HORIZON 2020

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

^{229}Th activities at Munich

Application to gas cell extraction efficiencies and chemistry

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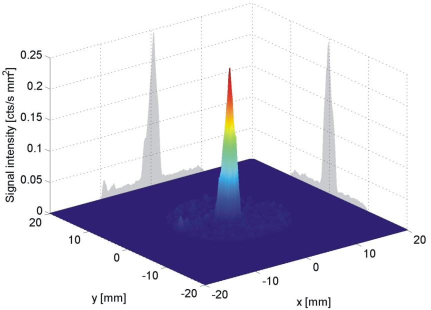
University of Munich

October 24th 2016

Contents


Signal intensity [cts/s mm^2]
0.25
0.2
0.15
0.1
0.05
0
20
10
0
-10
-20
y [mm]
-20
-10
0
10
20
x [mm]

Why ^{229}Th?

Total number of known isotopes: 3339

Total number of known levels: 175441

Total number of known γ transitions: 268089

^{229}Th possesses only known transition that could today allow for

Direct nuclear laser excitation!

^{229m}Th:

Lowest nuclear excited state of all isotopes[1]:

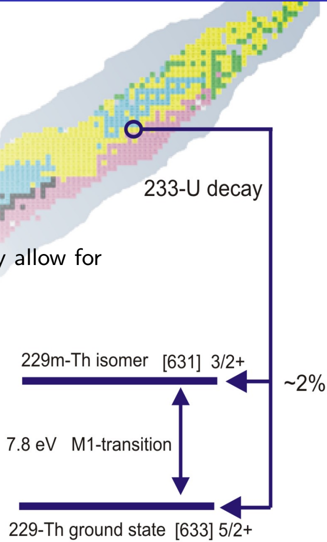
$$\Delta E = 7.8 \pm 0.5 \quad \text{eV}$$

Halflife in the range of hours:

$$\tau \approx 1 \cdot 10^4 \quad \text{s}$$

Linewidth exceptionally small:

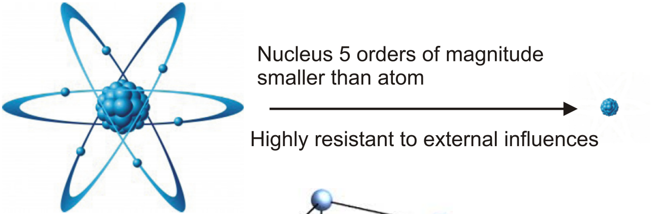
$$\Delta E / E \approx 1 \cdot 10^{-20}$$



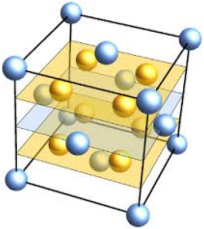
[1]B.R. Beck et al.: Phys.Rev.Lett. 98 (2007) 142501.

Application: a first nuclear-based clock

- Better performance due to higher resilience?



- Solid state clock feasible?



- Probe for time variations in fundamental constants?

10^{19} atoms in crystal instead of
10^{4} atoms in optical lattice

Challenges

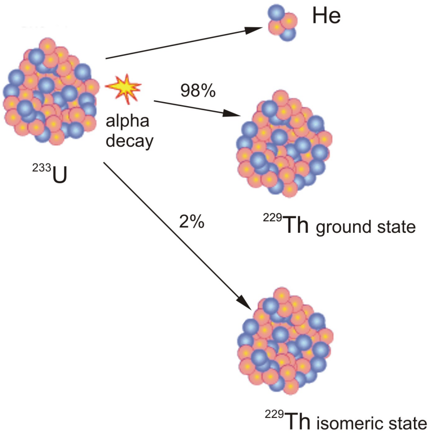
- Direct nuclear laser coupling has not been achieved so far
- By today ^{229}Th is the only candidate
- ^{229m}Th ground state transition not directly detected in 40 years
- Decay channel unknown (γ decay vs internal conversion)
- Lifetime unknown
- Transition energy not known precisely

Experimental objectives:

- Direct detection of isomeric decay
- Determine the half-life
- Improve the precision of the transition wavelength to less than 1 nm

How to get hold of the isomer?

