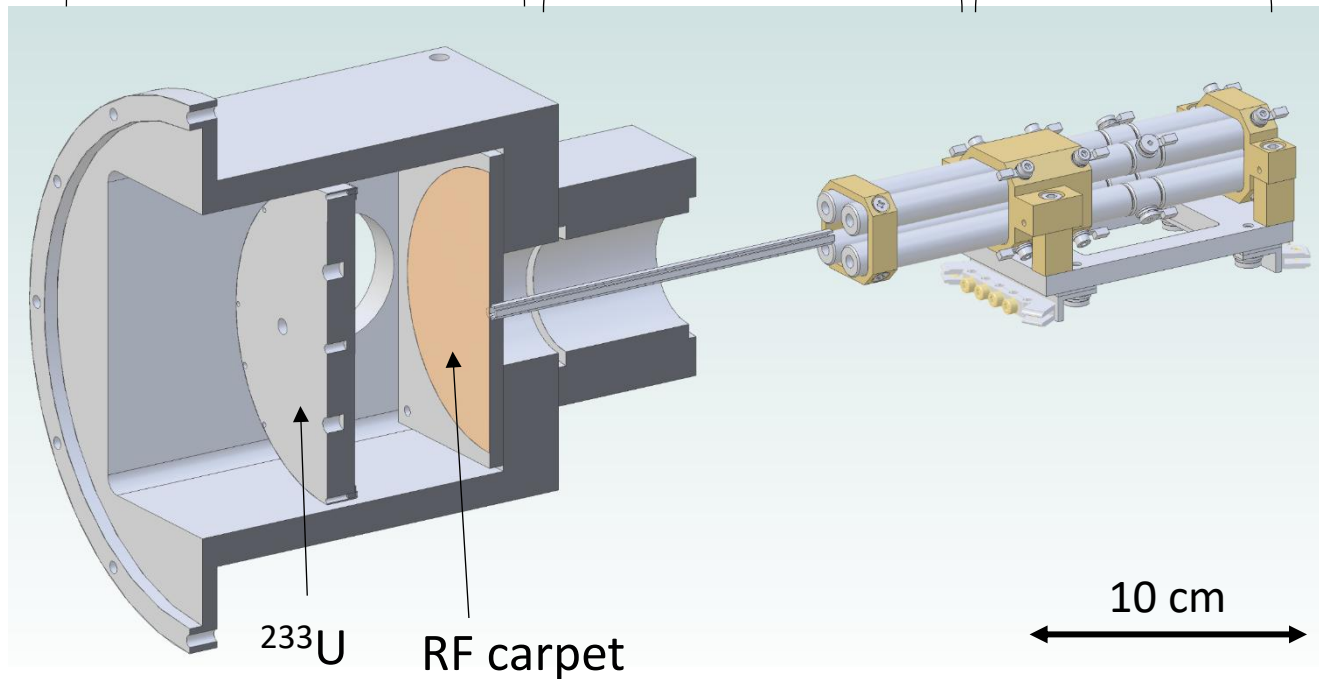
① Ion preparation
& extraction



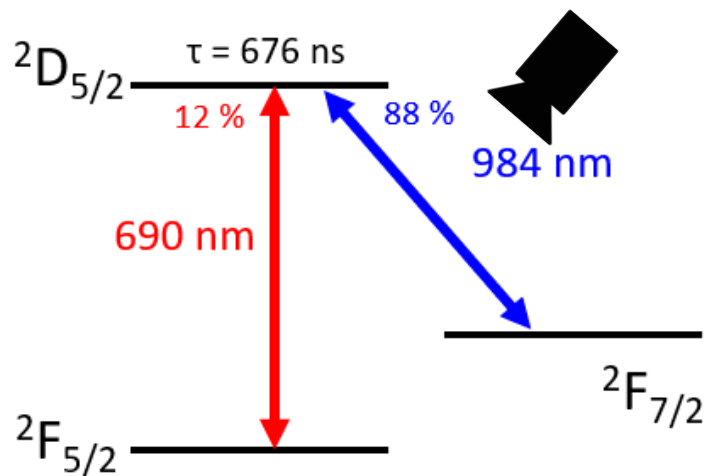
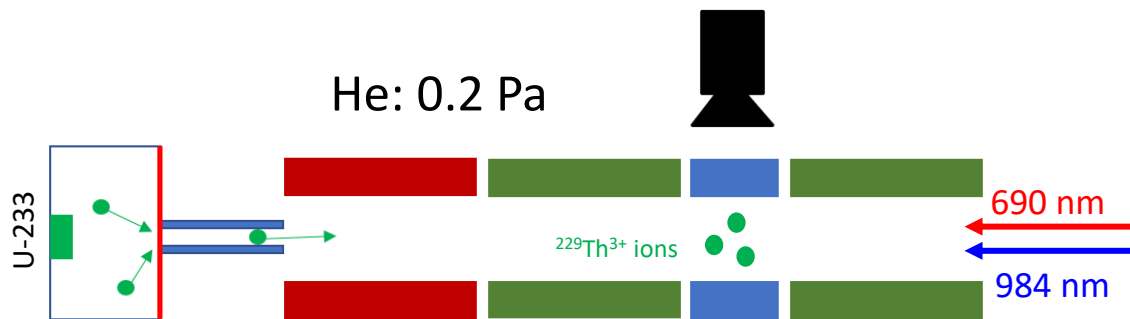
② Transportation



