Exploring the limits of nuclear existence

Work Package 5

Iain D. Moore – University of Jyväskylä, Finland

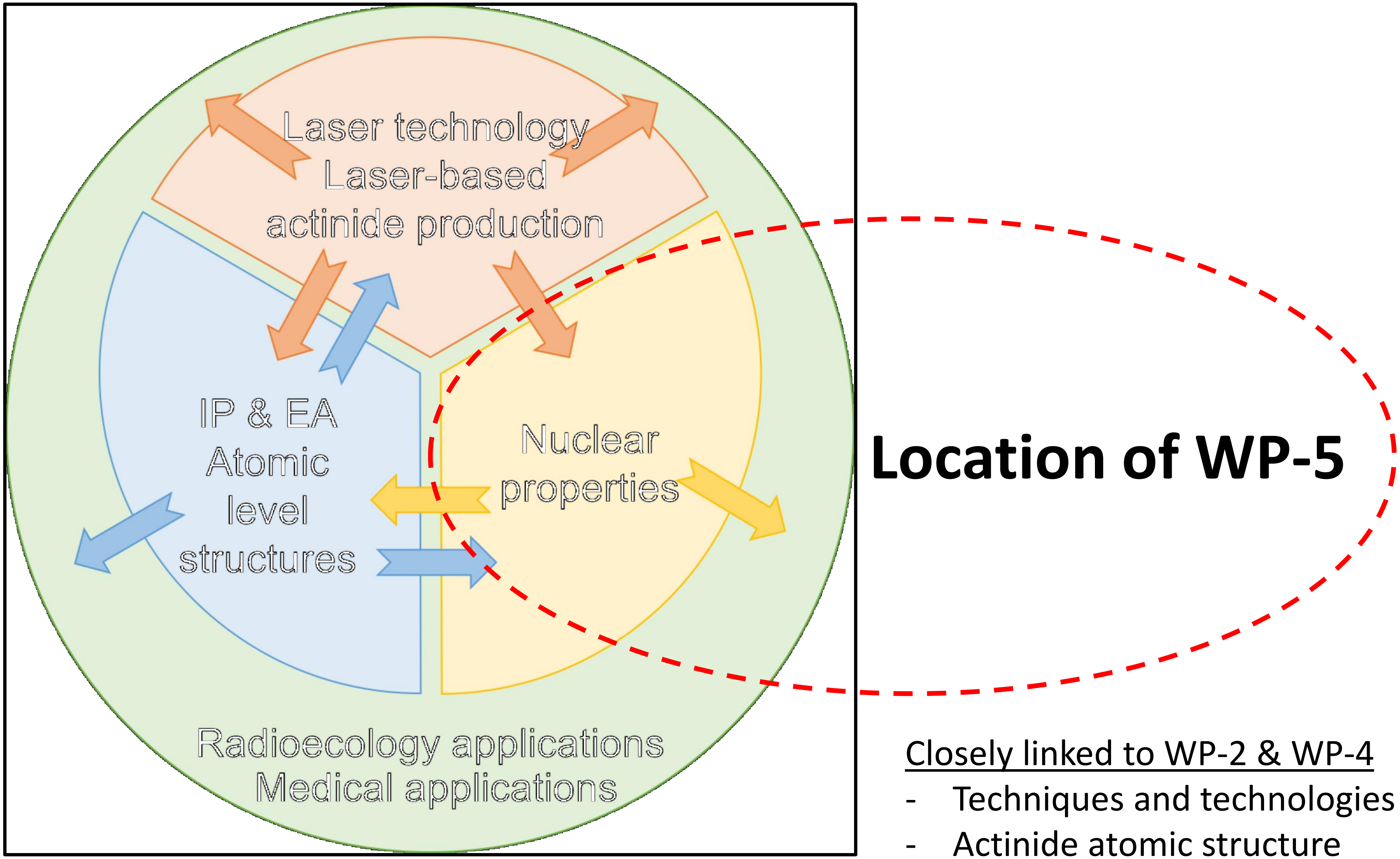
LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN) receives funding from the European Union's H2020 Framework Programme under grant agreement no. 861198

Content

- Introduction and objectives of WP-5
- Description of work and role of partners
- Milestones
- Deliverables
- Research highlights
- Conclusions

