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Studies of radioactive ion beams at IGISOL via decay spectroscopy and laser spectroscopy techniques

A. Raggio, I.D. Moore and IGISOL group

Accelerator Laboratory, Department of Physics, University of Jyväskylä, FIN-40014 Jyväskylä, Finland

Back to 2019


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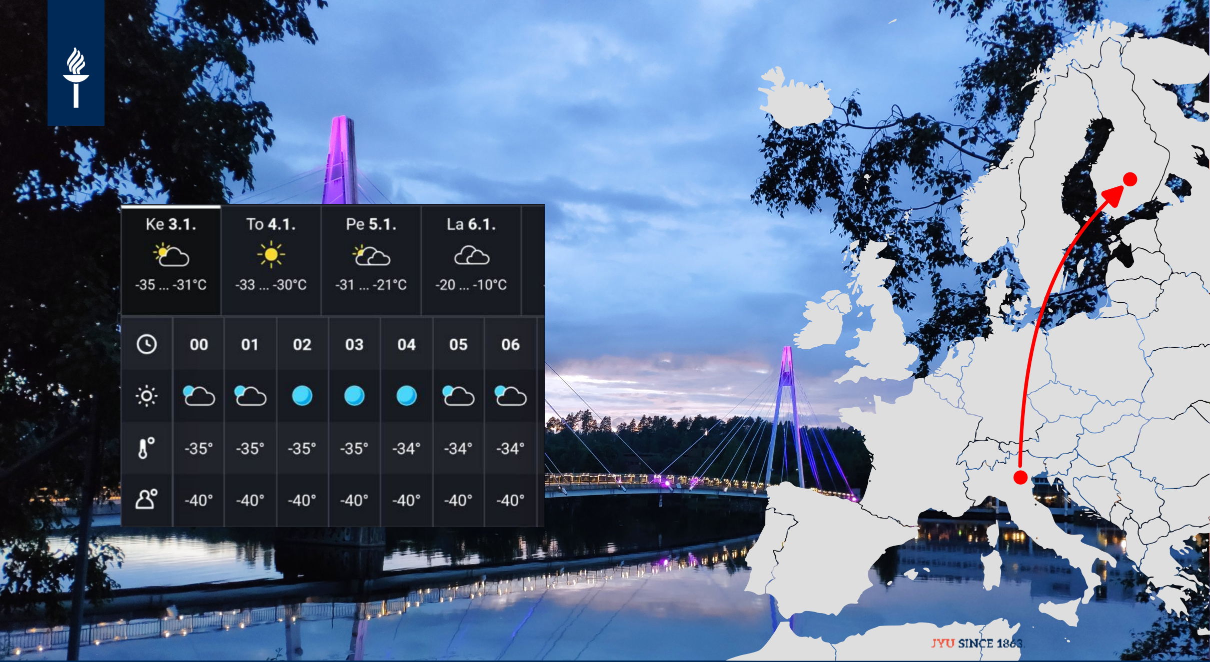
Ke 3.1.
-35 ... -31°C
To 4.1.
-33 ... -30°C
Pe 5.1.
-31 ... -21°C
La 6.1.
-20 ... -10°C
00 01 02 03 04 05 06
-35° -35° -35° -35° -34° -34° -34°
-40° -40° -40° -40° -40° -40° -40°
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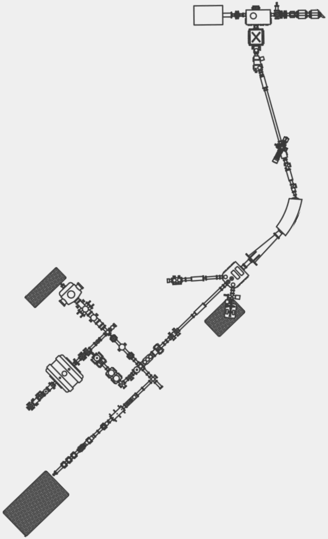
Content

Introduction

- JYFL-Acclab
- IGISOL and the ion-guide technique
- Optical spectroscopy for nuclear physics
- A focus on actinide elements



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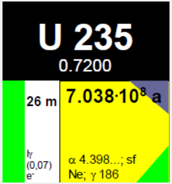
- Isomeric beam development



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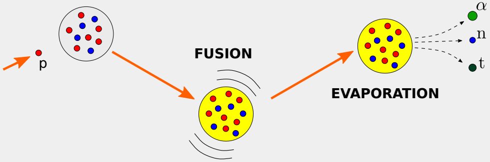
Towards neutron-deficient actinides

- Fusion-evaporation reactions on long-lived actinide targets
- Decay spectroscopy



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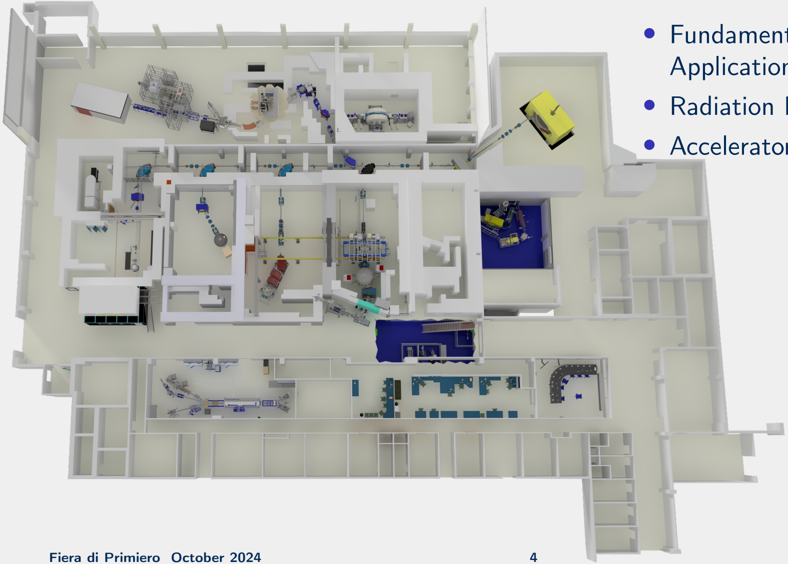
Introduction

