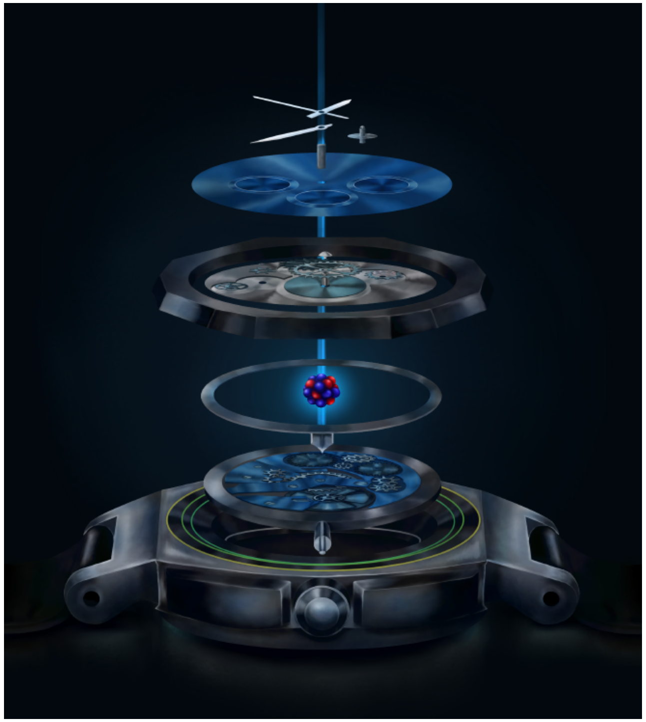
# The energy of the $^{229}$Th clock transition

Adriana Pálffy
Max Planck Institute for Nuclear Physics, Heidelberg



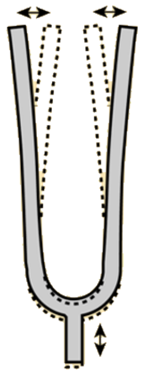
EMMI

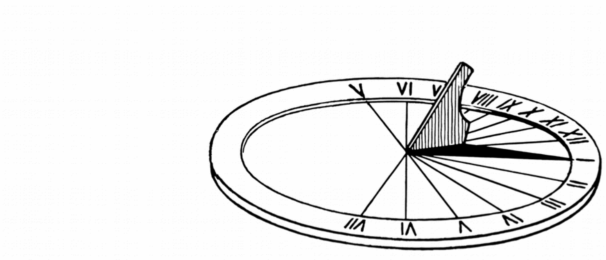
GSI

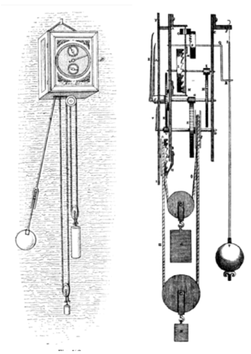
EMMI Featured Talk/GSI Colloquium
19 November 2019

# Clocks

involve a periodic event (oscillation) and a counting device.



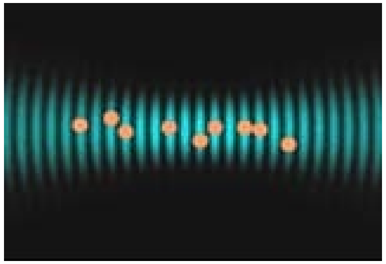
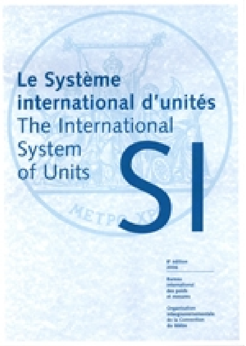




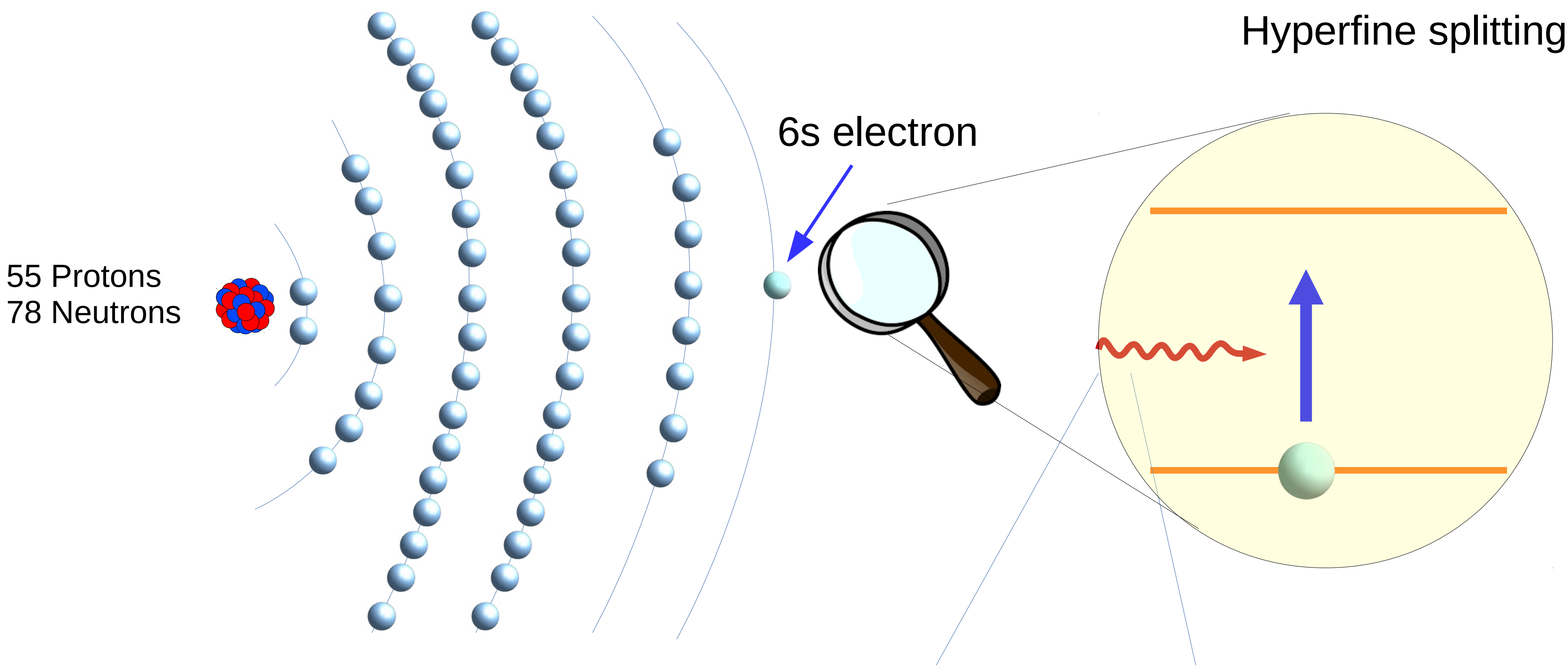
# Did you know?

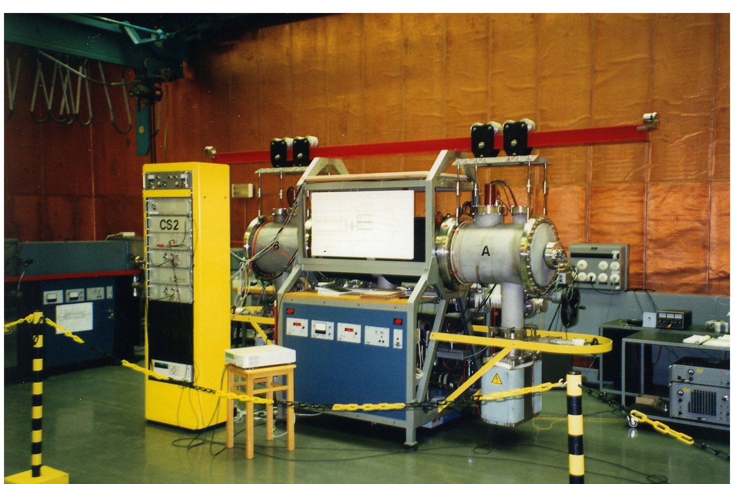
- The earliest clocks to display seconds appeared during the last half of the 16th century.
- The first pendulum clock was invented in 1656 by the Dutch scientist C. Huygens.
- In 1960, the SI second was defined as the fraction of 1/31,556,925.9747 of the tropical year for 1900 January 0th at 12 hours ephemeris - this lasted only until 1967.
- The SI second is close to 1/86,400 of a mean solar day in the mid-19th century. In earlier centuries, the mean solar day was shorter than 86,400 SI seconds, and in more recent centuries it is longer than 86,400 seconds.

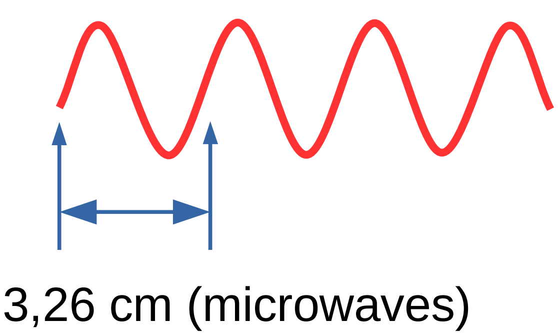


# Atomic clock transition in $^{133}Cs$



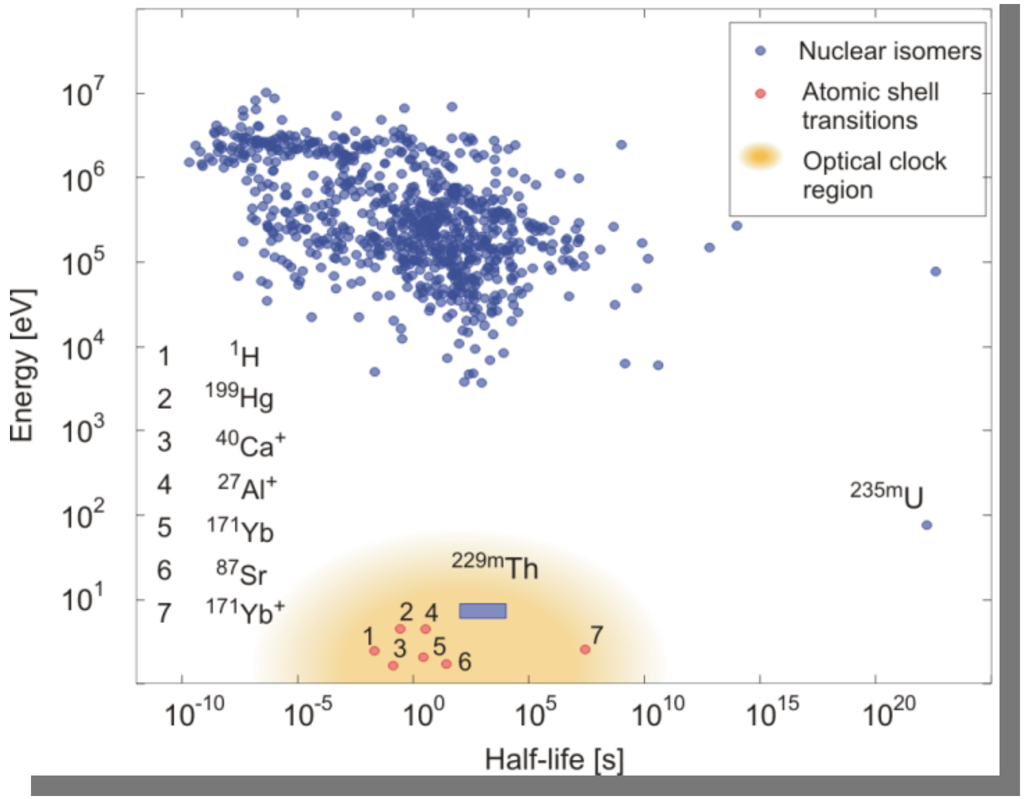






frequency of 9.192.631.770 per second

# A possible nuclear clock

→ lowest excitation energy of all ca. 176,000 presently known excited nuclear states




L. v.d. Wense, et al., Nature 533, 47-53 (2016)

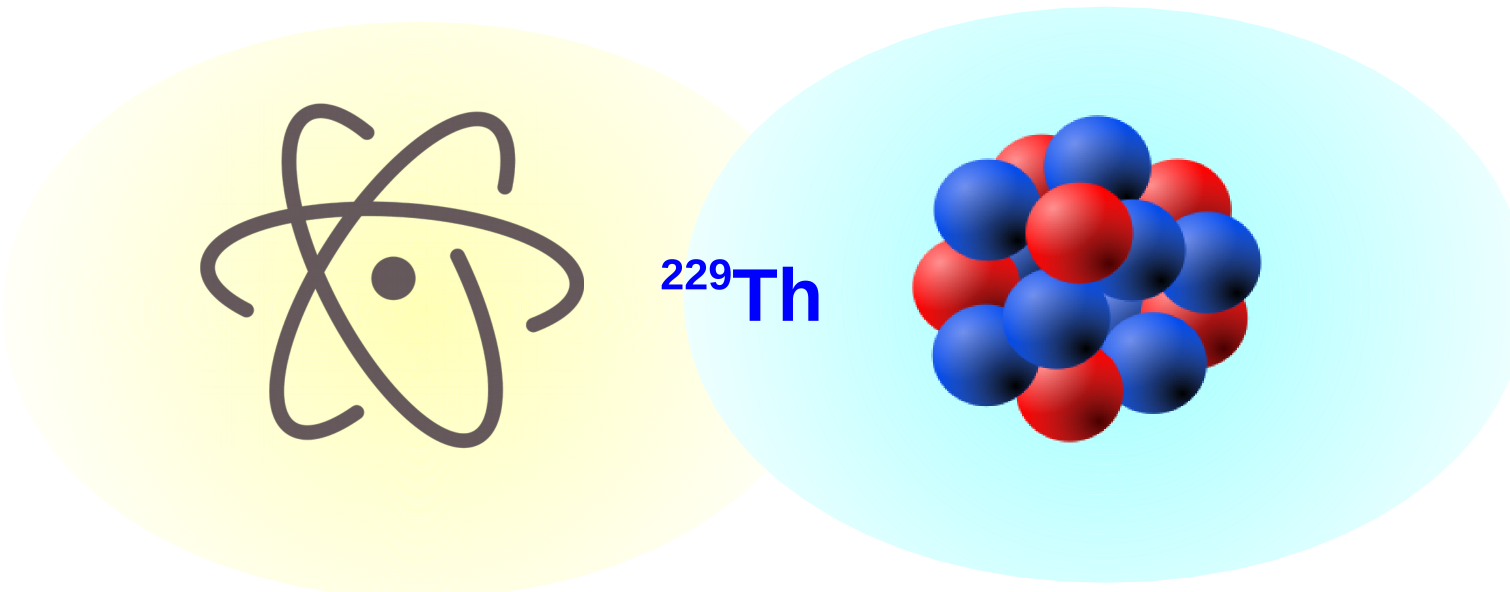
$^{229}$Th
E ~ 8.28 eV, λ ~ 150 nm
M1 (+E2) transition

Insensitivity of $^{229m}$Th nuclear transition frequency to external perturbations

small nuclear moments
largely immune to systematic frequency shifts:

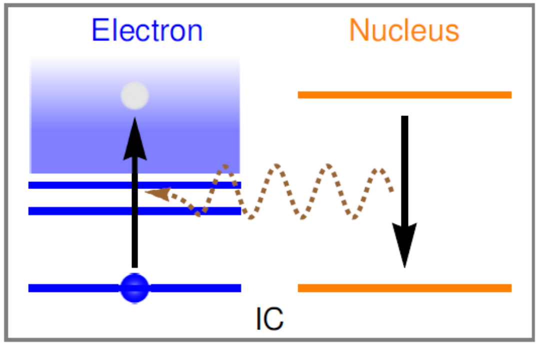
ultra-precise nuclear frequency standard ?

# Between atomic and nuclear physics




Nuclear decay processes that involve atomic electrons – internal conversion

Optical, UV, VUV lasers open control possibilities – direct excitation, electronic bridge



# Possible applications

- Enhanced GPS precision for cm positioning
- Variation of fundamental constants, not only $\dot{\alpha}/\alpha$ but also $m_q/\Lambda_{QCD}$
- Tests for Lorentz invariance
- 3D gravity sensors
- Search for new physics, topological dark matter, etc.