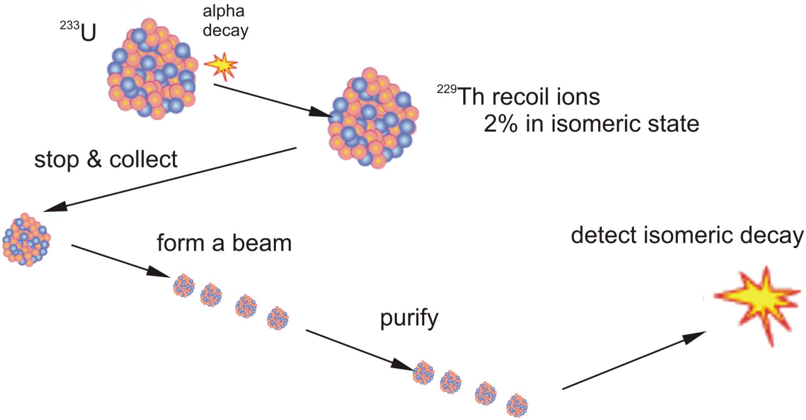
Populated by a 2% decay branch in the α decay of ^{233}U



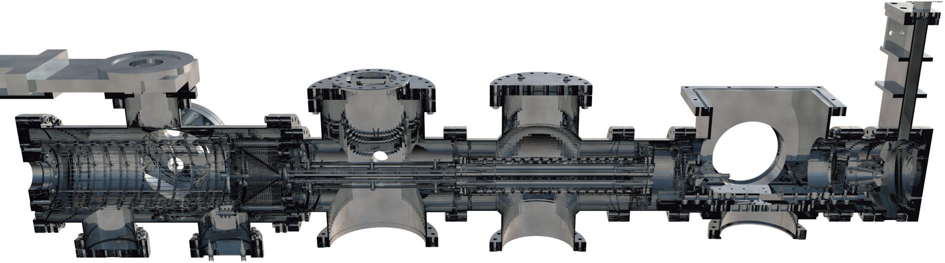
^{229}Th recoil ions

84 keV energy

Experimental Concept



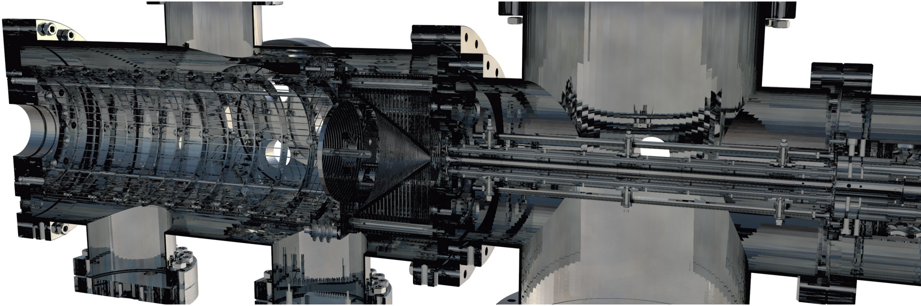
Experimental Setup



Stopping Cell RFQ QMS Detection Chamber

- 4 vacuum chambers
- 3 differential pumping stages
- overall length of about 2 m
- 3 turbopumps (from 40 mbar to below 10^{-6} mbar)

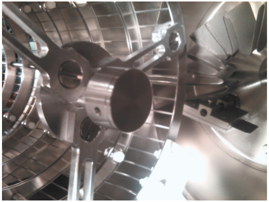
The Buffer Gas Stopping Cell

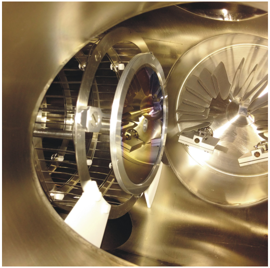


- strictly designed to UHV conditions, bakeable up to 180℃
- typical pressure of $2.8 \cdot 10^{-10}$ mbar is reached
- during operation filled with 40 mbar of ultra pure He (6.0)
- further catalytic purification (ppb level), cryotrap and getter pump