Interplay between LISA R&D activities

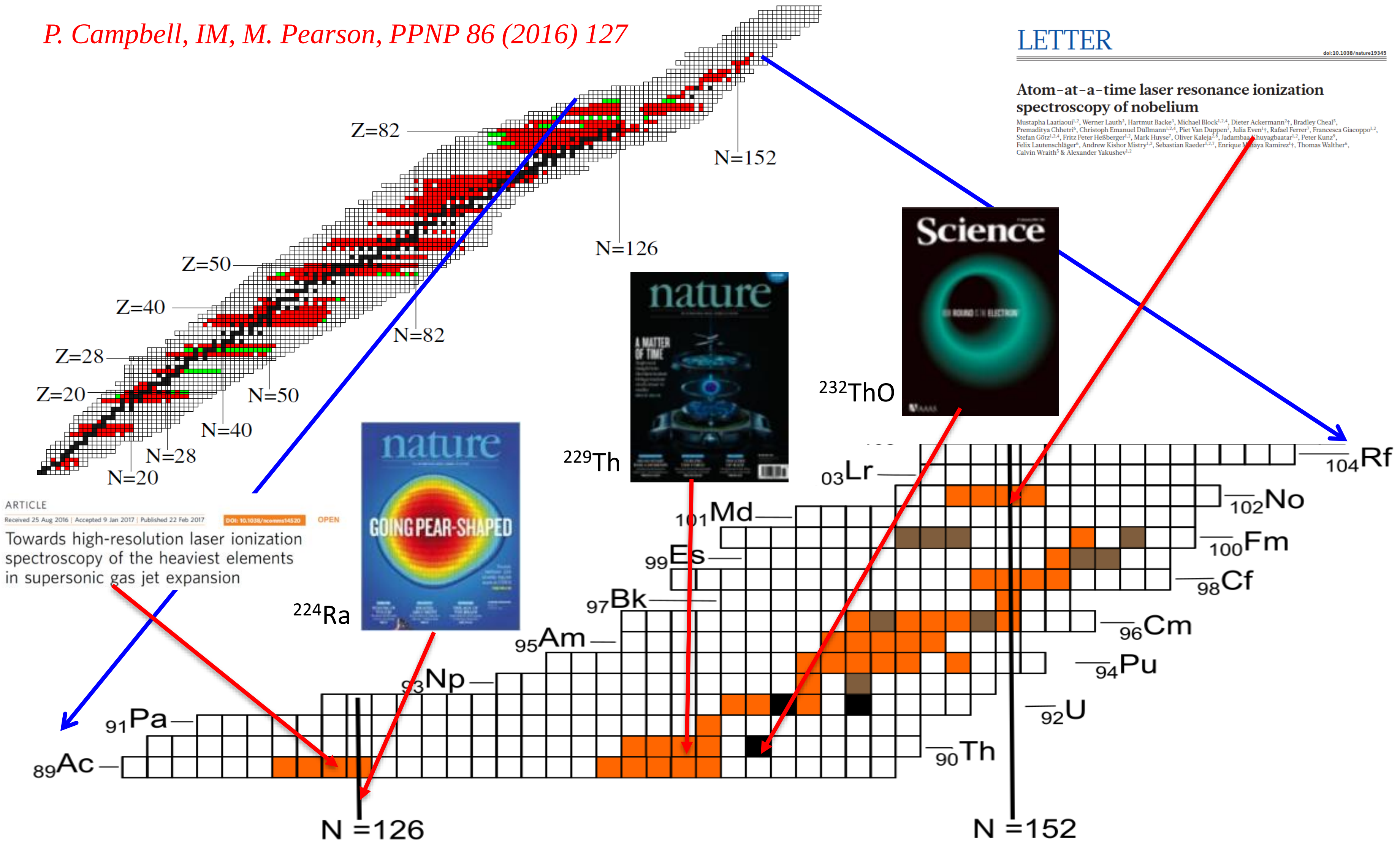


Location of WP-5

Closely linked to WP-2 & WP-4
- Techniques and technologies
- Actinide atomic structure

Optical spectroscopy of heavy elements

P. Campbell, IM, M. Pearson, PPNP 86 (2016) 127



Objectives and partner institutes in WP-5

1. Optimize actinide sample preparation and characterization techniques for the LISA network.

2. Perform laser spectroscopy using highly sensitive techniques on isotopes of both actinide and trans-actinide elements with the goal of probing fundamental atomic and nuclear properties and to benchmark state-of-the-art atomic and nuclear theoretical calculations.

