Towards an all-optical access to the lowest nuclear excitation in ^{229}Th

Lars v.d.Wense

LMU München/ Max-Planck-Institut für Quantenoptik

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- Detection

Summary

Introduction

Motivation: Generally known

Aim: Direct detection of isomeric transition

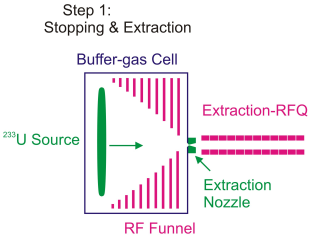
Improvement of precision of transition wavelength to better than 1 nm

Concept: Spatially decoupled population and deexcitation of isomeric state via 5 steps:

1. Buffer-gas cell with isomer extraction
2. Mass separation
3. Collection
4. UV fluorescence focusing
5. Detection

Setup Overview

Stopping and Extraction: Buffer-gas Cell

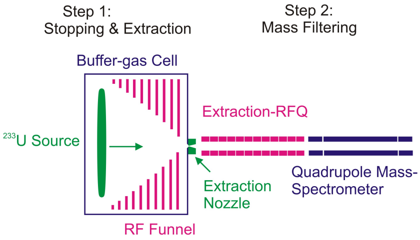


Step 1: Stopping and Extraction of ^{229}Th-Recoils

- ^{229}Th α-Recoils from ^{233}U are stopped in He buffer gas
- guided via RF-funnel to exit nozzle
- dragged out through (supersonic) Laval-nozzle together with He gas
- guided and phase-space-cooled by radio frequency quadrupole (RFQ)

Setup Overview

Mass-Filtering

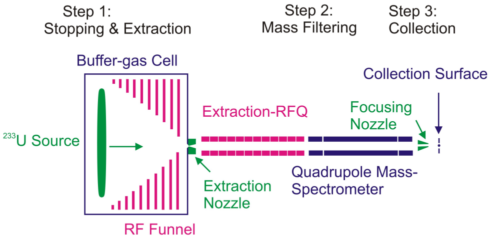


Step 2: Mass-Filtering of ^{229}Th^{2+}-ions

- High mass-resolved purification of ^{229}Th^{2+}-ions using QMS
- Suppression of other ^{233}U decay-chain products
- reduction of background
- unambiguous signal origin from ^{229}Th

Setup Overview

Collection

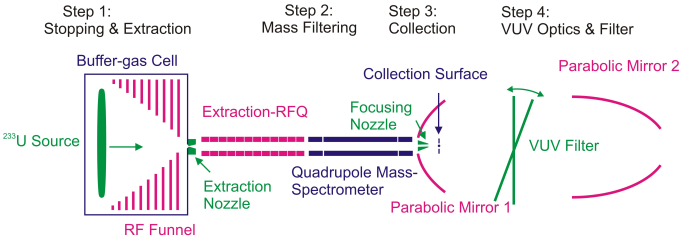


Step 3: Collection of $^{229}Th^{2+}$-ions

- Guiding and focusing with nozzle-like electrode system
- Collection on 50 μm diameter micro electrode
- small diameter for highly efficient photon optics
- coating to minimize non-radiative decay

Setup Overview

VUV-Optics and Energy Determination

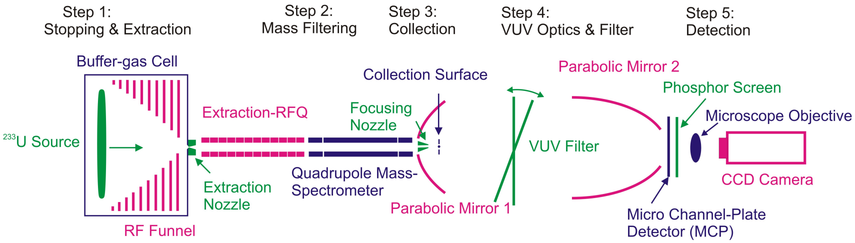


Step 4: VUV-Optics and Energy Determination of Isomeric Decay

- Isomeric decay on micro-electrode
- parallelization of decay photons using parabolic mirror 1
- Filter with sharp absorption edge for transition wavelength determination
- focusing of signal onto detector using second parabolic mirror