③ Trap

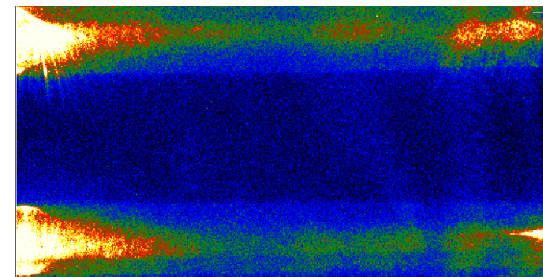


Trapping of $^{229}\text{Th}^{3+}$ ions

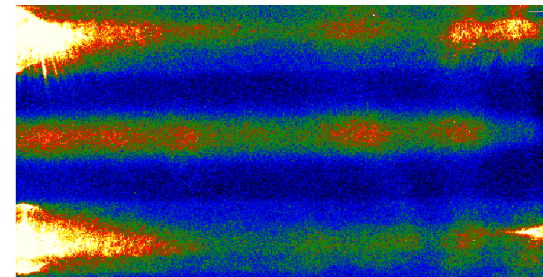


Electronic energy levels of Th^{3+}

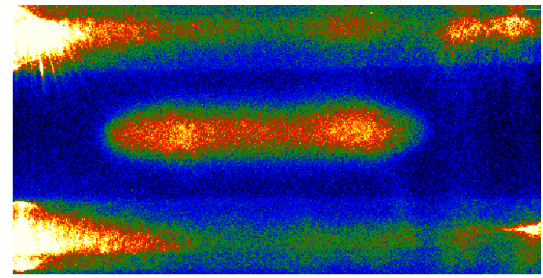