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 $m_q/\Lambda_{QCD}$

$$\frac{\delta\omega}{\omega} = K\frac{\delta\alpha}{\alpha}$$

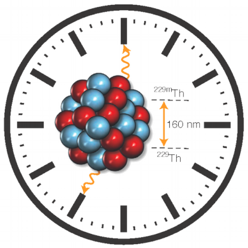
$$\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17}\mathrm{yr}^{-1}$$

**Rosenband et al., Science 319, 1808 (2008)**

# Outline

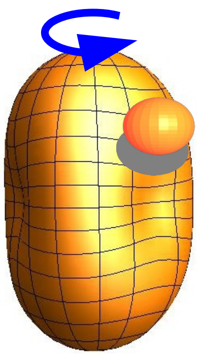
## I. What we know about $^{229}$Th

Short history
Experimental achievements
Coupling to atomic shell




## II. Nuclear structure perspective

Nuclear model
Excitation probabilities
Magnetic moments



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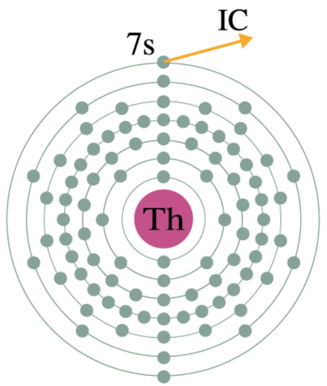
Internal conversion
Struggle with excited states
Extracted new energy value



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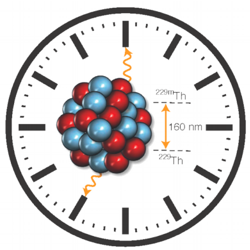


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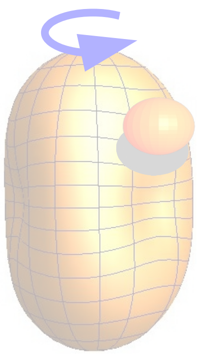

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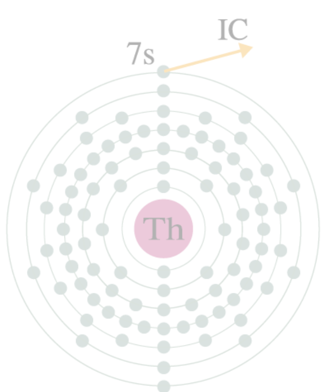
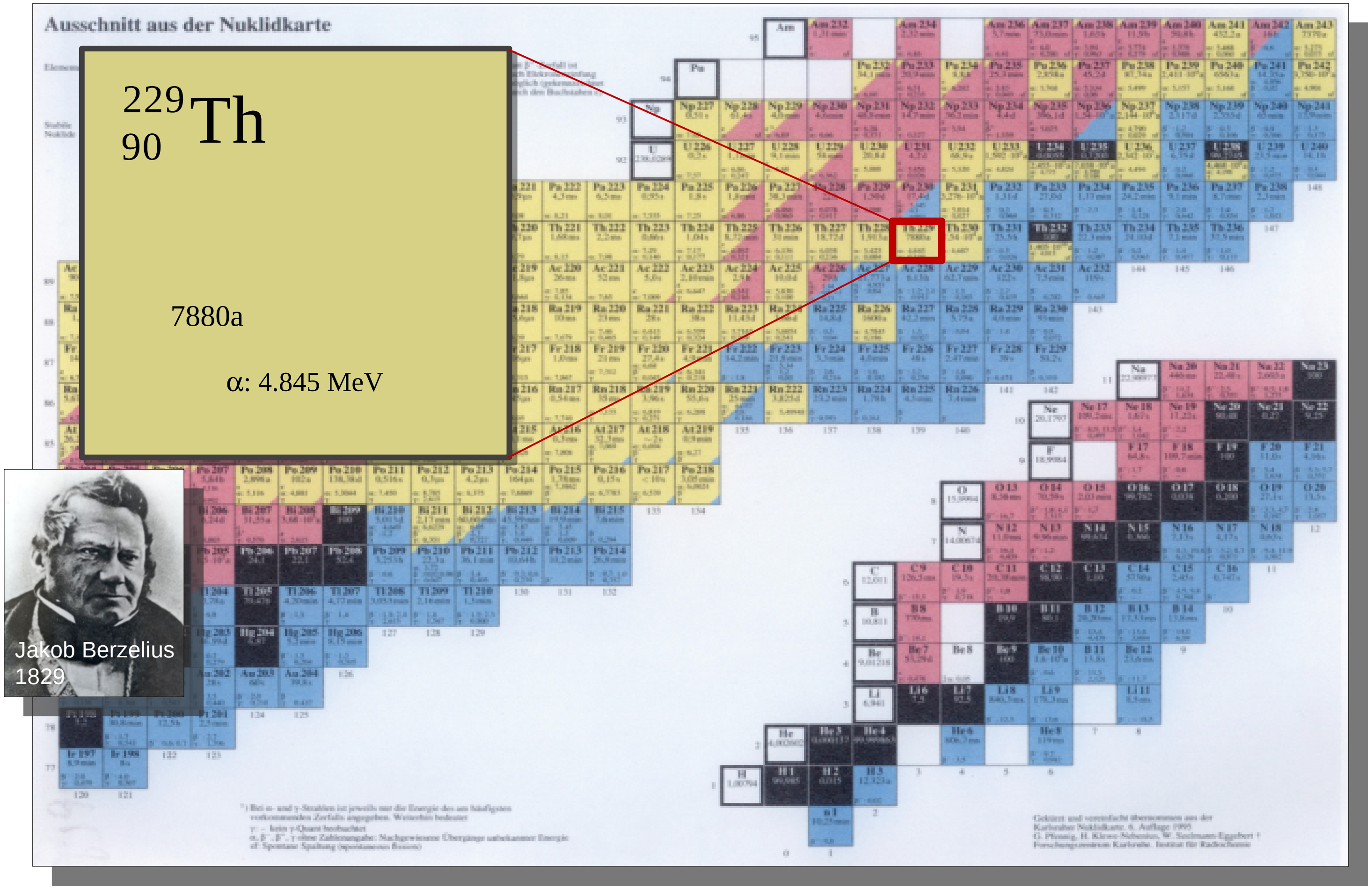


# The $^{229}$Th nucleus




**Thor**

1828 discovered by Morten Thrane Esmark on the Norwegian island of Løvøya.

# Chasing a phantom

**For 40 years nuclear physicists seemed to chase a phantom:**

presumed low-lying isomer in $^{229}$Th:

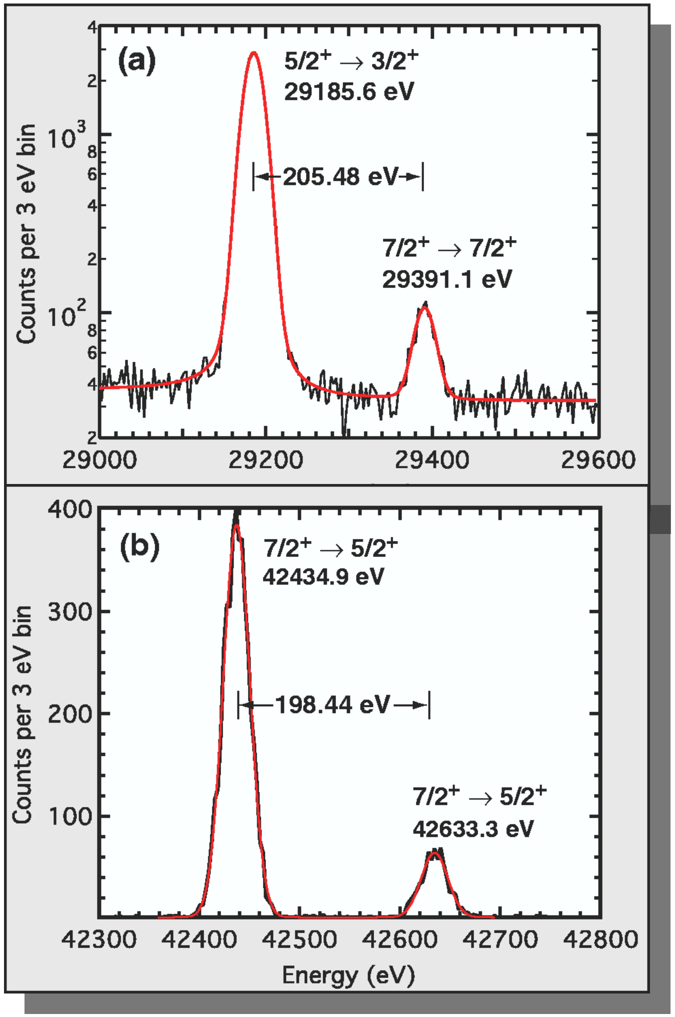
| | |
|---|---|
| 1976 (Kroger, Reich): | < 100 eV |
| 1990 (Reich, Helmer): | -1 ± 4 eV |
| 1994 (Reich, Helmer): | 3.5 ± 1 eV |
| 2005 (Guimaraes-Filho, Helene): | 5.5 ± 1 eV |
| 2007 (Beck et al.): | 7.6 ± 0.5 eV |

**energy: 7.8(5) eV (indirect evidence)**
**wavelength: 159(10) nm**
**radiative $\tau \approx 10^4$ s**
**→ $\Delta E/E \approx 10^{-20}$**
**→ $\Delta\nu \sim 10^{-4}$ Hz**

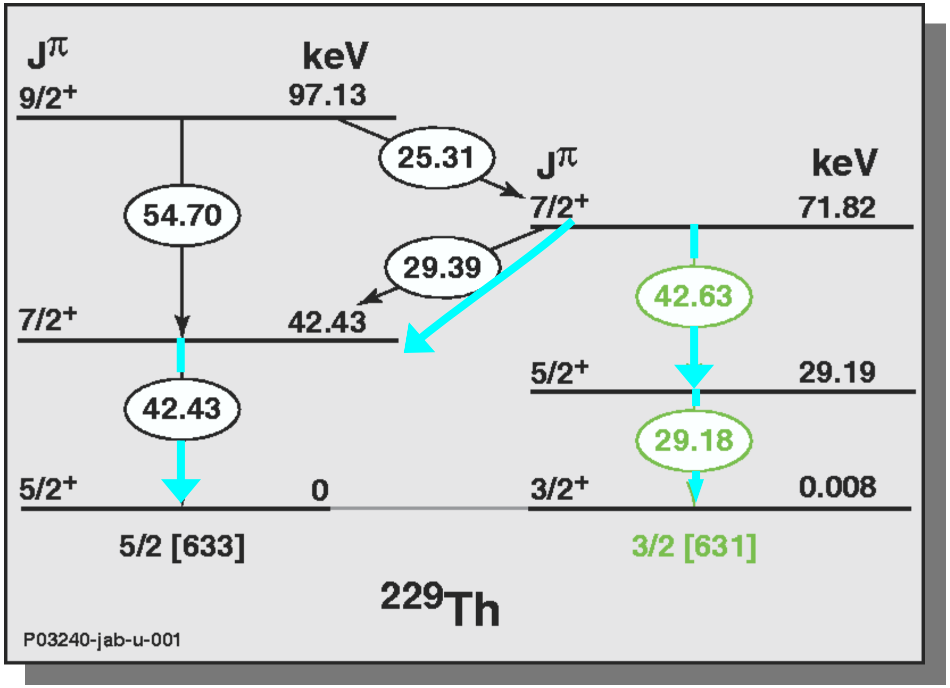
**B.R. Beck et al., LLNL-PROC-415170 (2009)**

# Indirect evidence

## data from X-ray micro-calorimeter:




E ($^{229m}$Th) = (7.8 ± 0.5) eV

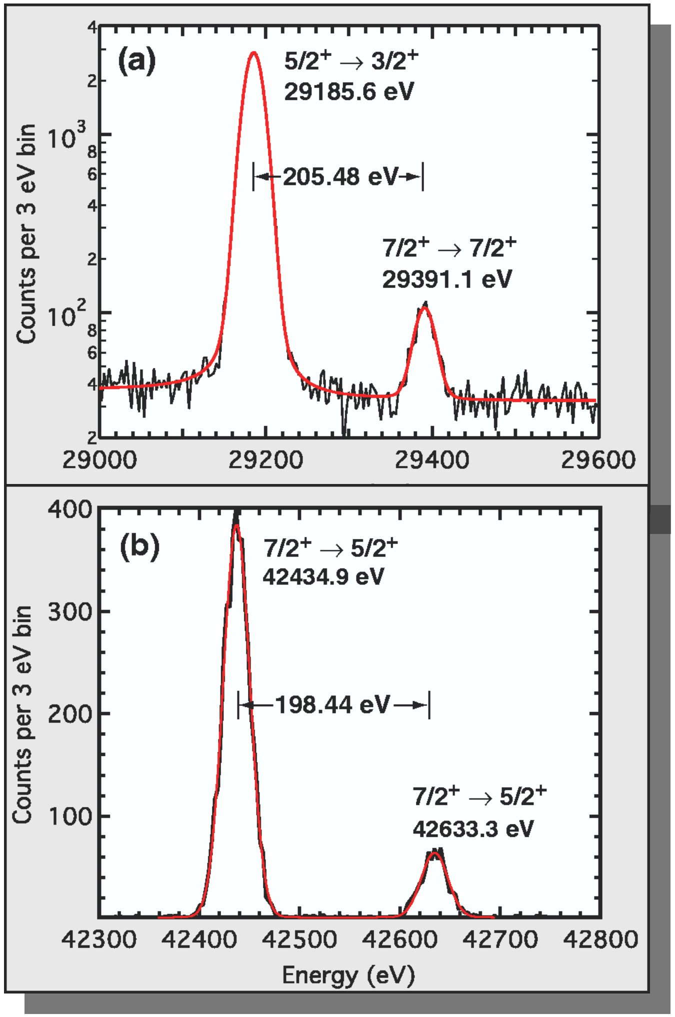



B.R. Beck et al., PRL 98 (2007) 142501
LLNL-PROC-415170 (2009)

from energy difference of high-energy transitions → low isomer excitation energy

# Indirect evidence

## data from X-ray micro-calorimeter:

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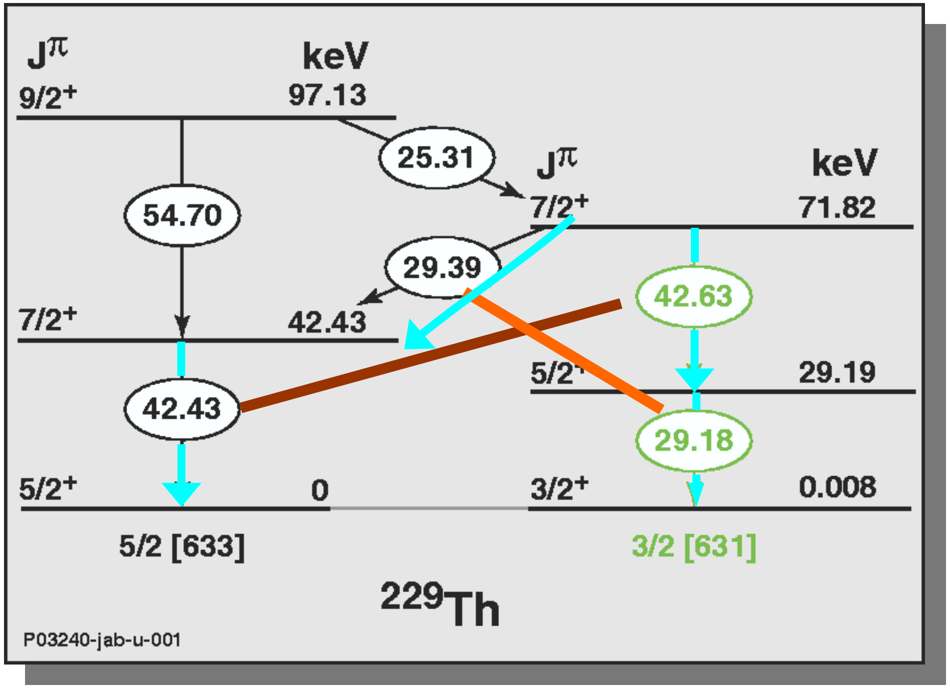



B.R. Beck et al., PRL 98 (2007) 142501
LLNL-PROC-415170 (2009)

