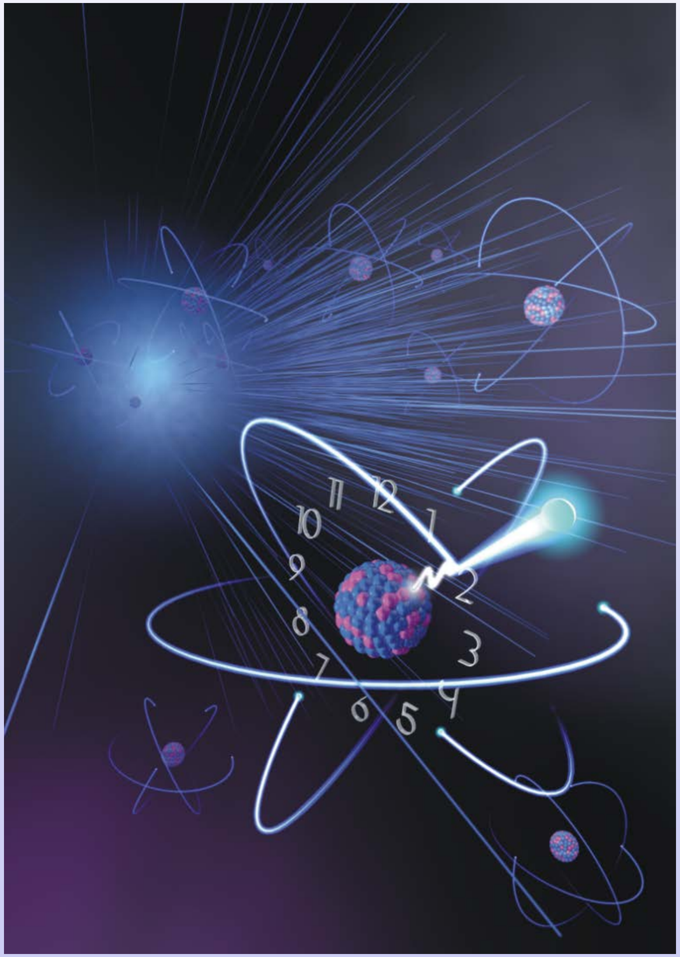
Direct identification of the elusive ^{229m}Th isomer: Milestone towards a Nuclear Clock

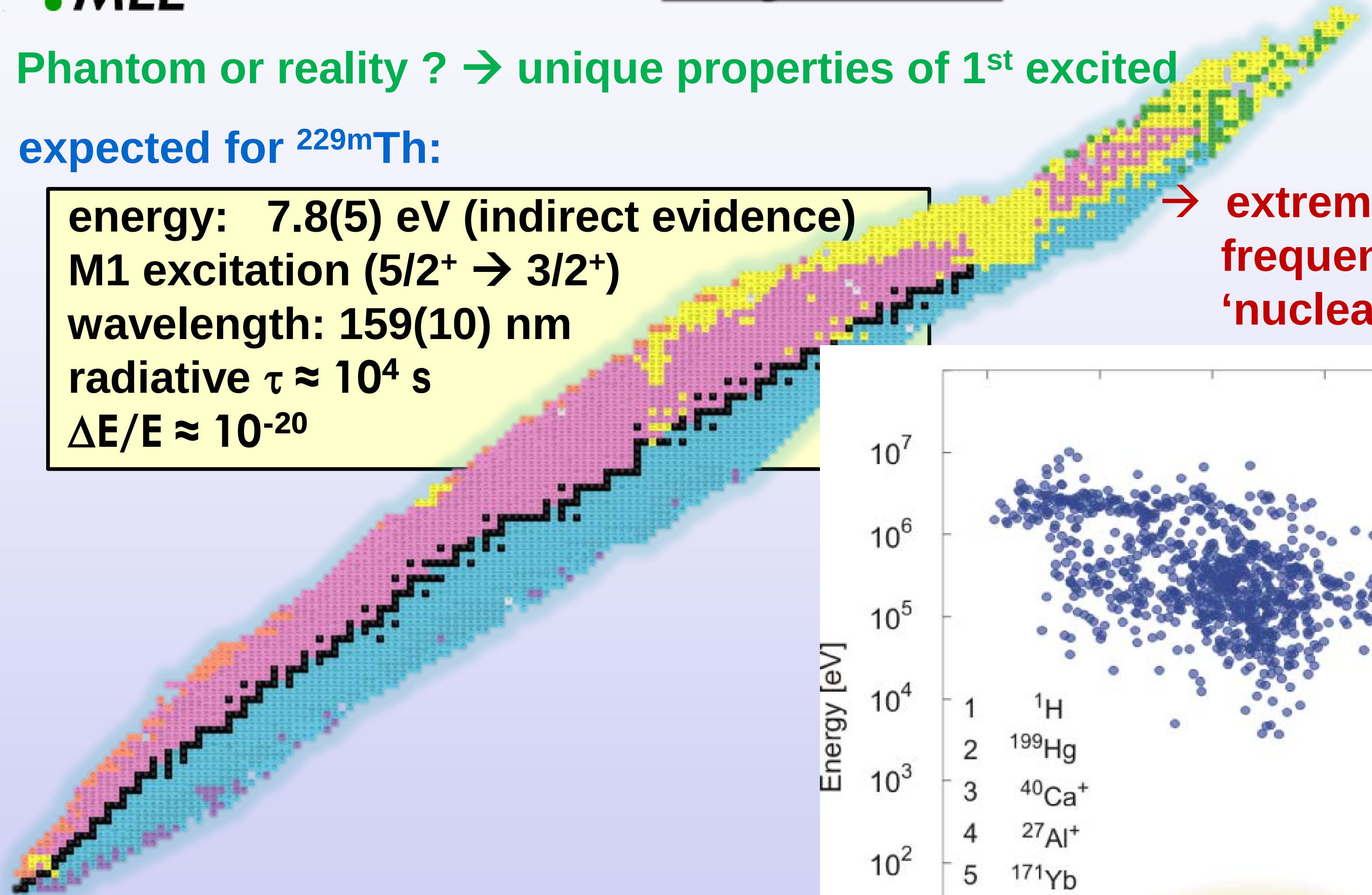
P.G. Thirolf, LMU München

- ^{229m}Th properties and prospects
- Experimental approach & setup
- Measurements on ^{229m}Th:
  identification, characterization
- Summary & Perspectives



Why searching 1 nuclear level for 40 years ?