The Ion Sources

^{229m}Th populated via 2% decay branch in α decay of ^{233}U



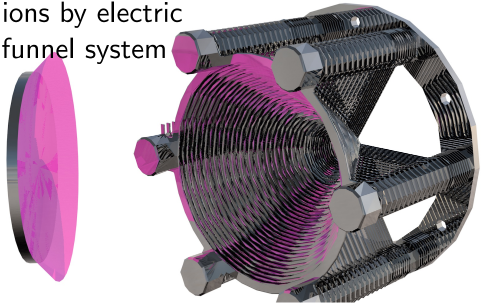


2 different ^{233}U sources used:

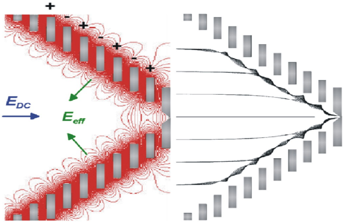
1. Source
   - 200 kBq $^{233}UF_4$ evaporated onto 20 mm Ø steel
   - not radio-chemically purified before deposition
   - ^{232}U contamination $\leq 10^{-6}$
2. Source (IRC Uni Mainz)
   - 290 kBq electro-deposited onto 90 mm Ø wafer
   - radio-chemically purified before deposition
   - ^{232}U contamination $\leq 10^{-6}$

Electric RF-Funnel

Guide the ions by electric
RF + DC funnel system

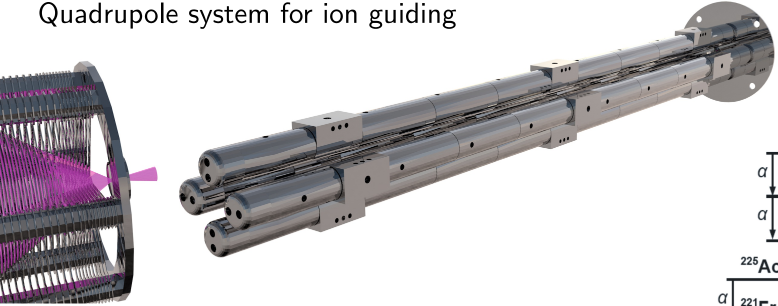


- 50 ring electrodes (115 mm max)
- 0.5 - 1.0 mm distance
- RF fields to prevent ions from charge capture (220 V_{pp}, 850 kHz)
- DC fields to guide ions towards chamber nozzle exit (4 V/cm)

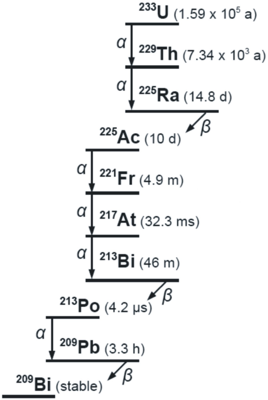


RF-Extraction Quadrupole

Quadrupole system for ion guiding



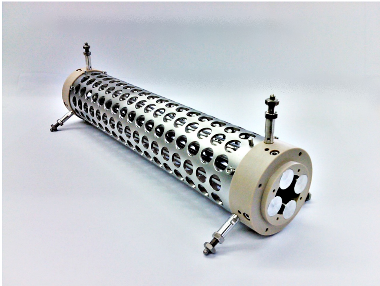
- 12 segments (voltage gradient: ~ 0.1 V/cm)
- removal of carrier gas ($10^{-2} - 10^{-3}$ mbar)
- phase-space cooling in remaining He
- ion beam of sub-mm diameter at exit
- daughter decay-products still contained



Quadrupole-Mass-Separator (QMS)