JYFL

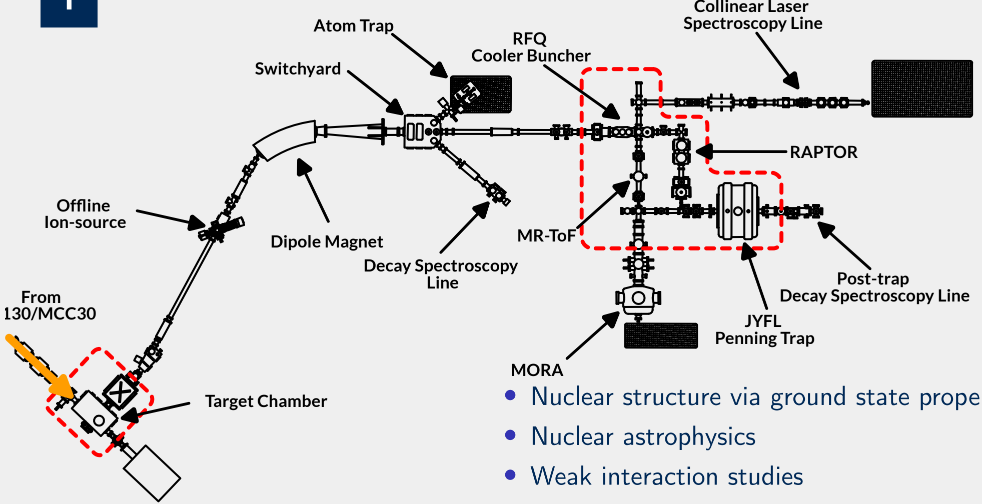
JYFL-Acclab



- Fundamental Nuclear Science and Applications
- Radiation Effects in Electronics
- Accelerator-Based Materials Science

K130
6000-7500 h/year
3 ECR ion sources
1 LIISA source

IGISOL



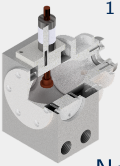
- Nuclear structure via ground state properties
- Nuclear astrophysics
- Weak interaction studies
- Fission studies

Ion-guide technique

The IGISOL toolbox

A versatile set of ion guides to cover a wide range of applications and reaction mechanisms, both off-line and on-line

- Fast extraction time (as fast as 1 ms in LIG!)
- Ideal for refractory elements



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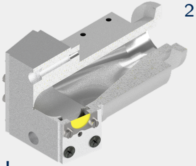

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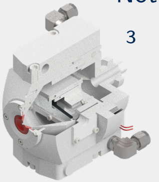
Not in scale!



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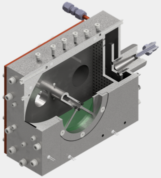

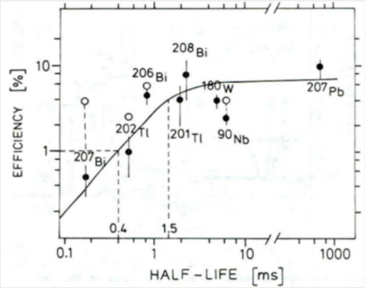

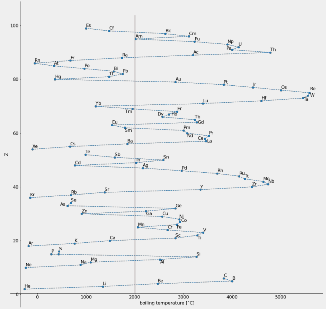

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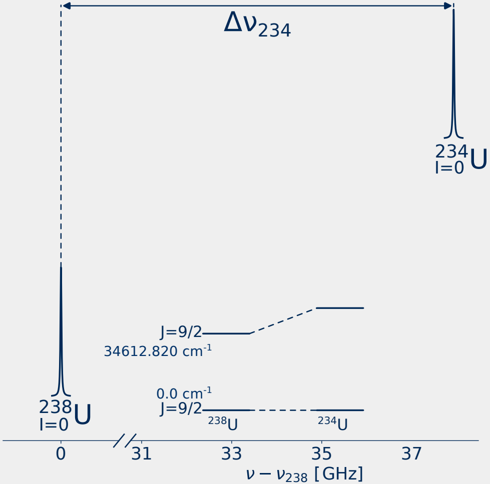
[1] I. Pohjalainen, I.M. et al., NIMB 376 (2016) 23
[2] J. Ärje, J. Äystö et al., PRL 54 (1985) 99
[3] J. Äystö et al., NIMB 26.1-3 (1987): 394-398.
[4] Mia A. Zenodo. https://doi.org/10.5281/zenodo.6675038

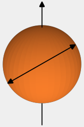
Optical spectroscopy for nuclear physics



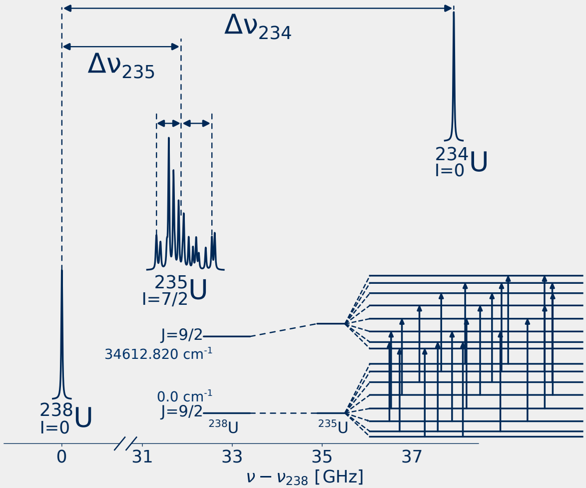
Isotope Shift

Nucleus finite size and mass

$$\delta\nu_{IS}^{AA'} = K_{MS}\frac{M_{A'} - M_A}{(M_A + m_e)(M_{A'} + m_e)} + F\delta\left\langle r_c^2\right\rangle^{AA'}$$



