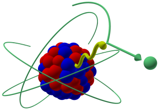

The elusive ^{229}Th isomer - characterization of its properties

Benedict Seiferle
LMU Munich

SPES-Nusprasen Workshop
Pisa 1-2 February 2018

Outline

1. Motivation
2. Experimental Setup
3. Lifetime Measurements
4. Energy Measurements
5. Conclusion & Outlook

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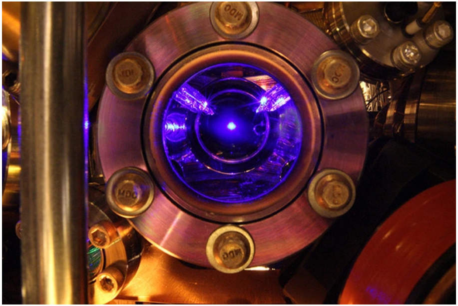
Optical Atomic Clocks



- ingredients:
  - → frequency reference: laser locked to a narrow atomic transition
  - → counter or clockwork
- best atomic clock: Strontium lattice clock at NIST
  - → frequency uncertainty [1]: 2.1×10^{-18}
  - → precision is only limited by external electric and magnetic fields

[1] T.L. Nicholson et al., Nature Communications 7896 (2015).

Can one do better? - A nuclear optical clock

Idea: Use nuclear transition for time measurement [2]

- expected frequency uncertainty: 1.5×10^{-19} [3]

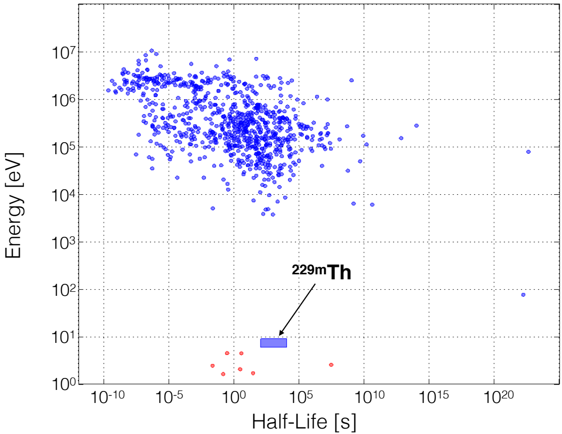
Expected advantages:

- nucleus is 5 orders of magnitudes smaller than the atom
  → highly resistant to external influences
- solid state clock feasible? [4]
  → 10^{19} atoms in crystal lattice *vs.* 10^{4} in an optical lattice

[2] E. Peik & C. Tamm, Europhys. Lett. 61 (2003) 181. [3] C. Campbell et al., Phys. Rev. Lett. 108 (2012) 120802. [4] W.G. Rellergert et al., Phys. Rev. Lett. 104 (2010) 200802.

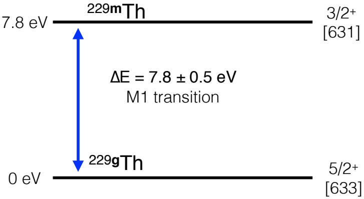
Requirements for a nuclear clock transition

- laser access
  - → transition energy in the eV range
- small linewidth
  - → lifetime in the range of at least some seconds



^{229}Th - What is known so far

- lowest excitation energy of all known nuclear states
  → E_I = 7.8 ± 0.5 eV (≈159 nm) [5]



[5] B. R. Beck et al., Proceedings of the 12th International Conference on Nuclear Reaction Mechanisms, Varenna, 2009, (CERN Proceedings Series, 2009). [6] E. V. Tkalya et al., Phys. Rev. C 92, 054324 (2015)

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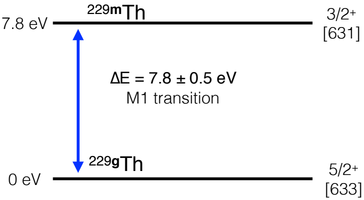
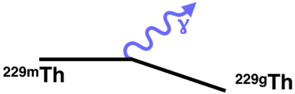
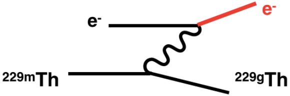


γ-decay



- emission of a photon
  → $E_\gamma = E_I$
- $\tau \approx 10^4$ s
  → $\Delta E/E \approx 10^{-20}$

internal conversion decay



- emission of an electron
  → $E_e = E_I - E_b$
- 0.6 μs < τ < 14 μs [6]
- only possible in neutral ^{229m}Th

[5] B. R. Beck et al., Proceedings of the 12th International Conference on Nuclear Reaction Mechanisms, Varenna, 2009, (CERN Proceedings Series, 2009). [6] E. V. Tkalya et al., Phys. Rev. C 92, 054324 (2015)

Why don't you simply build a nuclear clock?