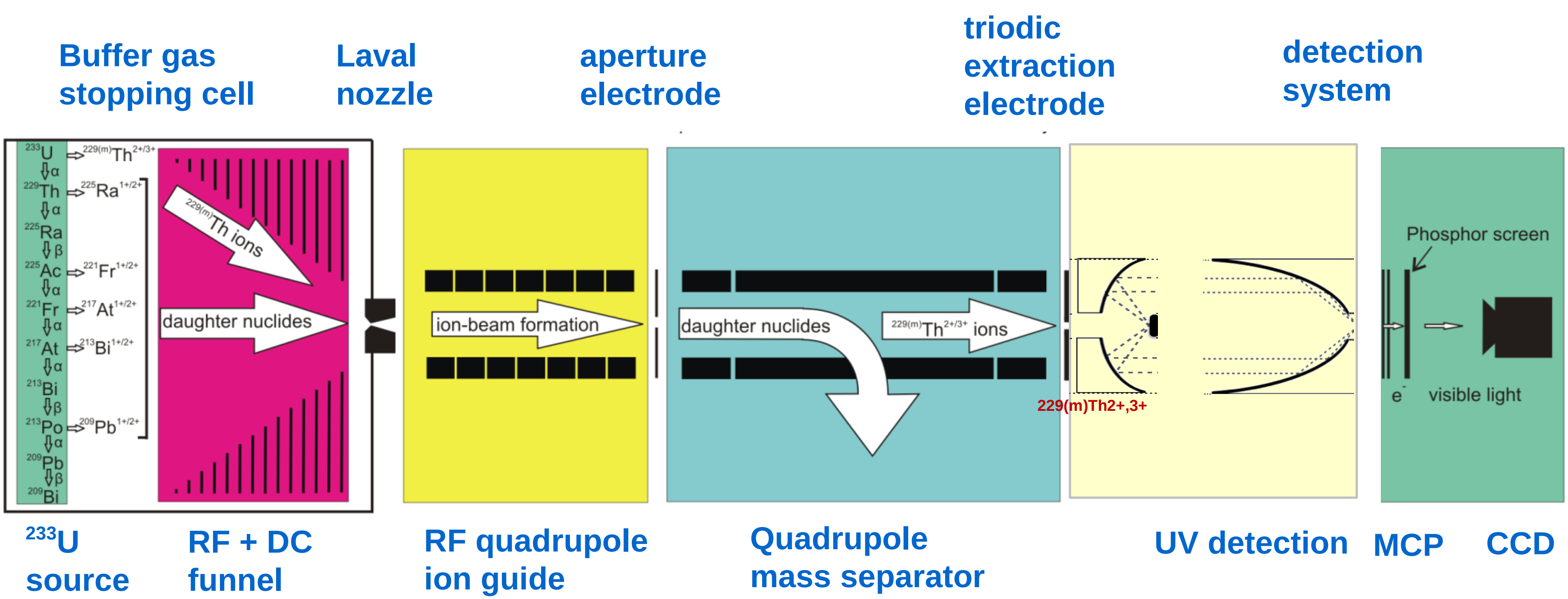
from energy difference of high-energy transitions → low isomer excitation energy

# The direct proof

Group of Peter Thirolf @ LMU München

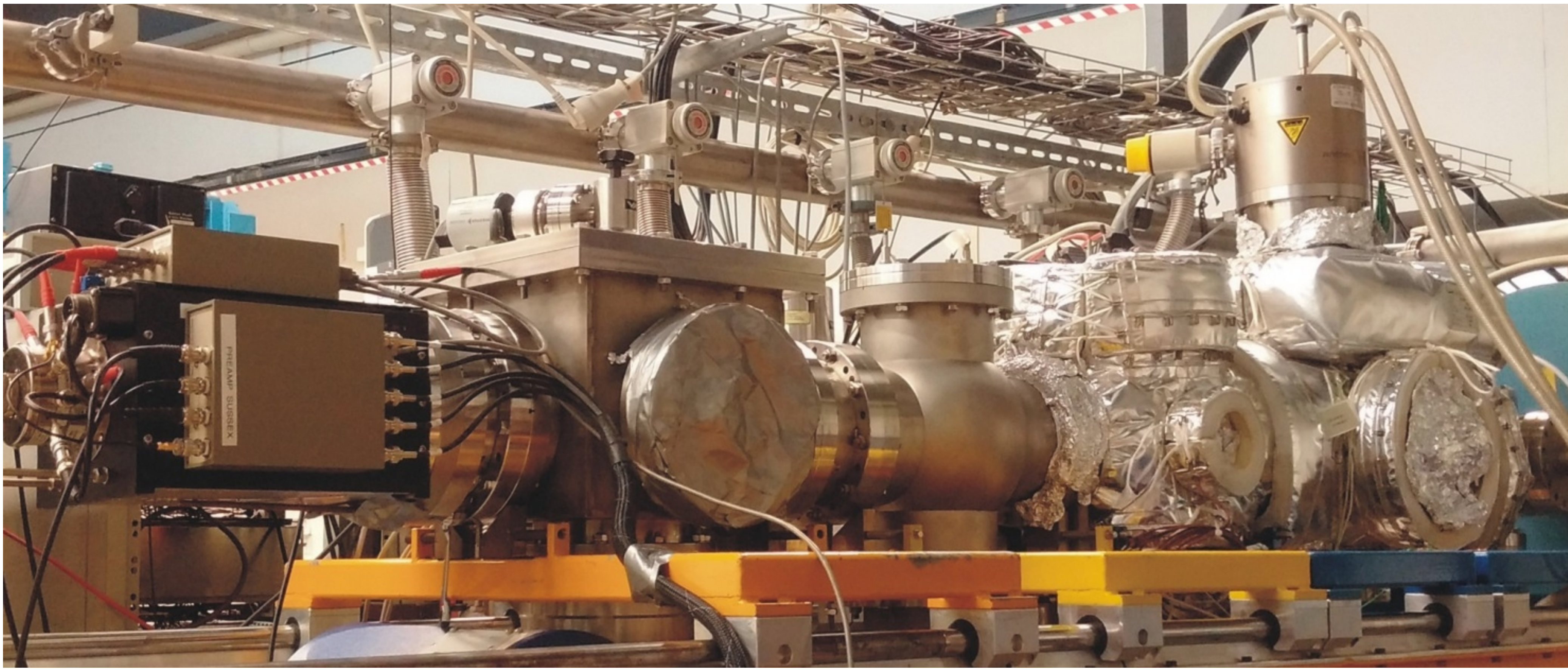
**concept:**

- 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
- detect the subsequently occurring isomeric decay




~30 mbar (He) $10^{-2}$ mbar $10^{-6}$ mbar

# Munich apparatus

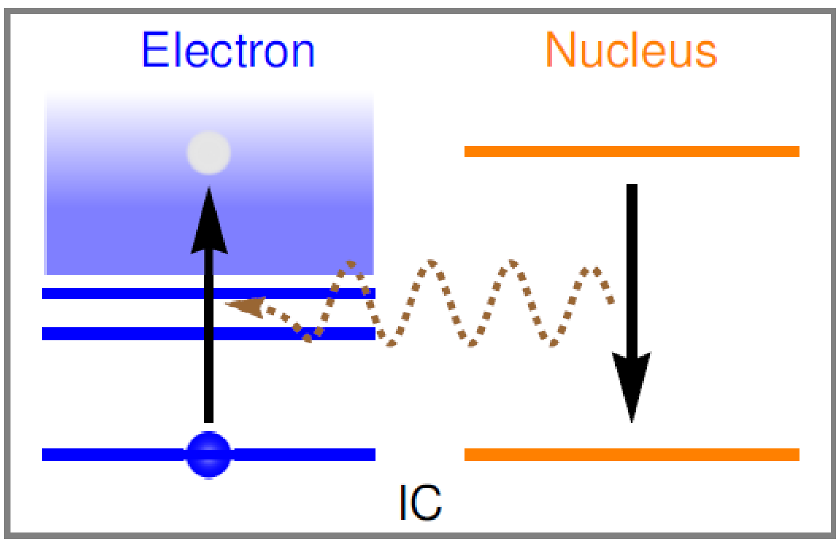


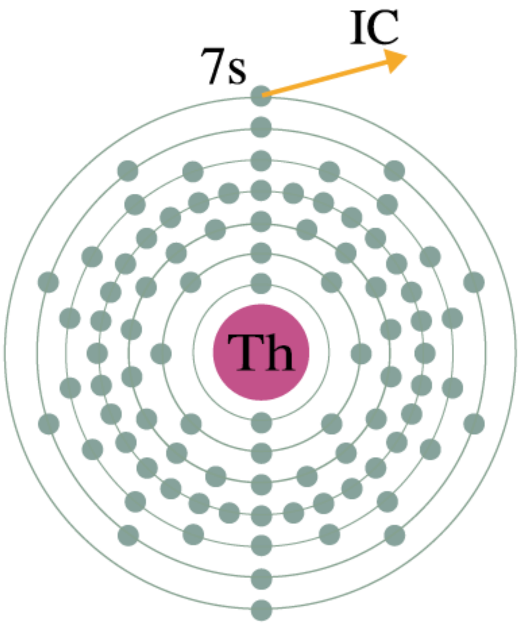

**located at Maier-Leibnitz Laboratory, Garching**

# No VUV photons!

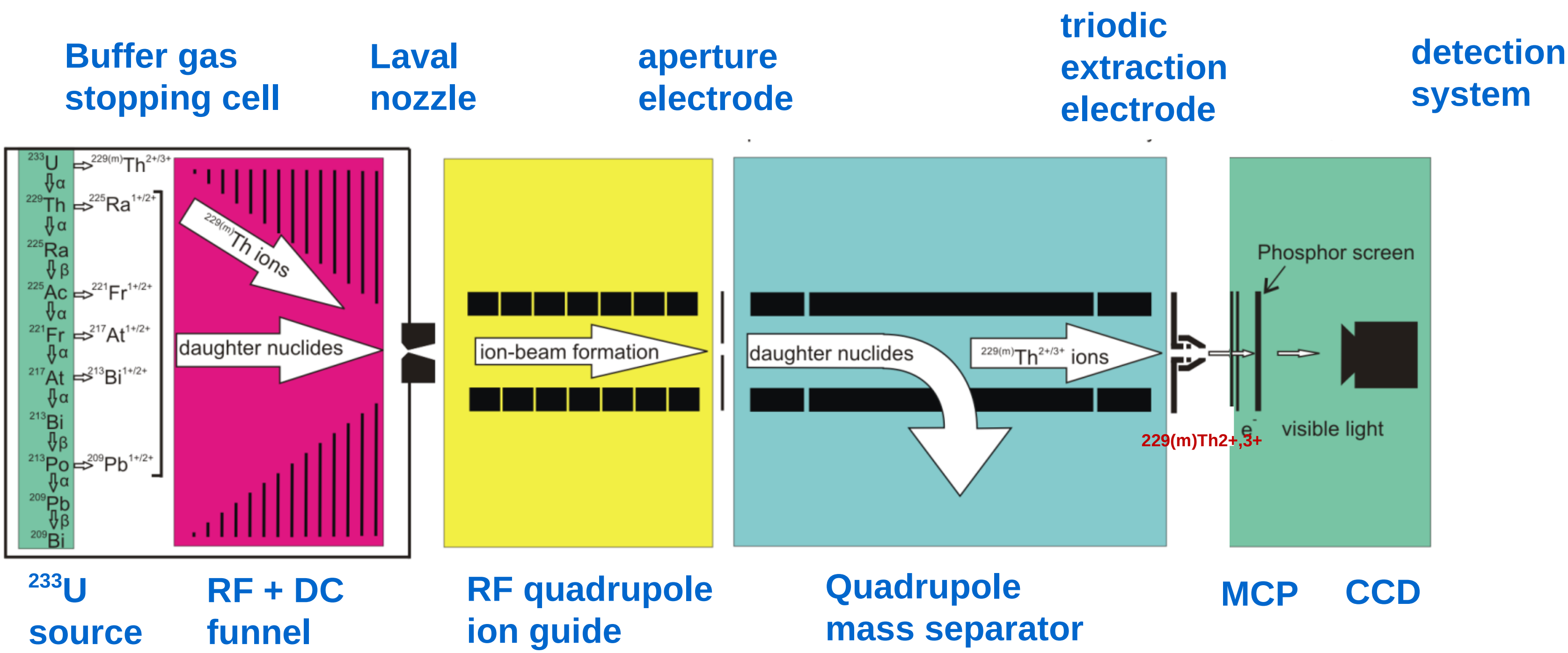
What else could have happened?

For low-energy transition, **internal conversion** is the preferred decay channel!