Optical spectroscopy for nuclear physics



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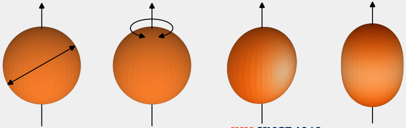
Hyperfine Structure

Access to nuclear moments:

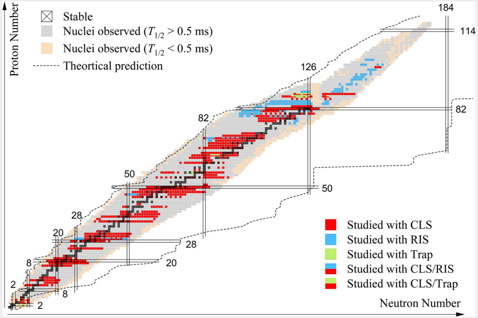
$$\Delta E_{hfs} = A\frac{K}{2} + B\frac{3K(K+1) - J(J+1)I(I+1)}{8I(2I-1)J(2J-1)}$$

$$A = \frac{\mu B_e(0)}{IJ}, \quad B = eQ_s\left\langle\frac{\partial^2 V}{\partial z^2}\right\rangle$$



Optical Spectroscopy for nuclear physics

A powerful tool to extract fundamental
nuclear ground-state (and isomeric) properties

5 

[5] X. F. Yang, et al. PPNP (2022): 104005.

Optical Spectroscopy for nuclear physics

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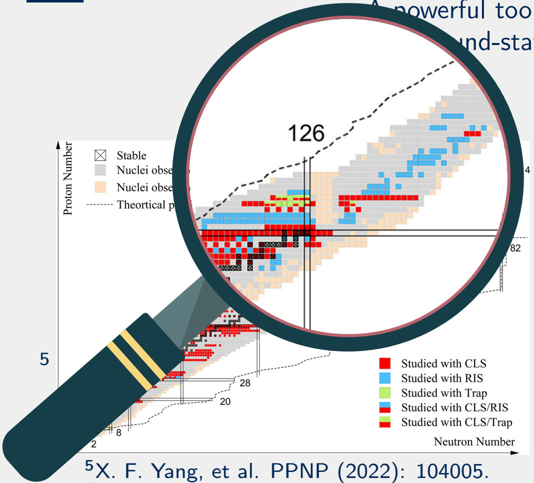

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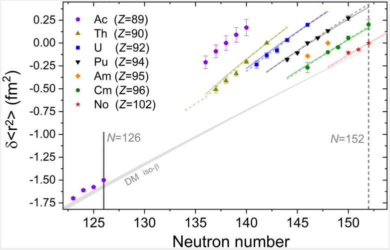
General lack of optical data

- Lack of Stable isotopes
- Challenging Production



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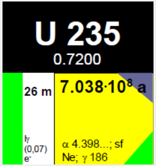
[5] X. F. Yang, et al. PPNP (2022): 104005.
[6] M. Block et al., PPNP, 116 (2021), 103834

^{235m}U isomeric state

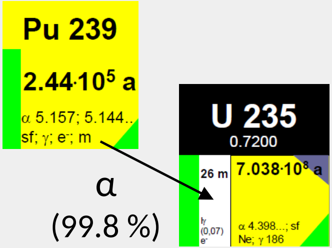


Second lowest isomeric state in the nuclide landscape

- 76 eV [7]
- ~26 minutes half life

[7] F. Ponce, et. al. PRC, 97.5 (2018): 054310.

^{235m}U isomeric state



Second lowest isomeric state in the nuclide landscape

- 76 eV [7]
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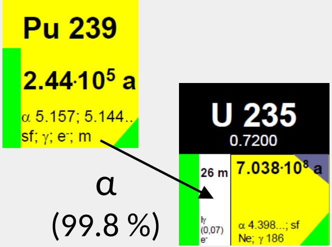
^{235m}U isomeric state



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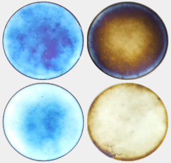
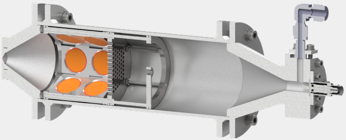
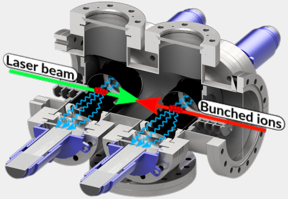
Alpha recoil sources



Gas-cell development



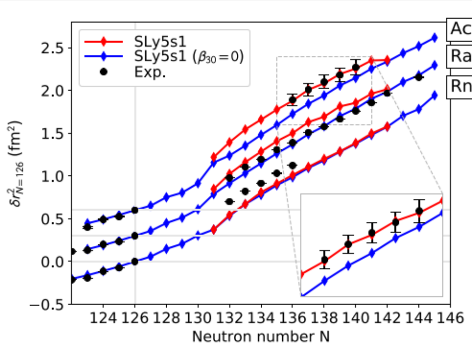
Collinear Laser Spectroscopy



[7]F. Ponce, et. al. PRC, 97.5 (2018): 054310.