Before loading ~ 1 mm



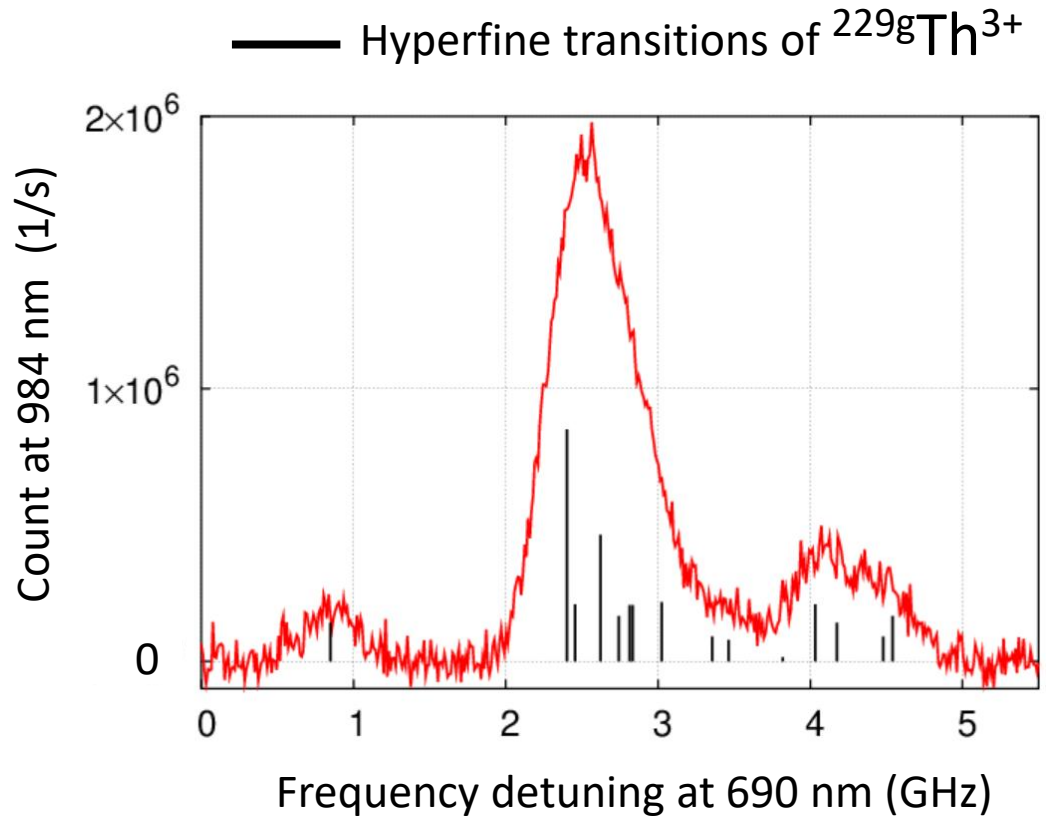
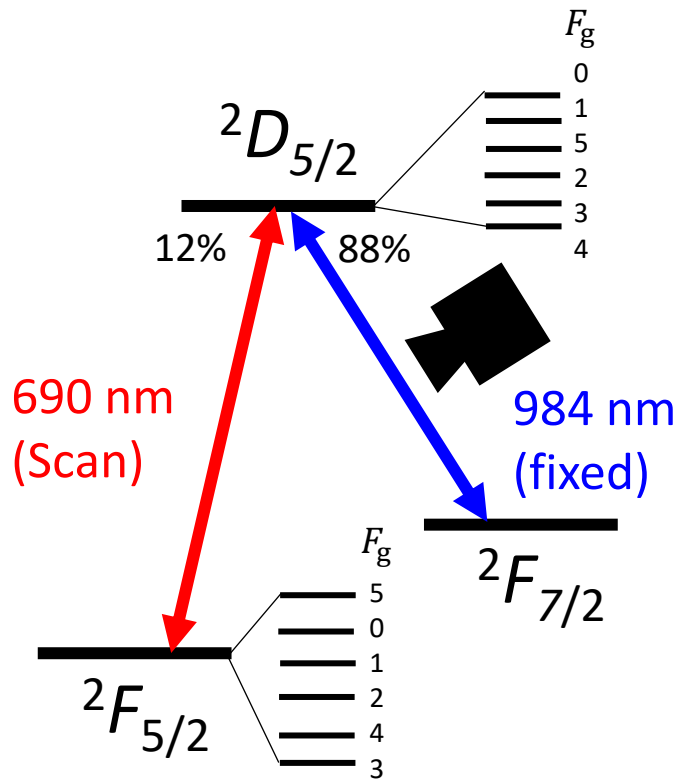
Ion loading (~ 60 s)



Ion trapping
(about a few 10^3 $^{229}\text{Th}^{3+}$ ions)