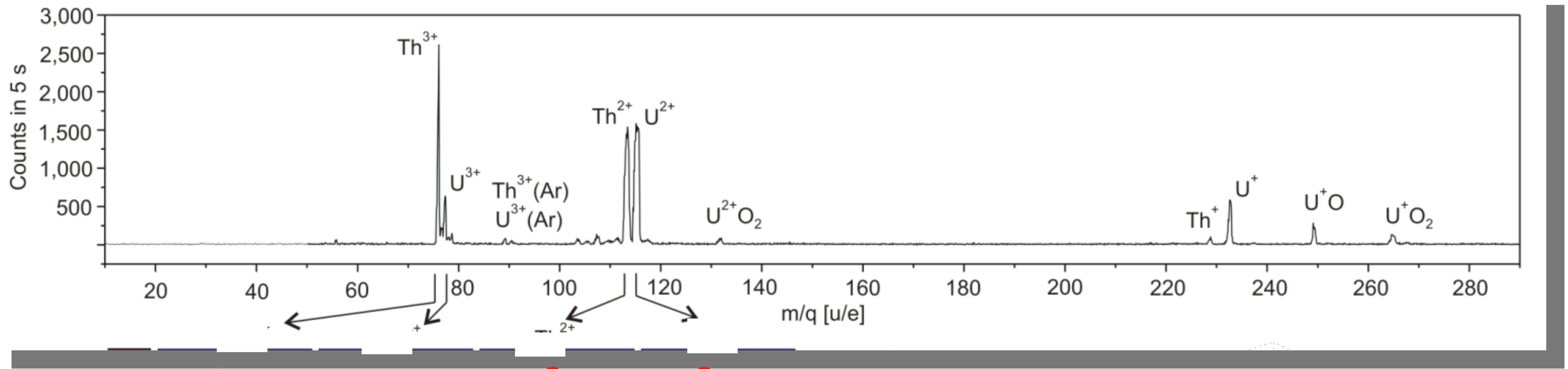
# Detection of IC electron

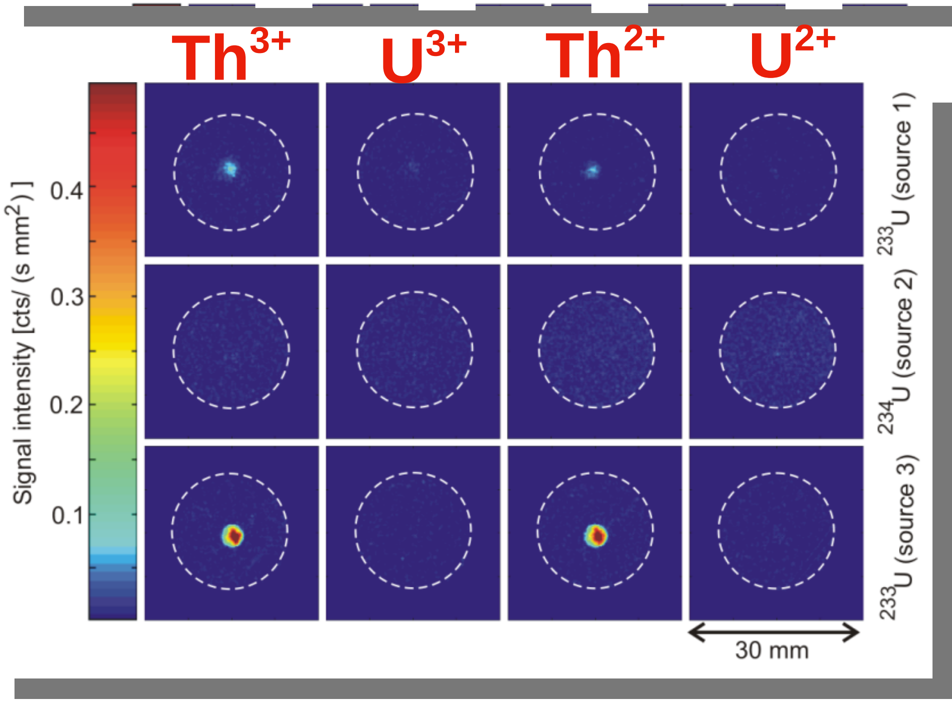


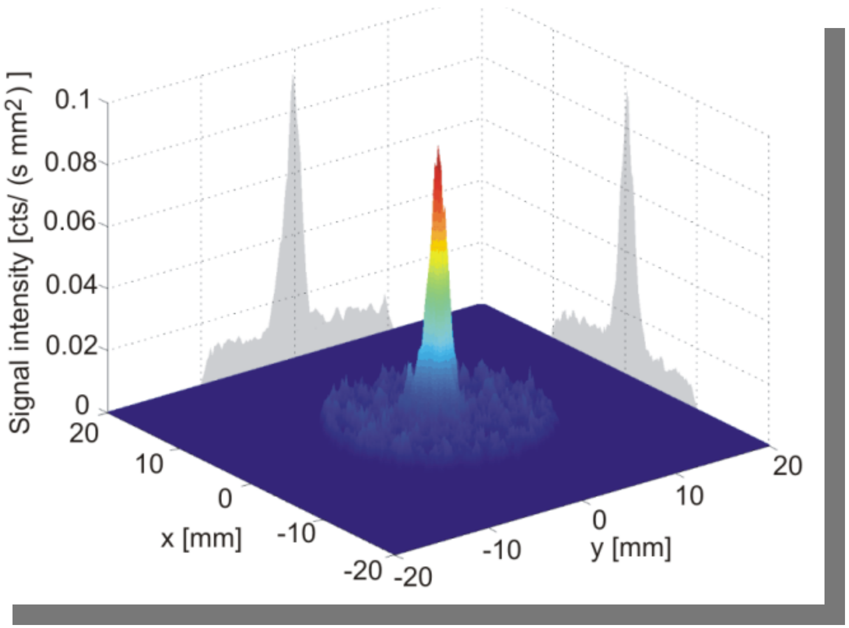

accumulate $^{229(m)}$Th ions directly onto MCP surface

# Direct IC signal

L. v.d. Wense, et al., Nature 533, 47-53 (2016)

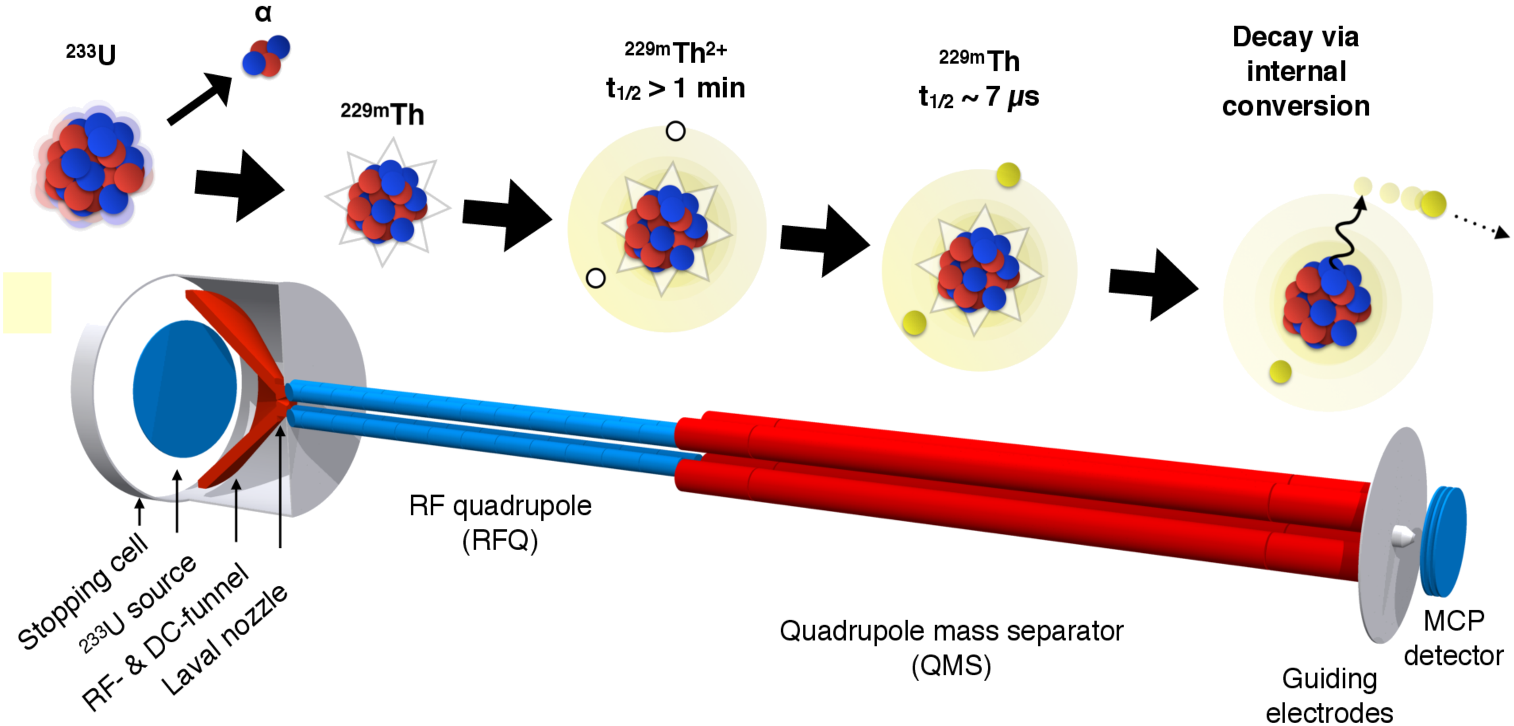


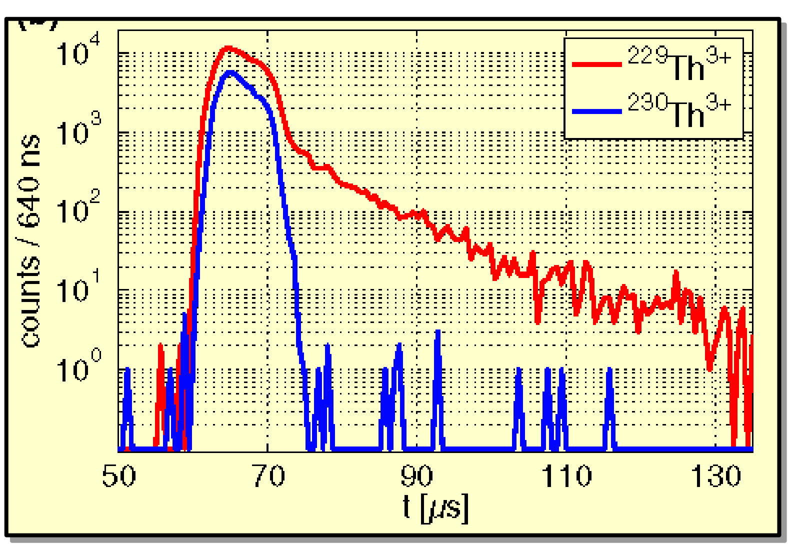



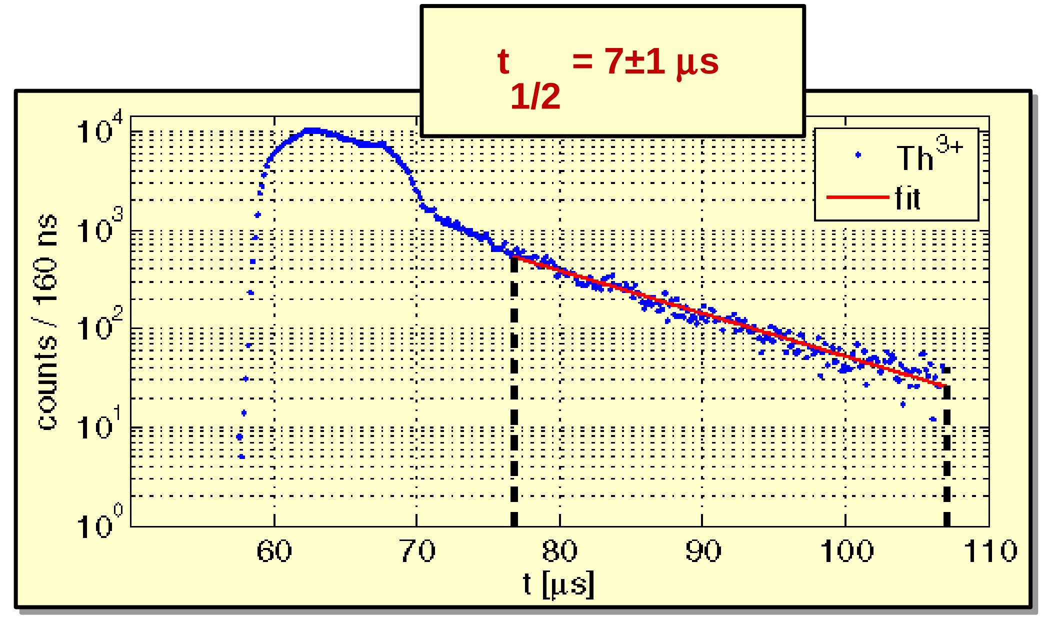




**clear signal from $Th^{3+}$, $Th^{2+}$ no signal from $U^{3+}$, $U^{2+}$**

# IC lifetime measurement



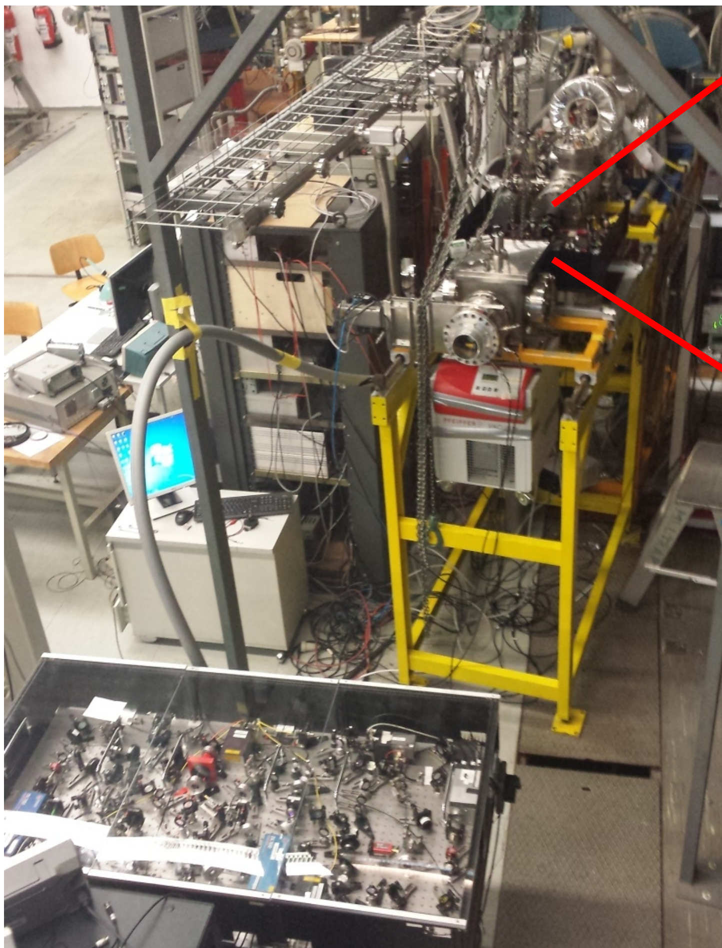



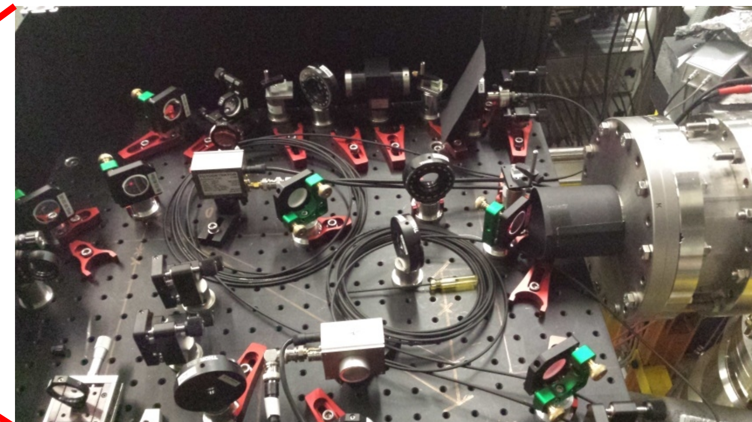

**Courtesy P. Thirolf**

# Collinear laser spectroscopy on $^{229m}$Th

**PTB Braunschweig, group of Ekkehard Peik**

isomer beam (LMU) + laser system (PTB) - resolve hyperfine structure of $^{229m}Th^{2+}$





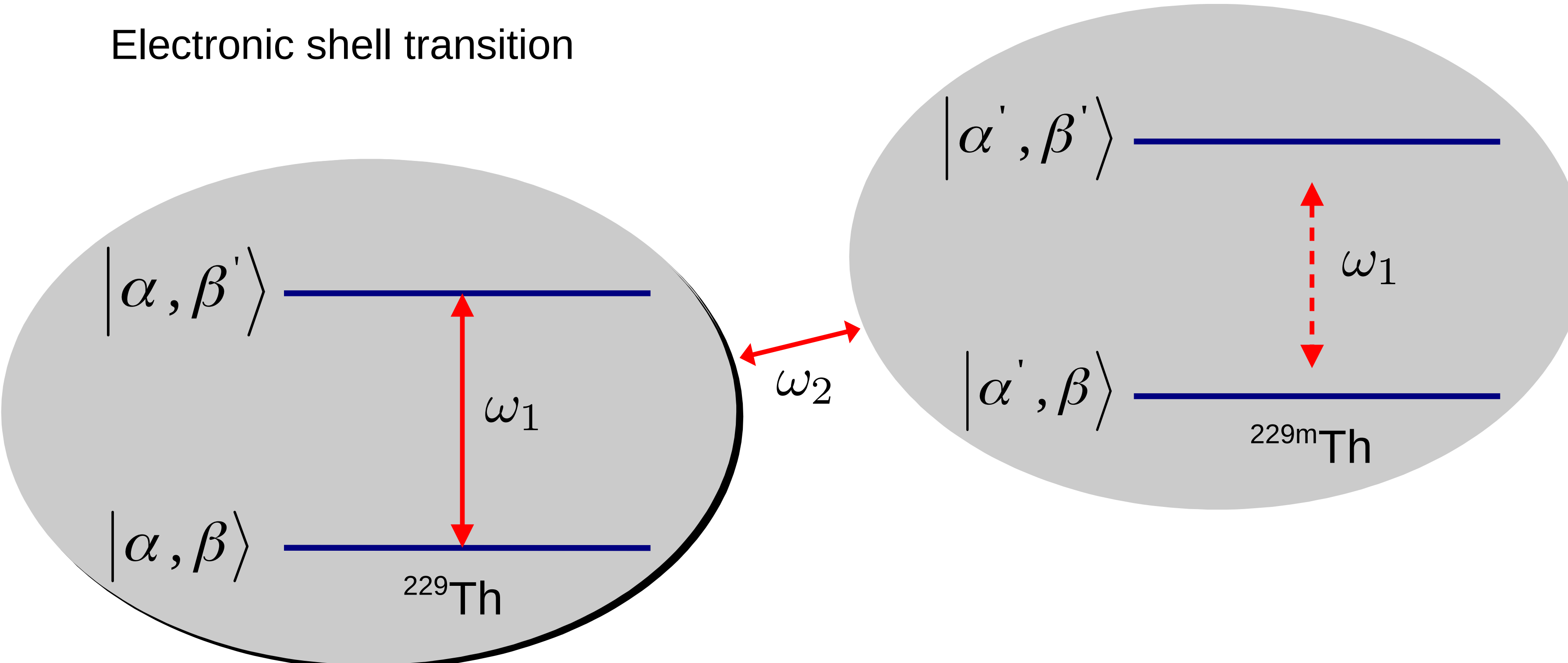
- laser excitation of $^{229(m)}Th^{2+}$ ions behind QMS:
  3 external-cavity diode lasers
  co- and counter-propagating laser beams

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

25

# Laser spectroscopy on hyperfine structure

Electronic shell transition




α: nuclear, β: electronic

**after nuclear transition**

change of nuclear moments, spin

change of hyperfine splitting, total angular momenta

$\omega_1$ out of resonance (~GHz)