Octupole deformation and charge radii

$$\langle r^2 \rangle = \langle r^2 \rangle_{sph} \left(1 + \frac{5}{4\pi}\left(\langle \beta_2^2 \rangle + \langle \beta_3^2 \rangle + \ldots\right)\right)$$



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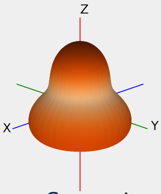

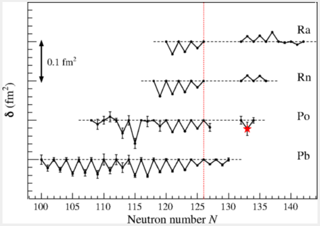

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- Comparison with EDF predictions.
- Need to extend to heavier actinide experimental data
- Correlation between odd-even staggering reversal and octupole deformation?
- **Production of n-deficient actinide beams at IGISOL?**

[8]E. Verstraelen et al.PRC 100, no. 4 (2019): 044321
[9]D. Fink et al., PRX 5 (2015) 011018

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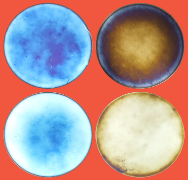
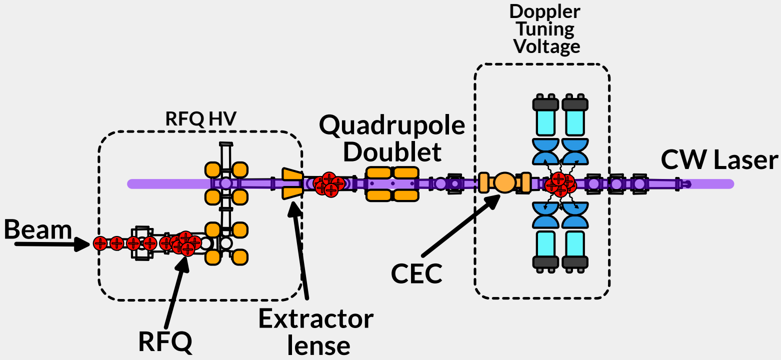
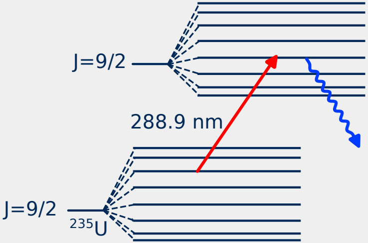
Production and study of ^{235m}U



Collinear laser spectroscopy



Detection of fluorescence
de-excitation of atom/ions
electronic states



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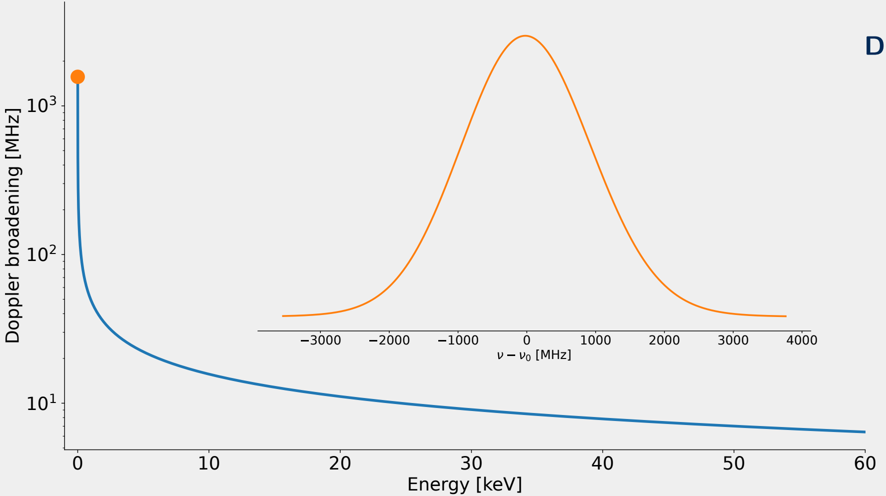
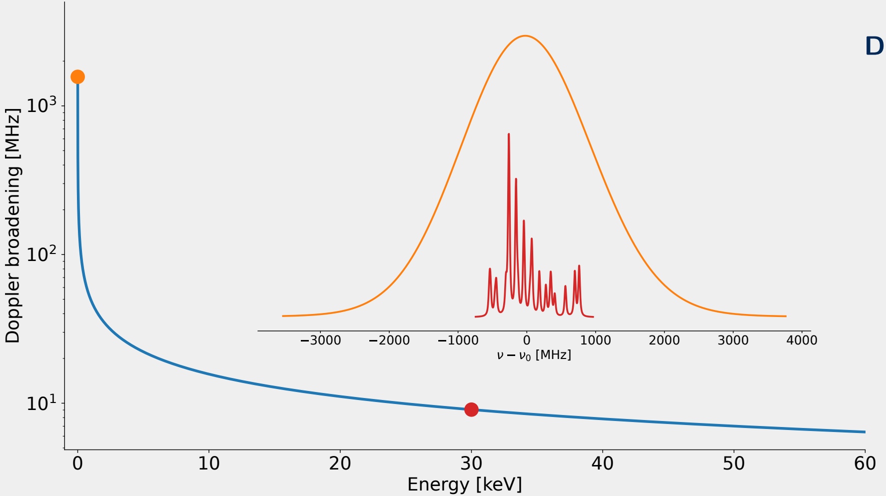