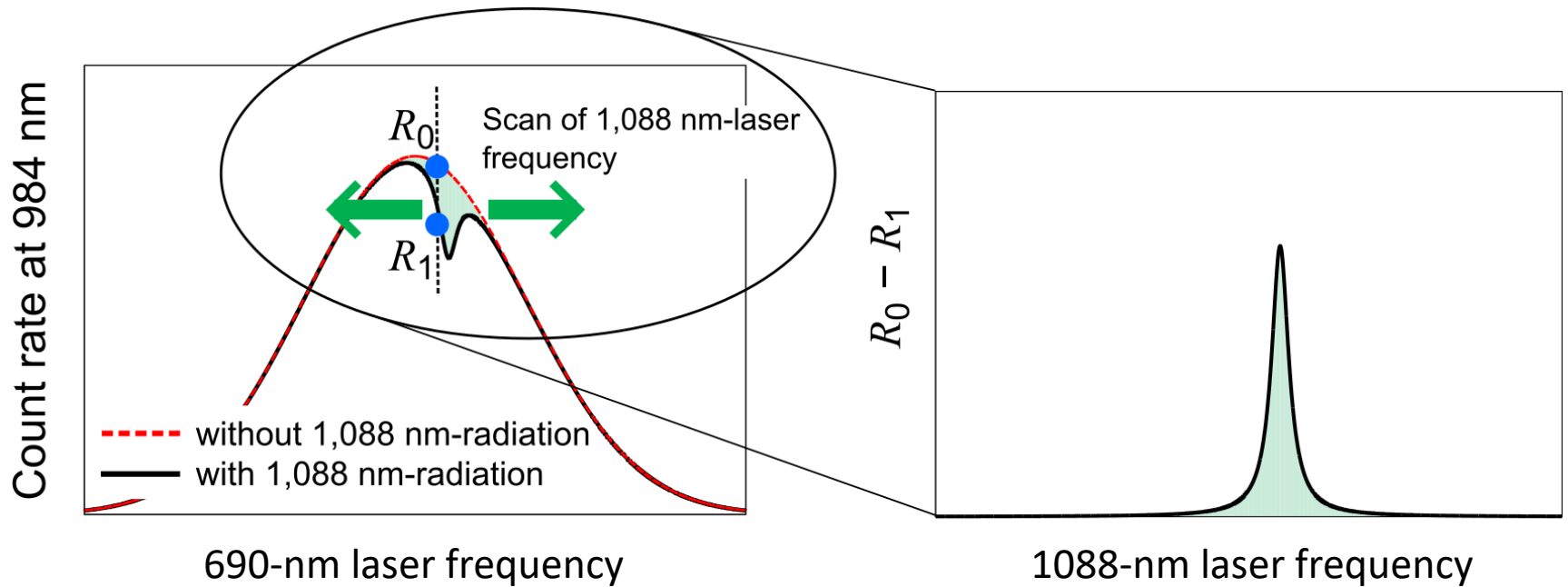
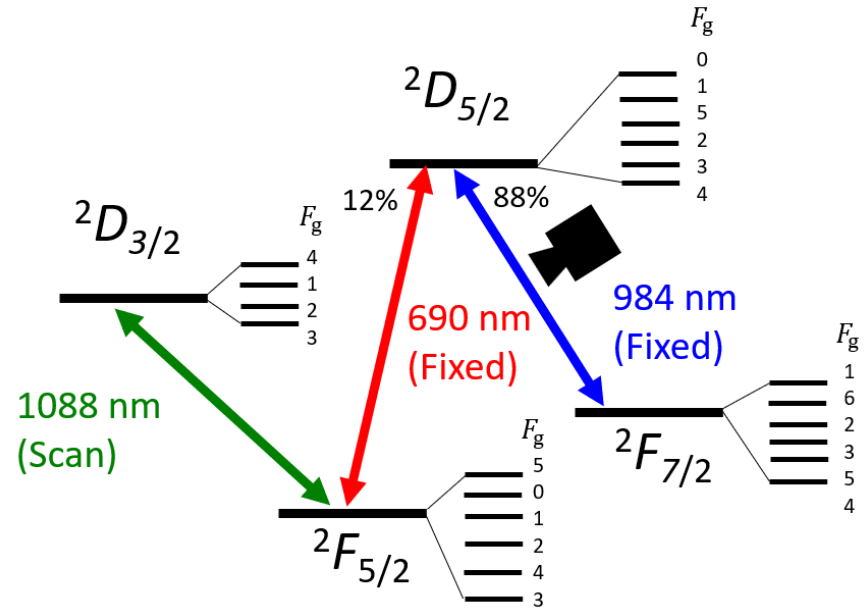
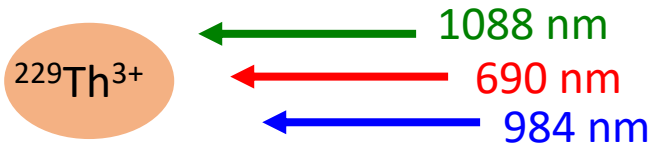


Spectroscopy of $^{229}\text{Th}^{3+}$ ions (Doppler broadened)