3. Characterize and optimize the novel in-gas-jet spectroscopy technique for final implementation at GANIL-S3.

ESRs and Work Package 5

- Andrea Raggio (JYU) – ESR 4

- Vaila Leask (KUL) – ESR 7

- Jessica Warbinek (GSI) – ESR 10

- Lauren Reed (JGU) – ESR 11

Description of work

TASK	SUMMARY	BENEFICIARIES
1	Advanced molecular plating & DOD printing for high-performance targets and picoliter applications; CLS of U isotopes/isomers	JGU, *LUH IRS (WP3), JYU*
2	Laser ablation source and time-gating techniques for collinear LS (CLS); laser ablation for gas cell approaches	JYU, *KUL*
3	CLS on ^{235m}U isomer following enriched ^{239}Pu α decay	JYU, *JGU*
4	CLS on n-deficient U isotopes produced on-line	JYU, *JGU*
5	RIS of heaviest actinides to Lr using RADRIS and atomic properties	GSI
6	Supersonic gas jet developments using de Laval nozzles	KUL, *GANIL (WP2)*

Atomic and nuclear structure theory support from WP4 (Task 3 & 4) – FSU/RUG

Milestones & schedule

MS21	Optimum filament setup for efficient Lr evaporation	GSI	M12	LISA technical design report
MS22	Pu targets for JYU	JGU	M15	Target delivered and verified with γ-ray spectroscopy
MS23	Offline study of atomic transitions in U: dye and Ti:sa	JYU	M18	Laser spectroscopy results on $^{234,235,238}U$
MS24	Identification of atomic states in Lr	GSI	M24	LISA scientific report
MS25	Picoliter injection system	JGU	M24	LISA technical design report
MS26	Setup for high-resolution in gas-jet spectroscopy	GSI	M36	LISA technical design report
MS27	First high-res online LS at GANIL-S3	KUL	M42	Resonance peak linewidth <300 MHz online

LISA start date 1 Nov. 2019; WP-5 start 1 March 2020.

M21 see highlight later; report in 1 month

M22 moved ~4-5 months

ESR 11 (Lauren) starts this week.

Deliverables

Deliverable	Deliverable title	Lead beneficiary	Due date
D5.1	Optimized geometry of the gas cell nozzle	KUL	24
D5.2	Laser ablation source	JYU	24
D5.3	Off-line U studies	JYU	30
D5.4	Preparation of characterization of samples for LISA	JGU	36
D5.5	Precise data of atomic and nuclear properties of Lr	GSI	42
D5.6	Exotic U studies (off- and on-line production)	JYU	48

Deliverables primarily produced as reports. D5.5 and D5.6 are ”other”.