- direct nuclear laser excitation has not been achieved so far
- lifetime is unknown
- transition energy is not known precisely

Experimental Objectives

- determine the lifetime
  - → for internal conversion (section 3)
  - → for γ-decay (outlook)
- improve the precision of the transition energy to better than 0.1 eV (ongoing)

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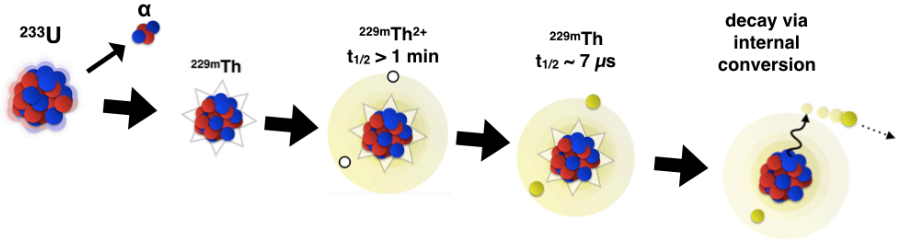
Experimental Principle



- populate ^{229m}Th via the 2% decay branch of the ^{233}U α-decay

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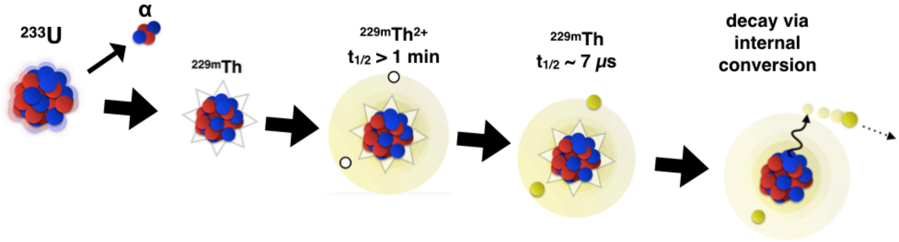

- populate ^{229m}Th via the 2% decay branch of the ^{233}U α-decay
- create a pure ^{229m}Th ion beam

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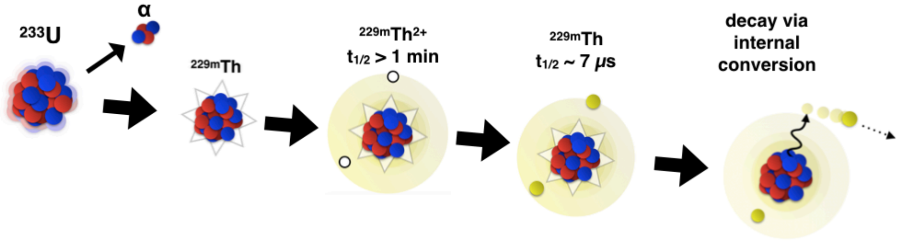

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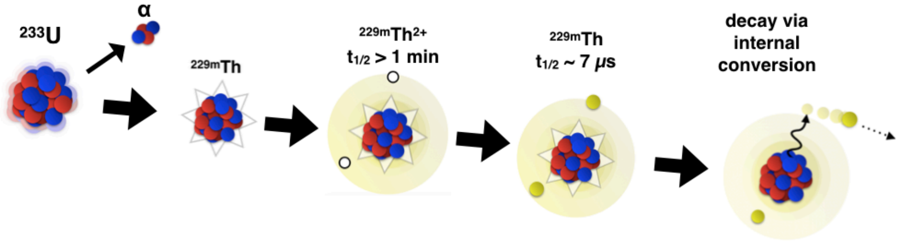
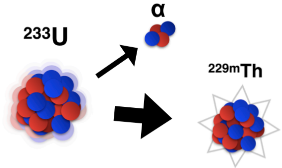
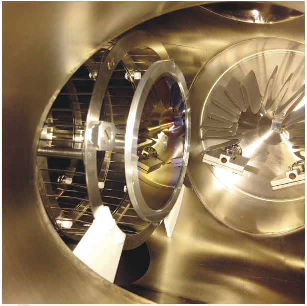