Doppler compression

$$\delta\nu = \nu_0 \frac{\delta E}{\sqrt{2Emc^2}}$$

RFQ $\delta E \sim 1$ eV

Collinear laser spectroscopy



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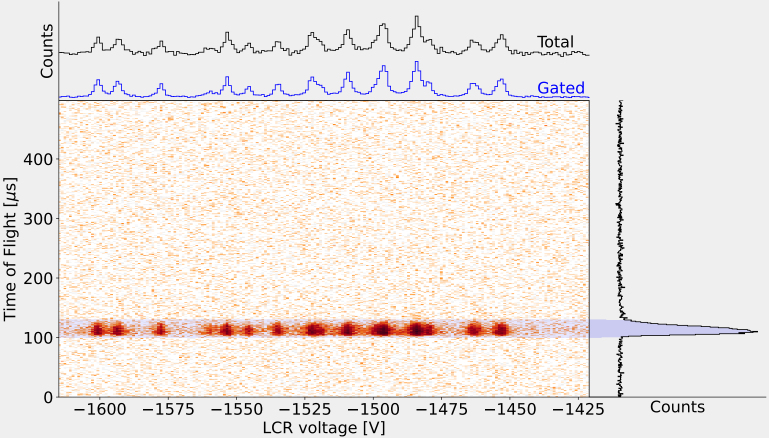
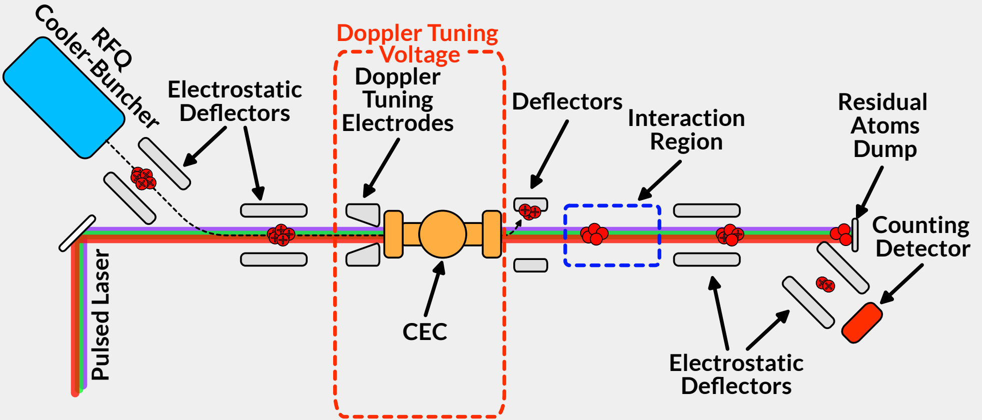


Bunched beam spectroscopy

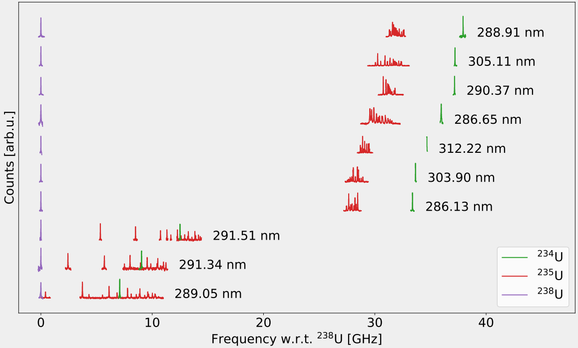
- Typical bunch width with endplate bunching $\sim 5\mu s$
- $\sim 10^4$ background reduction with respect to continous beam (for typical 100 ms cycle) [10]

[10] A. Nieminen, et al. PRL 88.9 (2002): 094801.

Collinear Resonance Ionization Spectroscopy

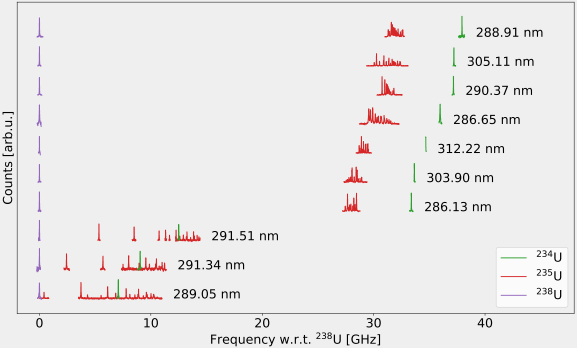


CLS of $^{nat}U^{1+}$



- ^{234}U 0.0054%, ^{235}U 0.7204%, ^{238}U 99.2742%
- Offline study of ionic transition in the UV range 288-314 nm

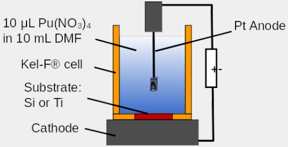
CLS of $^{nat}U^{1+}$



- ^{234}U 0.0054%, ^{235}U 0.7204%, ^{238}U 99.2742%
- Offline study of ionic transition in the UV range 288-314 nm
- HFS parameters for ^{235}U and isotopic shift for each studied level
- Optimum transition had a spectroscopy efficiency of $\sim$ 1/3000 photons/ion
- Performed with the original LCR (single segmented PMT)

Alpha recoil sources

Voltage: ~ 100 V (Constant current)
Deposition time: 75 mins



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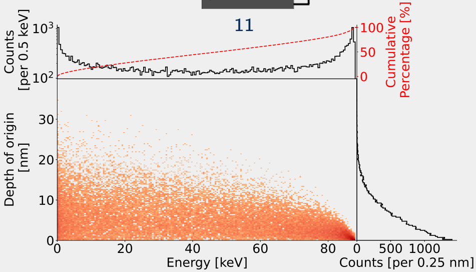
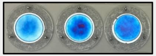
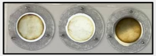
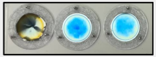




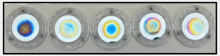
^{239}Pu
Substrate: Si
Thickness: 16 ug/cm^2
Activity: ~135 kBq



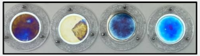
^{239}Pu
Substrate: 2x Si, 1x Ti
Thickness: 7 ug/cm^2
Activity: ~57 kBq