Setup Overview

Detection

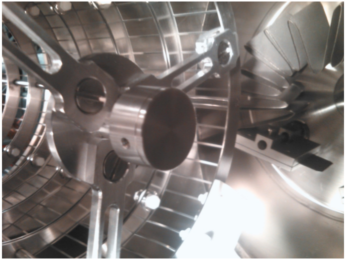


Step 5: Detection

- MCP used for position-sensitive single-photon detection
- Photons are converted to electron signals
- Phosphor screen to visualize electron signals
- CCD camera to monitor screen

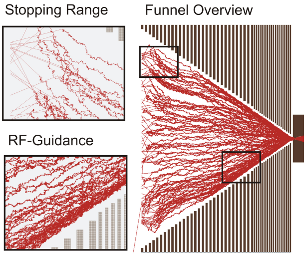
^{233}U-Source

- Presently: U_3O_8 evaporated on stainless steel backing
- effective ^{229}Th-recoil yield investigated by detailed numerical simulations
- Currently 5000 recoils per second (20 mm source diameter)
- Extension to 90 mm diameter electroplated source envisaged, leading to 80,000 recoils per second
- Source thickness: 13 nm
- 260 kBq ^{233}U source needed (license available)



Buffer-gas Stopping Cell

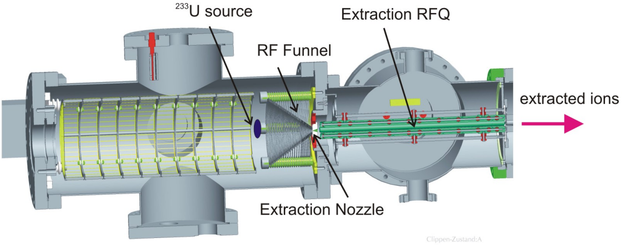
- Chamber: UHV standards, bakeable up to 180 °C
- catalytic purified He 6.0, electropolished gas tubing, cryotrap in gas line
- 2% population branch, 100 isomers/s enter stopping volume (later 1600/s)
- Recoils are stopped in 40 mbar ultra-pure He (∼ 10 mm stopping range)
- Ions are guided efficiently by RF-funnel (50 ring electrodes)
- DC gradient guides ions to nozzle-exit
- Extraction time is 1-2 ms. Prompt decays already in stopping cell



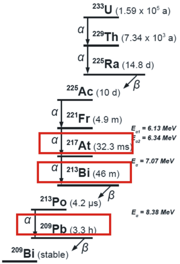
J. Neumayr et al.: Rev. Sci. Instr. 77 (2006) 065109

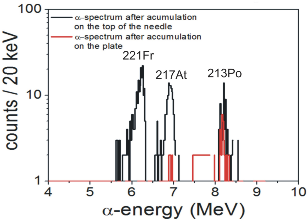
Nozzle and Extraction-RFQ

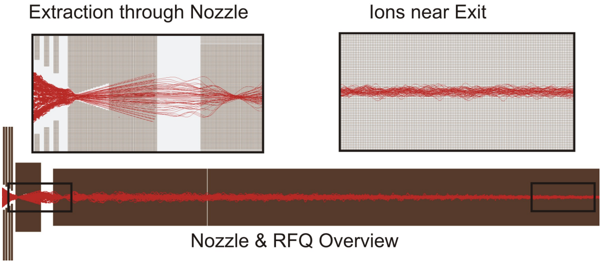
- Ion extraction together with He gas through 0.6 mm nozzle exit
- Laval nozzle designed for supersonic extraction into 10^{-2} to 10^{-3} mbar
- Ions caught by radio-frequency quadrupole (extraction-RFQ)
- Neutral He gas is removed by strong turbo molecular-pump
- Ambient gas pressure exploited for phase-space cooling of ions
- 48% total extraction efficiency measured from ^{223}Ra recoil source
- 10% extraction efficiency assumed for Thorium due to high reactivity
- about 10 isomers/s are extracted (later 160/s)