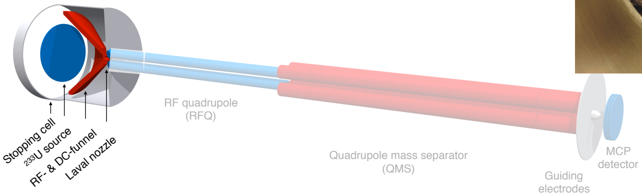
- populate ^{229m}Th via the 2% decay branch of the ^{233}U α-decay
- create a pure ^{229m}Th ion beam
- neutralize the ^{229m}Th ions
- detect the electron emitted during the internal conversion decay

^{233}U source and buffer gas stopping cell

- ^{233}U source (260 kBq)
  - → ^{229m}Th recoil ions (84 keV)
- buffer gas stopping cell (40 mbar He)
  - → ^{229}Th recoil ions are stopped
- electric RF- and DC-funnel guides ions towards a Laval Nozzle (Ø0.6 mm)
  - → supersonic gas jet created
  - → ions follow the jet into the next chamber







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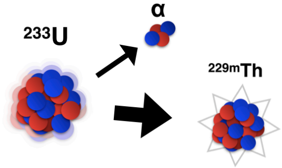
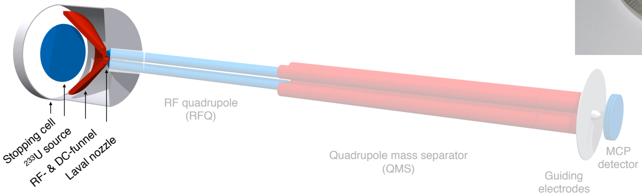
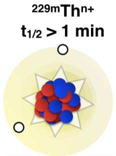
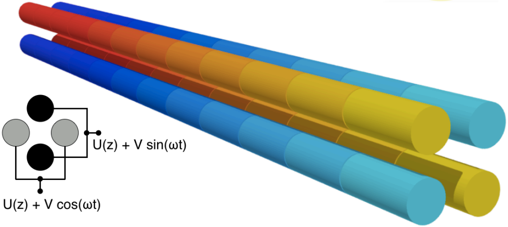


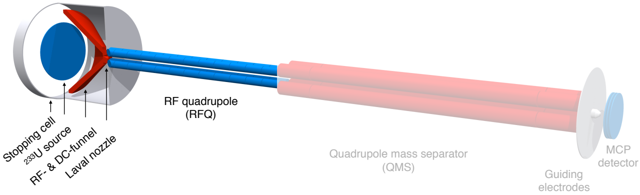


Radio Frequency Quadrupole (RFQ)

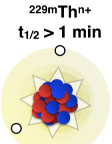


- segmented RF-quadrupoles
  - → f = 850 kHz
  - → $V_{pp} \approx 150$ V
- DC-gradient
  - → guide the ions through the remaining buffer gas
  - → cooled ion beam
  - → ion bunches



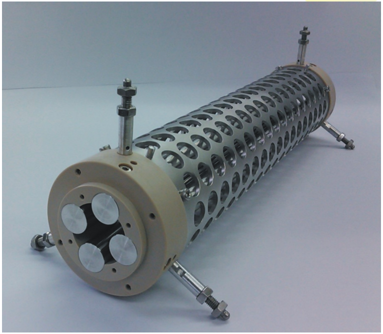


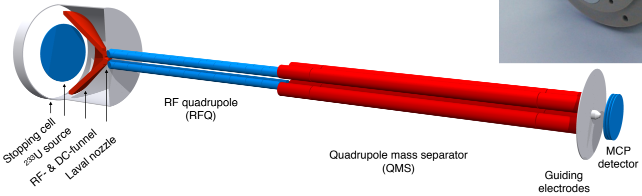
Quadrupole Mass Separator (QMS)