^{239}Pu
Substrate: 2x Si, 1x Ti
Thickness: 23 ug/cm^2
Activity: ~200 kBq



^{239}Pu
Substrate: Si
Thickness: 16-26 ug/cm^2
Activity: 3x ~75 kBq, 2x ~12 kBq



^{239}Pu
Substrate: 3x Si, 1x Ti
Thickness: 9-23 ug/cm^2
Activity: 75-200 kBq
Oven dried at 200C 1.5h

^{240}Pu
Substrate: 2x Si, 1x Ti
Thickness: 6-12 ug/cm^2
Activity: 200-400 kBq

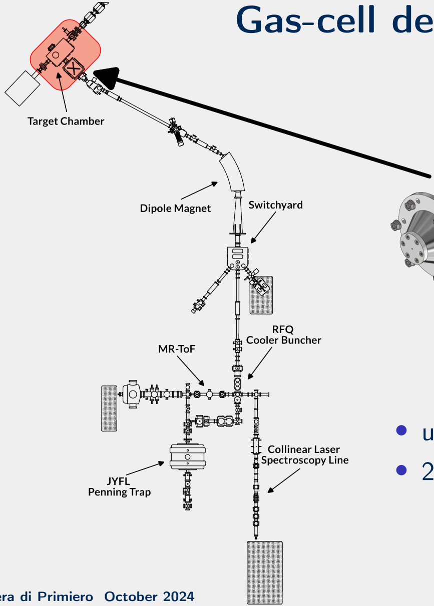
15 molecular plated ^{239}Pu sources created in collaboration with Mainz radiochemistry department

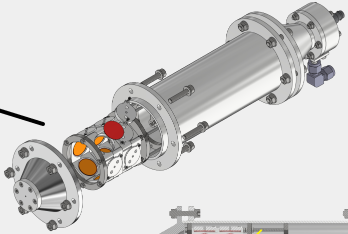
Characterization tests:

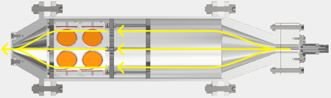
- SEM and radiographic imaging
- Alpha/gamma spectrometry
- Rutherford back-scattering

[11] A. Vascon et al., NIMA 721 (2013): 35

Gas-cell development



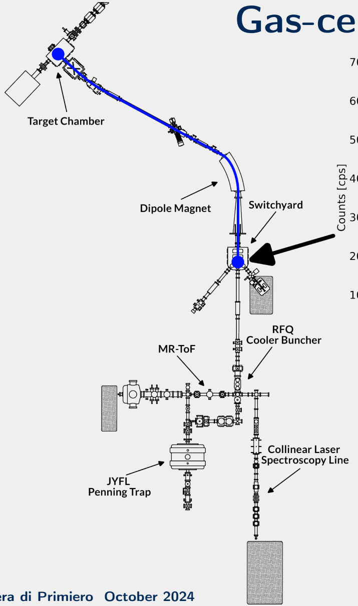


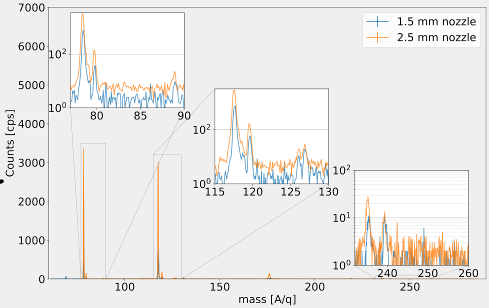


Mk. III - Large recoil gas-cell

- up to 12 ^{239}Pu sources
- 2.5 mm nozzle and 55 mbar He

Gas-cell development

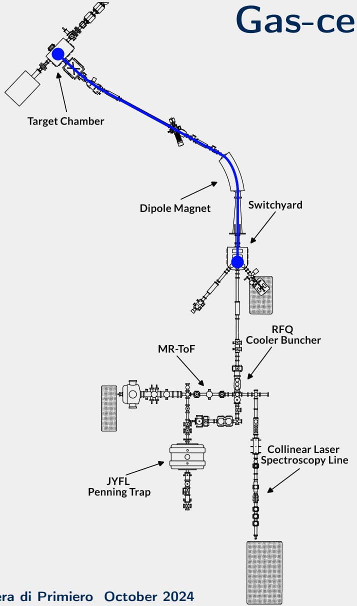


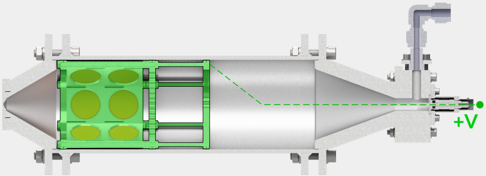


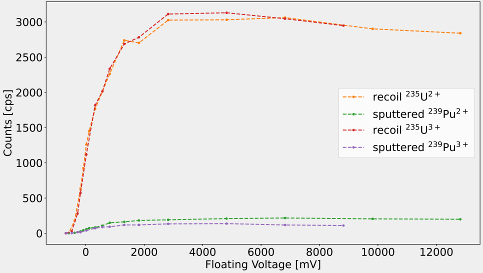
Yields

- ~3000 cps for both 3+ and 2+ charge states
- Minimized molecular formation
- Very little $^{235m}U^{1+}$

Gas-cell development







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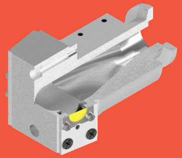
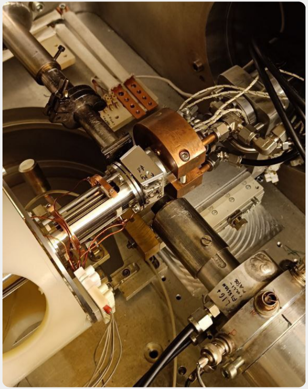
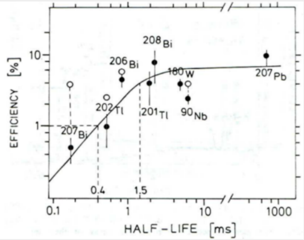
Neutron deficient actinides