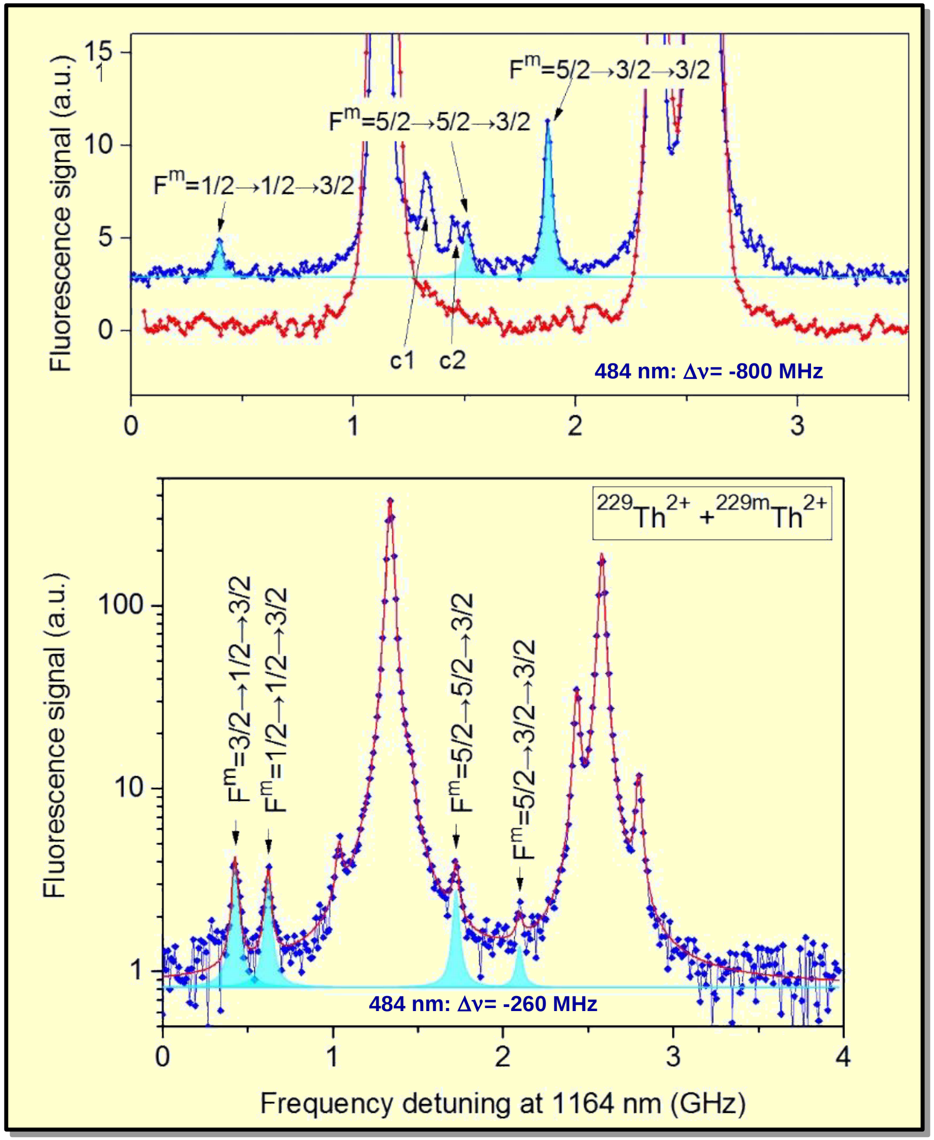
drop in resonance fluorescence

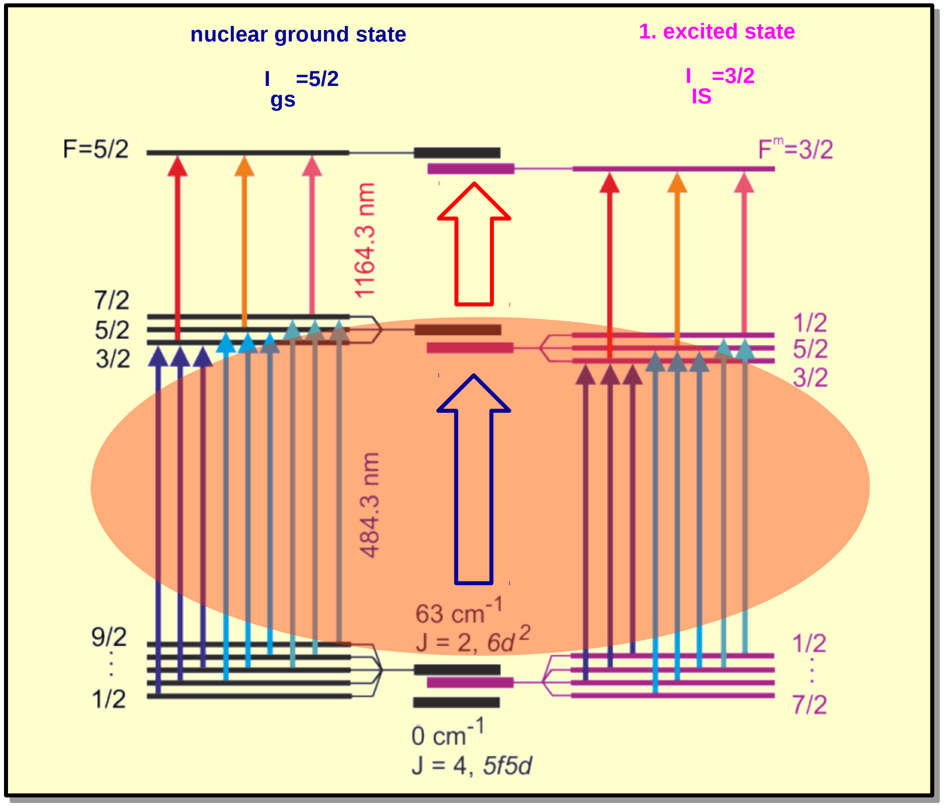
**Peik, Tamm, Eur. Phys. Lett. 61 (2003) 181**

# Hyperfine structure of $^{229m}$Th

**J. Thielking et al., Nature 556, 321-325 (2018)**

**2 examples from ca. 70 spectra:**




**ground state:** (I=5/2): 9 transitions

**isomeric state:** (I=3/2): 8 transitions

Determine the hyperfine constants A and B!

Press release @ PTB, Tagesschau, NDR, etc.

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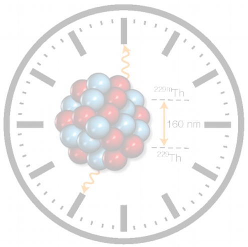

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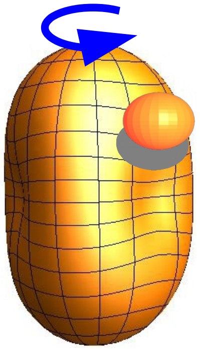

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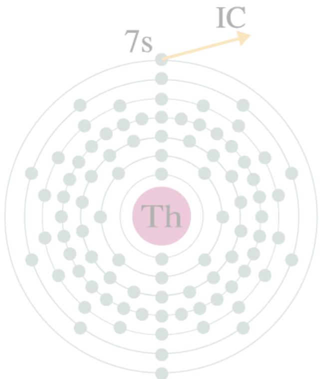
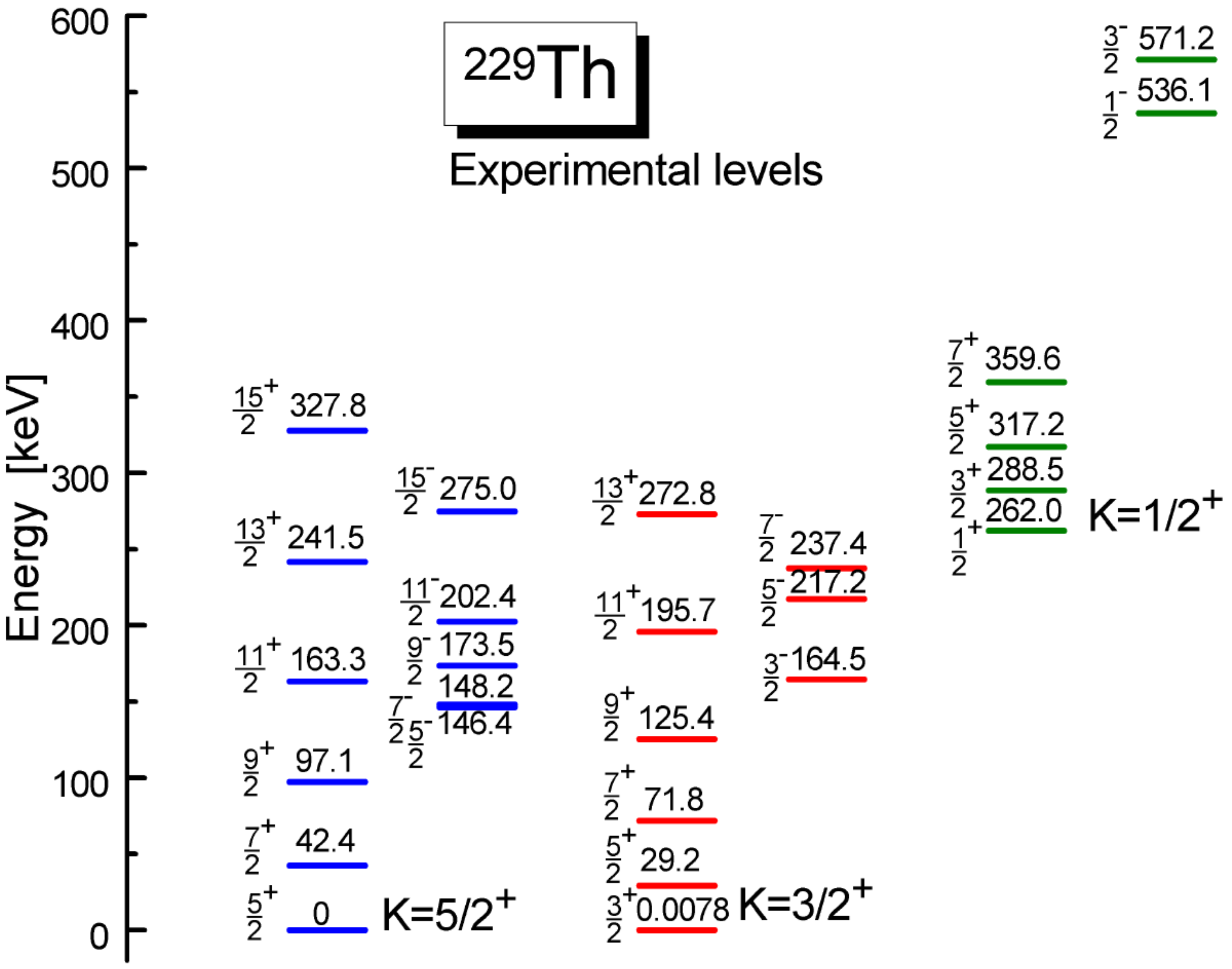


# $^{229}$Th experimental spectrum



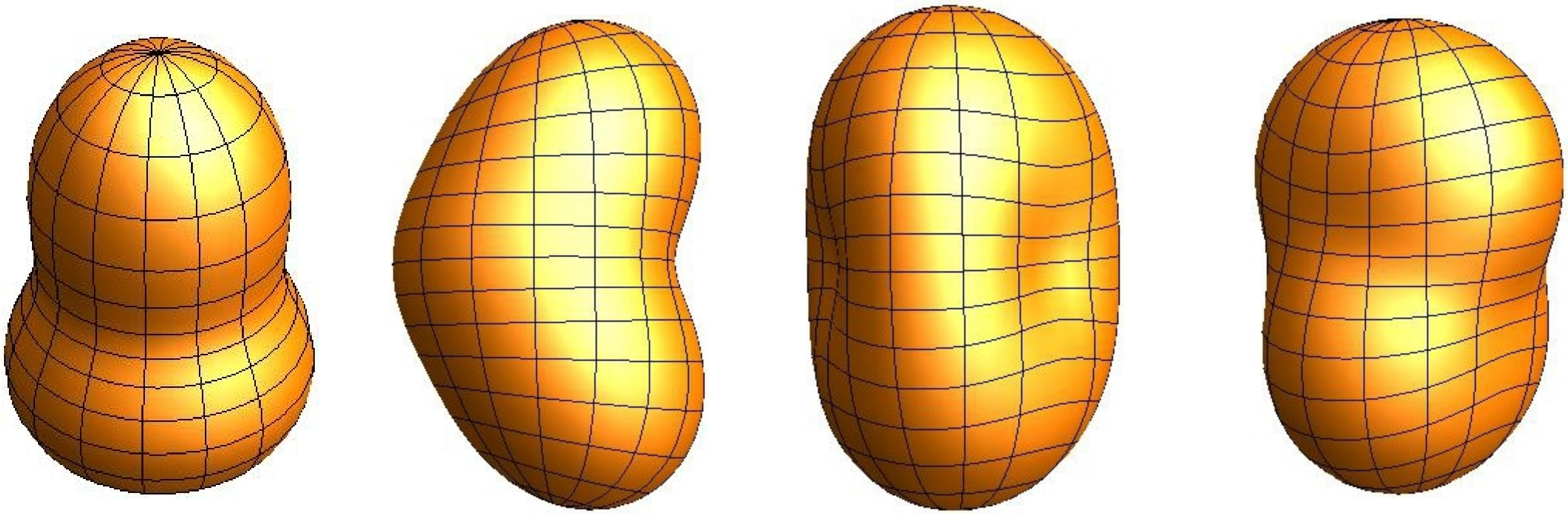
# Nuclear structure model

90 protons + 128 neutrons → Even – even core

+ one single neutron → Additional single particle

+ Coriolis interaction

Quadrupole – octupole deformation for core



$$\beta_{20} = 0.65$$

$$\beta_{3\mu} = 0.35$$

*P. Butler and W. Nazarewicz, RMP 68, 349 (1996)*

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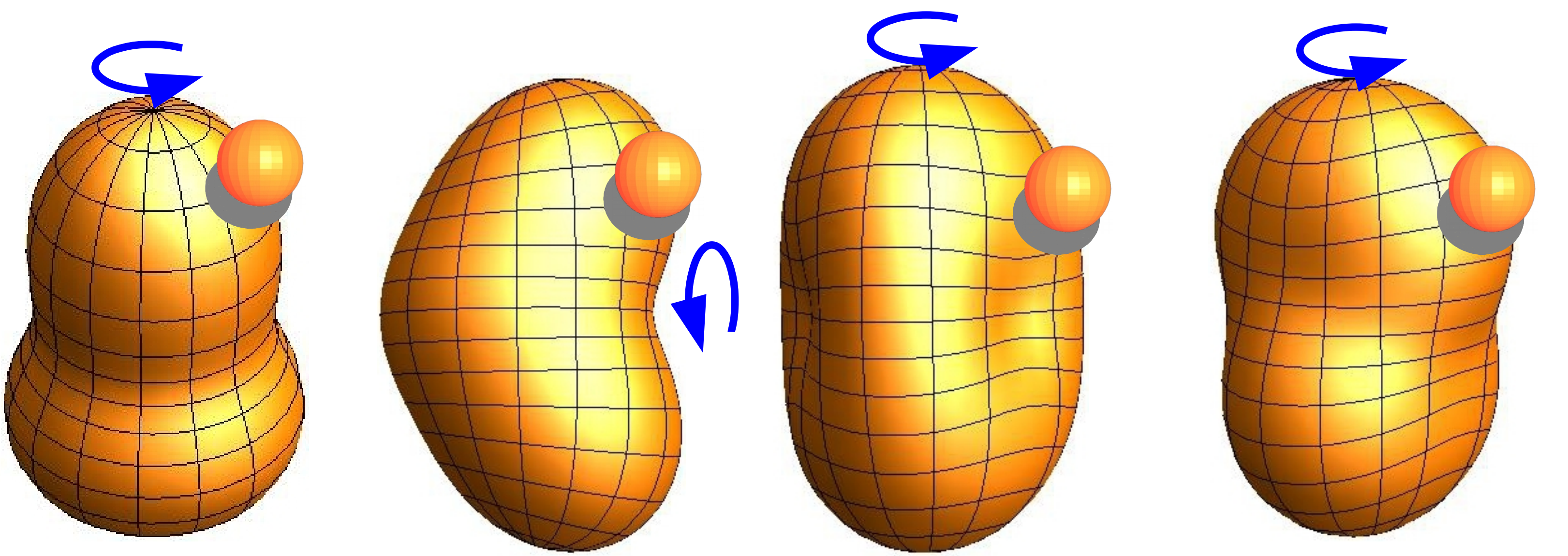