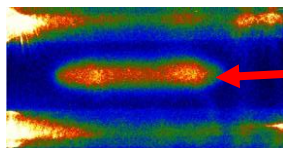
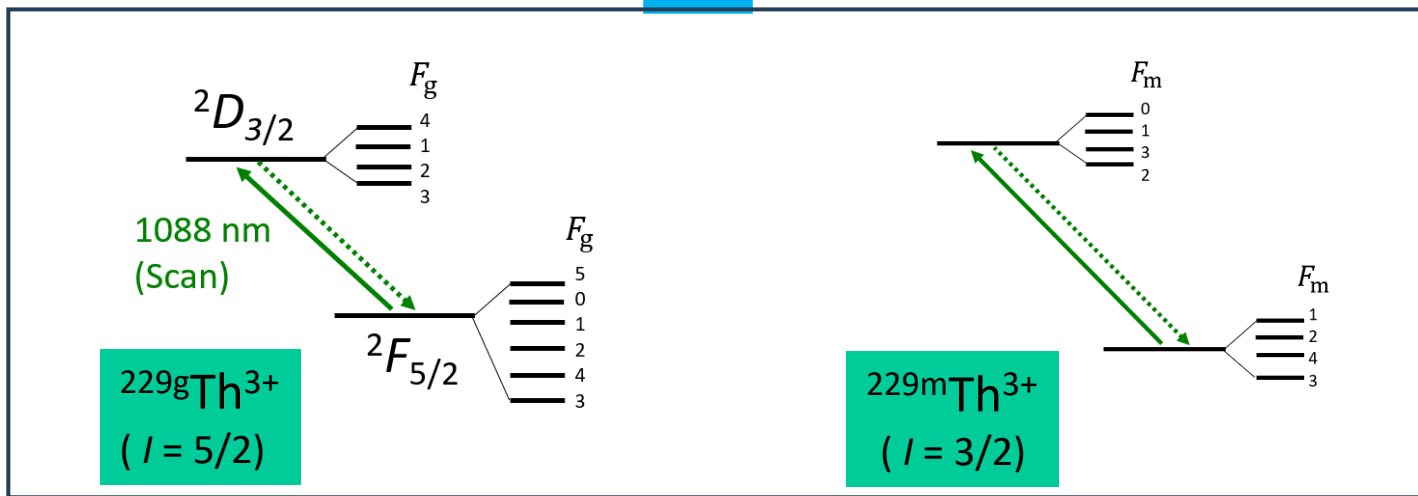
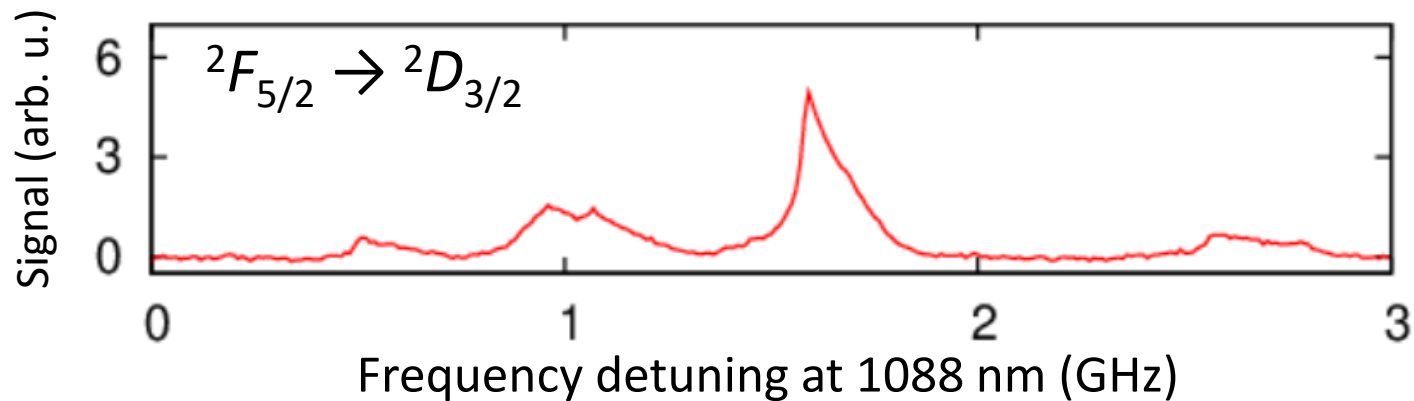


