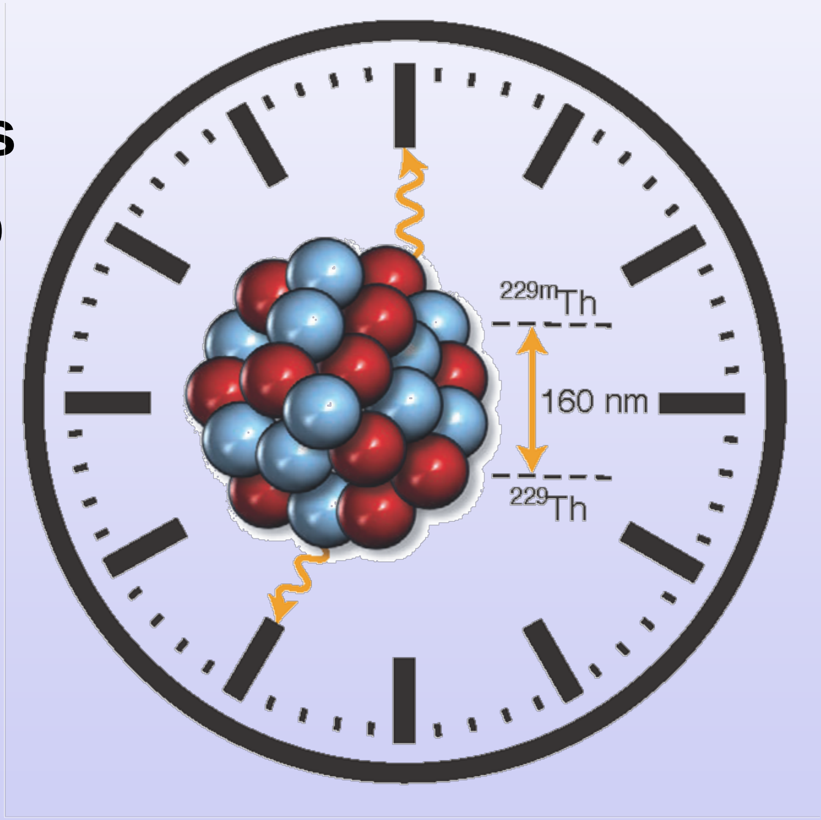
Latest results on the ^{229m}Th 'Nuclear Clock Isomer'

P.G. Thirolf, LMU München

- ^{229m}Th properties and prospects
- Experimental approach & setup
- Measurements on ^{229m}Th:
  - first direct identification
  - halflife
  - hyperfine structure
- Summary & Perspectives



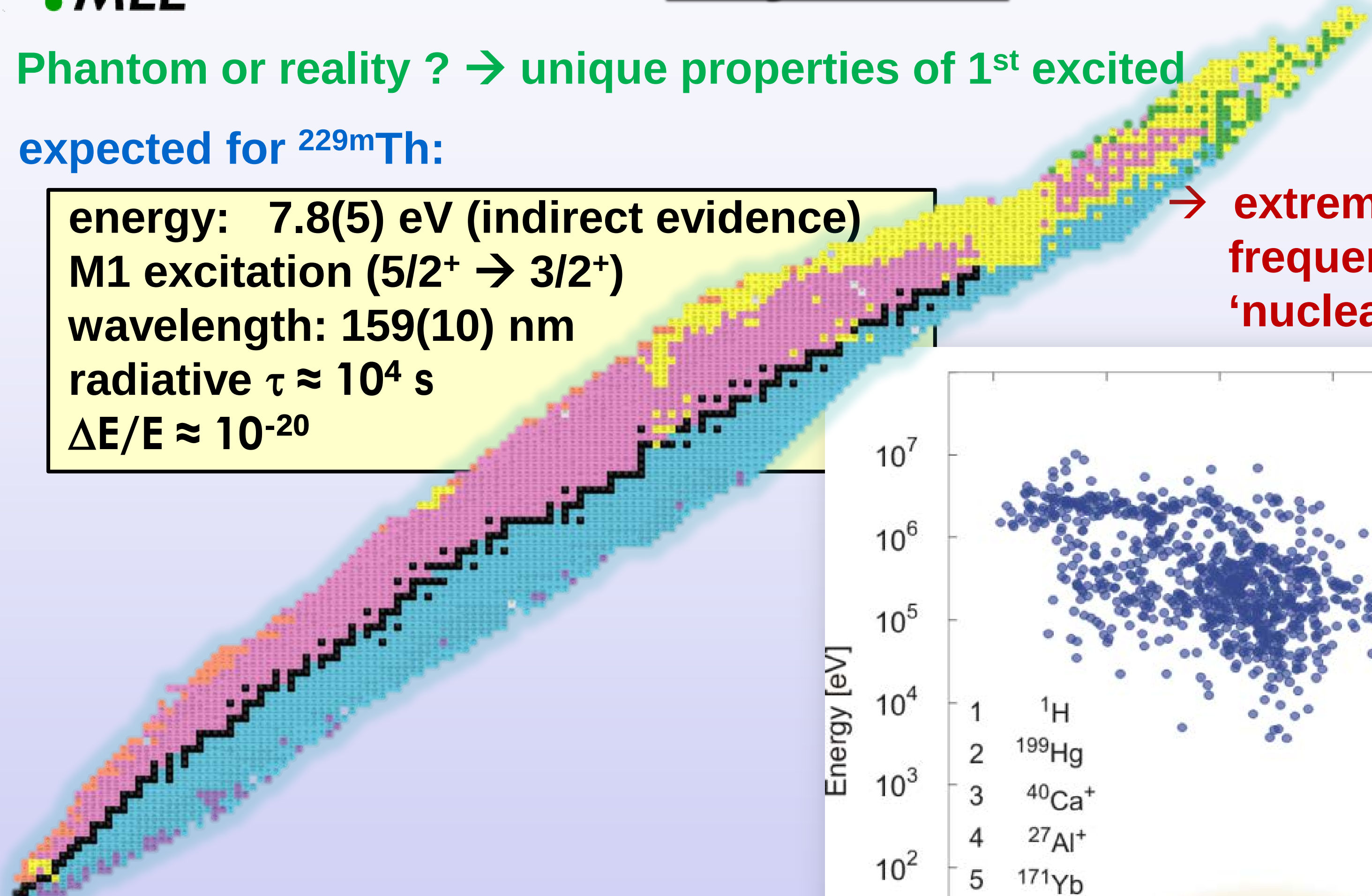
Why searching 1 nuclear level for 40 years ?

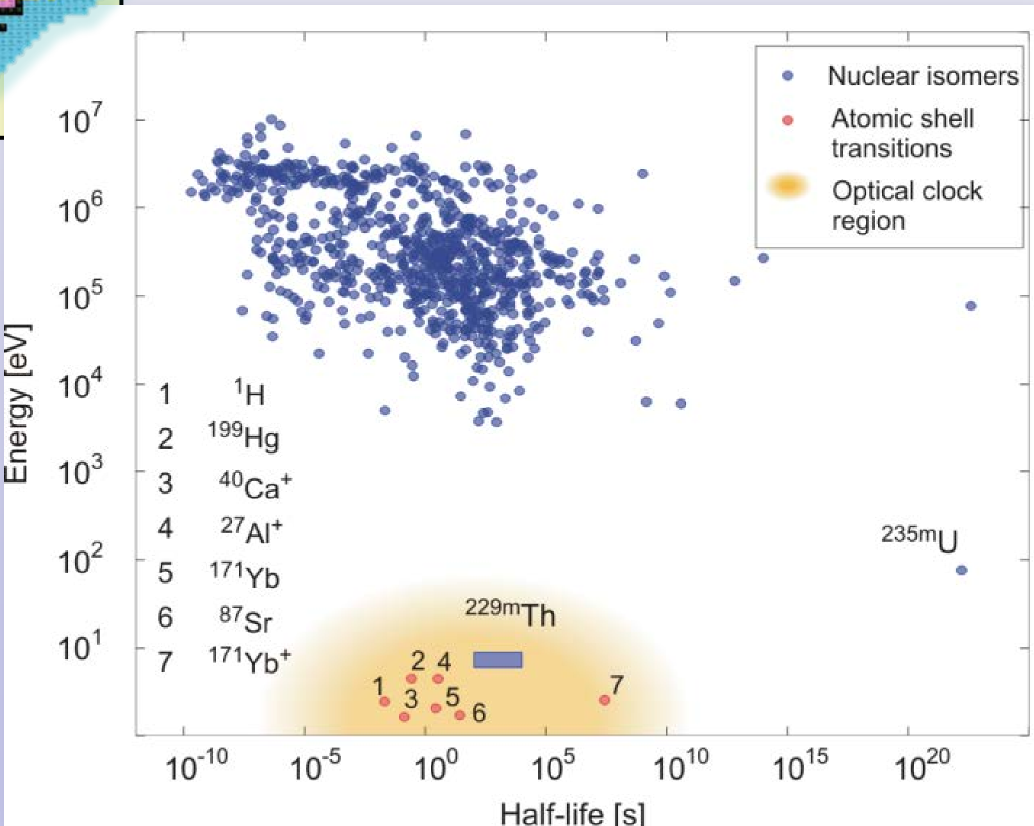
Phantom or reality ? → unique properties of 1st excited state of ^{229}Th:

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

Potential Applications of Nuclear Clocks

- **satellite-based navigation** (GPS, Galileo..):

  presently: ‘thermal’ microwave atomic clocks (Rb, Cs)
  positioning precision: 1-10 m

  goal: improved positioning precision to cm – mm
  - autonomous driving
  - freight-/ component tracking …

- **time variation of fundamental constants**

  - theoretical suggestion: temporal (spatial) variations of fundamental “constants”
  - current limit: $\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \cdot 10^{-17}\ \mathrm{yr}^{-1}$ Fujii et al., NP B 573, 377 (2000)
  - temporal variation in transition energy of ^{229m}Th may provide enhanced sensitivity by (10^2 – 10^5) for fine structure constant $\dot{\alpha}/\alpha$ and strong interaction parameter (m_q/Λ_{QCD})

- **3D gravity sensor:** ‘relativistic geodesy’

  - best present clocks: detect gravitational shifts of ± 2 cm
    → allows long-distance potential difference measurements
  - precise, fast measurements of nuclear clock network:
    e.g. monitor volcanic magma chambers, tectonic plate movements

$$\boxed{\Delta f / f = -\Delta U / c^2}$$

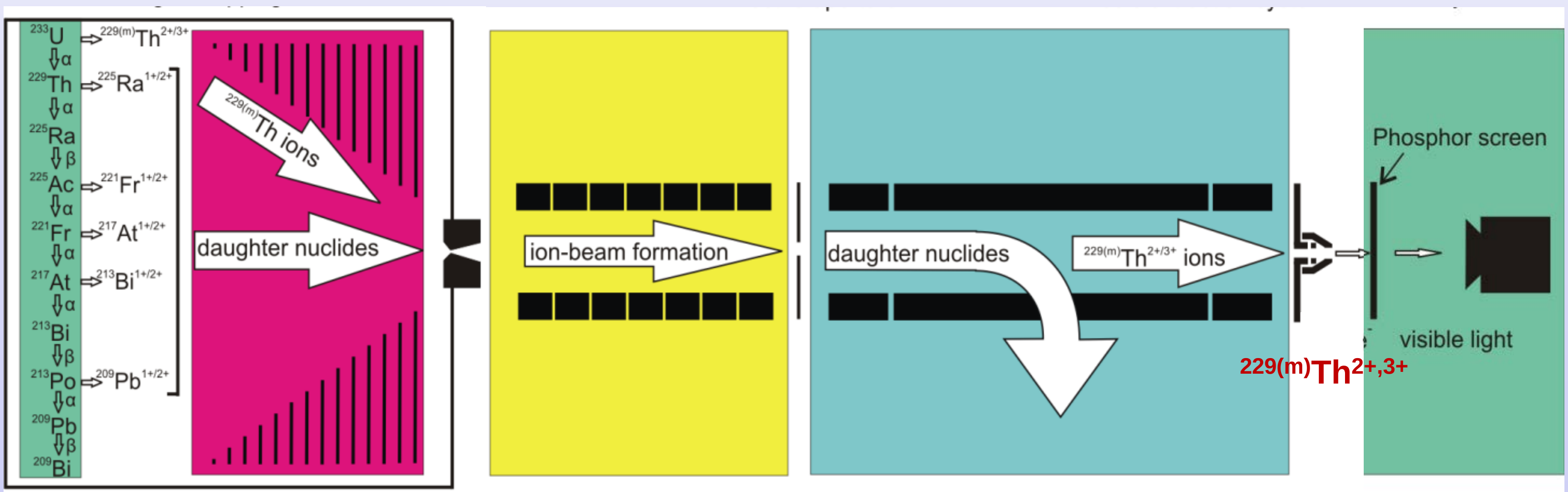
f: clock frequency
U: gravitat. potential

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

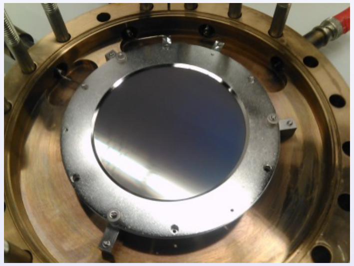
Buffer gas stopping cell | **Laval nozzle** | **aperture electrode** | **triodic extraction electrode** | **detection system**

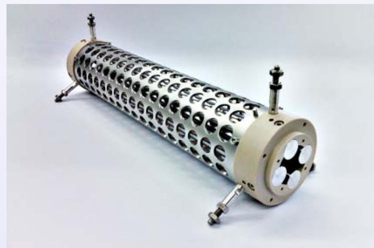


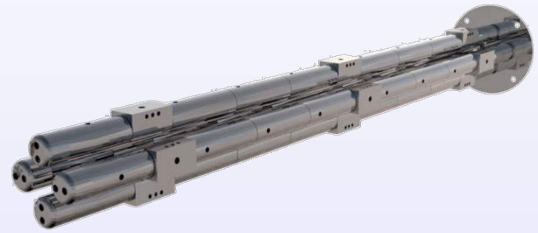
^{233}U source | **RF + DC funnel** | **RF quadrupole ion guide** | **Quadrupole mass separator** | **MCP** | **CCD**

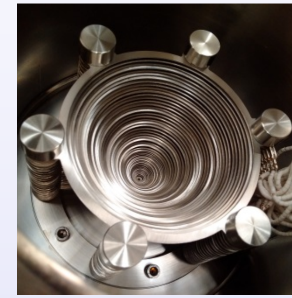
Experimental Setup

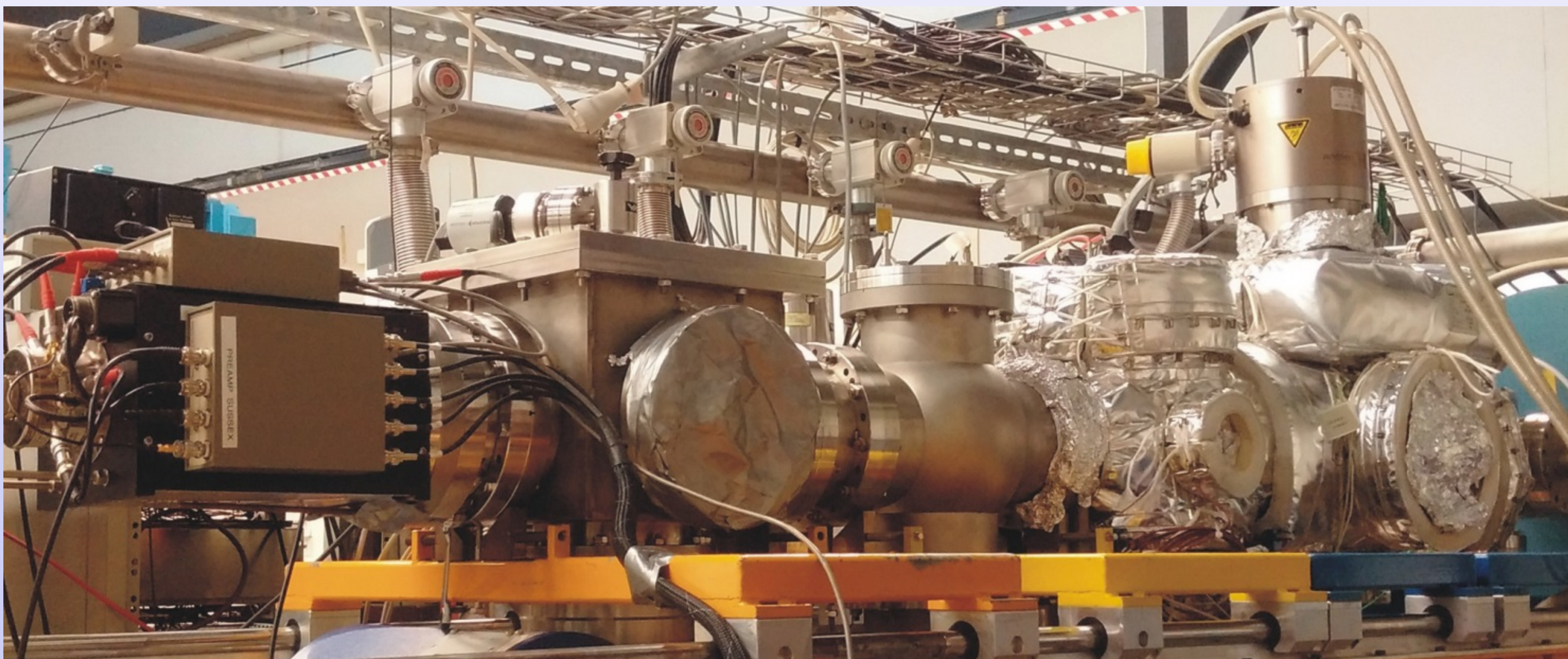
located at Maier-Leibnitz Laboratory, Garching:





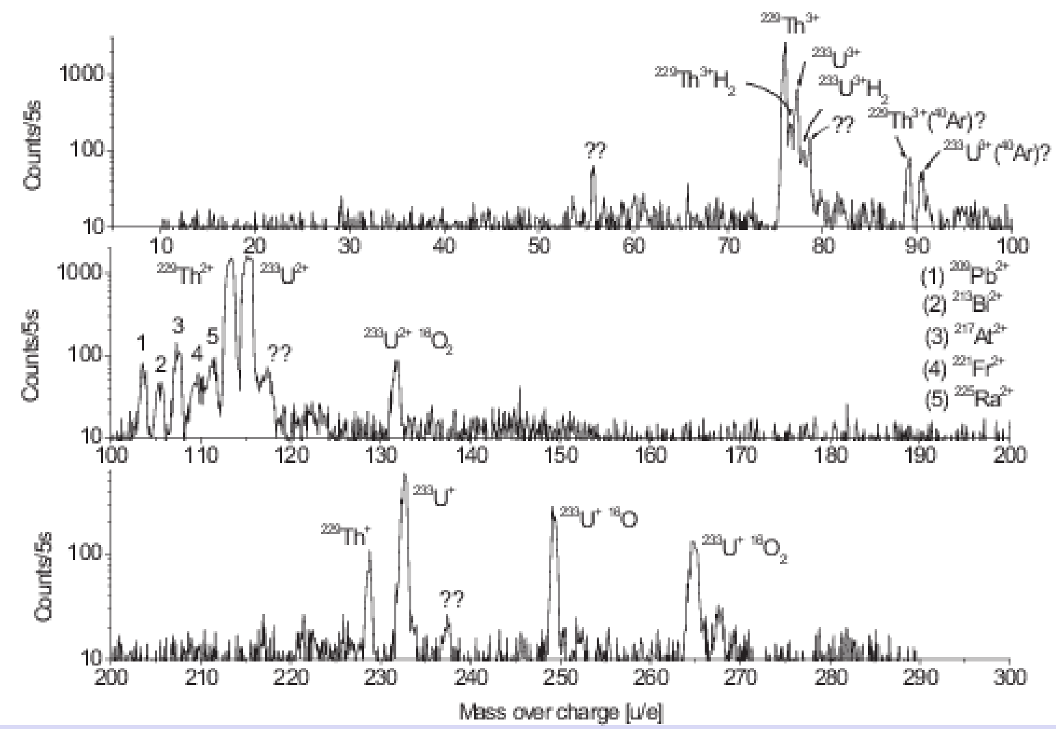


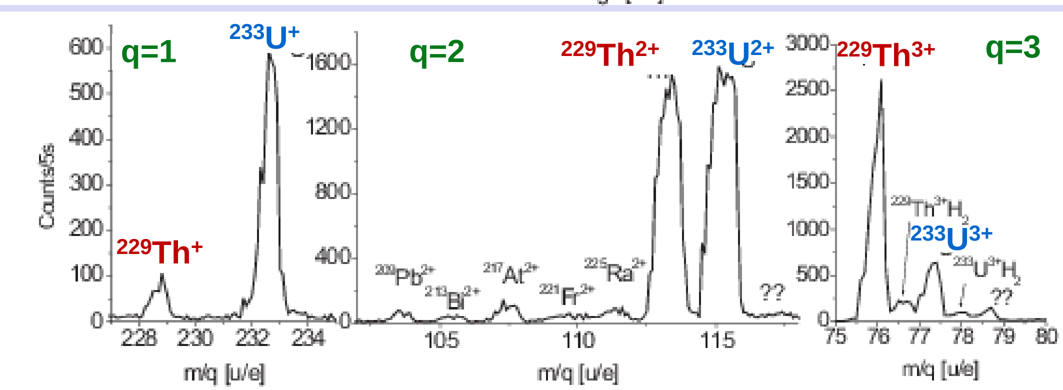




Ion Extraction from Buffer Gas Cell

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

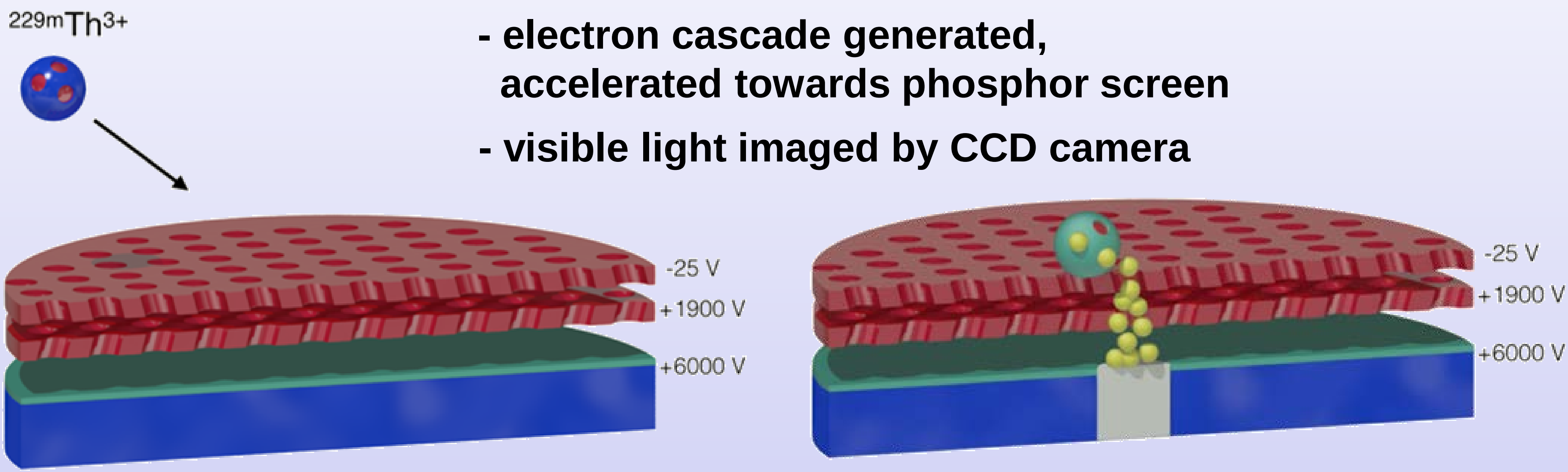
L. v.d. Wense, B. Seiferle, M. Laatiaoui, PT, EPJ A51, 29 (2015)

$I(He^+) = 24.6$ 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**



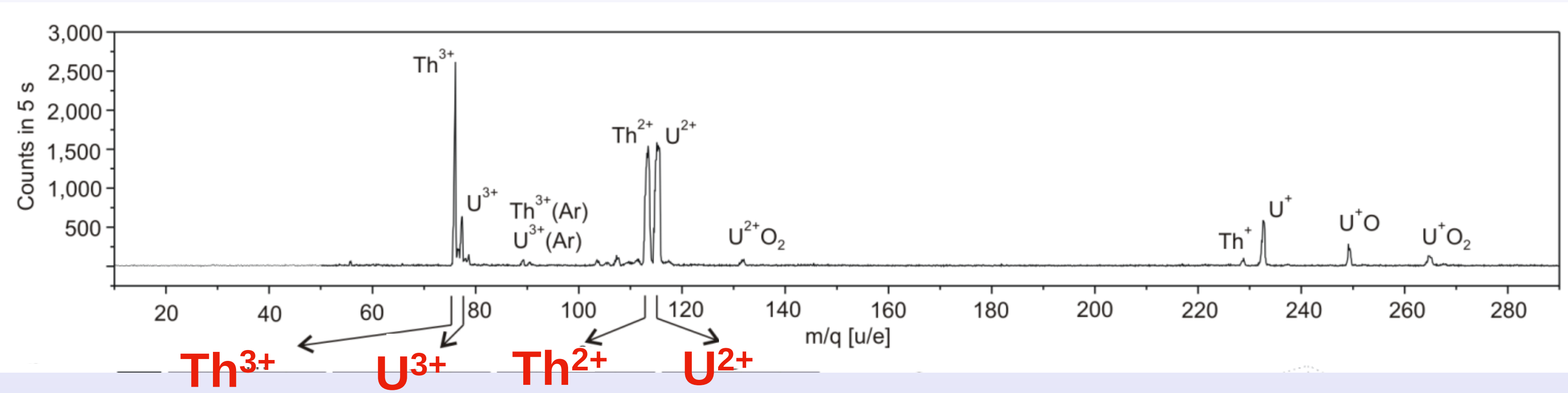
- internal conversion (IC) energetically allowed for neutral thorium:

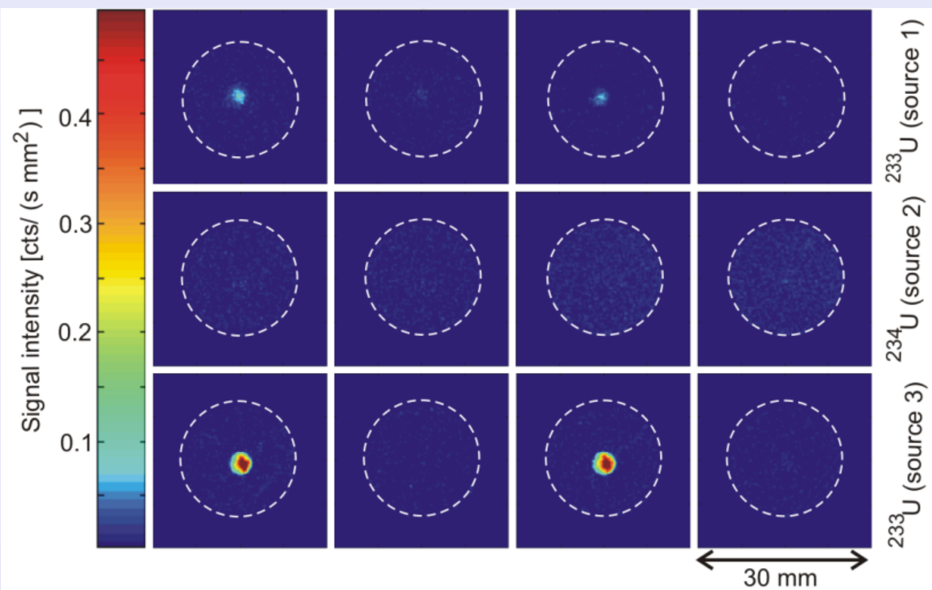
$$I(Th^{+}, 6.31\ eV) < E^{*}(^{229m}Th, 7.8\ eV)$$

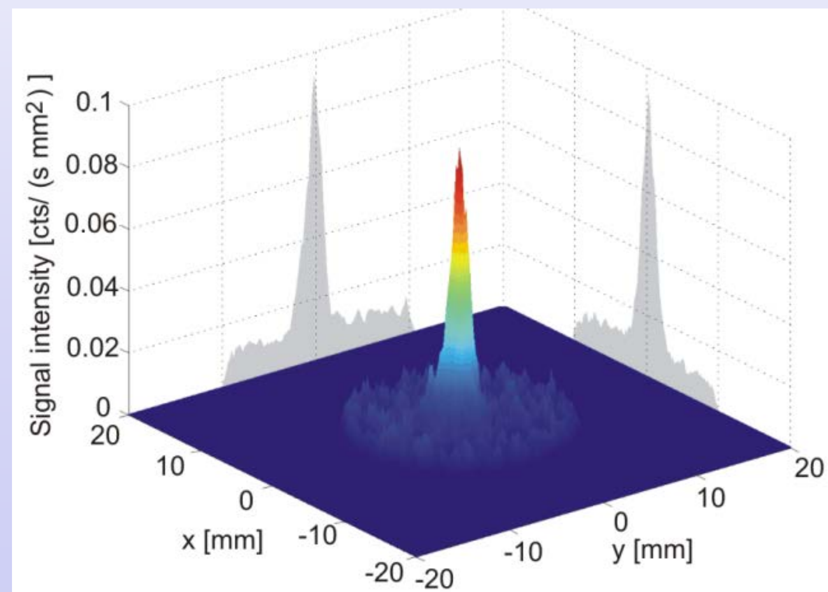
- isomer lifetime expected to be reduced by ca. 10^{-9} (from ~10^{4} s → ~ 10 μs)
- Th^{q+} ions: IC is energetically forbidden, radiative decay branch may dominate

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

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







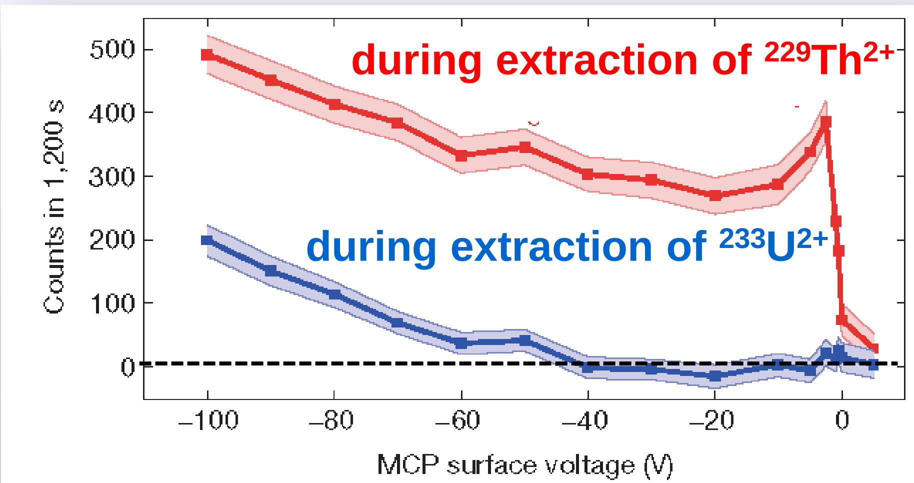
clear signal from Th^{3+}, Th^{2+}
no signal from U^{3+}, U^{2+}

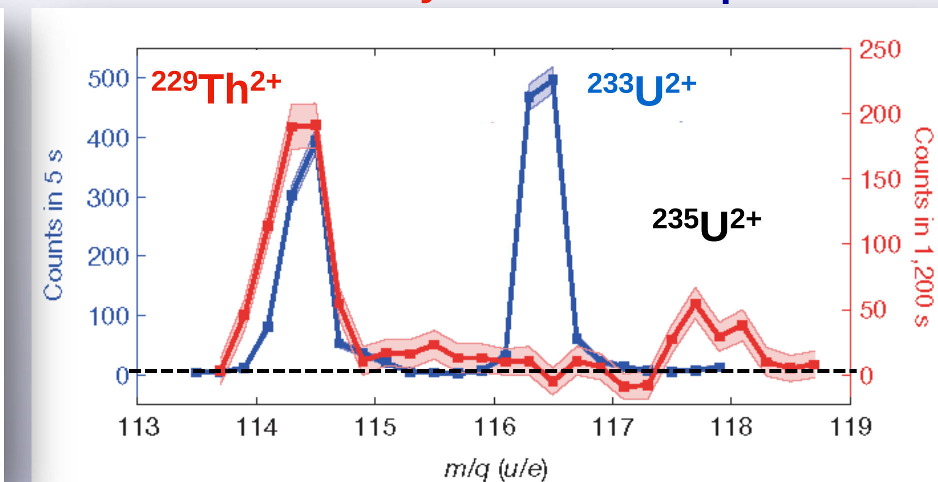
Verification Measurements

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)

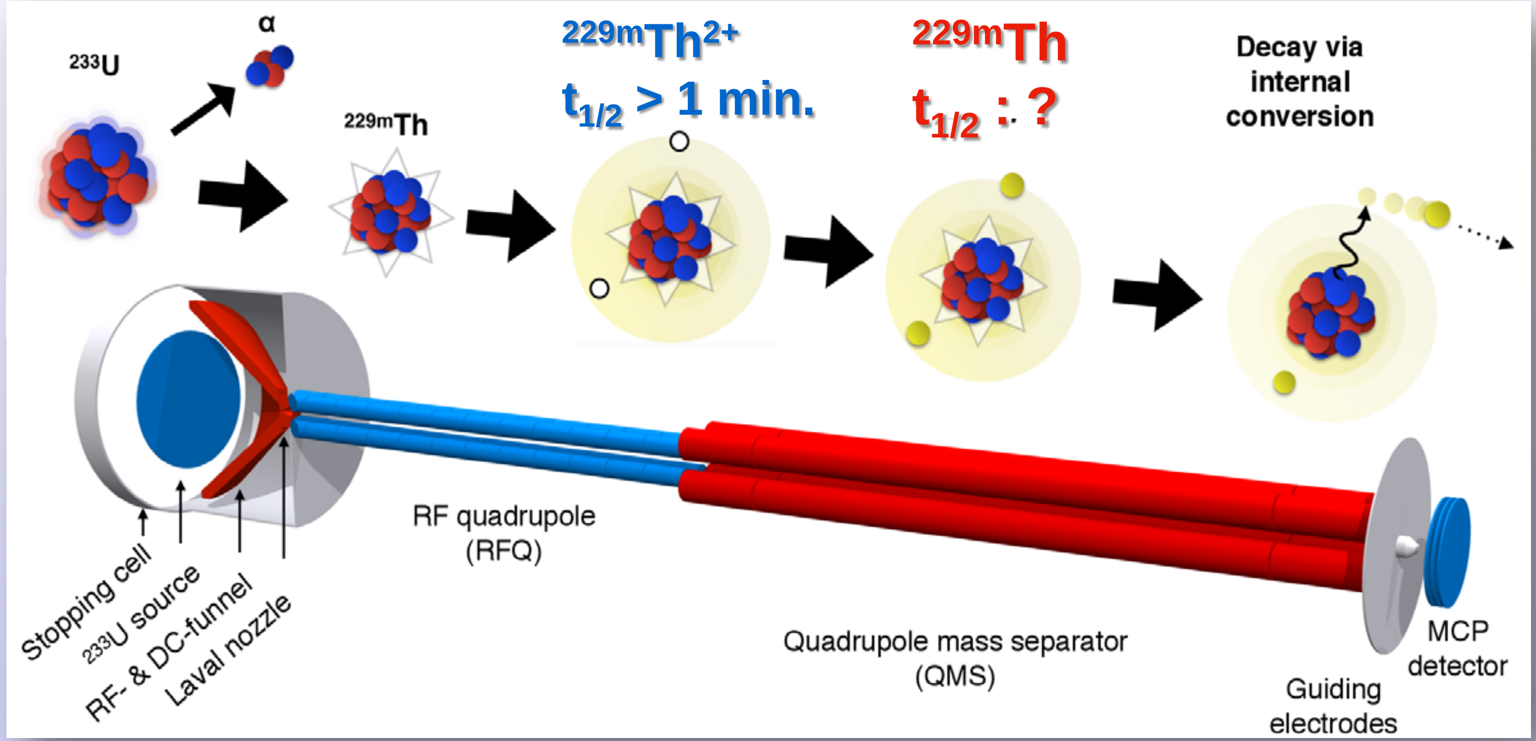
- comparable mass peak amplitudes for $^{229}Th^{2+}$, $^{233}U^{2+}$ ion impact signals
- for U_{MCP}= -25 V $^{233}U^{2+}$ signal vanishes
- $^{229}Th^{2+}$ signal remains