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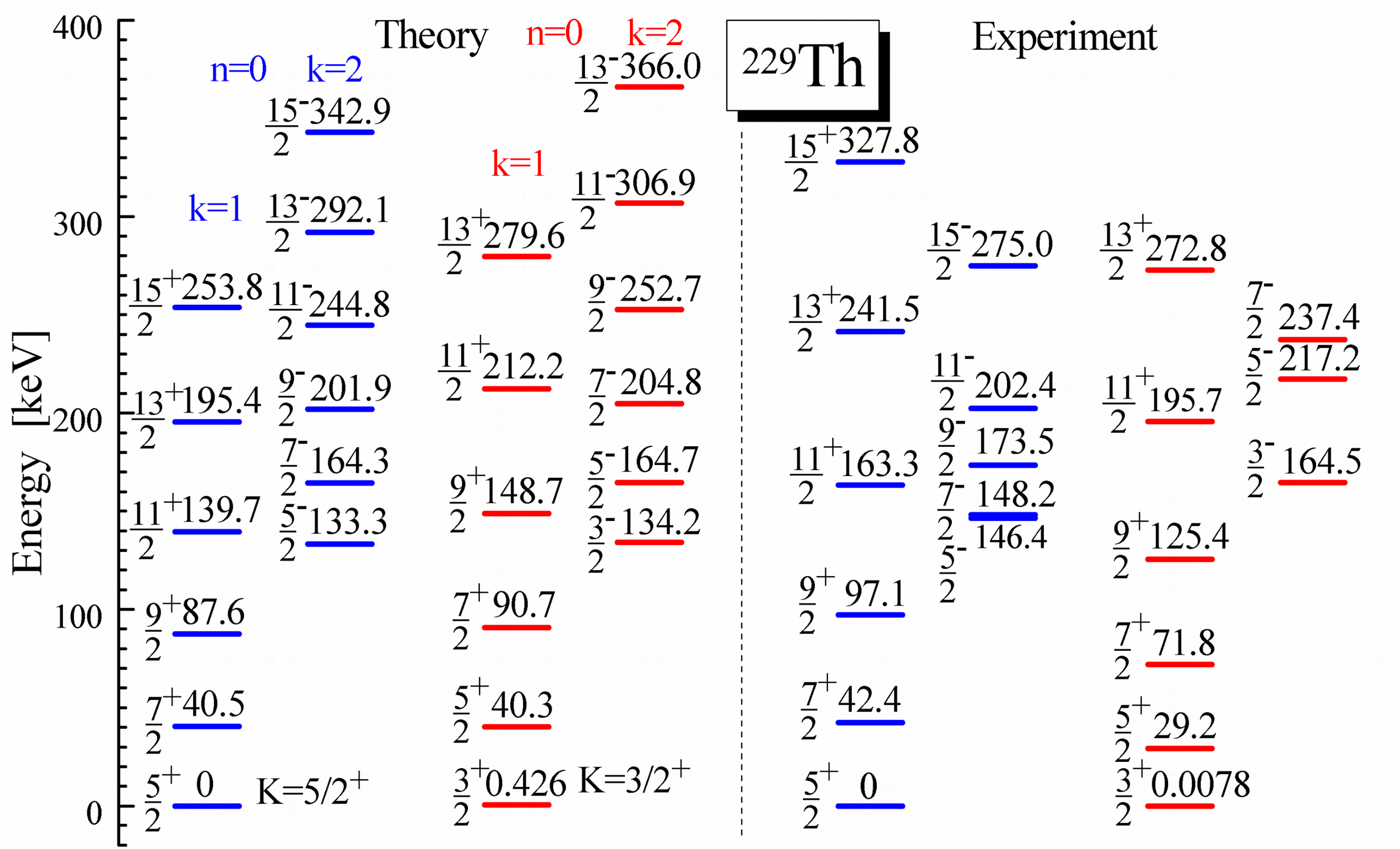
# Theoretical predictions



# Theoretical B(M1) and B(E2) values

| Type/Mult | Transition | Th1[Th2] (W.u.) | Exp (W.u.) |
|---|---|---|---|
| E2 | $7/2^+_{yrs} \to 5/2^+_{yrs}$ | 252 [267] | 300 (±16) |
| E2 | $9/2^+_{yrs} \to 5/2^+_{yrs}$ | 82 [85] | 65 (±7) |
| E2 | $9/2^+_{yrs} \to 7/2^+_{yrs}$ | 213 [224] | 170 (±30) |
| E2 | $9/2^+_{yrs} \to 5/2^+_{ex1}$ | 19.98 [17.37] | 6.2 (±0.8) |
| E2 | $\mathbf{3/2^+_{ex1}} \to \mathbf{5/2^+_{yrs}}$ | 27.04 [23.05] | ? |
| M1 | $7/2^+_{yrs} \to 5/2^+_{yrs}$ | 0.0093 [0.0085] | 0.0110 (±0.0040) |
| M1 | $9/2^+_{yrs} \to 7/2^+_{yrs}$ | 0.0178 [0.0157] | 0.0076 (±0.0012) |
| M1 | $9/2^+_{yrs} \to 7/2^+_{ex1}$ | 0.0151 [0.0130] | 0.0117 (±0.0014) |
| M1 | $\mathbf{3/2^+_{ex1}} \to \mathbf{5/2^+_{yrs}}$ | 0.0076 [0.0061] | ? |

$\mathrm{Th1} \to E(3/2^+) = 0.4263$ keV

$\mathrm{Th2} \to E(3/2^+) = 0.0078$ keV

Smaller than the previously used Theoretical value of 0.048 W.u.

*N. Minkov and AP, PRL 118, 212501 (2017)*

# Magnetic moment

Model Hamiltonian

$$H = H_{\rm qo} + H_{\rm s.p.} + H_{\rm pair} + H_{\rm Coriol}$$

Core plus particle magnetic dipole operator

$$\hat{M}1 = \sqrt{3/(4\pi)}\mu_N \left[ g_R(\hat{I} - \hat{j}) + g_s\,\hat{s} + g_l\,\hat{l} \right]$$

Magnetic moment is the matrix element

$$\mu = \sqrt{\frac{4\pi}{3}} \langle \widetilde{\Psi}_{IIK_b} | \hat{M}1_0 | \widetilde{\Psi}_{IIK_b} \rangle$$

***N. Minkov and AP, PRL 122, 162502 (2019)***

# Magnetic moment

Model Hamiltonian

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Core plus particle magnetic dipole operator

$$\hat{M}1 = \sqrt{3/(4\pi)}\mu_N \left[ g_R(\hat{I} - \hat{j}) + g_s\,\hat{s} + g_l\,\hat{l} \right]$$

**collective gyromagnetic factor**

Magnetic moment is the matrix element

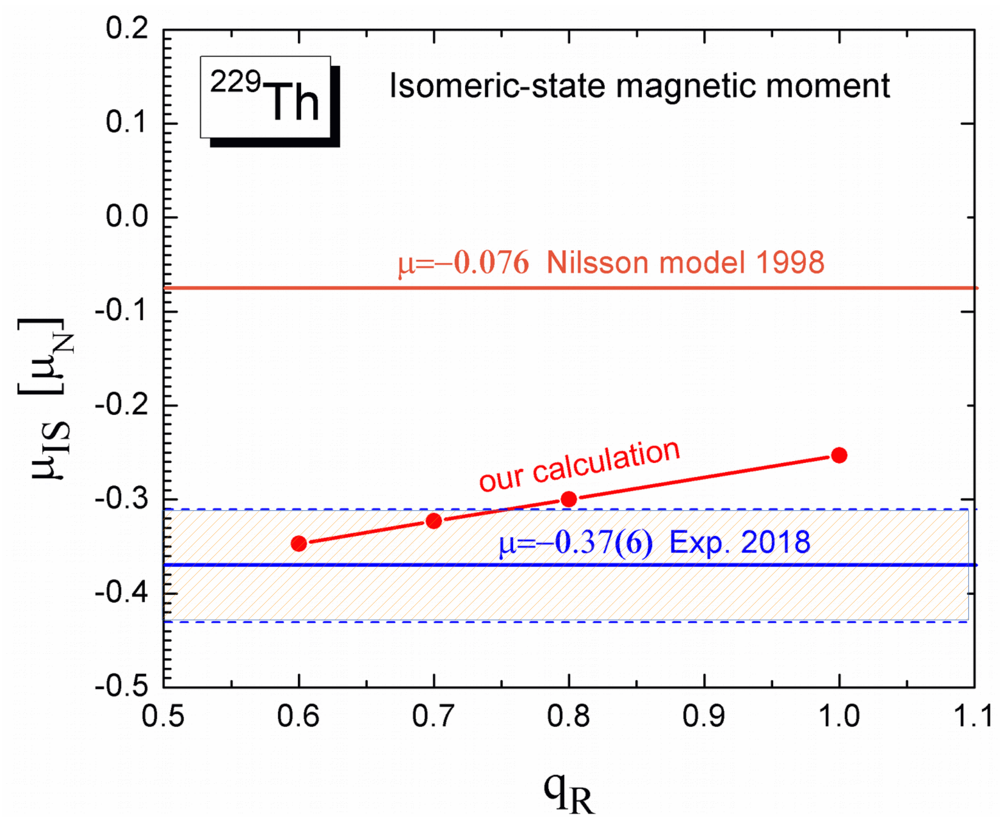
$$\mu = \sqrt{\frac{4\pi}{3}} \langle \widetilde{\Psi}_{IIK_b} | \hat{M}1_0 | \widetilde{\Psi}_{IIK_b} \rangle$$

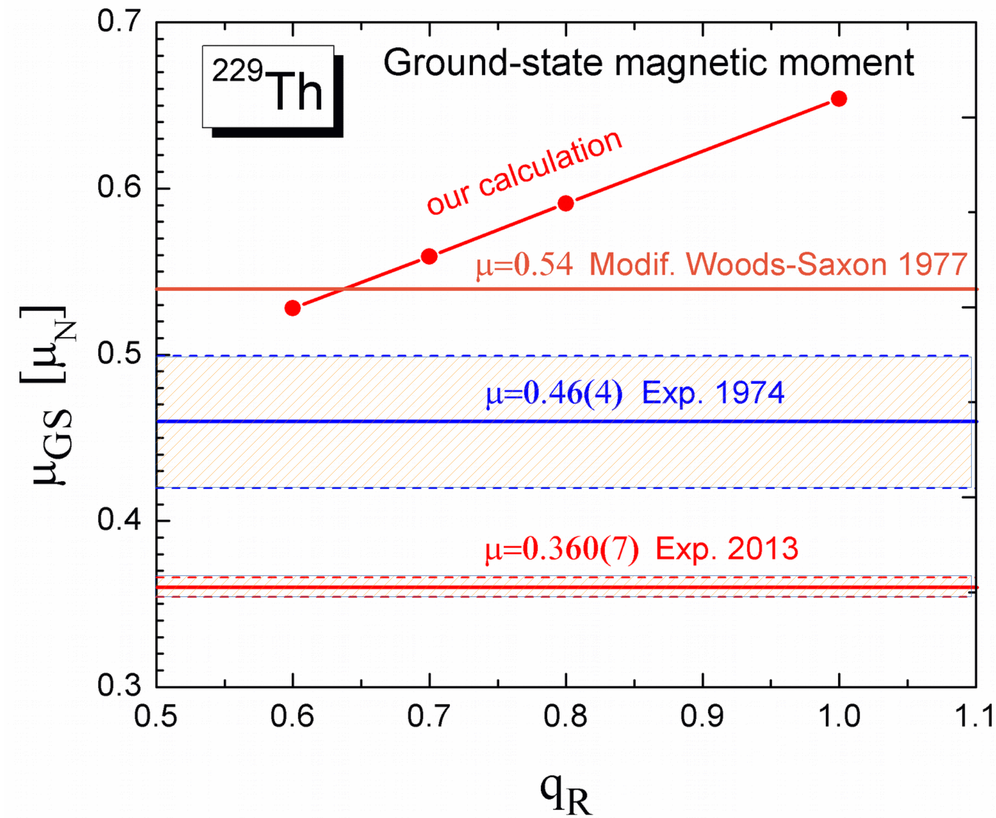
phenomenological $Z/A$

introduce quenching factor for deformed nuclei (20%-30% less)

***N. Minkov and AP, PRL 122, 162502 (2019)***

# Results

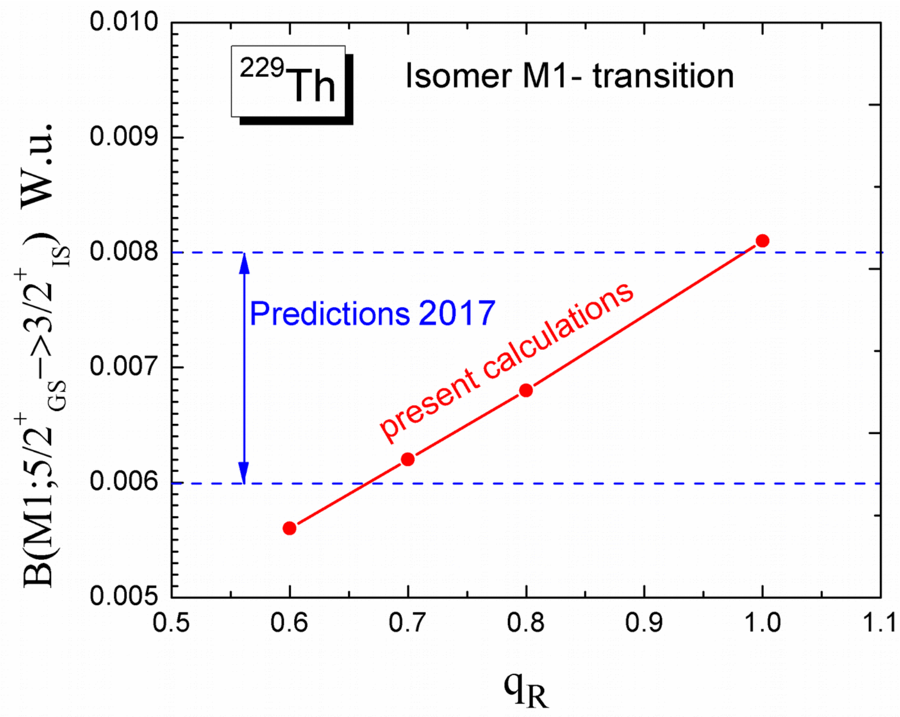


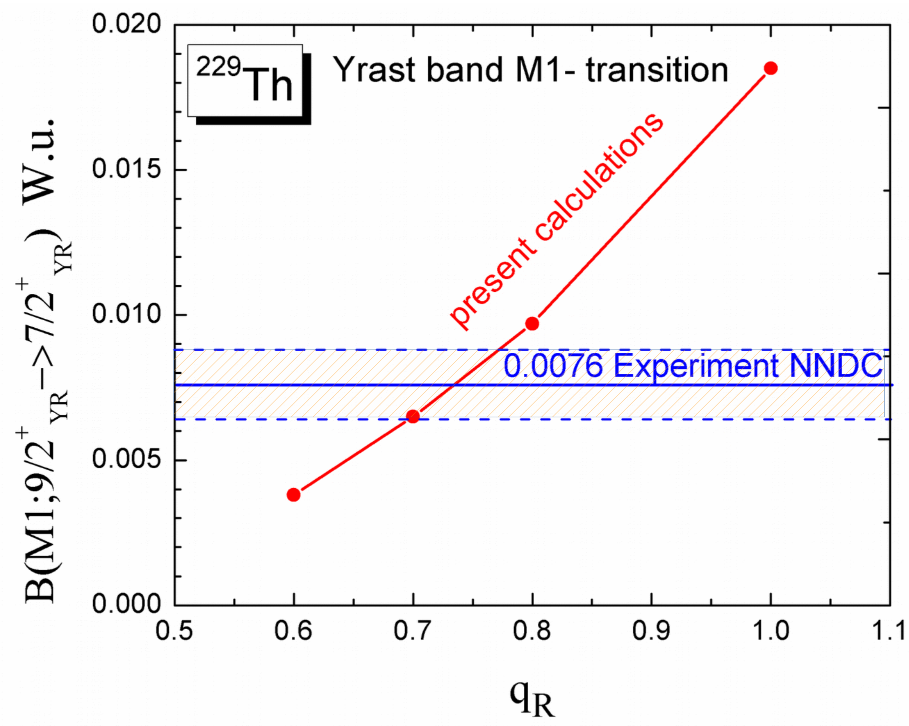




Model parameters from our previous work on B(M1) chosen to reproduce the low-lying energy spectrum

***N. Minkov and AP, PRL 122, 162502 (2019)***

# For B(M1)




It appears likely that B(M1) is even lower than previously estimated!