Simulation and preparatory measurement

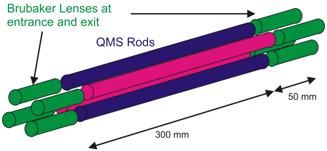




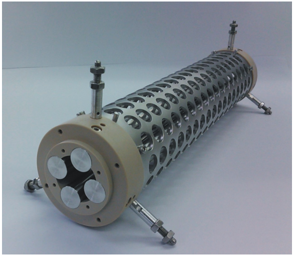


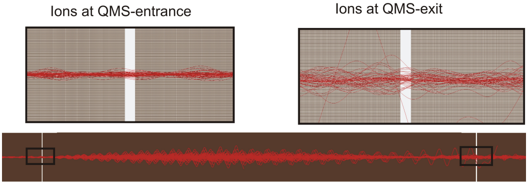
- Besides ^{229}Th also other isotopes of ^{233}U decay chain extracted
- Suppression of accompanying α-decay products required

Quadrupole Mass Spectrometer



- New QMS currently tested
- Improved design values* and high mechanical precision
- Active stabilization of RF amplitudes (10^{-3} precision)
- Efficiency at mass resolution $\frac{m}{\Delta m} \approx 160$: 80%
- Only one q/m-value: 70% in 2^+



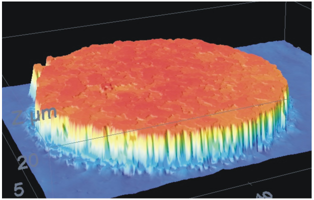


QMS overview

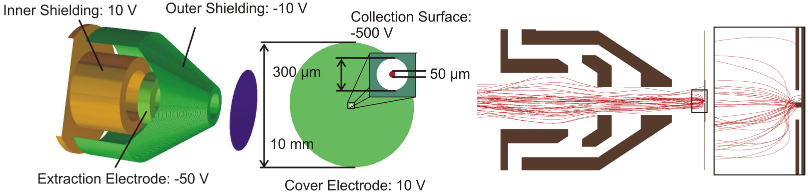
*E. Haettner: PhD thesis, Univ. Giessen (2011)

Ion Focusing and Collection

- Focusing of ions using specially designed electrodes
- Collection on $50\mu m$ diameter micro-electrode
- Electrode surface coated with MgF_2 to avoid quenching
- Total focusing and collection efficiency: $\sim 40\%$
- isomeric decay on collection surface expected
- number of expected decay photons in 4π: $10 \cdot 0.7 \cdot 0.8 \cdot 0.4 \approx 2.2$ per second (later 35/s)

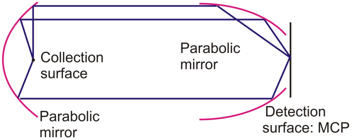


Microscopic image of collection surface



VUV-Optics

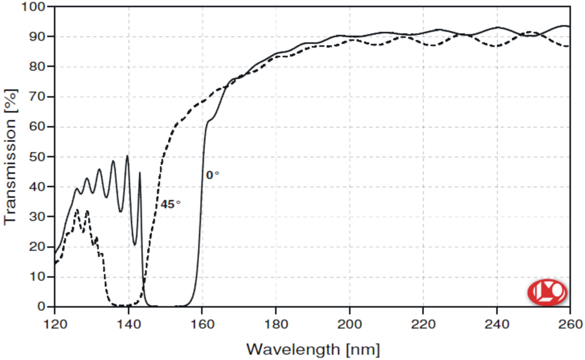
- Optical setup has been optimized using numerical 3D ray-tracing
- Best results for two parabolic VUV mirrors:
  - Entrance mirror for high numerical aperture, parabolic shape to avoid spherical aberration
  - Exit mirror to avoid intensity losses and changes in focal length due to uncertain wavelength
- 40 mm open aperture and 12 mm hole leading to 42% acceptance
- Each parabolic mirror has a reflectivity of about 70%
- Optical efficiency is about 20%



- For detailed discussion of alternative optics scenarios: see poster

Energy Determination

- Parallel light allows for spectral analysis using VUV absorption filters
- Filters with sharp absorption edge (∼1 nm) available in VUV region
- Filters can be rotated to change the absorption wavelength
- Suitable to measure wavelength to better than 1 nm accuracy



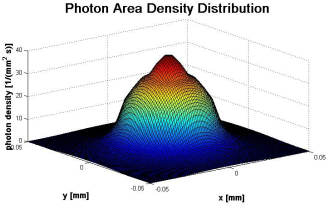
Detection

- Micro-Channel-Plate detector for VUV detection (CsI-coated)
- Phosphor screen to visualize electrons
- Expected (typical) quantum efficiency: $\sim$16%
- leading to possibility to detect $2.2 \cdot 0.2 \cdot 0.16 \approx 0.07$ photons per second
- But: Due to source extension not all photons within 10% of peak maximum
- Monitoring with CCD camera