Proton-Induced Fusion-evaporation reactions



- Long-lived actinide targets
- Production of neutron-deficient actinides
- Extraction times can be < 1ms



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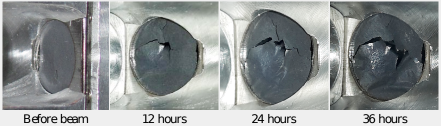
- Cross-section estimates not always reliable
- Experimental data is lacking
- Target durability and thickness
- Competition with other processes

50 MeV p beam - ^{232}Th metallic target ($2.6\ mg/cm^2$)



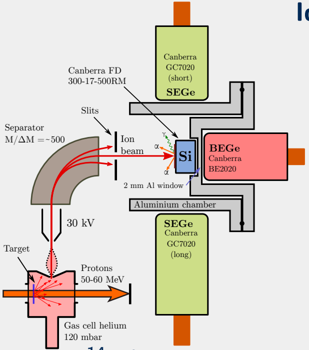
13

[12] J. Ärje, J. Äystö et al., Phys. Rev. Lett. 54 (1985) 99
[13] I. Pohjalainen. Ph.D. thesis, University of Jyväskylä (2018)

Decay spectroscopy with 232Th targets

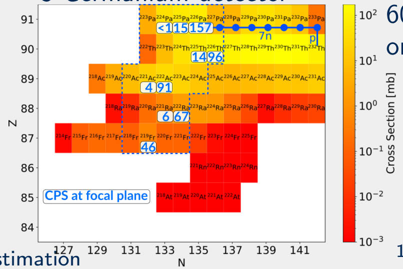
I245 - 2018

Exploration of actinide beams from proton-induced fusion-evaporation of ^{232}Th



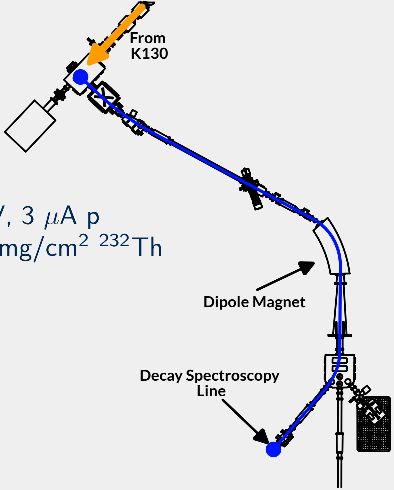
Identification of the produced isotopes

- Direct implantation in silicon detector
- 3 Germanium detector



60 MeV, 3 μA p on 3.3 mg/cm^2 ^{232}Th

[14] [15]

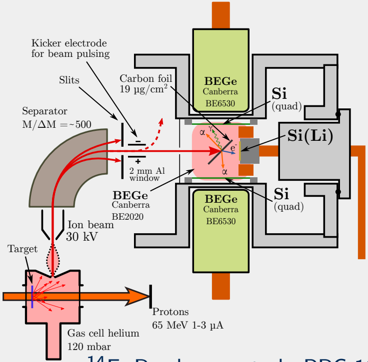


[14] Talys cross-section estimation
[15] I. Pohjalainen et al, I245, to be submitted

Decay spectroscopy with 232Th targets

I262 and Addendum - 2020

Mass measurements, decay spectroscopy and yield determination of actinides via the light-ion fusion-evaporation reaction ^{232}Th(p, x)Y

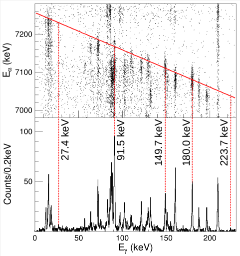


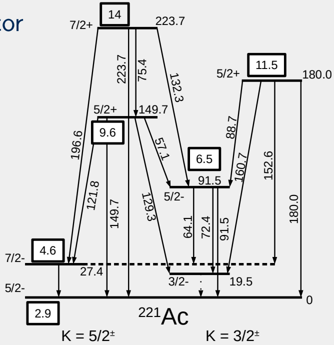
[14] E. Rey-herme et al., PRC 108(2023) 014304.

New detection setup

- Implantation on thin C foils ($\sim 19 \mu g/cm^2$)
- 4 BEGe detectors
- 2 quadrant silicon detectors
- LN_2 cooled Si(Li) detector

→ α-γ-e^- coincidences





Decay spectroscopy with 232Th targets

I262 and Addendum - 2020 + 2024

Mass measurements, decay spectroscopy and yield determination of actinides via the light-ion fusion-evaporation reaction ^{232}Th(p, x)Y

Yields closer to ^{232}Th

Decay spectroscopy not suitable

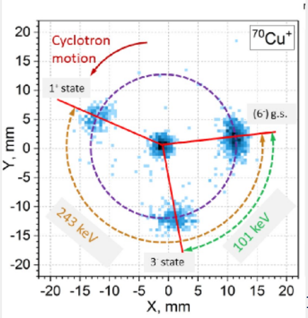
$\delta\nu(^{229}\text{Th}, ^{229}\text{Pa}) \sim 0.7$ Hz