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

Next step: Halflife determination

→ pulsed extraction from RFQ

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

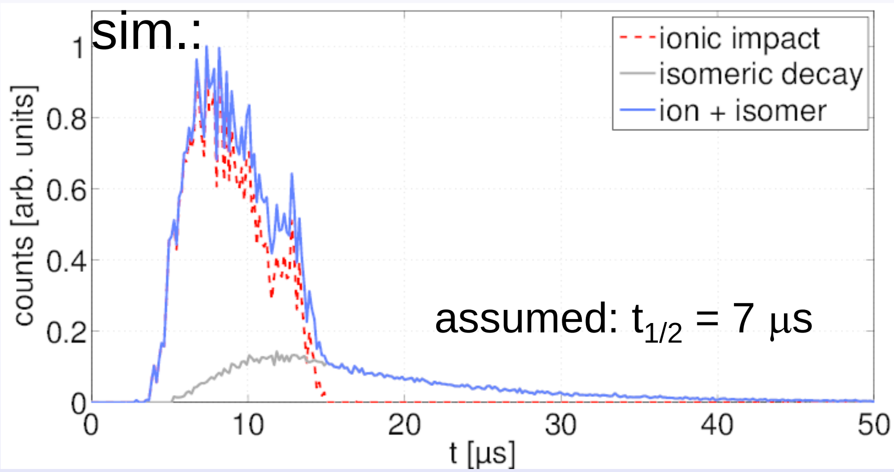


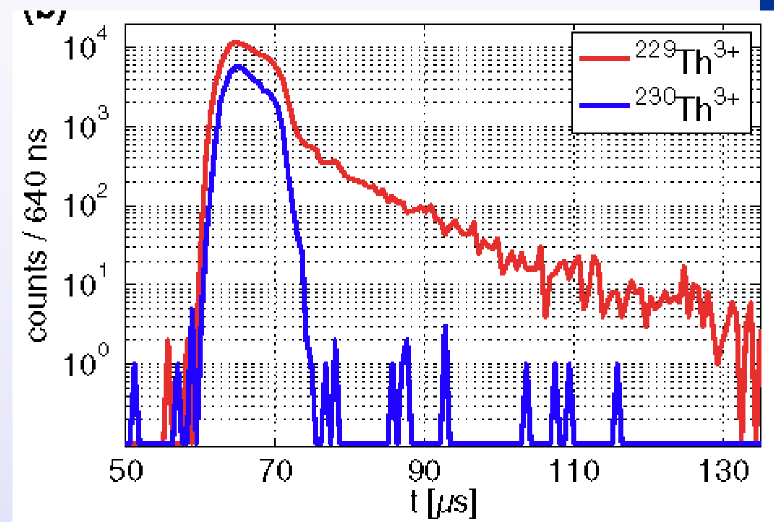
- expected conversion coefficient: $\alpha = N_e/N_\gamma \sim 10^9$

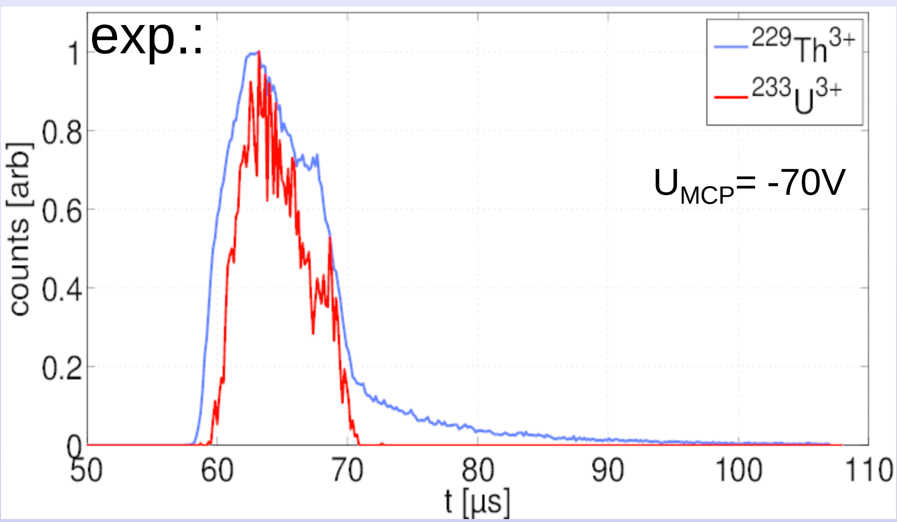
→ provides constraint for strength of photonic decay branch
(if IC cannot be suppressed, e.g. by suitable crystal lattice implantation)

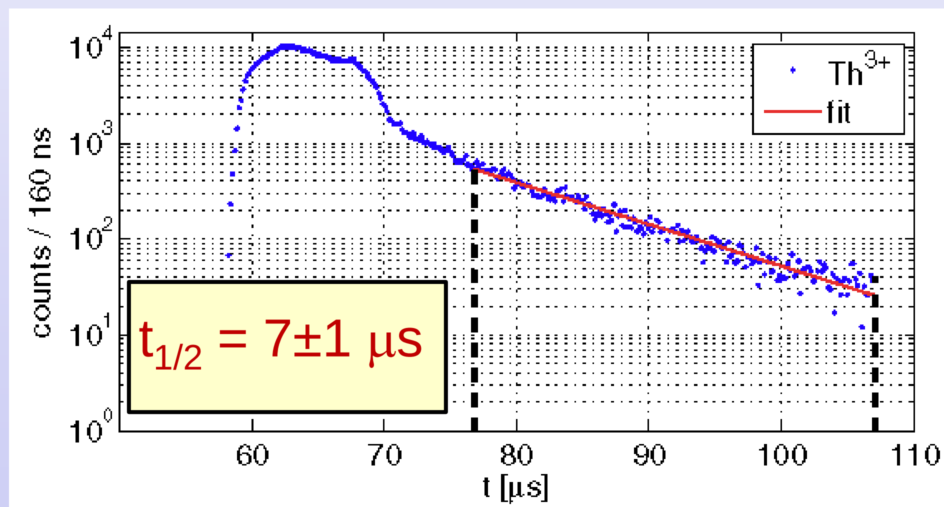
Halflife: Neutral ^{229m}Th

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

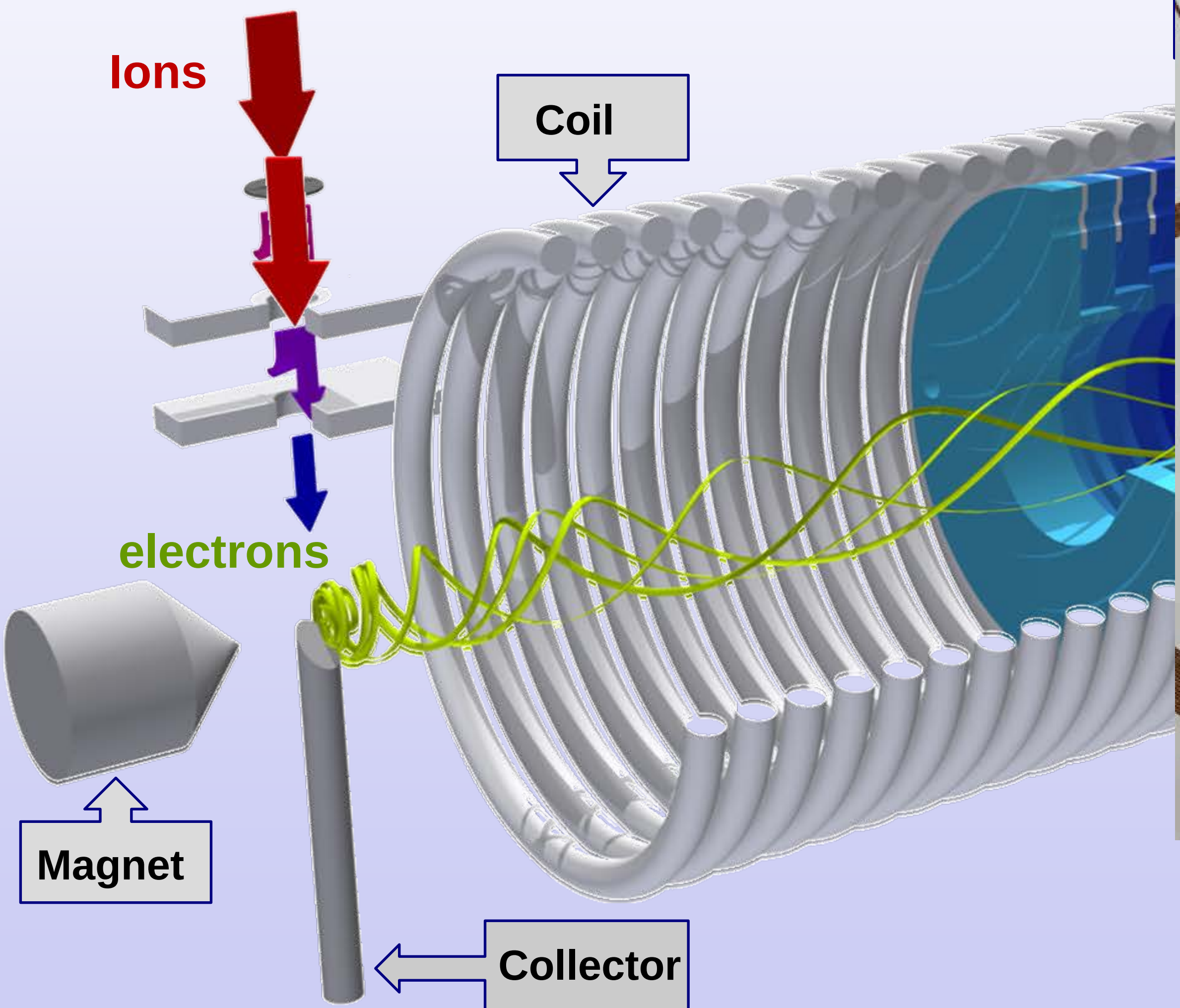
→ confirms expected conversion coefficient: ~10^9
→ photonic decay branch ??