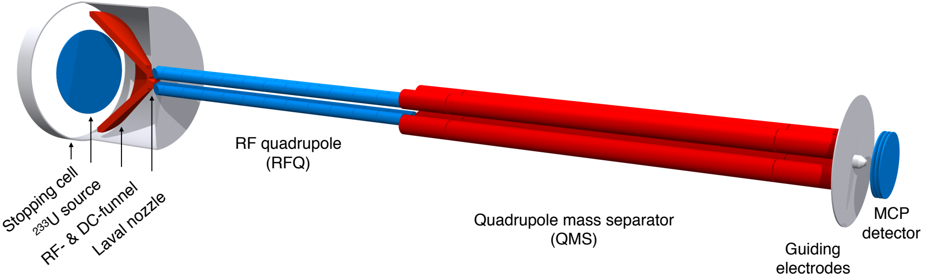
- ion beam contains ^{233}U daughter isotopes
- QMS purifies ion beam [7]
  → $m/\Delta m = 150$ @ 80% efficiency
- behind the QMS: electrostatic lens

[7] Design values taken from: E. Haettner et al., Nuclear Inst. and Methods in Physics Research, A 880 (2018) 138-151.





Experimental Setup - Overview



Pure ^{229m}Th ion beam/bunches:

continuous extraction mode:

- ≈10 000 ^{229}Th^{3+} ions per second
- ≈8 000 ^{229}Th^{2+} ions per second

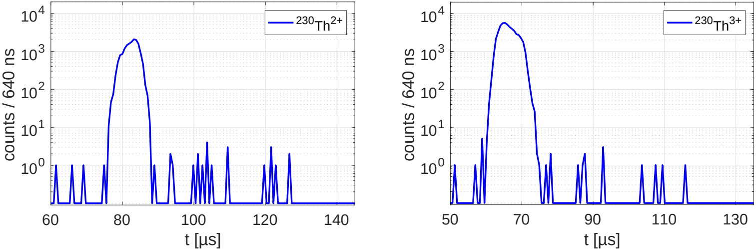
continuous extraction mode:
bunch mode:

- ≈400 ^{229}Th^{3+}/≈300 ^{229}Th^{2+} ions per bunch @ 10 Hz repetition rate
- ΔTOF$_{\text{FWHM}}$ $< 10\ \mu$s
  → high (peak) flux: $4{\times}10^7$ 1/s

Lifetime Measurements

Measurements with ^{230}Th:

- clear signal from ionic impact for $^{230}\text{Th}^{2+,3+}$



[8] B. Seiferle, L.v.d. Wense & P.G. Thirolf, PRL 118, 042501, (2017)

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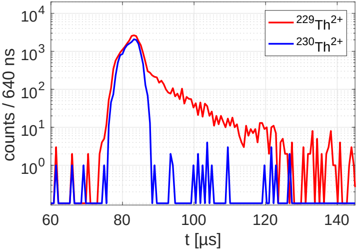

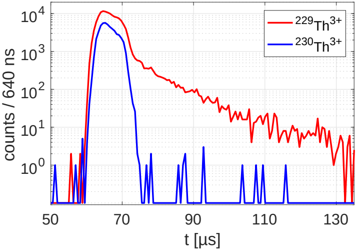

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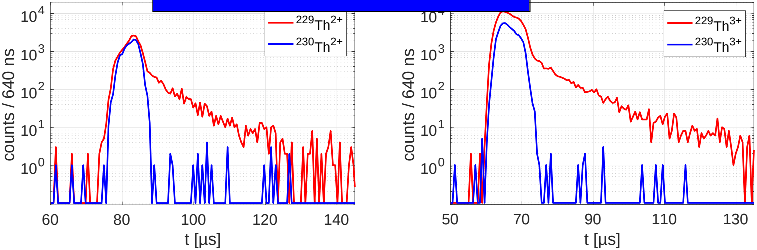
$$t_{1/2} = 7 \pm 1\ \mu\mathrm{s}$$



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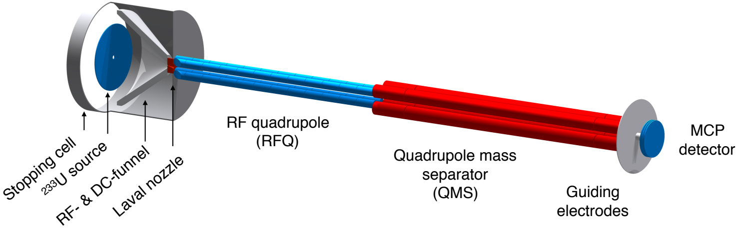
Experimental Setup - Overview

measure the kinetic energy of the IC electrons!