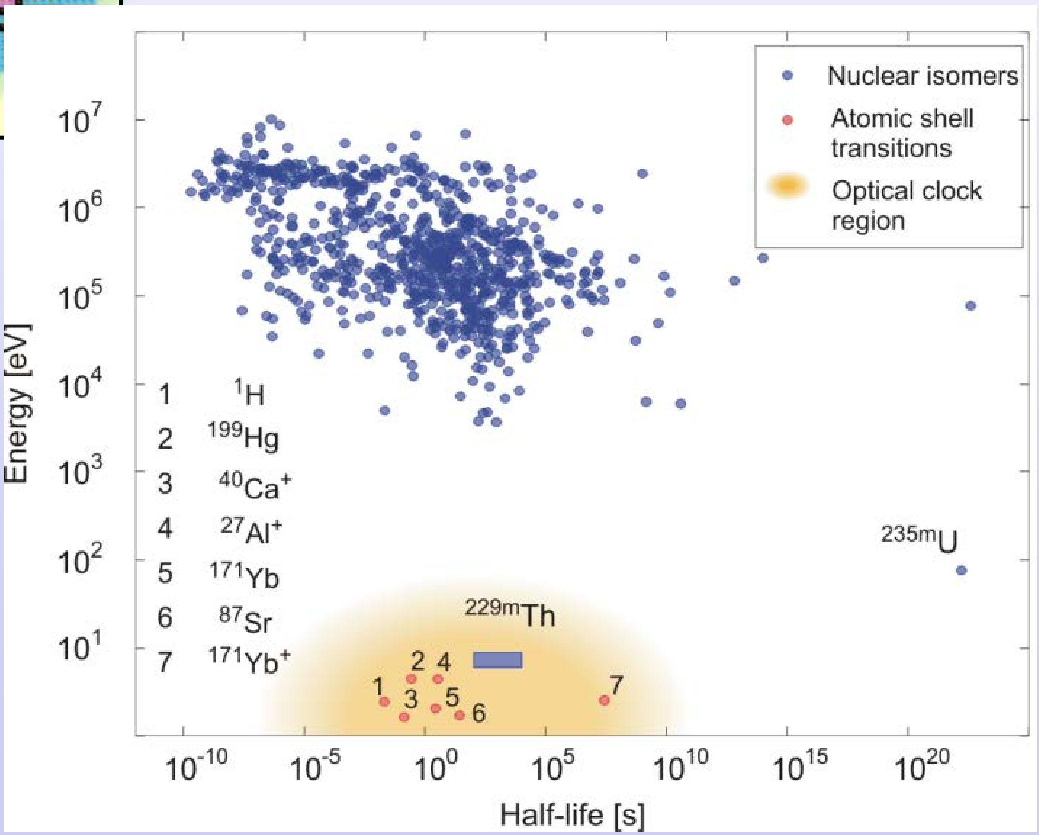
Phantom or reality ? → unique properties of 1st excited state of ^{229}Th:



expected for ^{229m}Th:

energy: 7.8(5) eV (indirect evidence)
M1 excitation ($5/2^+ \rightarrow 3/2^+$)
wavelength: 159(10) nm
radiative $\tau \approx 10^4$ s
$\Delta E/E \approx 10^{-20}$

→ extremely stable nuclear frequency standard: 'nuclear clock'



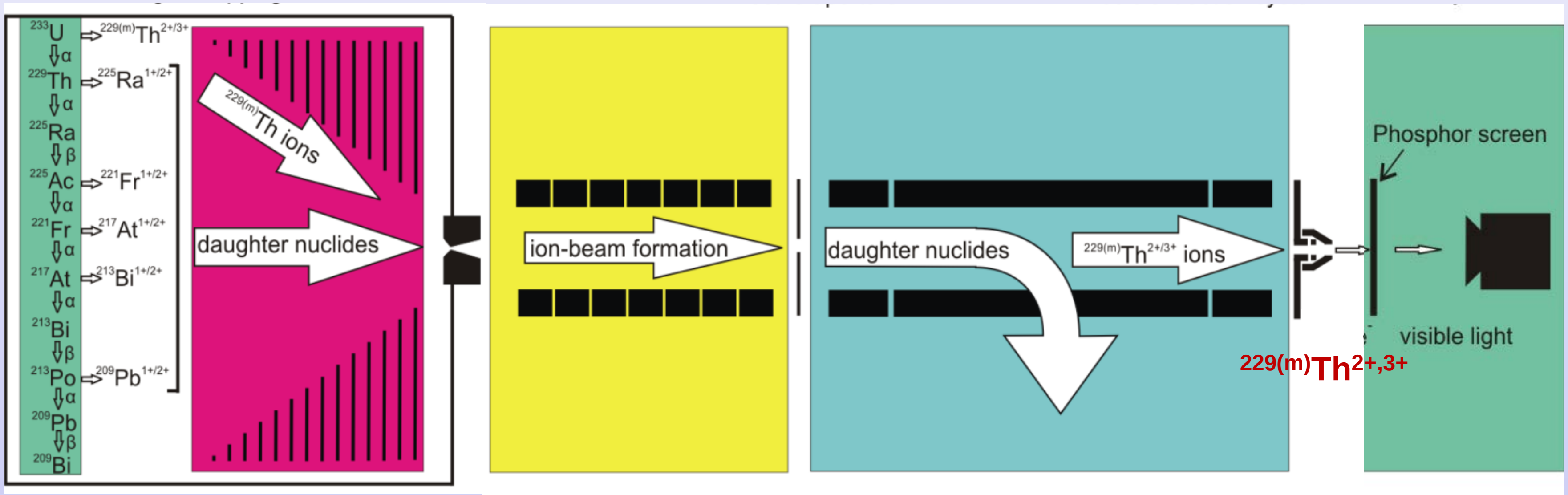
lowest E* of all ca. 176000 presently known nuclear excited states

L.A. Kroger and C.W. Reich, Nucl. Phys. A 259 (1976) 29
B.R. Beck et al., PRL 98 (2007) 142501

Experimental Approach

concept:
- populate the isomeric state via 2% decay branch in the α decay of ^{233}U
- spatially decouple $^{229(m)}Th$ recoils from the ^{233}U source: avoid background
- detect the subsequently occurring isomeric decay