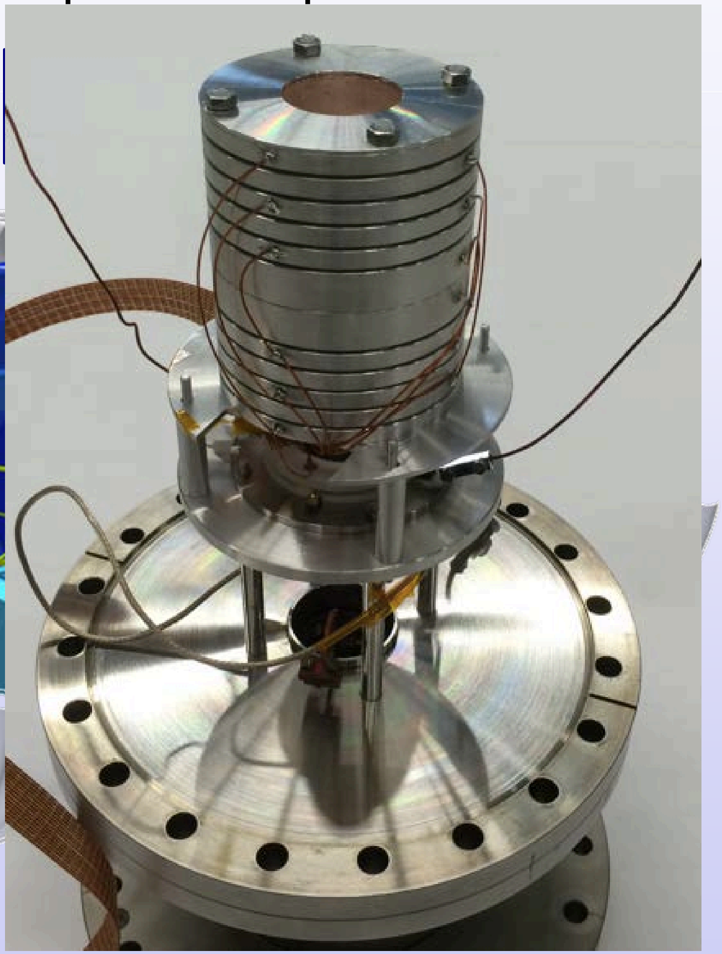
"Holy Grail": Excitation Energy

presently: 6.31 eV < E(^{229m}Th) < 18.3 eV

- Magnetic-bottle spectrometer: large angular acceptance required

  10000 ^{229}Th ions extracted/sec. → 200 e$^-$/s





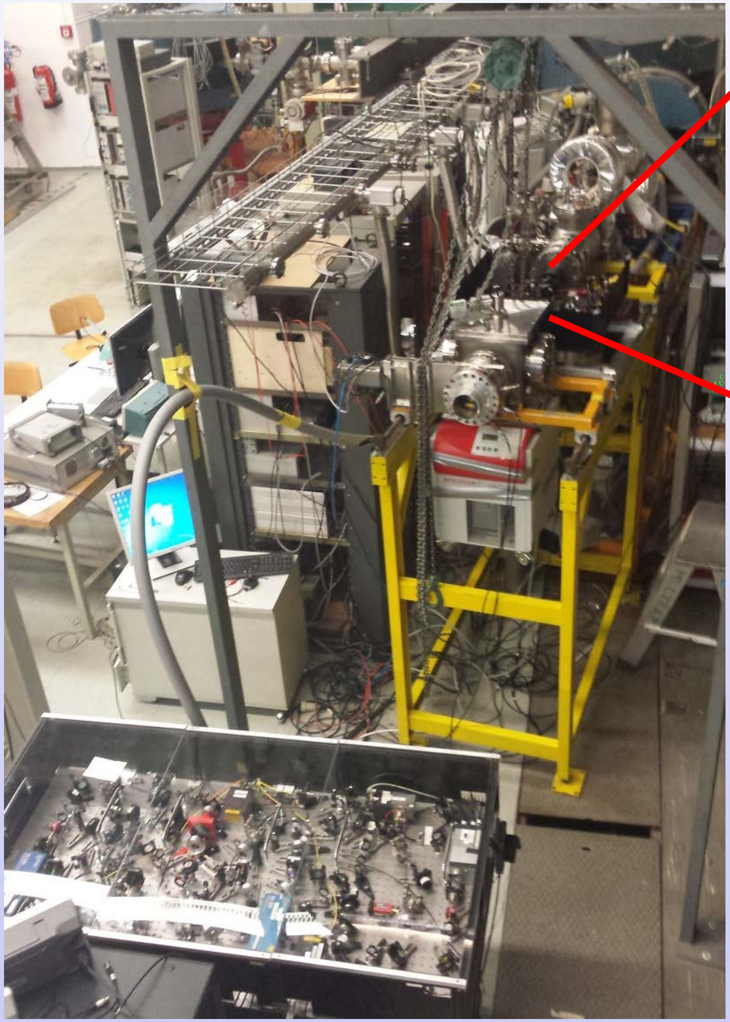
expected:

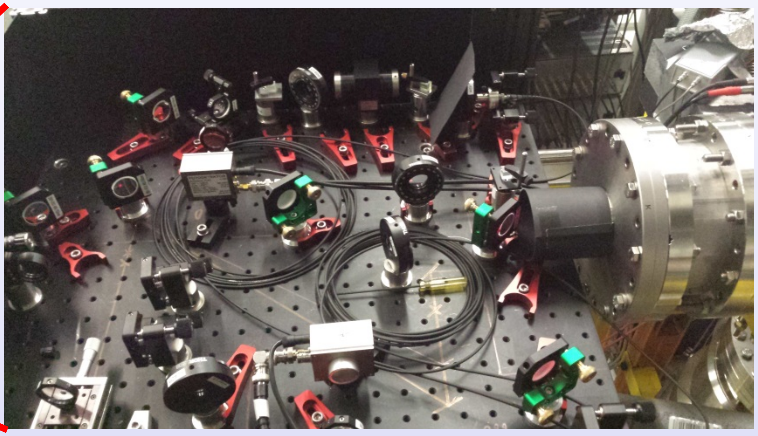
ΔE ~ 0.05 - 0.1eV

Collinear Laser Spectroscopy of ^{229m}Th

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

  Goal: resolve hyperfine structure of $^{229m}Th^{2+}$: derive signature for nuclear excitation





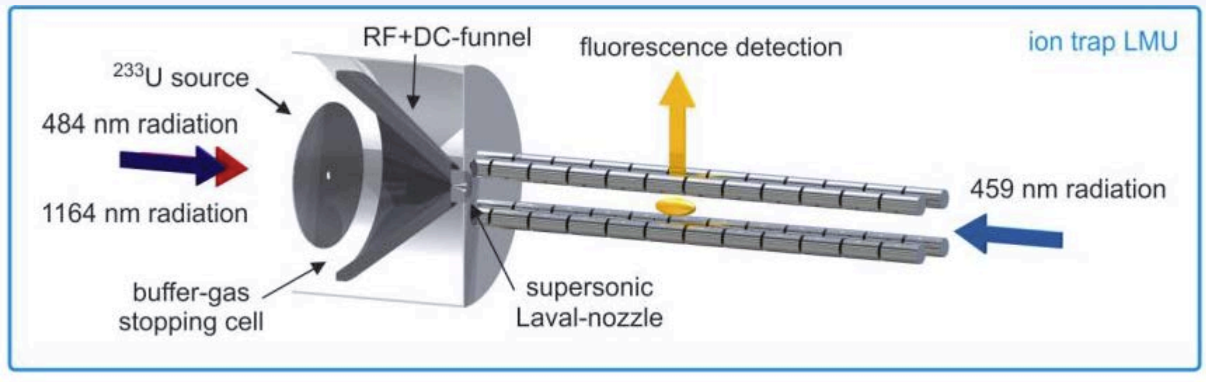
- laser excitation of $^{229(m)}Th^{2+}$ ions behind QMS:

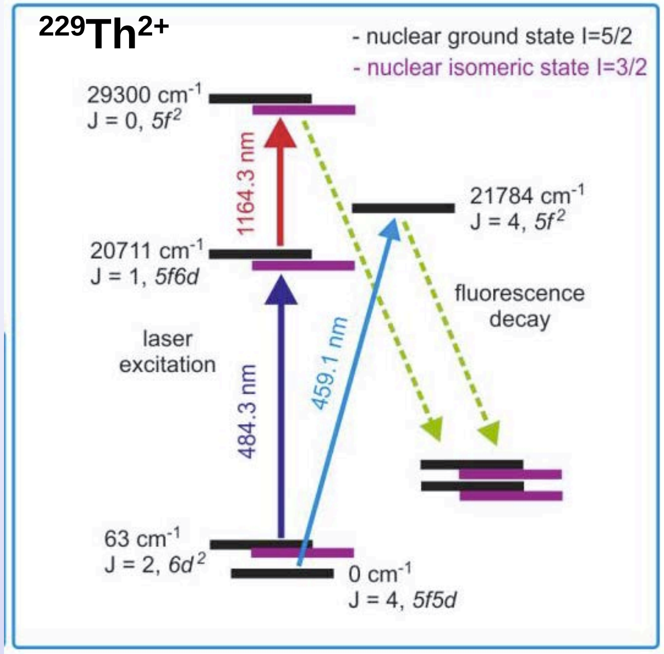
  → 3 external-cavity diode lasers

  → co- and counter-propagating laser beams

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

Hyperfine Structure of ^{229m}Th



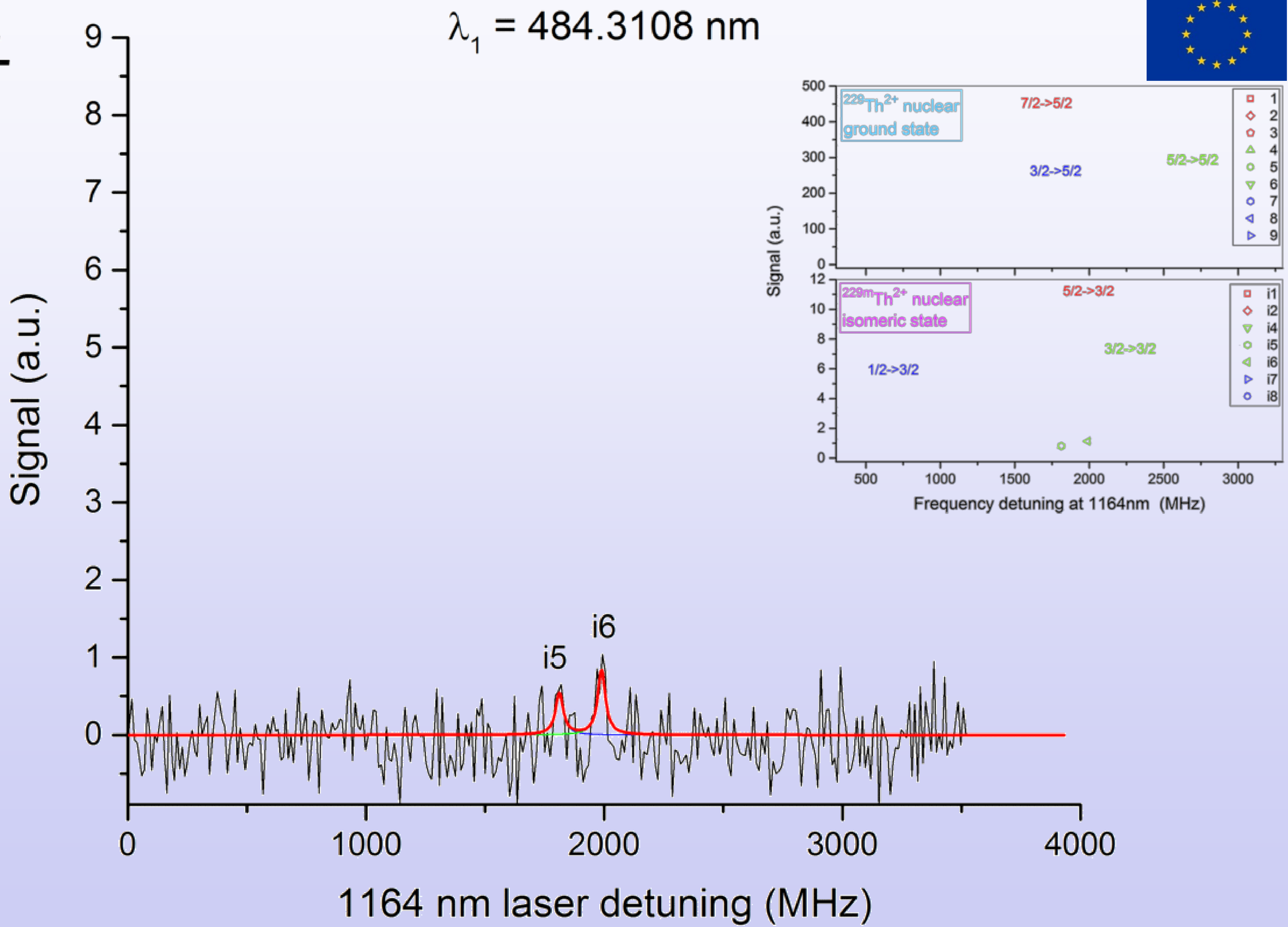


- Doppler-free two-step laser excitation (J=2→1→0):
  - i) 484.3 nm: excites narrow velocity class of ions from thermal distribution to intermediate state
    - tuned in 35 steps of 120 MHz within Doppler profile
  - ii) 1164.3 nm: intermediate state probed by tunable resonant excitation to final state
    - at each step of i): continuous scan over ≥ 4 GHz

gs: (I=5/2): 9 HFS components
is: (I=3/2): 8 HFS components

- Sensitive fluorescence detection:
  - decay channels at other wavelengths, free from laser stray light
- 3rd laser at 459.1 nm: single-photon excitation to monitor amount of $^{229m}Th^{2+}$ in trap
  → normalization of fluorescence signals from HFS components

Hyperfine Structure of ^{229m}Th



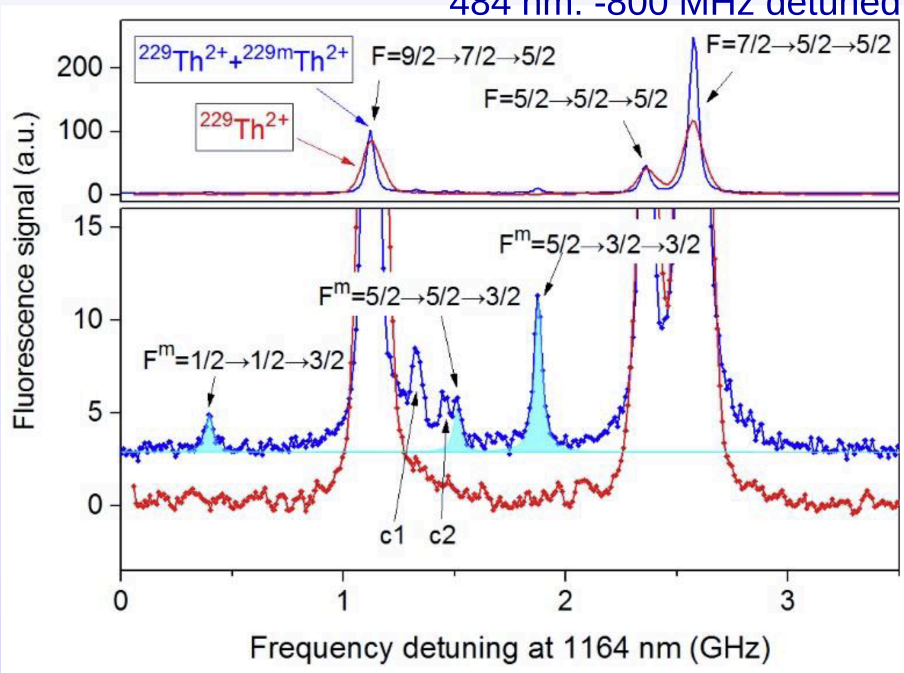
P.G. Thirolf, LMU München
NUSTAR Annual Meeting, GSI/FAIR 2.3.2018