- replace MCP detector with metallic surface in an electron spectrometer



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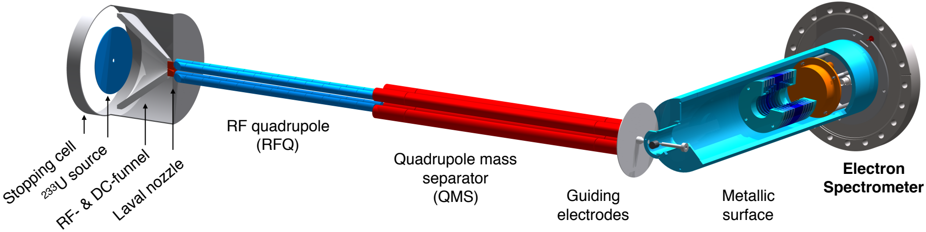

IC Electron Spectroscopy

$$E_I = E_e + E_B$$

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Neutralization on a surface

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Surface cleanliness

- monolayer formation time @ 10^{-8} mbar: $\approx$ 300 s
- cleanliness affects the surface properties
  - → work function reduction
  - → binding energies of e^- ($\approx$ eV)

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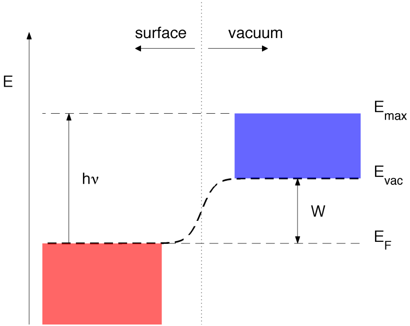
We need surface-independent measurement principle!

From Photoelectron Spectroscopy to IC Electron Spectroscopy

Monochromatic light source $h\nu$ + metallic surface:

- electron binding energies are broadly distributed
- zero binding energy: fermi-edge
  - → electron from fermi edge have maximum kinetic energy E_{max}



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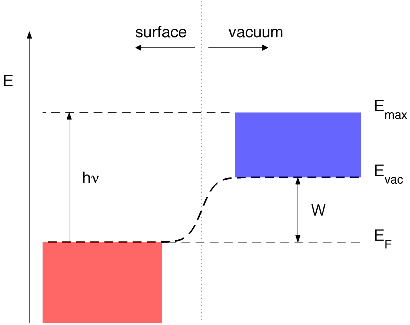


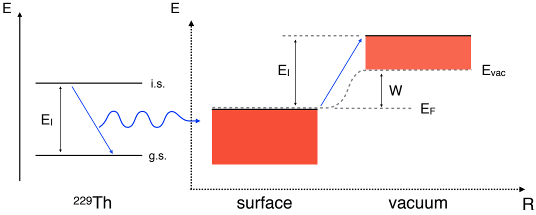
Measure kinetic energy with spectrometer:

- apply offset voltage to sample U
- spectrometer work-function W_S
  - → $E_{\text{max}} = h\nu - W_S - U$
  - → independent from sample work-function

$$\boxed{h\nu = E_{\text{max}} + U + W_S}$$

From Photoelectron Spectroscopy to IC Electron Spectroscopy

- collect $^{229\text{m}}$Th on a metal surface
- electrons are delocalized
  - → replace $h\nu$ with E_I



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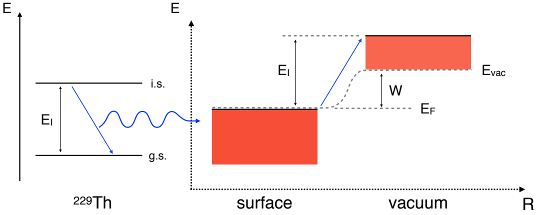
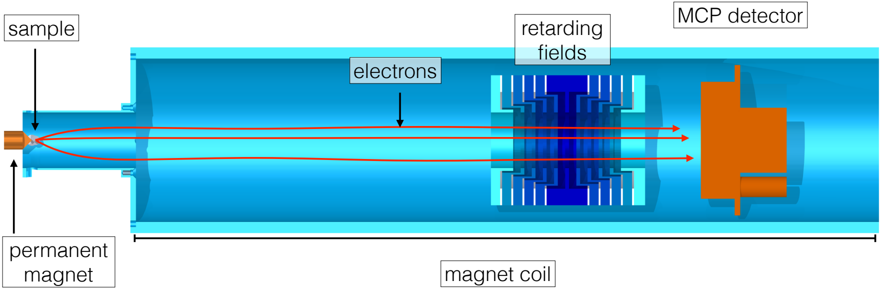