1 s accumulation time

$\downarrow$

0.05 Hz resolution

PI-ICR



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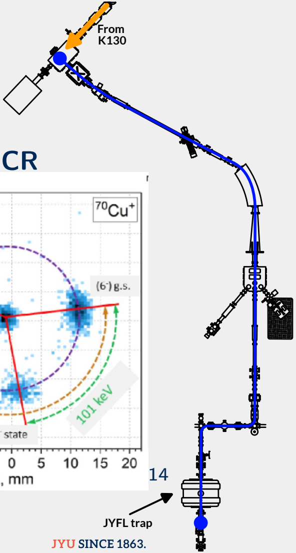
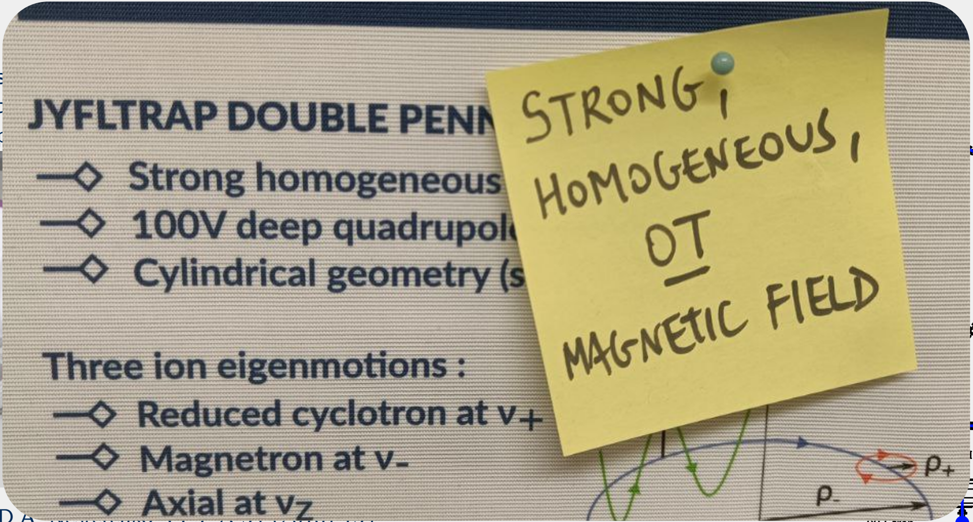


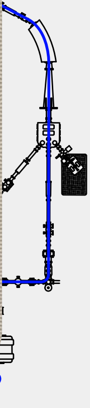
[14] D.A. Nesterenko, EPJ. A 54 (2018) 154

Decay spectroscopy with 232Th targets

I262 and

Mass meas
determinat
fusion-evap



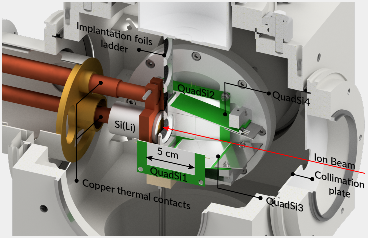


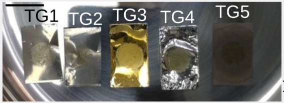
[14] D.A.

Decay spectroscopy with 232Th targets

I263 - 2022

Yield measurements and decay spectroscopy using Drop-on-Demand ^{233}U targets

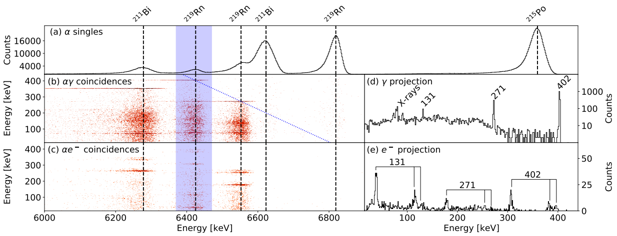




[15]

Versatile Actinides DEcay spectRoscopy setup[14]

- Implantation foils facing the Si(Li) detector
- 4 slots foil ladder
- 2 additional silicon quadrant detectors



[14] A. Raggio ,NIM B, 540 (2023): 148-150.
[15] R. Haas et al., NIMA 874 (2017) 43

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Summary and Outlook

Summary

Offline production and study of actinide beams

→ ^{235m}U isomeric state investigation

- CLS measurement on stable U isotopes .
- Production of isomeric beam using alpha recoil sources.

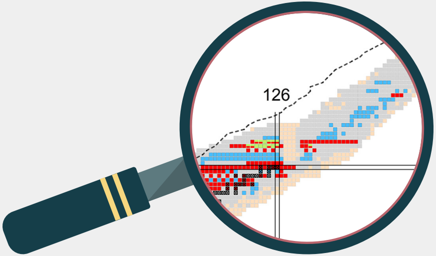
Towards neutron-deficient actinides

→ Use of LIG with long-lived actinide targets

- Experiments to asses the yields with ^{232}Th targets.

→ Decay spectroscopy in the region

- Improvement of the decay spectroscopy setups.
- Decay schemes give insights on collective properties.

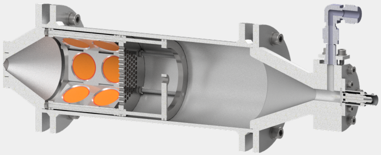


Outlook

^{235m}U isomeric state investigation

→ Possibilities to improve the small 1+ fraction under investigation.

→ Gas-flow simulations to characterize and further improve the gas-cell design.



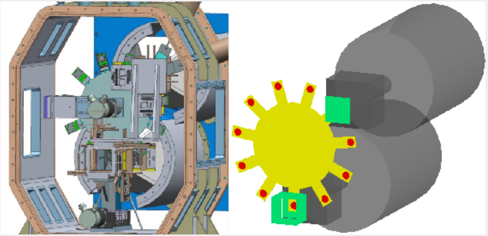
Outlook

^{235m}U isomeric state investigation

→ Possibilities to improve the small 1+ fraction under investigation.
→ Gas-flow simulations to characterize and further improve the gas-cell design.

Online reactions

→ Installation and commissioning of SEASON.
→ Test new DoD targets (^{239}Pu, ^{237}Np, ^{231}Pa ...).



LISA

LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

D. Bettaney, M. Block, P. Campbell, B. Cheal, C. Düllmann, T. Eronen,
R. de Groote, A. Koszorus, I. Moore, I. Pohjalainen, L. Reed, D. Renisch,
M. Reponen, J. Saren, J. Warbinek and IGISOL group

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