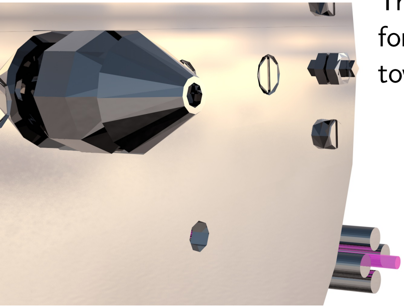
Mass separator to suppress daughter nuclides

- design values from [1]
- active voltage stabilization ($\leq 10^{-3}$)
- Brubaker lenses at entrance and exit
- 80 % efficiency at mass resolution $\frac{m}{\Delta m} \approx 150$

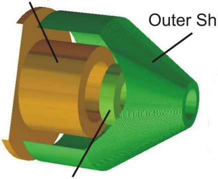


[1] E.Haettner, PhD Thesis, Univ. Giessen (2011)

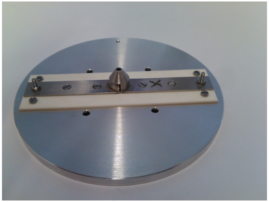
Triode Extraction System



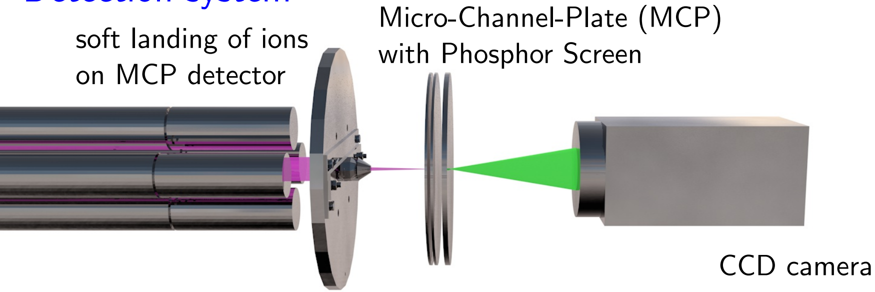
Triode extraction system
for guiding the ions out of the QMS
towards MCP detector

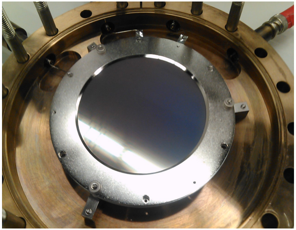


- 3 electrodes with nozzle-like design
- 2 mm diameter opening (spotsize)
- -50 V extraction voltage



Detection system





- spatially resolved detection of any decays
- highest detection efficiency for low energy electrons
- low dark-count rate 0.01 cps/mm^2

$\Rightarrow$ very sensitive to any decay events

Setup overview

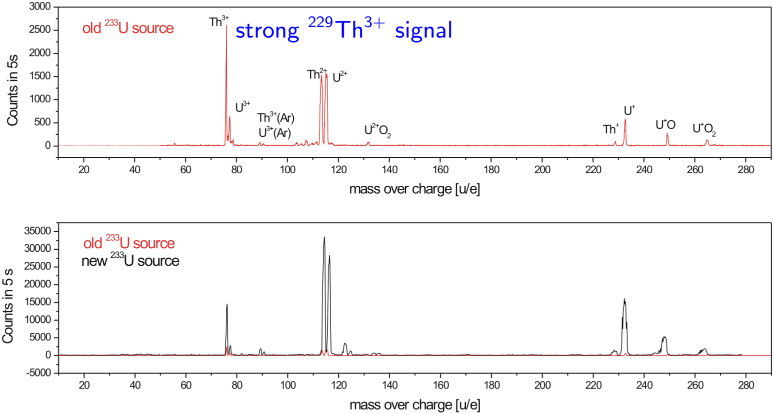
- ^{233}U source 290 kBq
- $\sim$ 34% α-recoil efficiency
- $\sim$ 10^5 ^{229}Th ions/s leaving the source