***N. Minkov and AP, PRL 122, 162502 (2019)***

# Summary

- Collective CQOM + microscopic DSM+BCS + Coriolis interaction

- Quenching of collective gyromagnetic factor

- Predictions for **magnetic moments** $\mu_{GS} = 0.528\mu_N$ too large

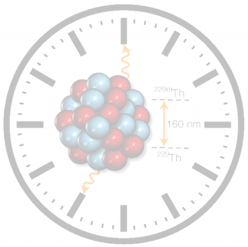
  $\mu_{IS} = -0.347\mu_N$ surprisingly good

- **B(M1):** will very likely be smaller than previously predicted, 0.0056 W.u.

- New search through model parameters planed.
  Interestingly, Coriolis mixing factor affects only ground state magnetic moment!

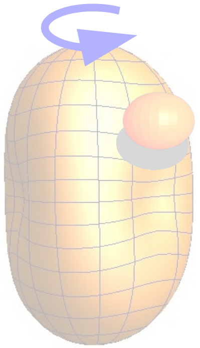
# Outline

## I. What we know about $^{229}$Th



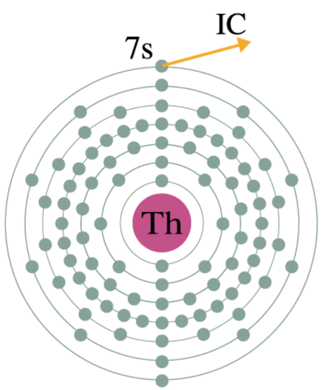
Short history
Experimental achievements
Coupling to atomic shell

## II. Nuclear structure perspective



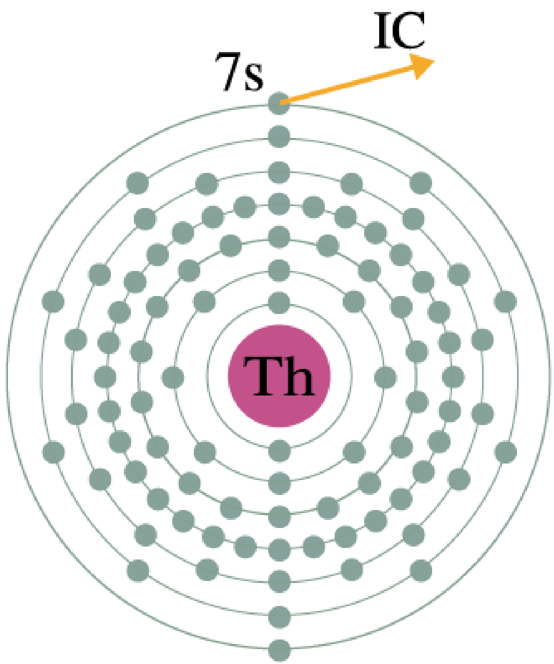
Nuclear model
Excitation probabilities
Magnetic moments

## III. New energy measurement




Internal conversion
Struggle with excited states
Extracted new energy value

# Internal conversion



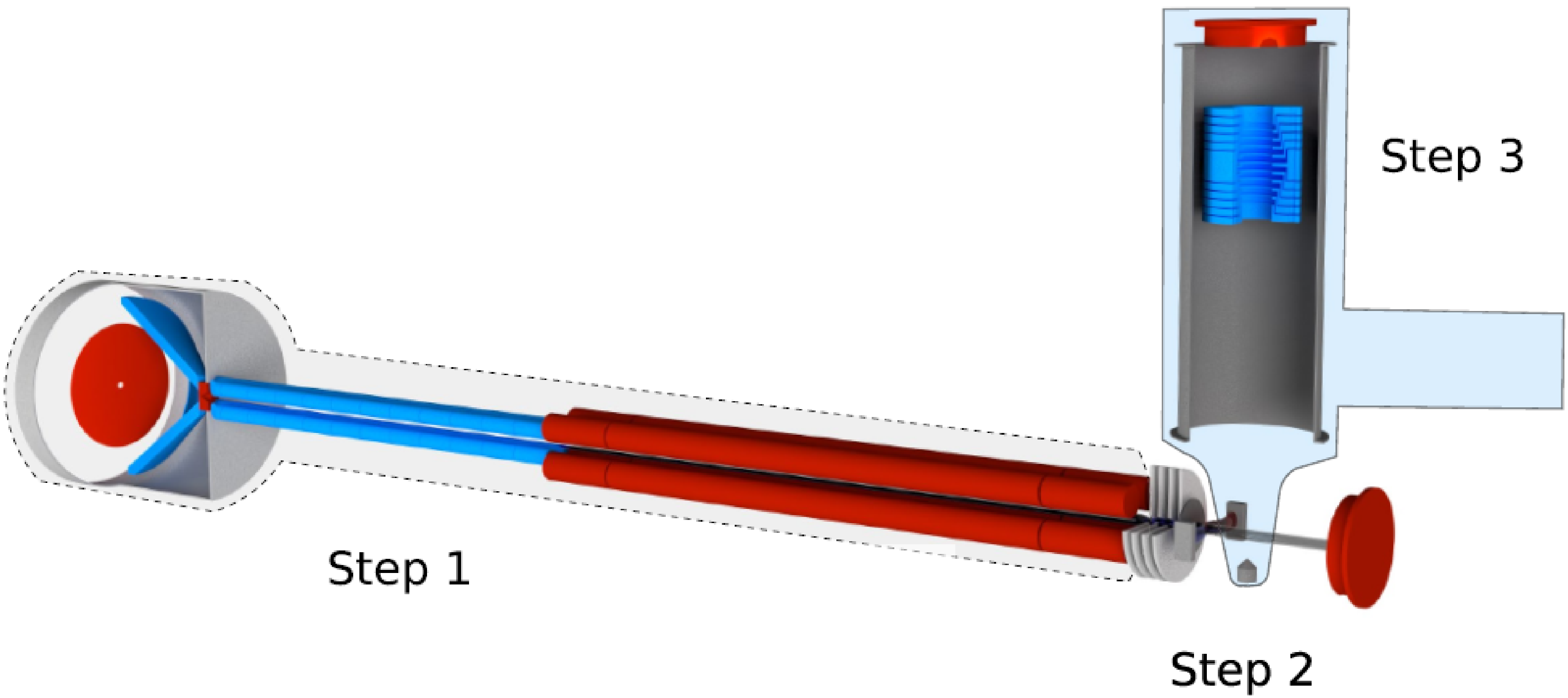

IC coefficient $\alpha = \frac{\text{IC rate}}{\gamma\text{-decay rate}}$

For M1-transition at $E \simeq 10$ eV
$\gamma$-decay rate $\propto E^3$ is small
$\Rightarrow \alpha$ is large

In neutral atom of $^{229}\mathrm{Th}$ $\alpha \simeq 10^9$
F. F. Karpeshin *et al.* Phys. Rev. C **76**, 054313 (2007)

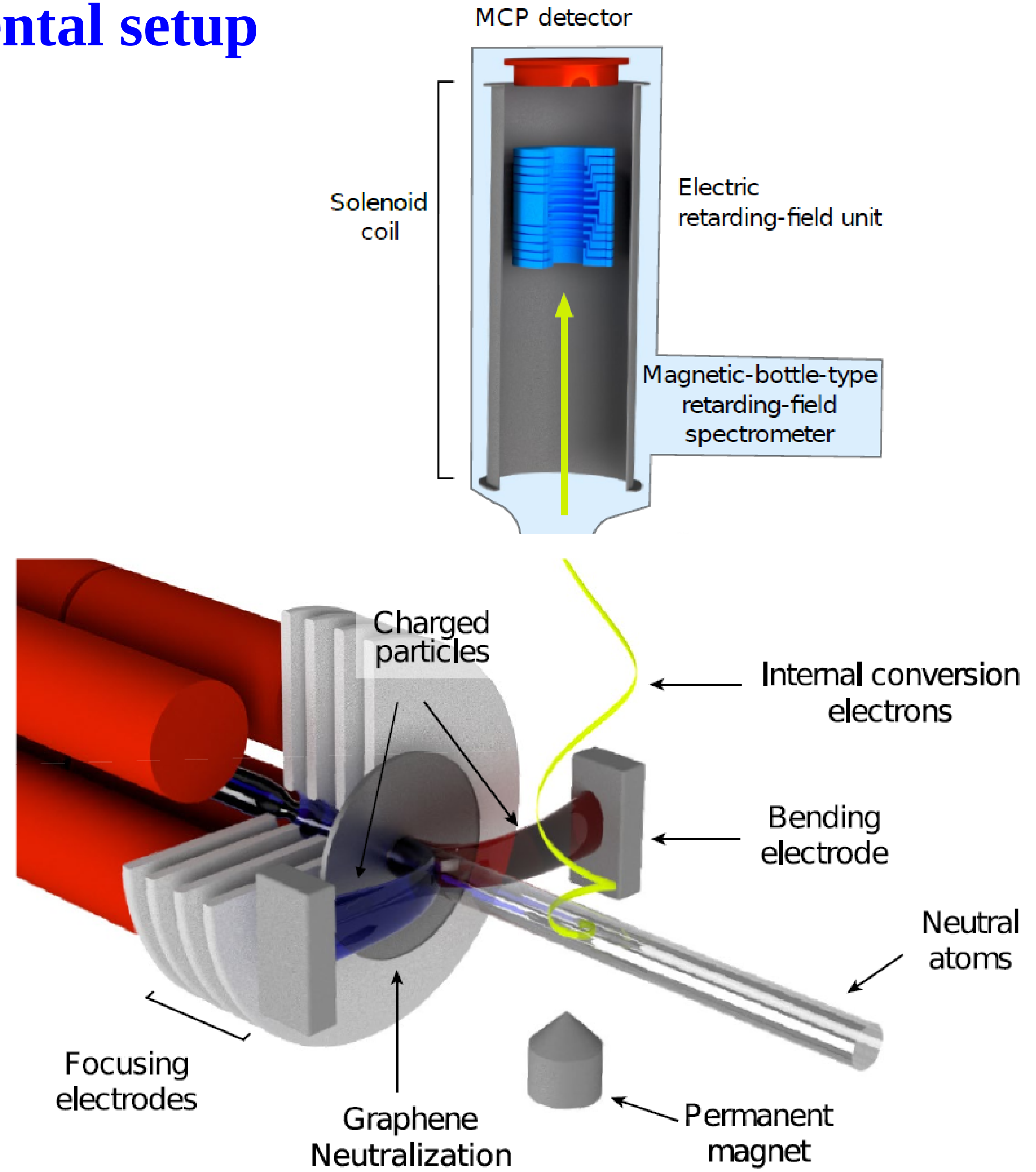
| Ion charge | 0 | 1+ | 2+ | 3+ | 4+ |
|---|---|---|---|---|---|
| Ion. threshold (eV) | 6.3 | 12.1 | 20.0 | 28.7 | 58 |

# Experimental setup

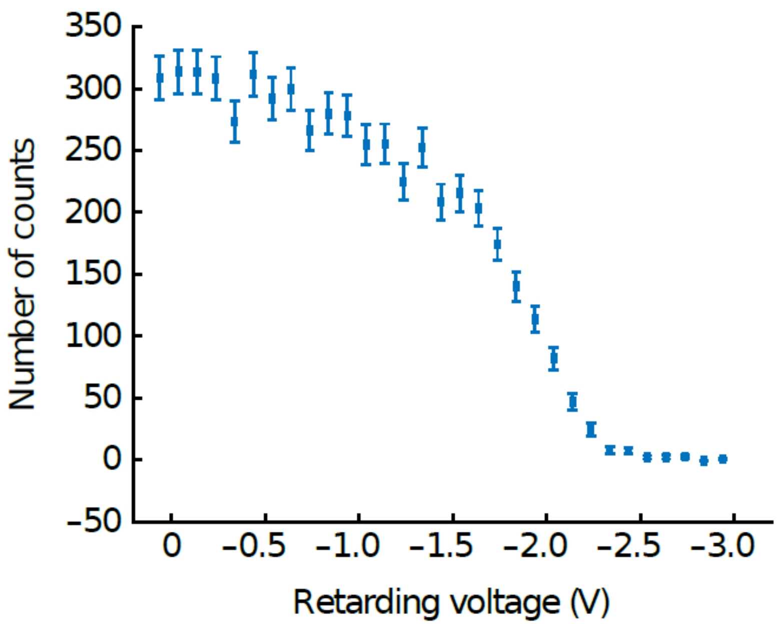



LMU Munich
Group of Peter Thirolf

# Experimental setup



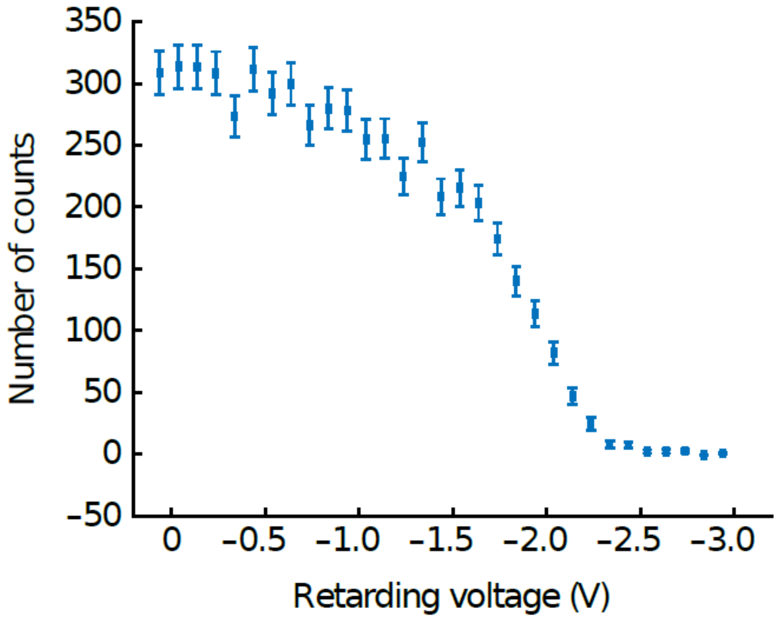
# Spectrum



350
300
250
200
150
100
50
0
−50
Number of counts
0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Retarding voltage (V)


$E_m$ − ?