Nuclear spin: $I = 5/2$ for ^{229}gTh

Hole-burning spectroscopy



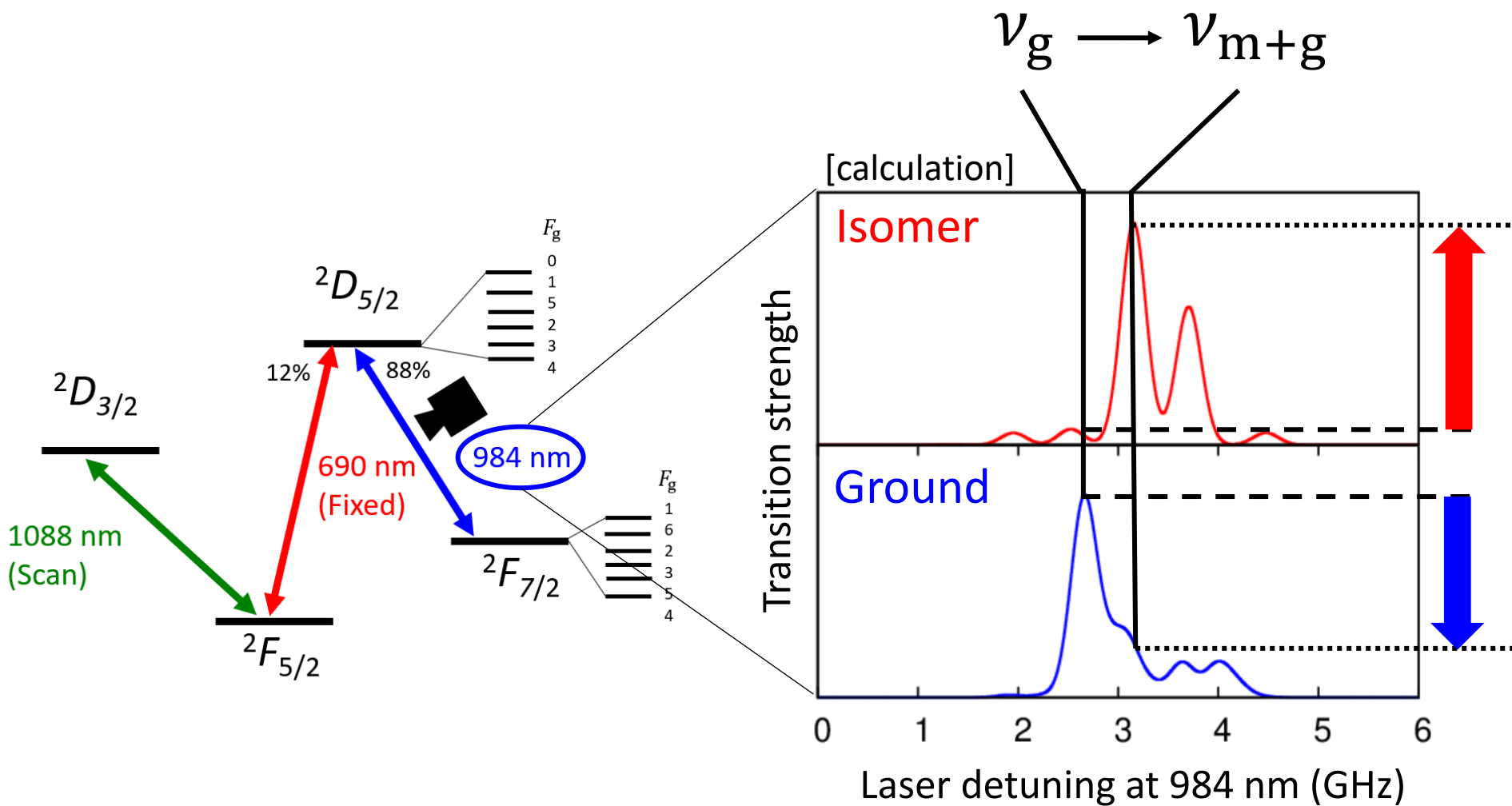
Hyperfine spectra of $^{229}\text{Th}^{3+}$