- $\sim$10% measured extraction and purification efficiency for $^{229}Th^{3+}$
- $\sim 10^4$ $^{229}Th^{3+}$ ions/s at detector
  - $\sim$2% in the isomeric state
  - $\sim$200 isomers/s at detector
    - $\sim$1.5% MCP detection efficiency
    - $\sim$3 detected isomeric decays/s
      - 2 mm diameter spotsize
      - MCP dark-count rate 0.01 cps/ mm^2

$\Rightarrow$ expected signal to background rate: $\sim$100:1

Mass scans and cell chemistry

Comparison of mass scans from old and new ^{233}U sources



- Oxide and Argon molecule formation
- $^{229}Th^{3+}$ signal extremely sensitive to buffer-gas purity level

Ion extraction efficiencies

Extraction efficiency analysis performed with first source[1]

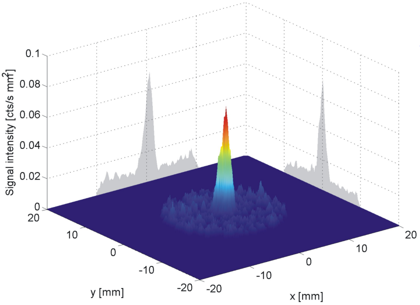
Element	$q = 1+$ [%]	$q = 2+$ [%]	$q = 3+$ [%]	total [%]
Thorium	0.34 ± 0.07	5.5 ± 1.1	10 ± 2.0	16 ± 3.2
Radium	n.a.	36 ± 7.2	n.a.	n.a.
Francium	21 ± 4.2	16 ± 3.2	$\leq 1.6 \cdot 10^{-3}$	37 ± 7.4
Radon	5.8 ± 1.2	9.3 ± 1.9	$(5.3 \pm 1.1) \cdot 10^{-2}$	15 ± 3.0
Astatine	8.6 ± 1.7	13 ± 2.6	$(3.3 \pm 0.7) \cdot 10^{-2}$	22 ± 4.4
Polonium	7.3 ± 1.5	8.1 ± 1.6	$\leq 2.1 \cdot 10^{-3}$	15 ± 3.0
Bismuth	4.3 ± 0.9	21 ± 4.2	$(8.3 \pm 1.6) \cdot 10^{-2}$	25 ± 5.0
Lead	2.2 ± 0.4	11 ± 2.2	$\leq 1.2 \cdot 10^{-2}$	13 ± 2.6

- Only thorium is extracted to a significant amount in the 3+ charge state
- Physical reason: Th^{2+} ionization potential is 18.3 eV ($<$ 24.6 eV of He)

[1] L.v.d.Wense et al., Eur. Phys. J. A 51: 29 (2015).

Isomer detection

A signal is detected![1]



Is this really the ^{229m}Th decay?

Sources of potential (nontrivial) background:

- a) from ionic impact or charge state
- b) from short-lived daughters
- c) from the Th shell (long-lived excited shell state, chemical reaction)

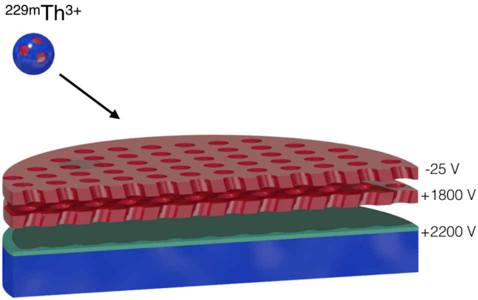
All types of background could be excluded

Signal as obtained after 2000 s integration during extraction of $^{229}Th^{2+}$ from source 1.

[1] L.v.d.Wense et al., Nature 533 (2016) 47.