# Spectrum



350
300
250
200
150
100
50
0
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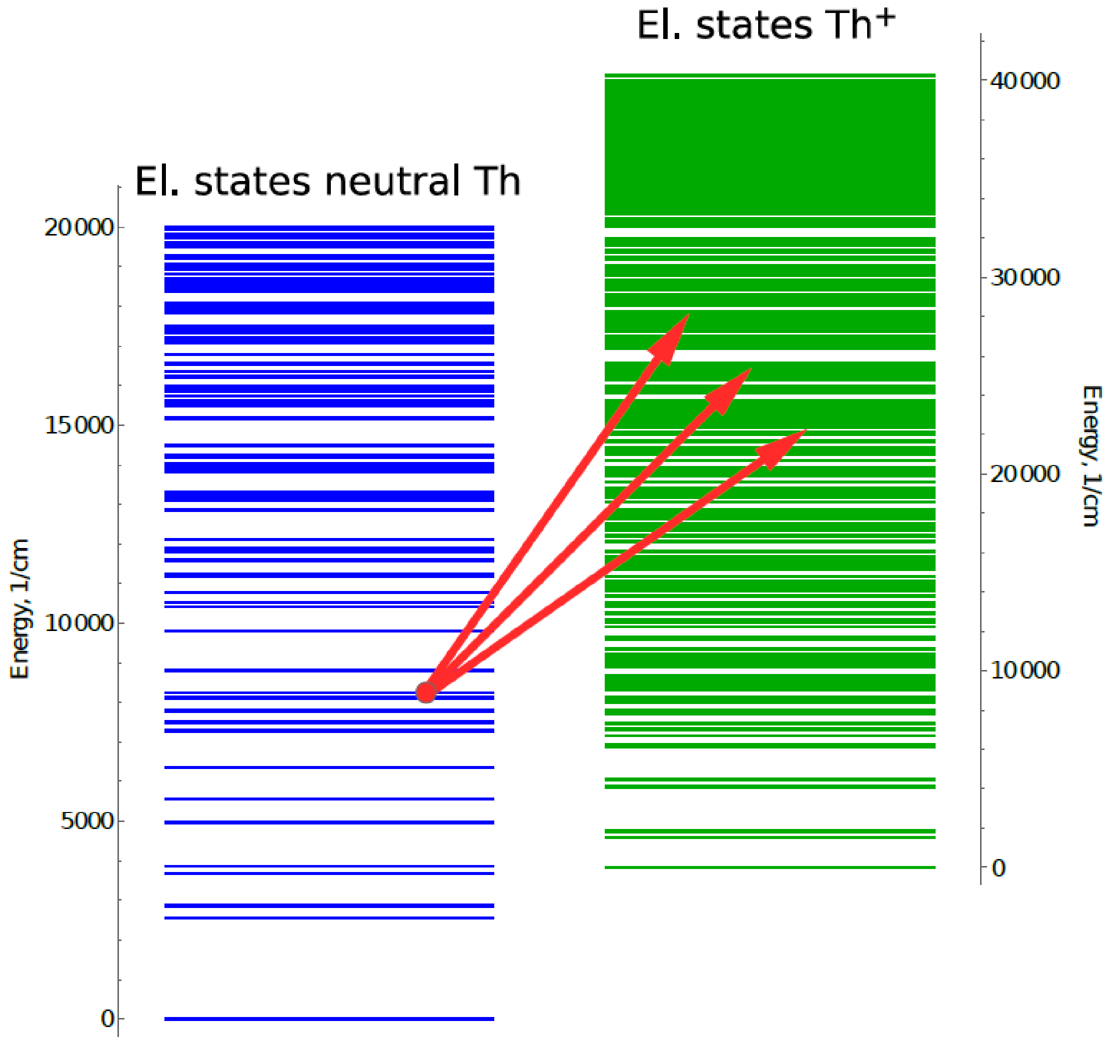
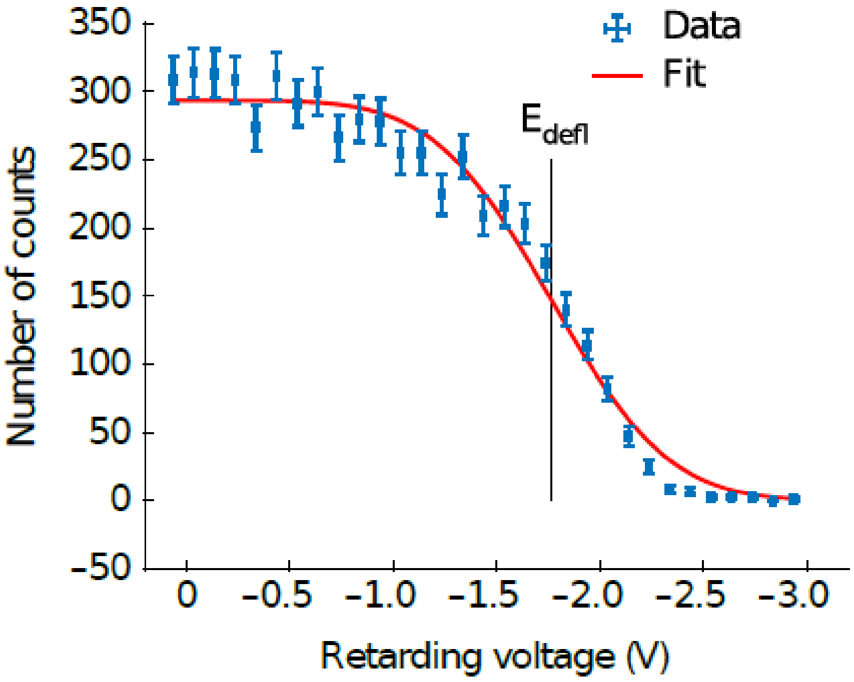
Number of counts
0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Retarding voltage (V)


$E_m - ?$



El. states neutral Th
El. states Th+
Energy, 1/cm
20000
15000
10000
5000
0
40000
30000
20000
10000
0
Energy, 1/cm

# The isomer energy



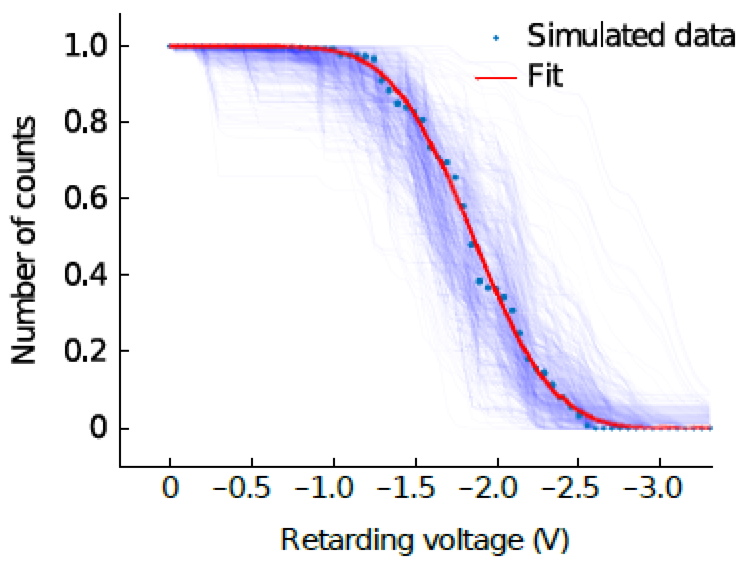

$$f(U) = a\left\{1 - \mathrm{erf}\left[\frac{U - E_{\mathrm{defl}}}{b}\right]\right\}$$

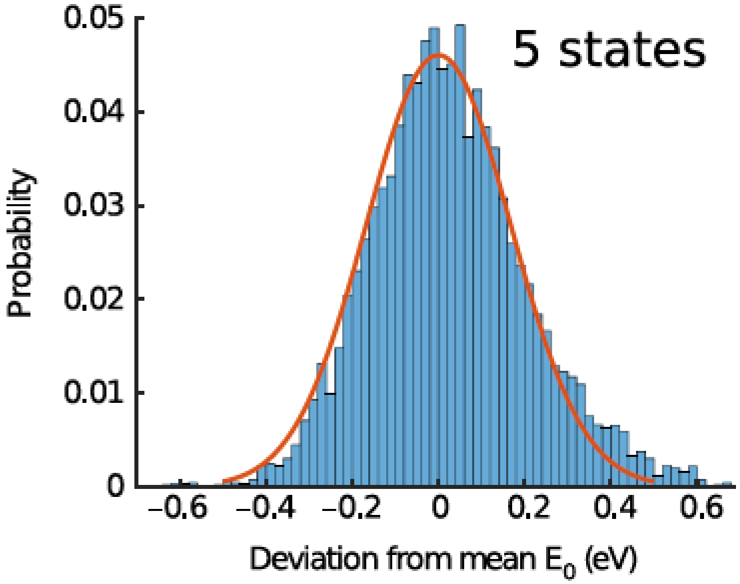
$$E_{\mathrm{defl}} = 1.77 \pm 0.03\ \mathrm{eV}$$

$$E_{\mathrm{m}} = E_0 + E_{\mathrm{defl}}$$

$$E_0 - ?$$

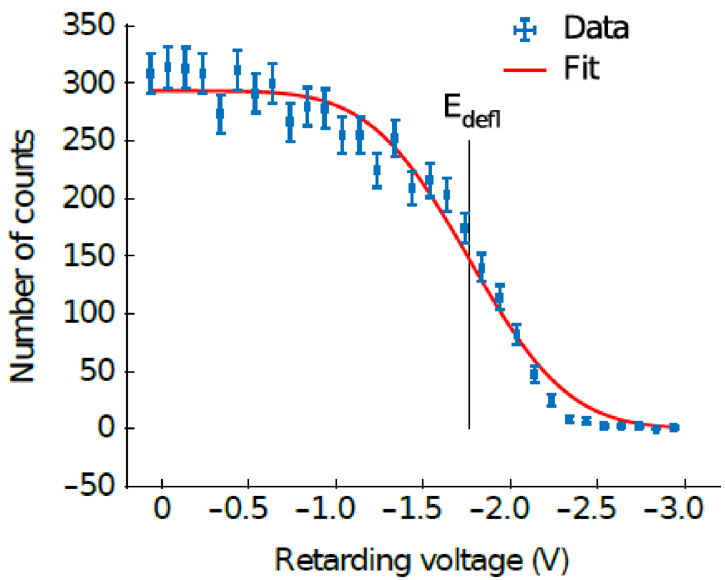
# The isomer energy




| Number of excited states ($n$) | $E_0$ | Width of the distribution $\sigma$ |
|---|---|---|
| 2 | 6.56±0.02 | 0.22 |
| 4 | 6.517±0.003 | 0.18 |
| 5 * | 6.506±0.001 | 0.16 |
| 10 | 6.504±0.001 | 0.12 |
| 20 | 6.492±0.001 | 0.09 |
| 30 | 6.494±0.001 | 0.06 |
| 40 | 6.493±0.001 | 0.05 |

# The isomer energy



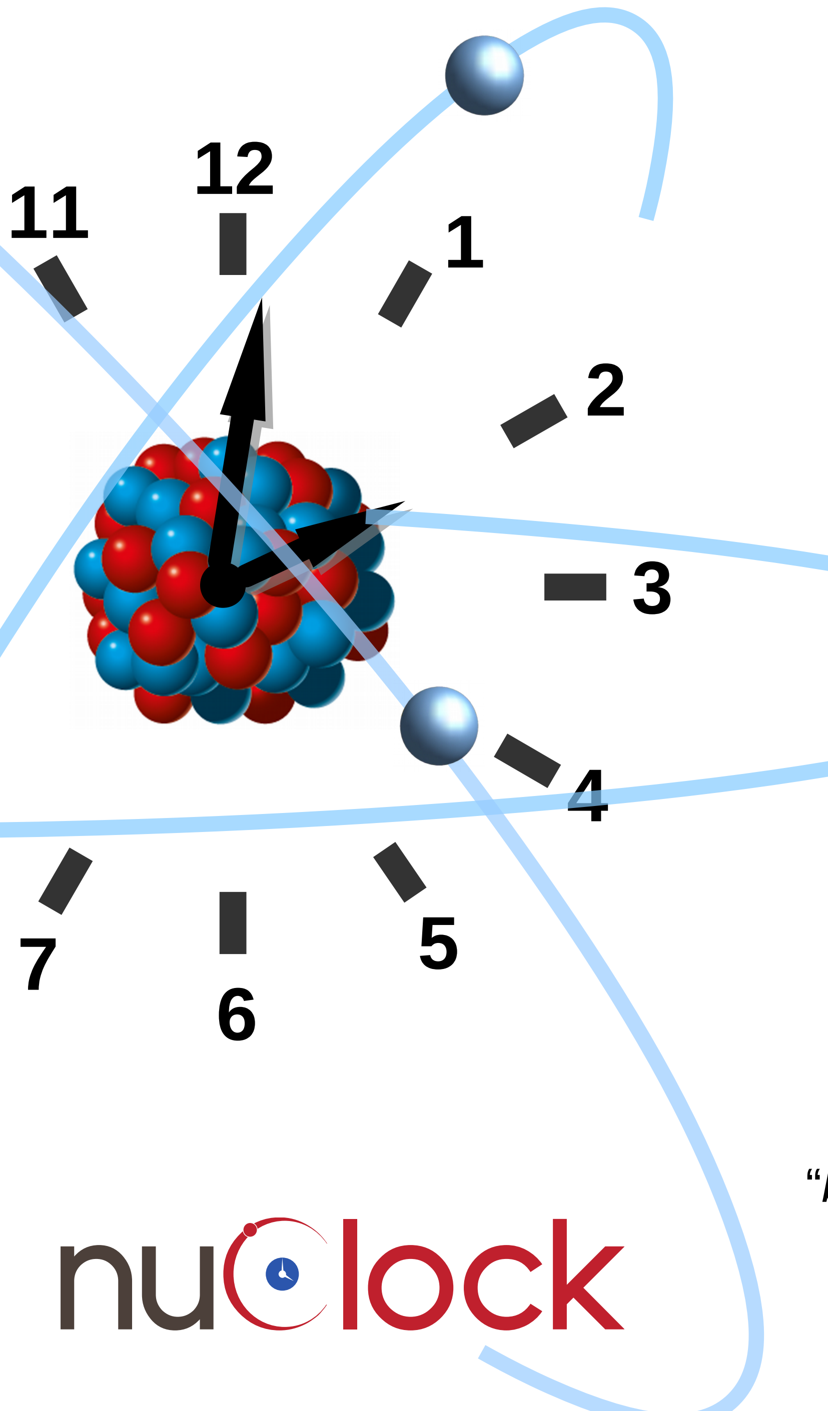


IC calculations to extract the energy value from the measured spectrum

$$E_m = 8.28 \pm 0.17\,\mathrm{eV}$$

B. Seiferle *et al.*, Nature **573**, 243246 (2019)

# Conclusions




$^{229}$Th could provide a unique chance to develop a nuclear frequency standard, stable, compact, with increased accuracy.

Appealing applications:
GPS
variation of fundamental constants
tests for new physics

$$E_m = 8.28 \pm 0.17\,\mathrm{eV}$$

Optical (VUV) control of the transition requires more time - “needle in the haystack” + laser development

“*but we know much better how this needle should look like!*”
Peter Thirolf

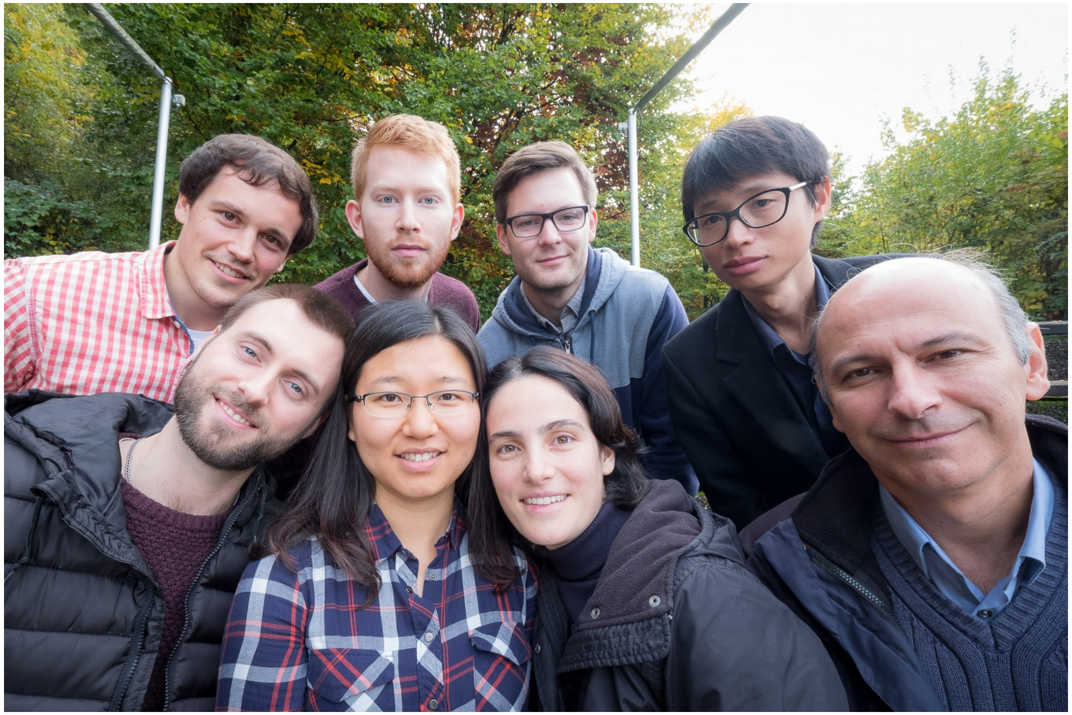
nuClock

# Thanks

*Atomic and nuclear quantum dynamics*

Brenden Nickerson
Pavlo Bilous
Wen-Te Liao
Nikolay Minkov

Jose Crespo



Peter Thirolf
Lars von der Wense
Benedict Seifere

Thorsten Schumm

**THANK YOU FOR YOUR ATTENTION!**