Results of numerical simulation:

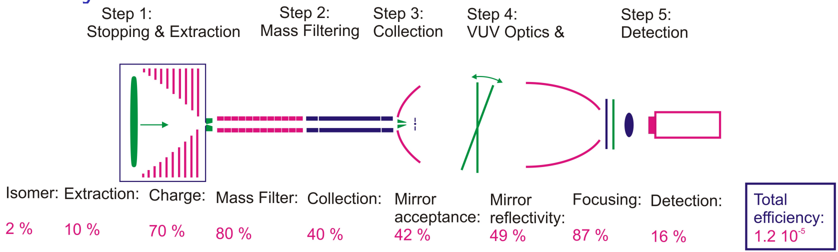
(Values at 10% of peak maximum)

Spot size (diameter)	70 μm
Photons in spot	87%
Expected count rate	0.06 s^{-1}
Image intensity	18 $s^{-1}mm^{-2}$
Signal contrast*	360



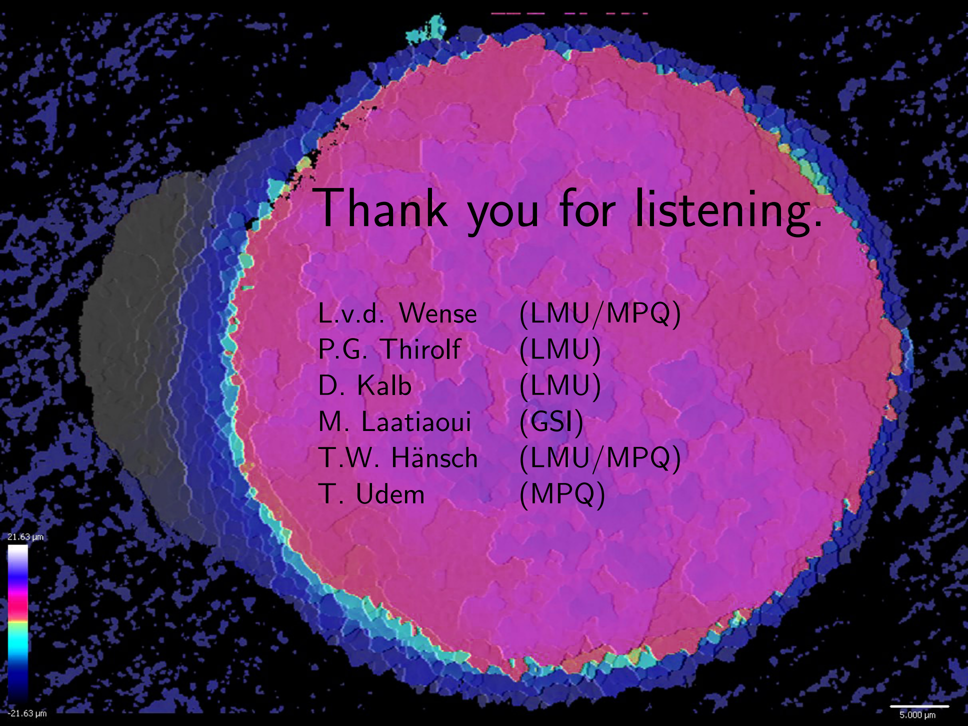
* Dark count of MCP: 0.05 $s^{-1}mm^{-2}$ typical value

Summary



- Current source intensity: 5000 Th/s $\rightarrow$ 0.06 counts/s
- 70 μm spot size $\rightarrow$ signal to background of 360:1
- increase to 80,000 Th/s possible $\rightarrow$ 1 count/s
- no significant change in spot size $\rightarrow$ signal to background of 5600:1

$\Rightarrow$ High probability for direct detection of ^{229m}Th and improved accuracy of transition wavelength



Thank you for listening.

L.v.d. Wense	(LMU/MPQ)
P.G. Thirolf	(LMU)
D. Kalb	(LMU)
M. Laatiaoui	(GSI)
T.W. Hänsch	(LMU/MPQ)
T. Udem	(MPQ)