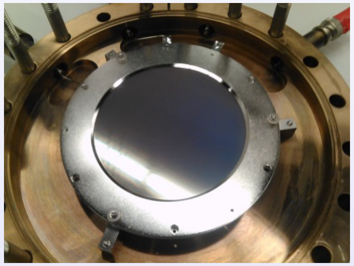
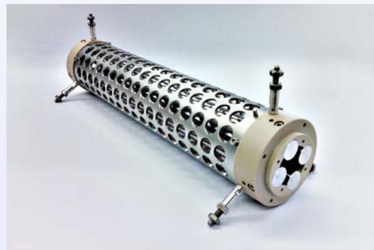
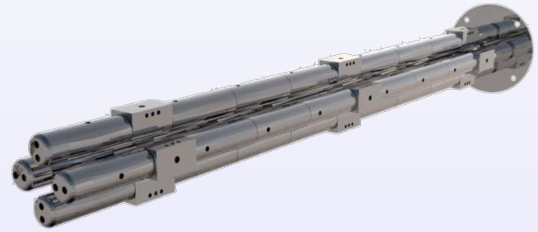
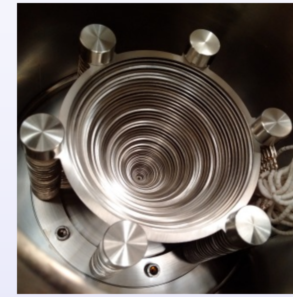
Buffer gas stopping cell | **Laval nozzle** | **aperture electrode** | **triodic extraction electrode** | **detection system**



^{233}U source | **RF + DC funnel** | **RF quadrupole ion guide** | **Quadrupole mass separator** | **MCP** | **CCD**

Experimental Setup

located at Maier-Leibnitz Laboratory, Garching:

Ion Extraction from Buffer Gas Cell

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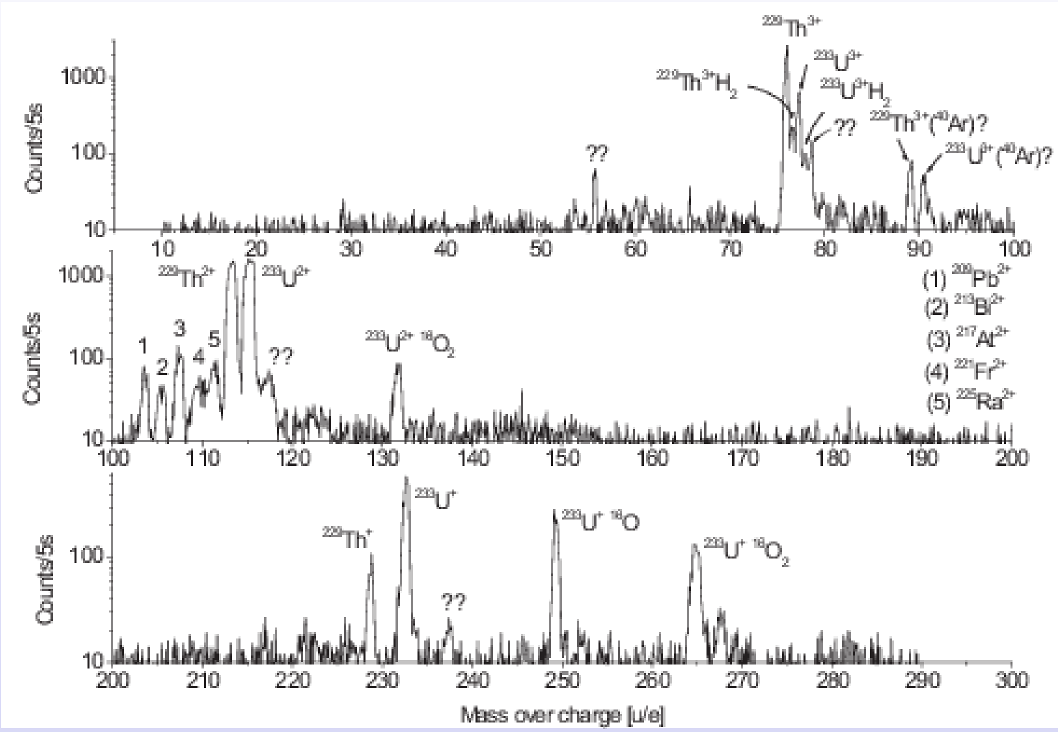
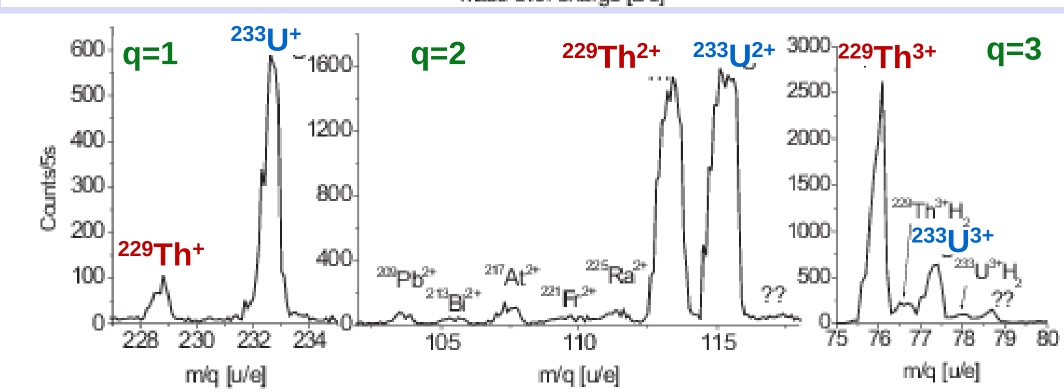
MLL

nuClock

mass scan of extracted ion species: efficient $^{229(m)}Th^{3+}$ extraction





element	1+ [%]	2+ [%]	3+ [%]
Th	0.37(7)	5.5(11)	10(2)
Fr	21.0(42)	16.0(32)	≤ 1.5.10^{-3}
Rn	5.8(12)	9.3(19)	0.053(11)
At	8.6(17)	13.0(26)	0.033(7)
Po	7.3(15)	8.1(16)	≤ 0.0021
Bi	4.3(9)	21.0(42)	0.083(16)
Pb	2.2(4)	11.0(22)	≤ 0.012

element	1+ [eV]	2+ [eV]	3+ [eV]
U	6.1	11.6	19.8
Th	6.3	11.9	18.3
Ra	5.3	10.1	31.0
Fr	4.1	22.4	33.5
Rn	10.7	21.4	29.4
At	9.3	17.9	26.6
Po	8.4	19.3	27.3
Bi	7.3	16.7	25.6

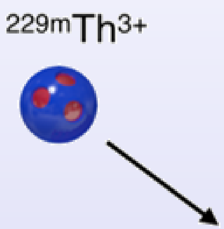
L. v.d. Wense, B. Seiferle, M. Laatiaoui, PT, EPJ A51, 29 (2015)