Research highlights

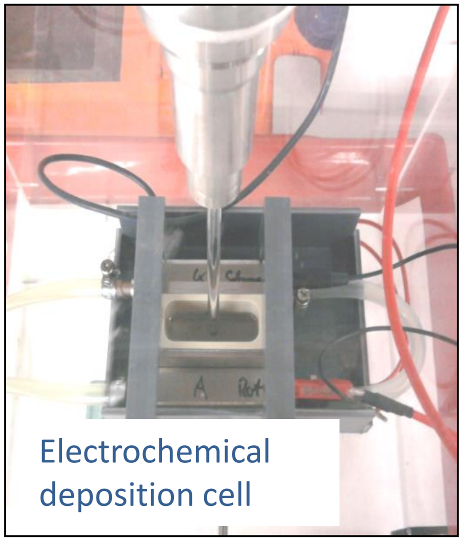
Preparation of actinide targets

Task 1

Production methods

Molecular plating

Electrochemical deposition from organic solution onto conducting substrate

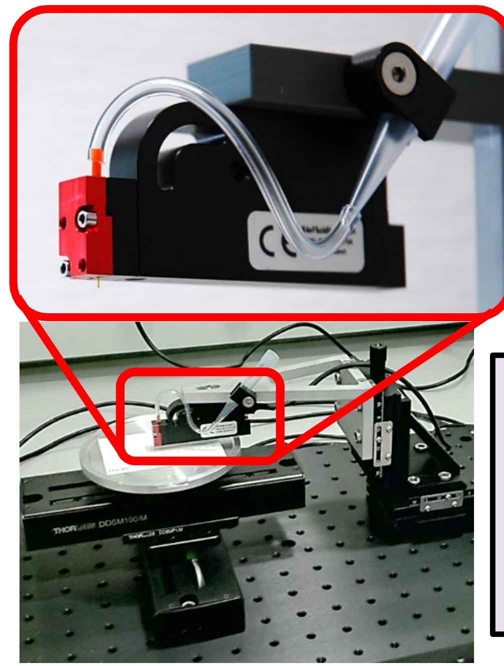


^{233}U recoil source for ^{229m}Th

Wense et al., Nature 533 (2016) 47
Thielking et al., Nature 556 (2018) 321
Seiferle et al., Nature 573 (2019) 243

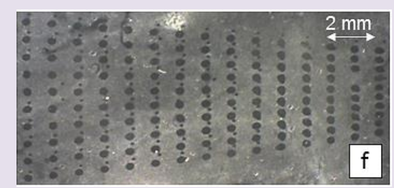
W. Parker et al., NIM 16 (1962) 355
A. Vascon et al., NIMA 696 (2012) 180

Drop-on-Demand Inkjet printing (DoD)



BioFluidix PipeJet® P9 NanoDispenser with 200 µm tip

Deposition on substrate on xy translation stage



Individual drops with ^{32}P/^{35}S

R. Haas et al., NIMA 874 (2017) 43

Characterization of actinide targets

Task 1

Characterization techniques

Deposition yield:

Direct:

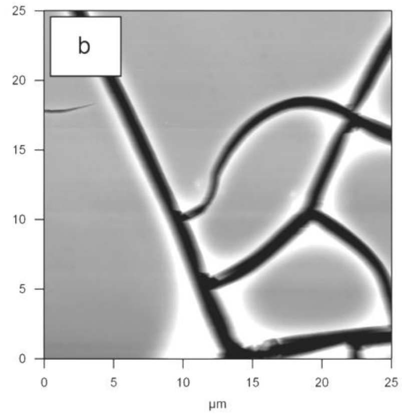
- **α-particle decay spectroscopy**
- **γ-ray spectroscopy**

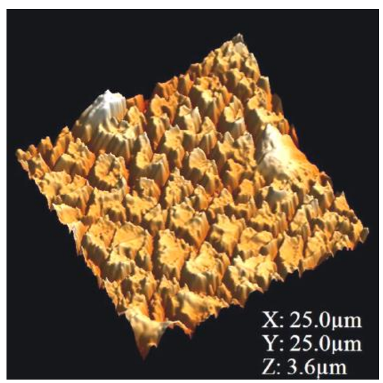
Indirect:

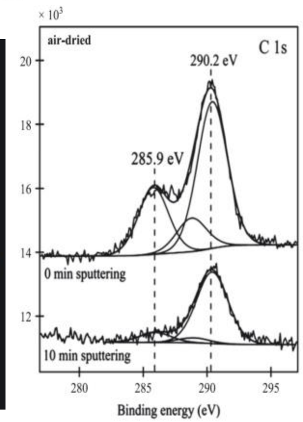
- **Neutron Activation Analysis**

Layer morphology / homogeneity / composition:

- **α-particle decay spectroscopy**
- **Radiographic Imaging**
- **Electron Microscopy (w/ EDX)**
- **Atomic force microscopy**
- **X-ray Photoelectron Spec.**