Hyperfine Structure of ^{229m}Th

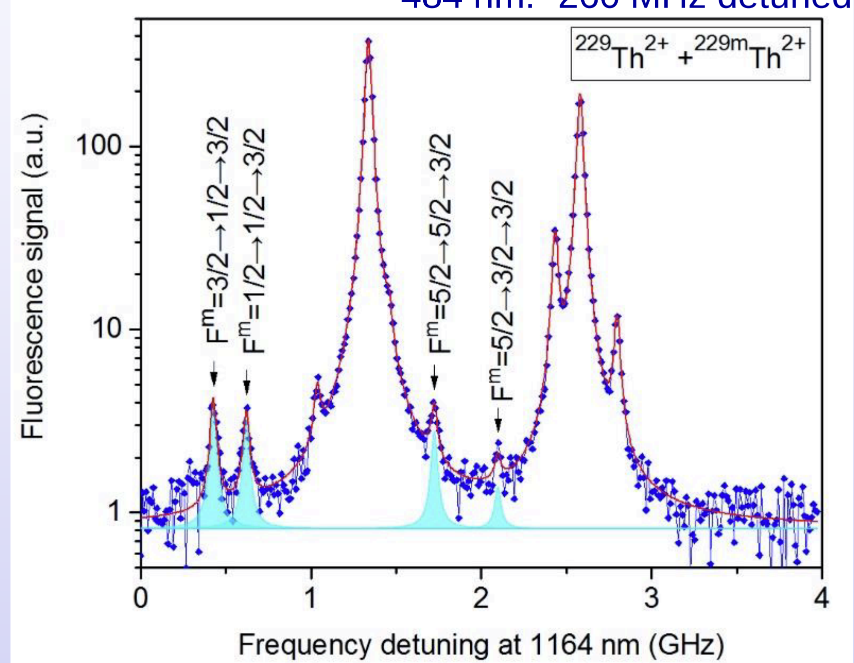
J. Thielking et al., Nature (2018), in print, arXiv:1709.05325 [nucl-ex]

- Hyperfine components from ^{229m}Th observed:

484 nm: -800 MHz detuned



484 nm: -260 MHz detuned



$$E_{HFS}(JIF) = \frac{1}{2} A K + B \frac{(3/4)K(K+1) - I(I+1)\,J(J+1)}{2I(2I-1)\,J(2J-1)}$$

hyperfine constants A, B

(intrinsic) electric quadrupole moment:
Q_0^m = 8.7(3) eb (prolate)
magnetic dipole moment:
μ^m = -0.37(6) μ_N
charge radius:
$\langle r^2\rangle^{229m} - \langle r^2\rangle^{229}$ = 0.012(2) fm^2

Summary & Perspectives

- 229-Thorium isomer exists: first direct detection via IC decay channel
- constraints of ^{229m}Th properties: $6.3\ \text{eV} \leq E^* \leq 18.3\ \text{eV}$, $\tau > 60\ \text{s}$ — Nature 533 (2016)
- Half-life of neutral ^{229m}Th: $t_{1/2} = 7\ \mu s \rightarrow \alpha_{IC} \sim 10^9$ — PRL 118 (2017)
- Hyperfine structure of ^{229m}Th measured via collinear laser spectroscopy:
  → nuclear moments, charge radius, (prolate) deformation — Nature (accepted, 2018)
- 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 — 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 ….

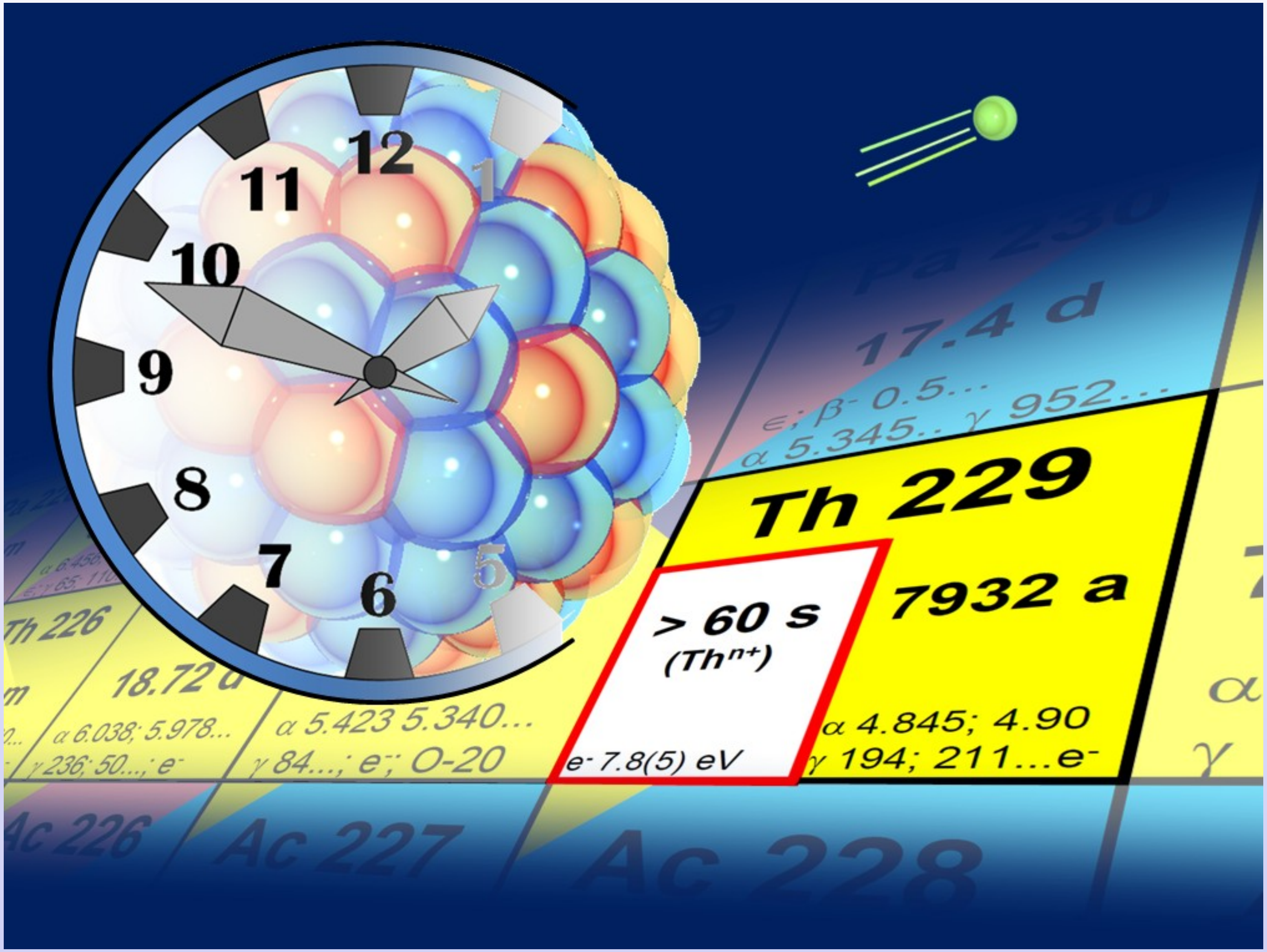


Figure: Ch. E. Düllmann

optical control of ^{229m}Th still resembles a needle in the haystack – but now we know much better how this needle looks like …

Thanks to ….

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

PTB Braunschweig: J. Thielking, P. Glowacki, D.M. Meier, M. Okhapkin, E. Peik

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

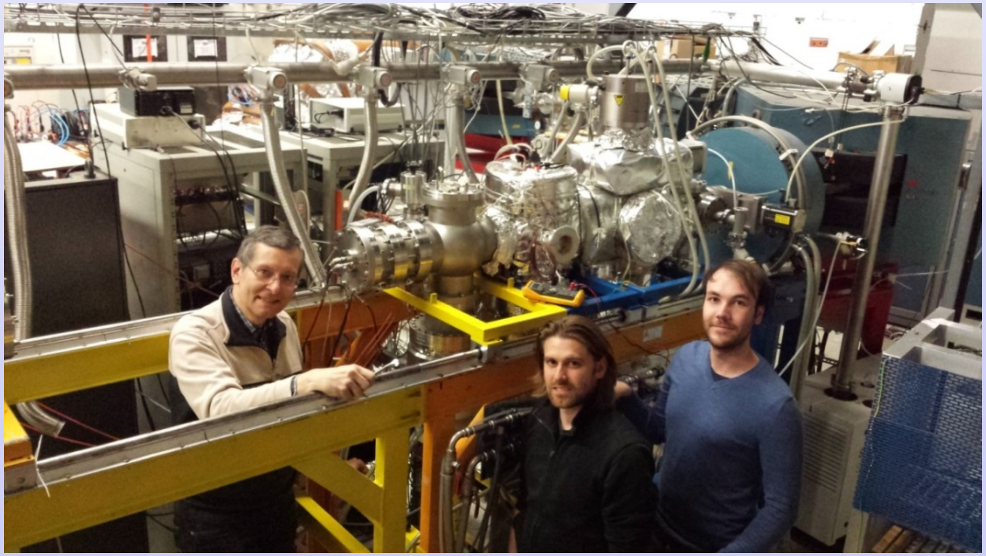
M. Laatiaoui

Helmholtz-Institut Mainz & Johannes Gutenberg-Universität Mainz:

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

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION HORIZON 2020

DFG Deutsche Forschungsgemeinschaft



Thank you for your attention !