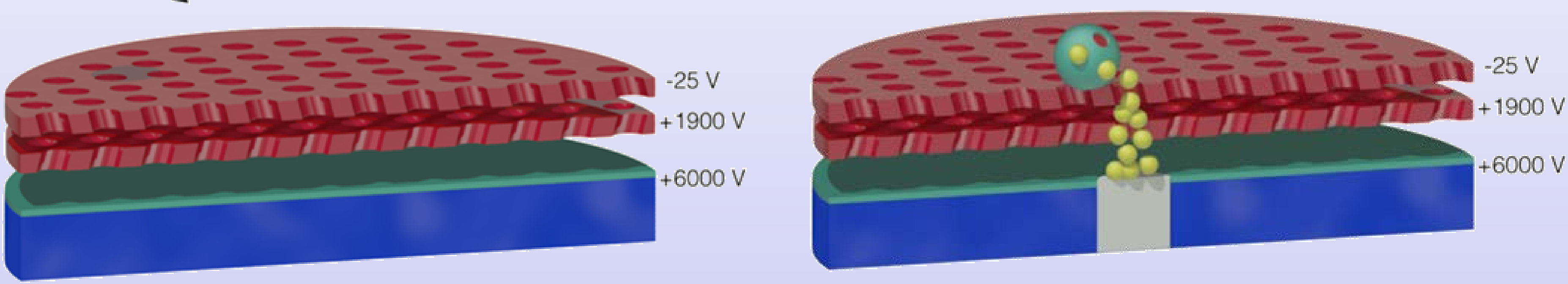
I(He$^+$) = 24.6 eV

Isomer Detection Process

extracted $^{229(m)}Th^{3+}$ ions:

- impinging directly onto MCP surface behind triode exit
- 'soft landing' on MCP surface
- neutralization of Th ions
- isomer decay by Internal Conversion: electron emission
- electron cascade generated, accelerated towards phosphor screen
- visible light imaged by CCD camera





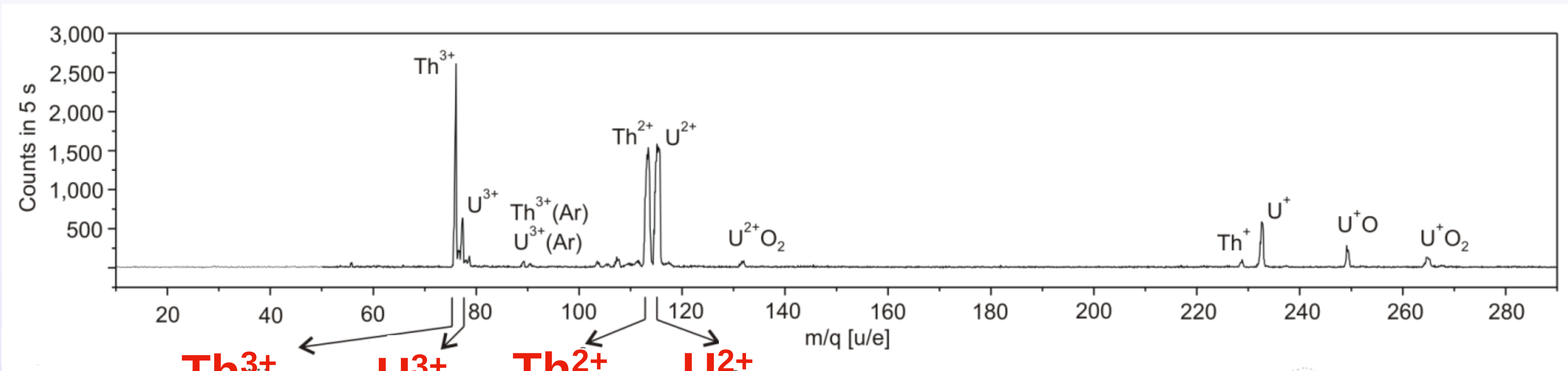
- internal conversion (IC) energetically allowed for neutral thorium:

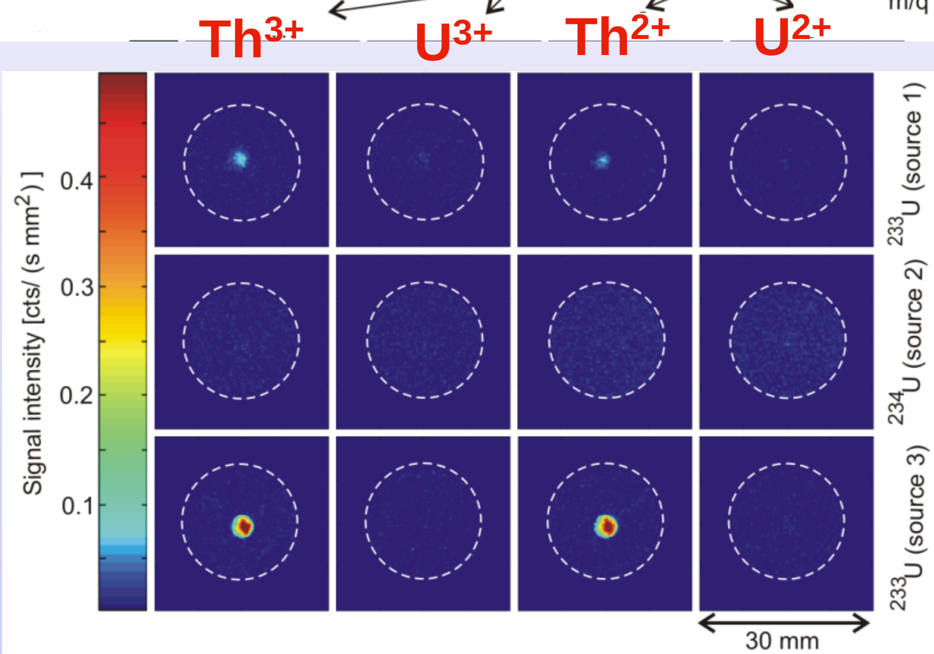
  $I(Th^{+}, 6.31\ eV) < E^{*}(^{229m}Th, 7.8\ eV)$