$$E_I = \underbrace{E_{\text{max}}}_{\text{measured with isomer}} + \underbrace{\boxed{U + W_S}}_{\text{calibration measurements}}$$

measured with isomer

calibration measurements

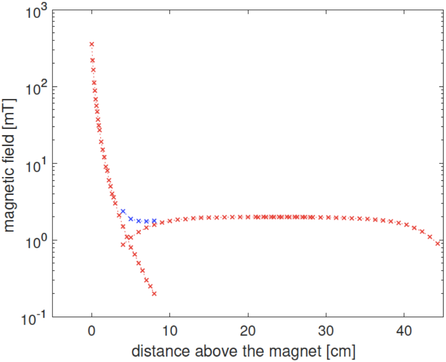
Magnetic Bottle Spectrometer [9]

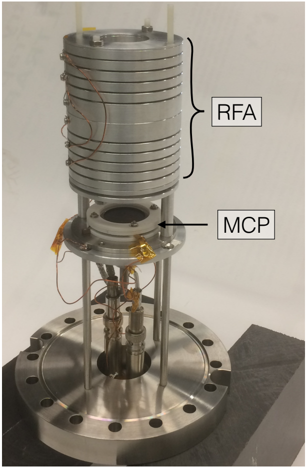


- (IC) electrons are emitted from a metallic sample
- strong permanent magnet → strongly inhomogeneous magnetic field
- magnetic coil → weak homogenous magnetic field
  - → electrons are collected and guided towards weak magnetic field
  - → collimated electron beam
- retarding field analyzer
  - → electrons with energy larger than some blocking voltage reach detector

[9] Y. Yamakita et al., Review of Scientific Instruments 71, 3042 (2000).

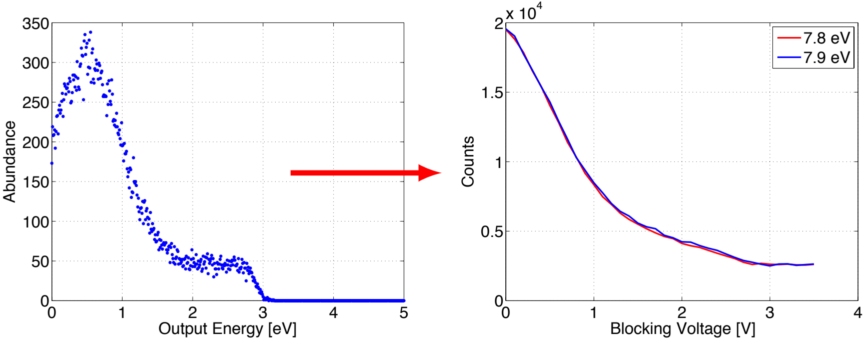
Magnetic Bottle Spectrometer [9]





What kind of spectra do we expect?

- integrated spectrum
- how to obtain E_{max}?
  - → fit indefinite integral of the Fermi function to high-energy part of the spectrum