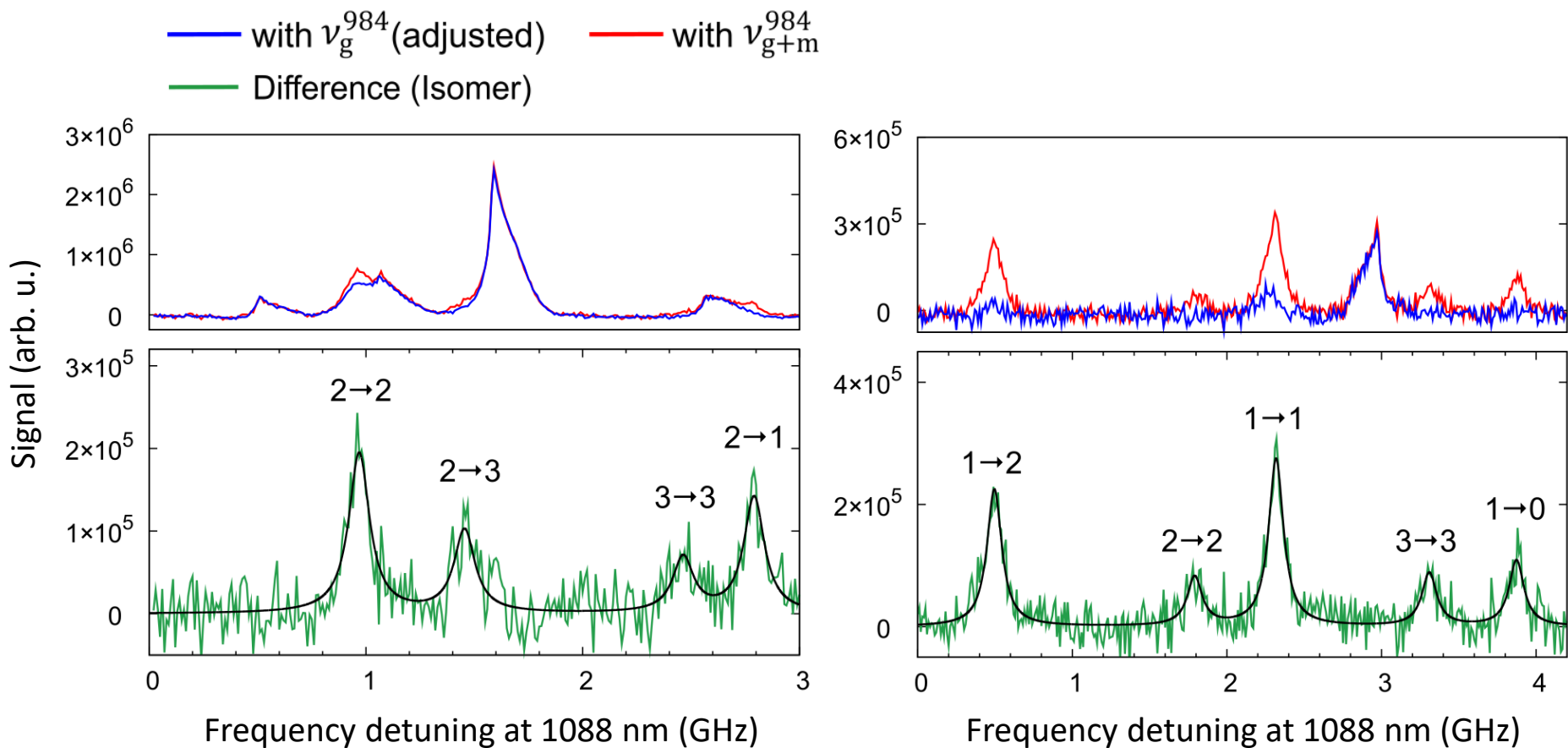
$^{229}\text{gTh}^{3+} : ^{229}\text{mTh}^{3+} = 98\% : 2\%$

How to extract $^{229}\text{mTh}^{3+}$ spectra?

Nuclear-state-selective spectroscopy



Observation of the $^{229m}\text{Th}^{3+}$ signal



Nuclear properties of $^{229\text{m}}\text{Th}$

Hyperfine structure constants of the $^2\text{D}_{3/2}$ state of $^{229\text{m}}\text{Th}^{3+}$

$$A_m(^2\text{D}_{3/2}) : -267(3) \text{ MHz}$$

$$B_m(^2\text{D}_{3/2}) : 1288(10) \text{ MHz}$$

Isomer shift of the $^2\text{F}_{5/2} \rightarrow ^2\text{D}_{3/2}$ (1088 nm) transition