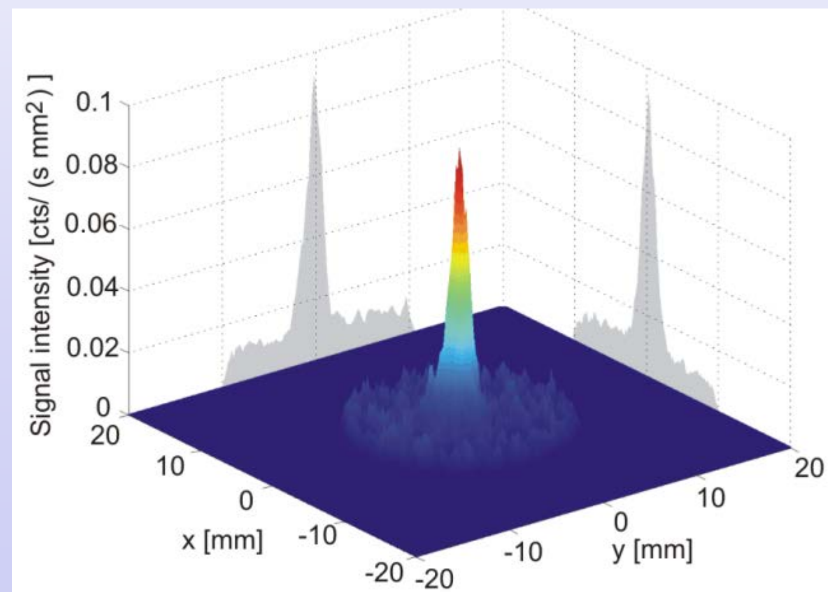
- isomer lifetime expected to be reduced by ca. 10^{-9} (from $\sim 10^{4}$ s → ~ 10 μs)
- Th^{q+} ions: IC is energetically forbidden, radiative decay branch may dominate

Direct Signal of IC Decay from ^{229m}Th

L. v.d. Wense, PT et al., Nature 533, 47-51 (2016)







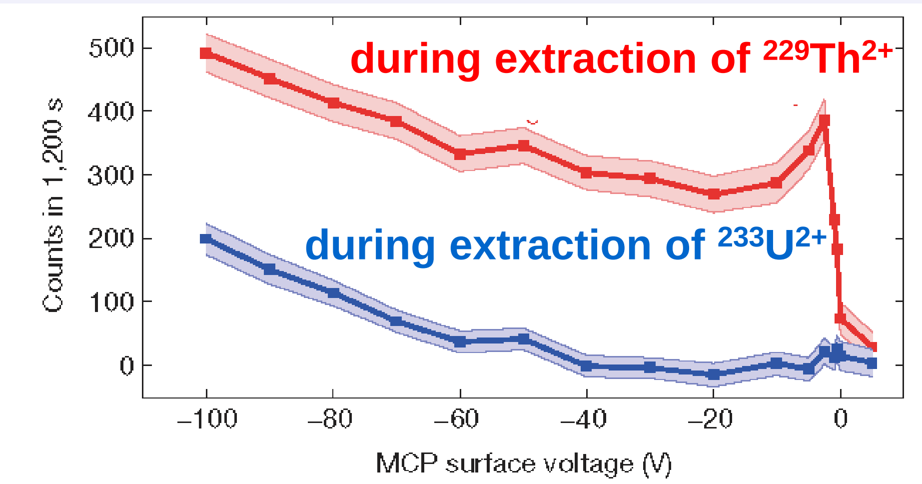
clear signal from Th^{3+}, Th^{2+}
no signal from U^{3+}, U^{2+}

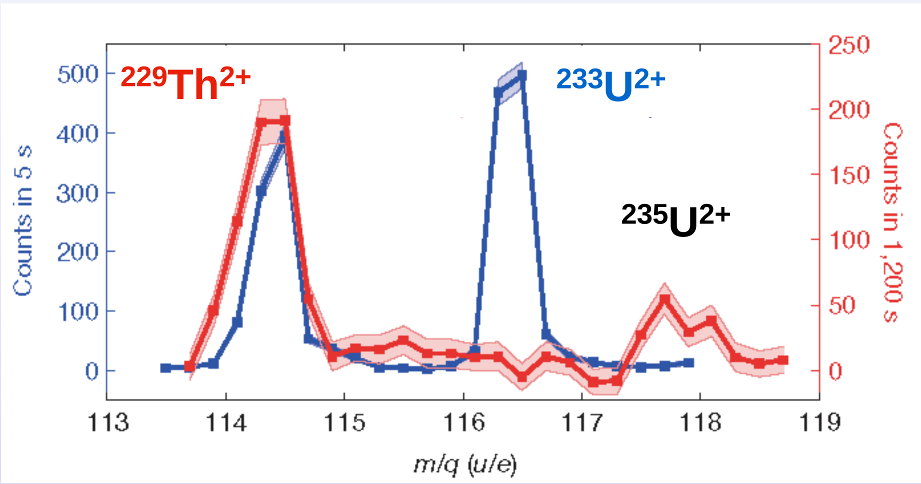
Verification Measurements

Background-corrected isomeric decay signals:

U_{MCP}= -25 V → isomeric decay

U_{MCP}= -2000 V → ionic impact





- ionic impact signal decreases with U_{MCP}
- $^{233}U^{2+}$ signal drops to zero
- $^{229}Th^{2+}$ signal remains, cutoff at E_{kin}=0

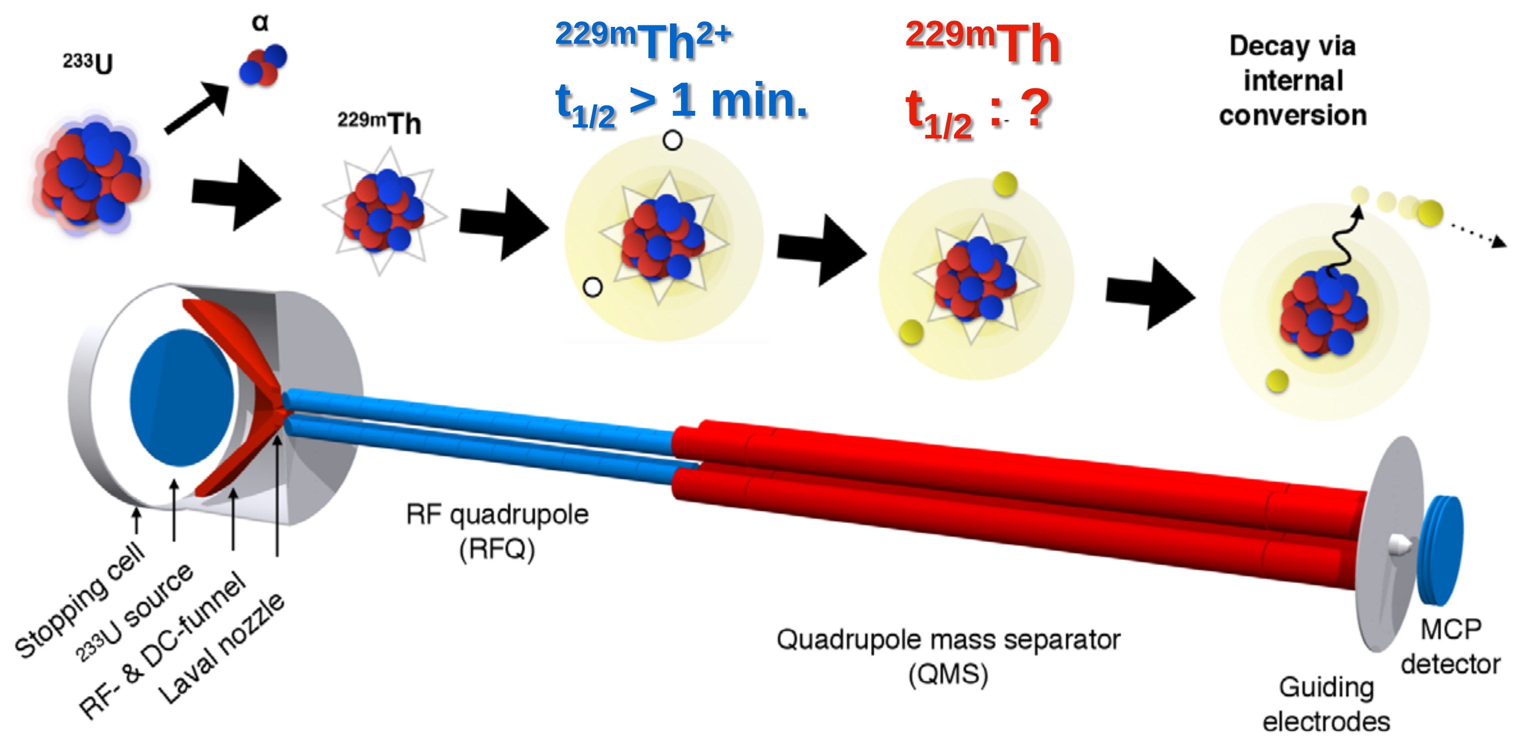
  (rise: IC electrons back-attracted to MCP surface)