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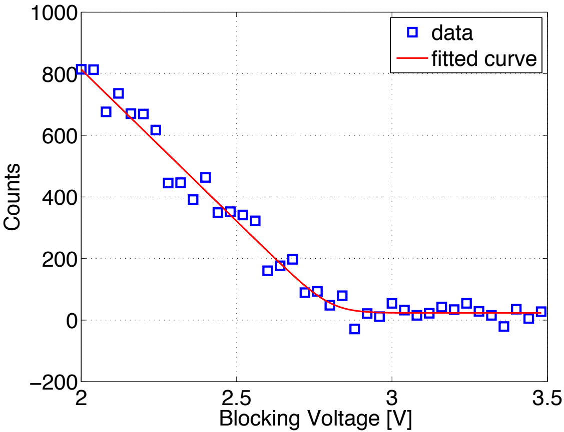
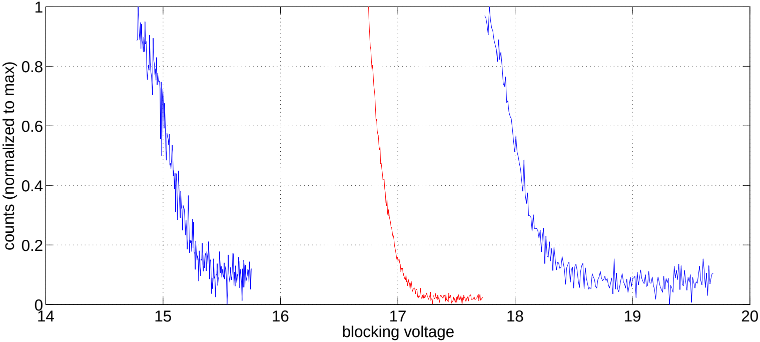


Calibration Measurements

- $\boxed{h\nu = E_{\text{max}} + U + W_S}$
- calibration: measure $U + W_S$ (@ U= -15 V)
- spectrometer is calibrated with three lines
  - → $h\nu = 4.888$ eV (Hg discharge 254 nm)
  - → $h\nu = 6.705$ eV (Hg discharge 185 nm)
  - → $h\nu = 7.897$ eV (F_2 excimer laser 157 nm)



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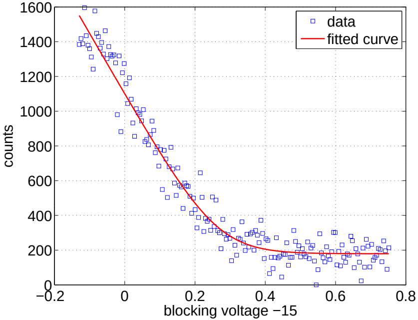

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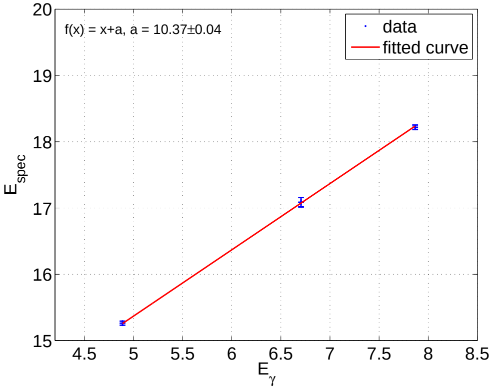

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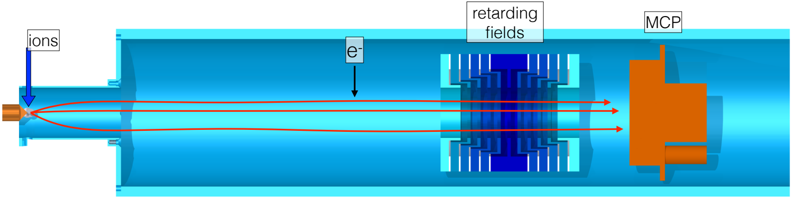
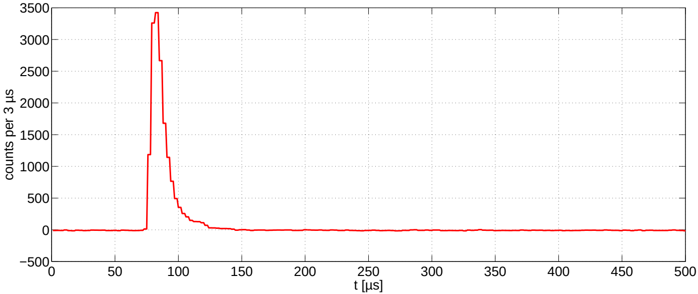
- for the following measurements
  - → $U + W_S = -10.59 \pm 0.05$ eV

IC Electron Measurements



- collect bunched $^{229\mathrm{m}}\mathrm{Th}^{2+}$ ion beam on a platinum surface (set to -15 V)
- -15 V blocking voltage
- clear (decay) signal
  $\rightarrow E_I > 4.4$ eV