Isomer detection process

- collect ions on the MCP detector



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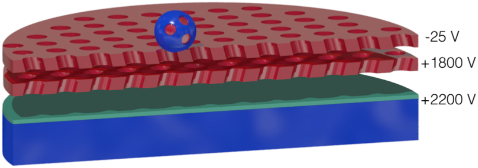
Isomer detection process

- collect ions on the MCP detector



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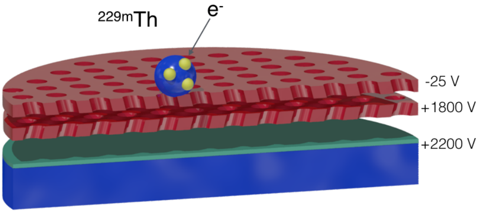
Isomer detection process

- collect ions on the MCP detector
- ions neutralize on the MCP surface
  - IC decay-channel is open
  - reduced half-life



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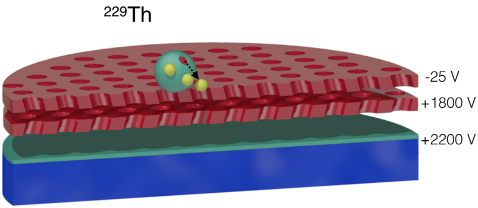
Isomer detection process

- collect ions on the MCP detector
- ions neutralize on the MCP surface
  - IC decay-channel is open
  - reduced half-life
- isomer decays via internal conversion



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Isomer detection process

- collect ions on the MCP detector
- ions neutralize on the MCP surface
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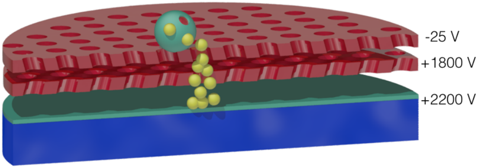
    - reduced half-life
- isomer decays via internal conversion
- electron cascade is generated...



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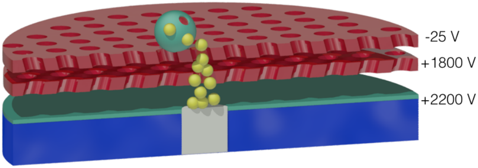
Isomer detection process

- collect ions on the MCP detector
- ions neutralize on the MCP surface
  - IC decay-channel is open
  - reduced half-life
- isomer decays via internal conversion
- electron cascade is generated...
- ... and accelerated onto an anode where it can be read out



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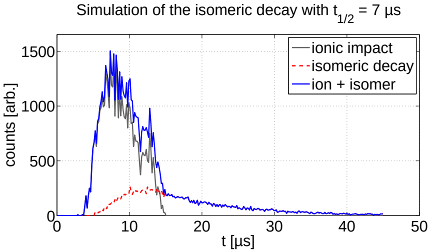
Lifetime Measurements

MC simulations:

- use measured bunch as an input (800 ions per bunch)
- 2% of the ions are in the isomeric state
- 48 h measurement time (≈35000 bunches)
- $t_{1/2} = 7\ \mu s$



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Lifetime Measurements

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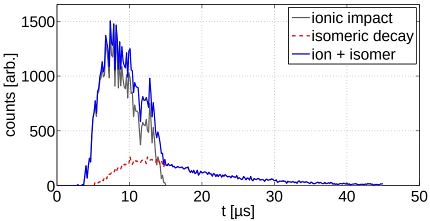
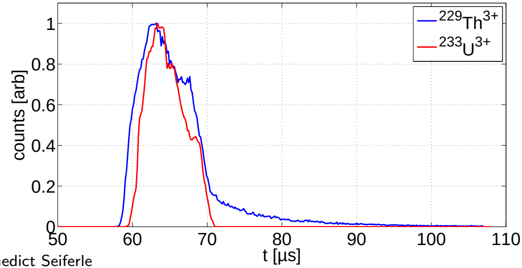
Simulation of the isomeric decay with $t_{1/2}$ = 7 µs



Measurement



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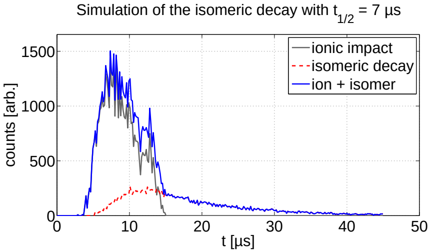
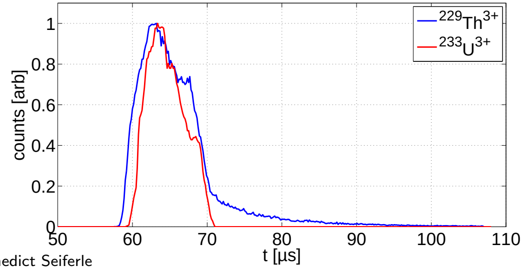