- comparable mass peak amplitudes for $^{229}Th^{2+}$, $^{233}U^{2+}$ ion impact signals
- for U_{MCP}= -25 V $^{233}U^{2+}$ signal vanishes
- $^{229}Th^{2+}$ signal remains

all potential background contributions could be excluded, mostly by several ways

Next step: Halflife determination

- charged $^{229m}Th^{2+}$: $t_{1/2}$ > 1 min. (limited by RFQ storage time)
- neutral ^{229m}Th: pulsed extraction from RFQ

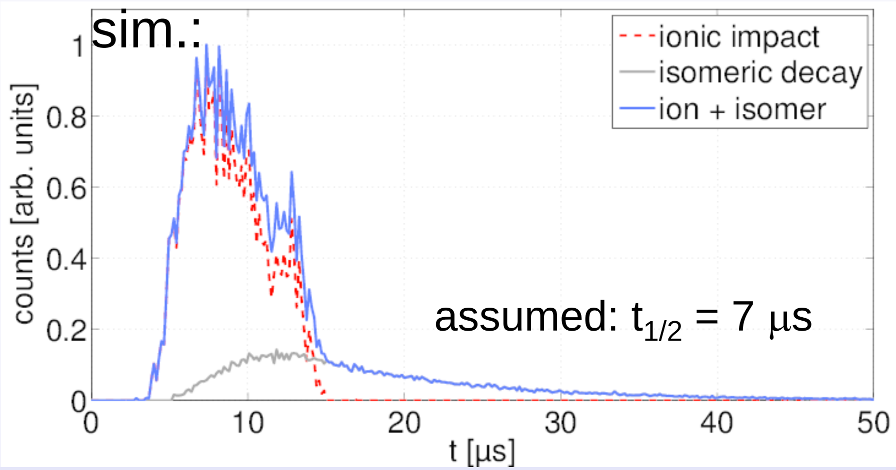


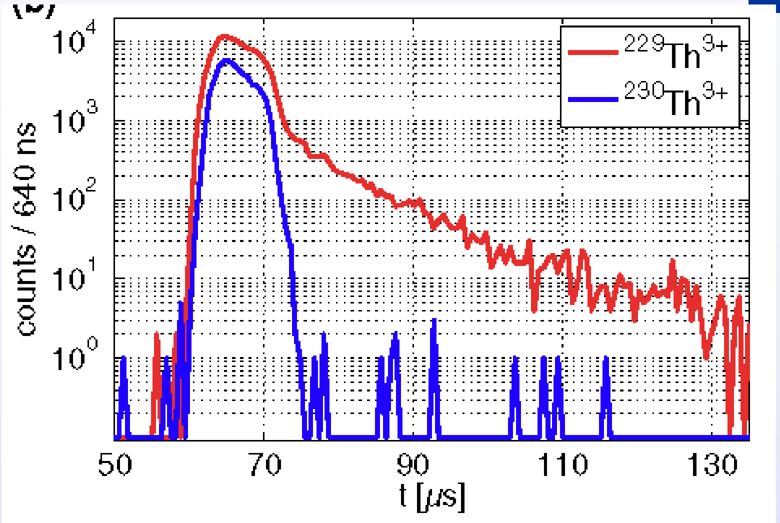
- expected conversion coefficient: $\alpha = N_e/N_\gamma \sim 10^9$

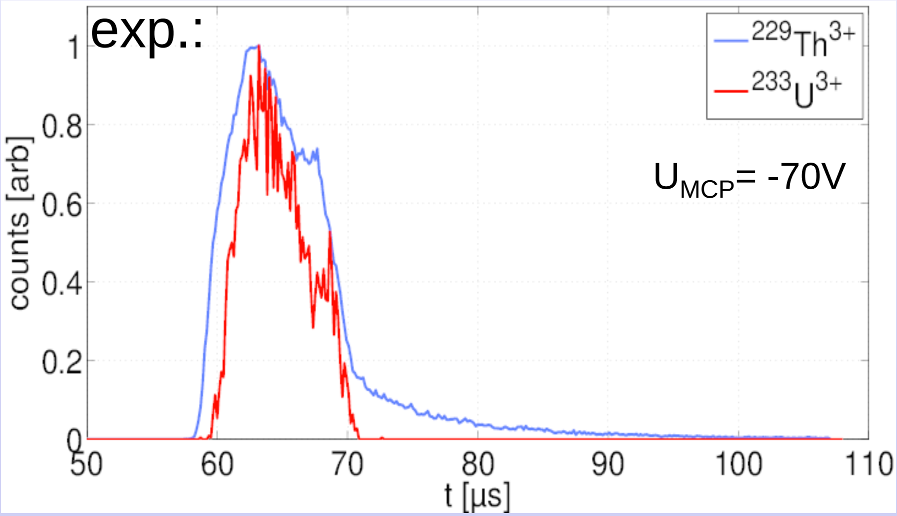
→ provides constraint for strength of photonic decay branch
(if IC cannot be suppressed, e.g. by suitable crystal lattice implantation)