IC Electron Measurements

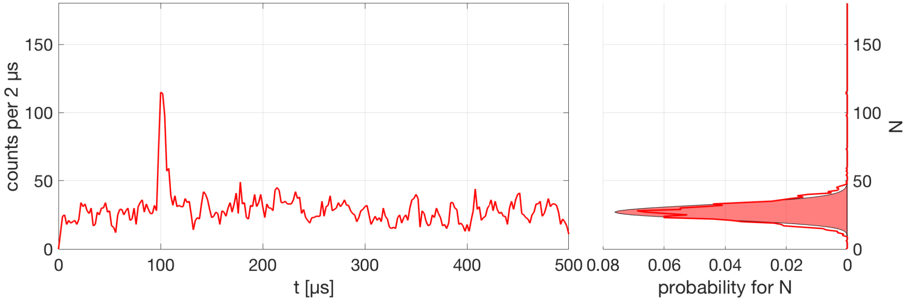


- collect bunched $^{229\mathrm{m}}$Th^{2+} ion beam on a platinum surface (set to -15 V)
- -15 V blocking voltage
- clear (decay) signal

  → $E_I > 4.4$ eV

IC Electron Measurements

- 19.0 V blocking voltage correspond to 8.41 ± 0.05 eV
- clear signal above Poisson distributed noise



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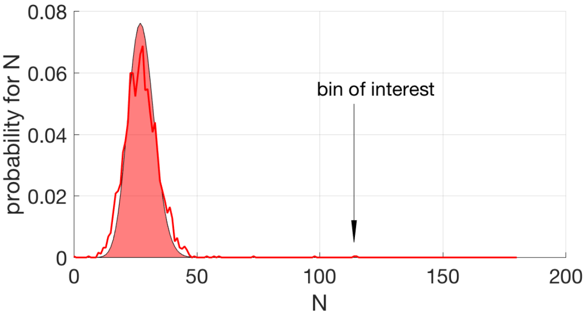

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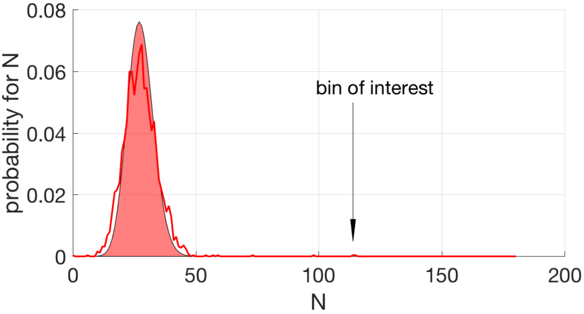
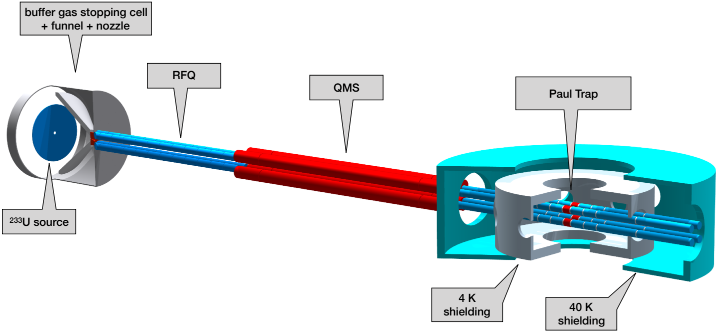


Outline

1. Motivation
2. Experimental Setup
3. Lifetime Measurements
4. Energy Measurements
5. Conclusion & Outlook

Outlook



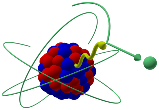
Lifetime Measurement of the γ decay channel (... and someday Th nuclear laser spectroscopy)

- requires long storage times (without any direct manipulation)
  - → Cryogenic Paul Trap (CryPTEx design, MPIK Heidelberg [10])
- Sympathetic laser cooling with Sr^{+}

[10] L. Schmöger et al., Science 347, 1233-1236 (2015).

Conclusion

- ^{229}Th is a special nucleus
  - → lowest energy of all known nuclear levels
  - → nuclear optical clock
- lifetime measurement of the internal conversion decay channel
  - → $t_{1/2} = 7\ \mu$s
  - → how strong is the surface-dependence?
- energy measurement of IC electrons ongoing



Thank you for your attention!

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Deutsche Forschungsgemeinschaft

European Commission

Horizon 2020
European Union funding
for Research & Innovation