Measurement



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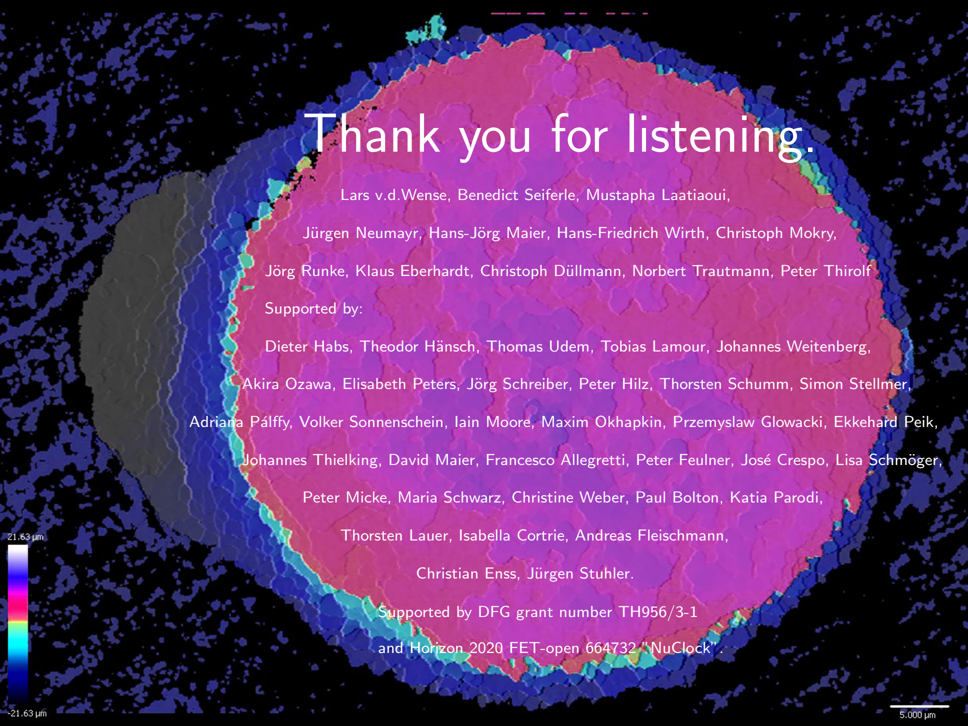
Conclusion

- High $^{229}Th^{2+/3+}$ extraction efficiencies can be achieved
- First time direct detection of ^{229}Th isomeric decay
- Paves the way for first nuclear laser excitation
- Promising for nuclear clock development

Exciting new experiments are in reach!



Thank you for listening.