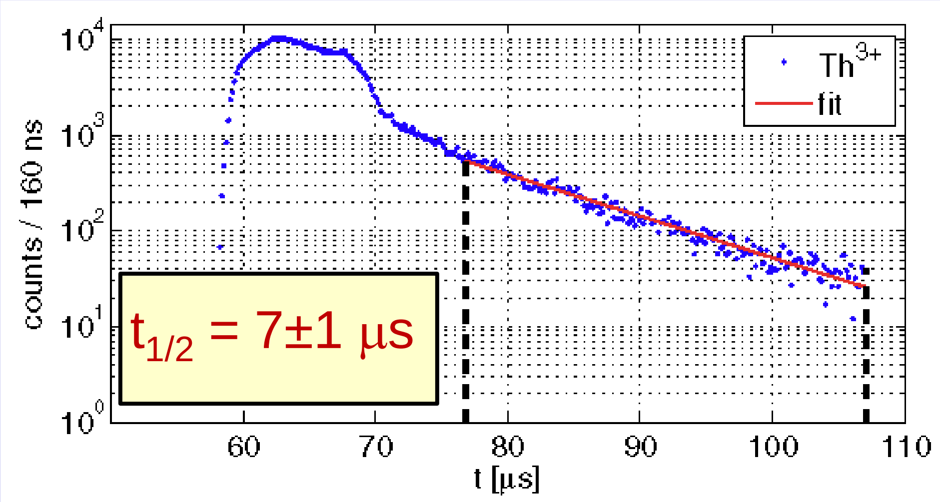
Halflife: Neutral ^{229m}Th

B. Seiferle, L. v.d. Wense, PT, PRL 118, 042501 (2017)









- bunch width: ca. 10 μs
- ca. 400 $^{229(m)}Th^{2+,3+}$ ions/bunch

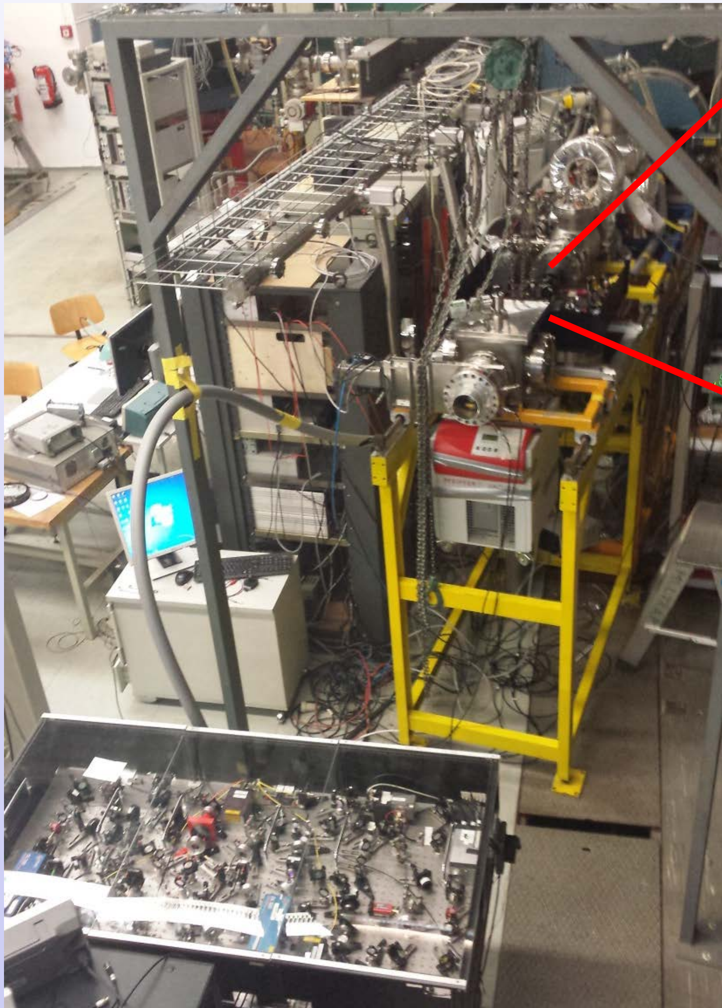
→ confirms expected conversion coefficient: ~10^9

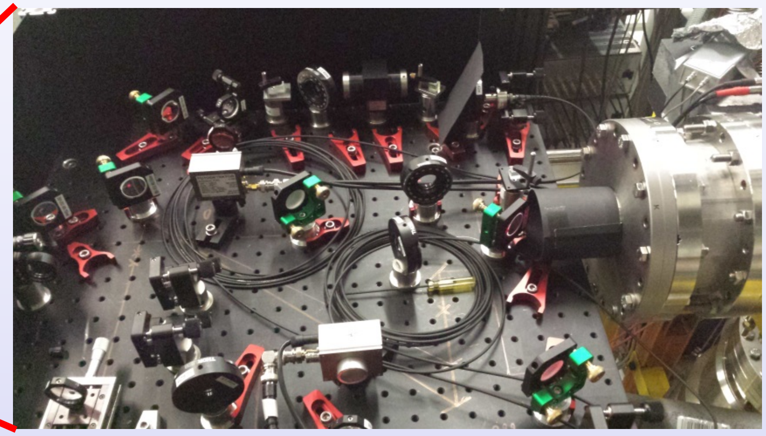
→ photonic decay branch ??

Collinear Laser Spectroscopy of ^{229m}Th

- Collaboration with PTB Braunschweig: (E. Peik, M. Okhapkin et al.):