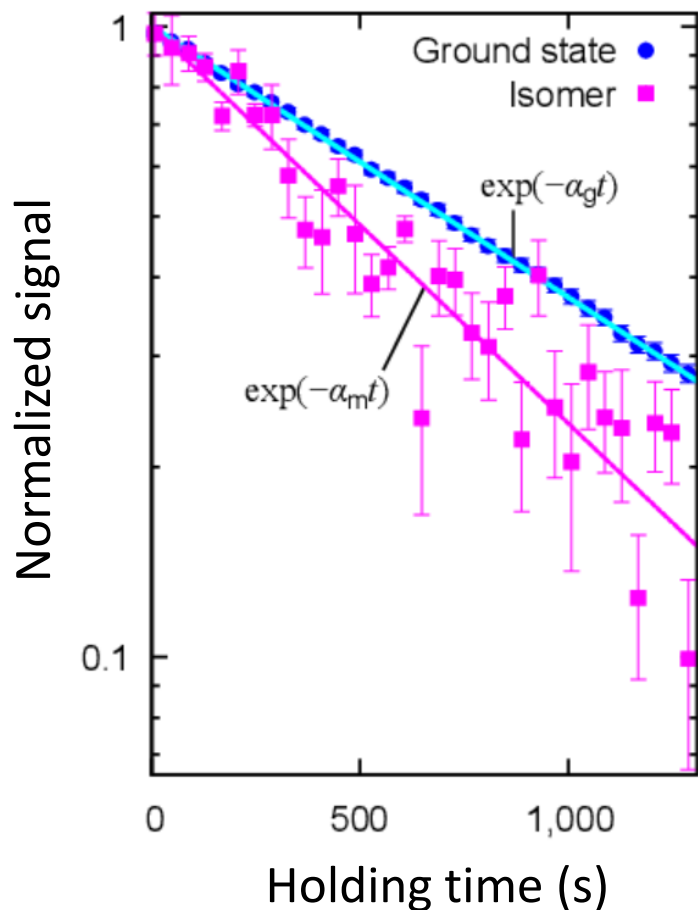
$$\nu_0^m - \nu_0^g = 320(30) \text{ MHz}$$



$^{229\text{m}}\text{Th}$ nuclear parameters

Magnetic dipole moment, μ_m	-0.378(8) μ_N
Electric quadrupole moment, Q_{0m}	8.84(10) eb
$\langle r^2_{229m} \rangle - \langle r^2_{229} \rangle$	0.0097(26) fm²

Nuclear decay lifetime of $^{229m}\text{Th}^{3+}$



$$\alpha_g = \alpha_c$$

$$\alpha_m = \alpha_c + \alpha_n$$

α_c : Reaction rate between Th^{3+} and impurity gasses

α_n : nuclear decay rate

$$\alpha_n = 5.1(1.5) \times 10^{-4} \text{ s}^{-1}$$

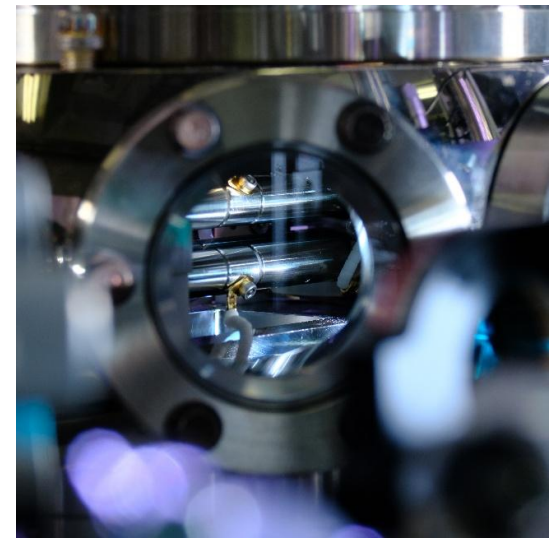
$$T_{1/2} = 1400^{+600}_{-300} \text{ s}$$

Natural linewidth: 80(20) μHz
Quality factor $f_0/\Delta f = 2.5 \times 10^{19}$

Summary

Towards a nuclear clock, we performed

- trapping of $^{229\text{g}}\text{Th}^{3+}$ and $^{229\text{m}}\text{Th}^{3+}$ ions
- Laser spectroscopy of $^{229\text{m}}\text{Th}^{3+}$ and determination of its nuclear parameters



Prospects

- Laser cooling of $^{229\text{g}}\text{Th}^{3+}$ and $^{229\text{m}}\text{Th}^{3+}$ ions
- Direct laser excitation of the 8.4 eV (= 148 nm) nuclear transition in a trap