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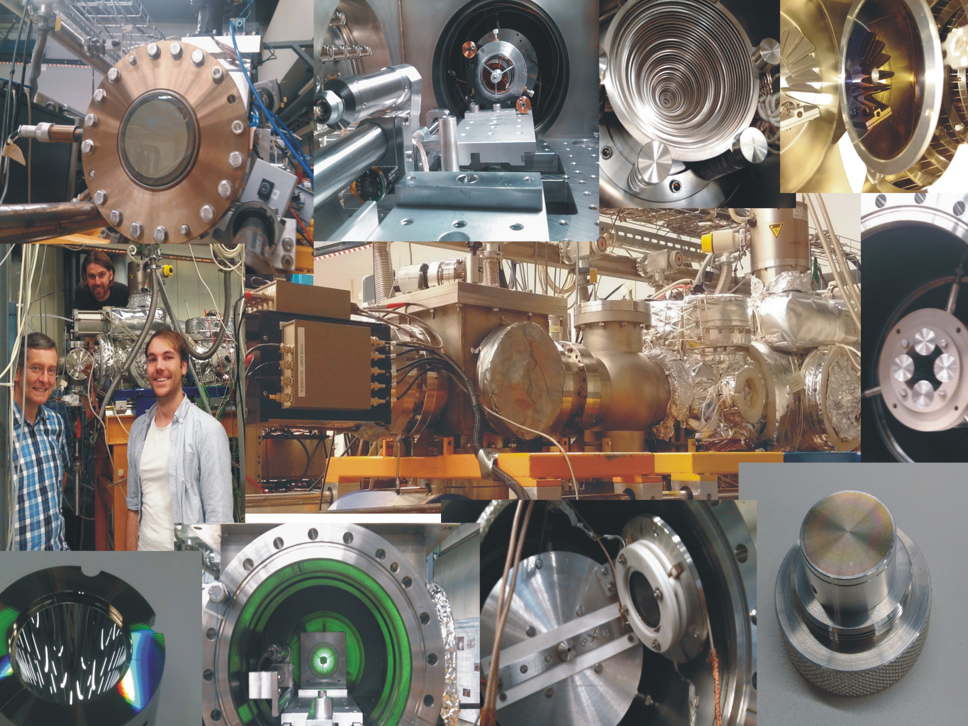
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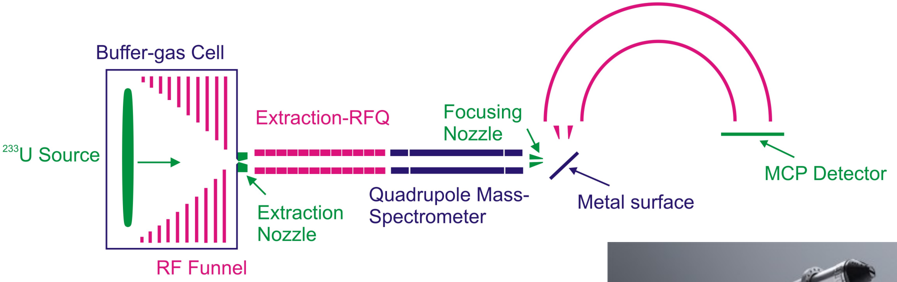
Perspectives: Energy determination

Applying a hemispherical electron-energy analyzer



Objective:
- Energy determination to ≤ 0.1 eV

Challenges:
- low energy (7.6 eV-6.3 eV $\approx$ 1.3 eV)
- low absolute electron rate: ~ 100 /s in 4π with source 2

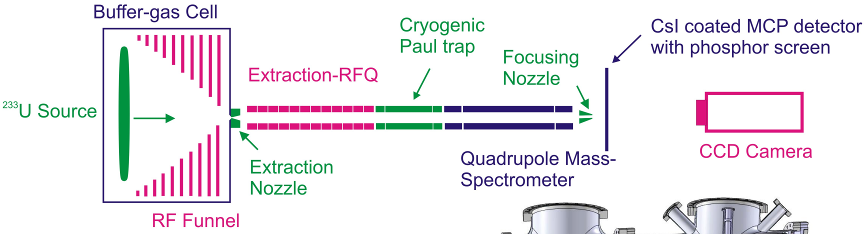
Scienta Omicron

Perspectives: Half-life determination

Half-life in $^{229}Th^{2+}$ determined to $\geq$ 1 min. (by ion storage in RFQ)

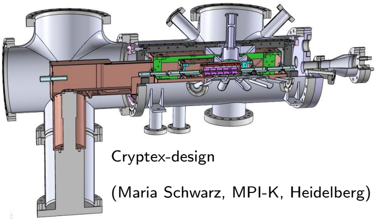
Problem: RFQ not clean enough to allow for longer storage times

Solution: Applying a cryogenically cooled linear Paul trap (in cooperation with MPI-K)



Objective: ▶ Storage times of $\geq$ 10 h

Challenge: ▶ long measurement times



Cryptex-design

(Maria Schwarz, MPI-K, Heidelberg)