  Goal: resolve hyperfine structure of $^{229m}Th^{2+}$





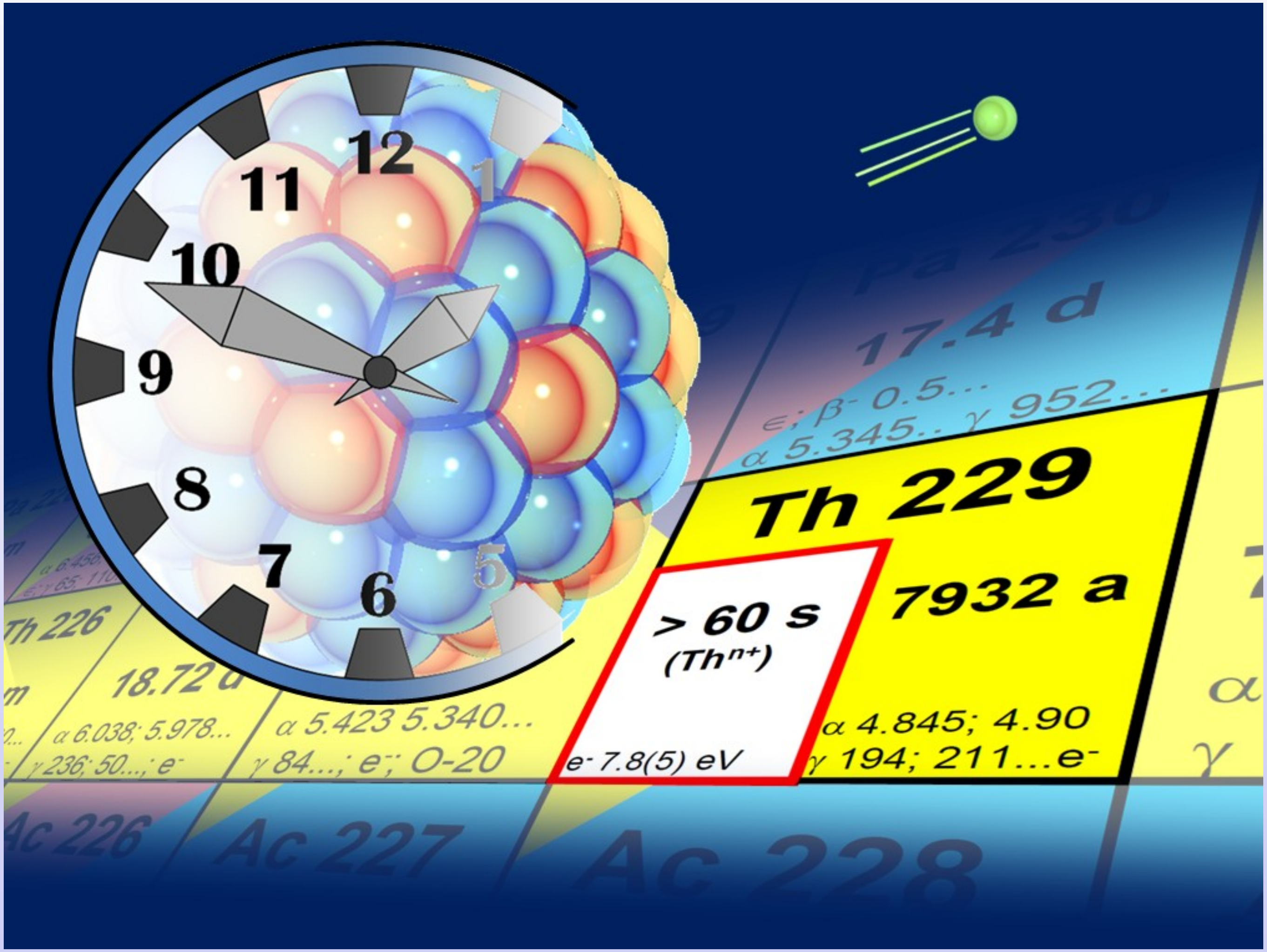
- laser excitation of $^{229(m)}Th^{2+}$ ions behind QMS:
  - → 3 external-cavity diode lasers
  - → co- and counter-propagating laser beams

- preparatory experiments on ^{229}Th at PTB Paul trap

Summary & Perspectives

- 229-Thorium isomer exists: first direct detection via IC decay channel
- constraints of ^{229m}Th properties: $6.3 \text{ eV} \leq E^* \leq 18.3 \text{ eV}$, $\tau > 60$ s — Nature 533 (2016)
- Half-life of neutral ^{229m}Th: $t_{1/2} = 7\ \mu s$ → $\alpha \sim 10^9$ — PRL 118 (2017)
- Hyperfine structure of ^{229m}Th measured via collinear laser spectroscopy:
  →nuclear moments, charge radius, (prolate) deformation — revision submitted to Nature
- isomeric excitation energy: — method: EPJ A53 (2017)
  measurements with (retarding field) magnetic bottle electron spectrometer in progress
- contrary to general paradigm: laser excitation of ^{229m}Th feasible with existing laser technology → experiment in preparation — method: PRL 119 (2017)
- charged ^{229m}Th: needs longer storage time
  → setup of a cryogenic Paul trap in progress

we made a big step towards the ultimate goal of a Nuclear Clock ....



but many more are yet to come ....

Thanks to ....

LMU Munich: **L. v.d. Wense, B. Seiferle**, N. Arlt, B. Kotulski, J.B. Neumayr, H.-J. Maier, H.-F. Wirth

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GSI Helmholtzzentrum f. Schwerionenforschung, Darmstadt & Helmholtz-Institut Mainz:

M. Laatiaoui (now: KU Leuven)

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C. Mokry, J. Runke, K. Eberhardt, C.E. Düllmann, N.G. Trautmann

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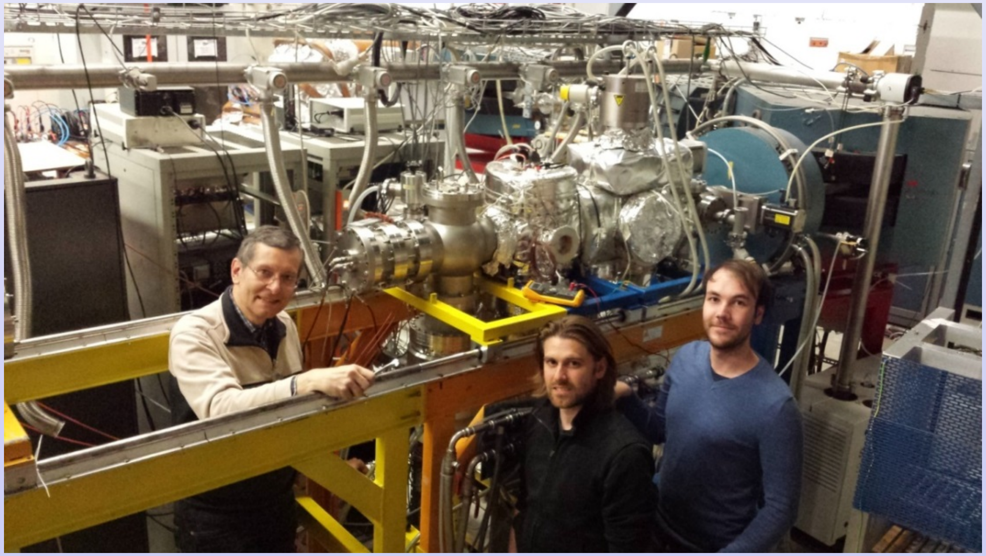

Thank you for your attention !