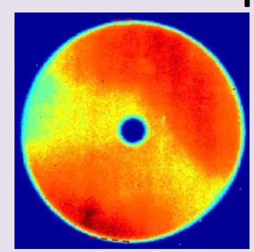




^{233}U DoD targets for beam experiments

Task 4

^{233}U recoil source for ^{229m}Th



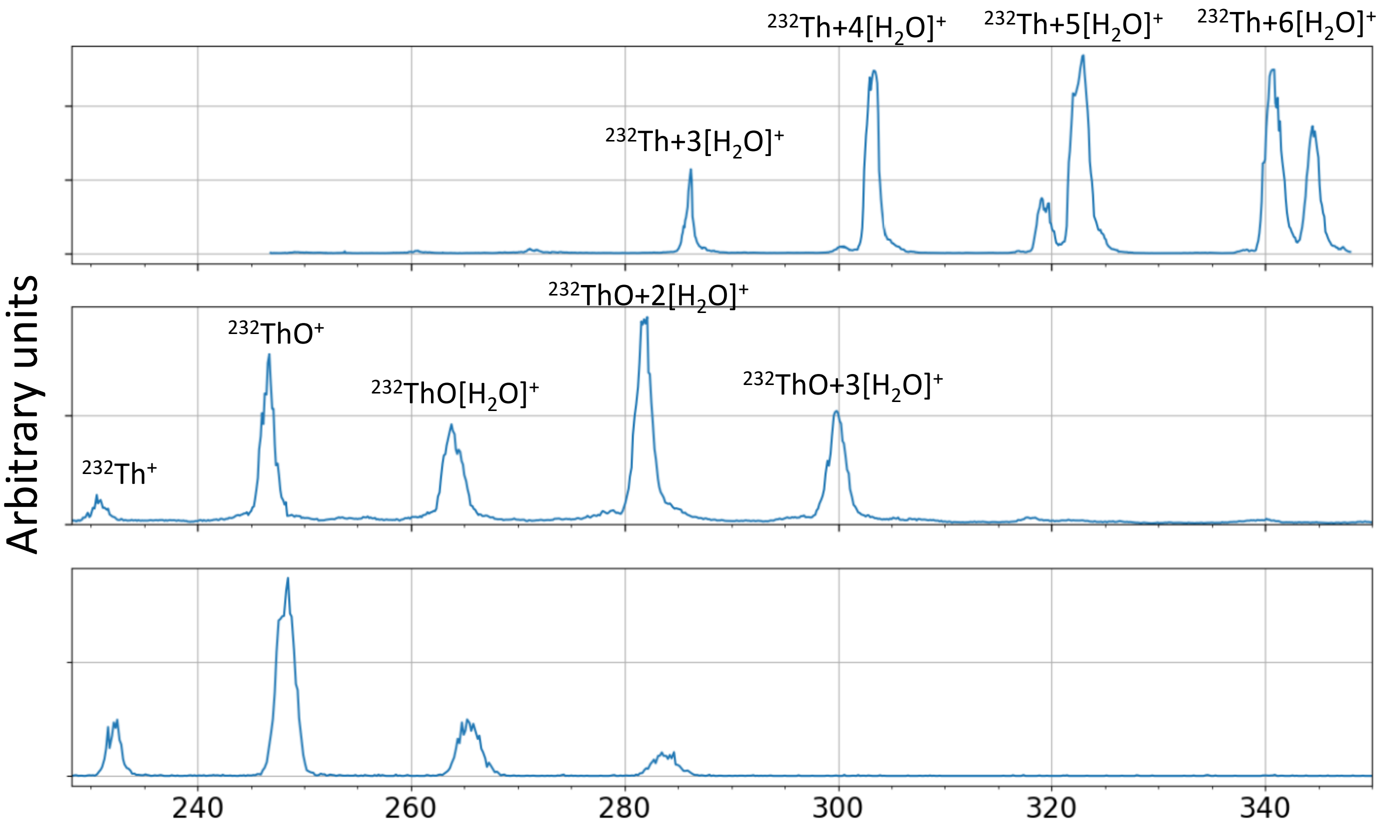
Task 3

Ch.E. Düllmann, D. Renisch *et al*.

^{232}Th production via laser ablation

Task 2

In-gas cell laser ablation at KU Leuven



Only sideband molecules, Th[H_2O)]$_n$ with up to n=7, observed in the first experiments.

Improving gas cell cleanliness, gas cell chamber and vacuum conditions decreased H_2O. ThO can be explained by long exposure of Th foil in air.

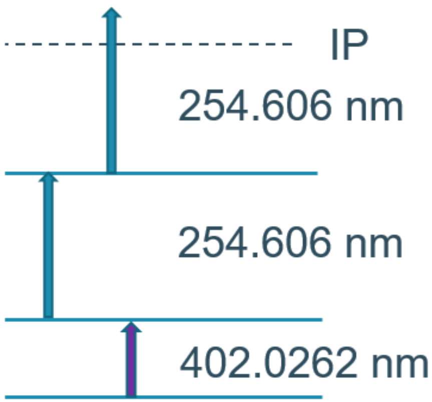
Few days of pumping the gas cell chamber reduces the water significantly. Oxide layer does not seem to disappear from target surface that easily

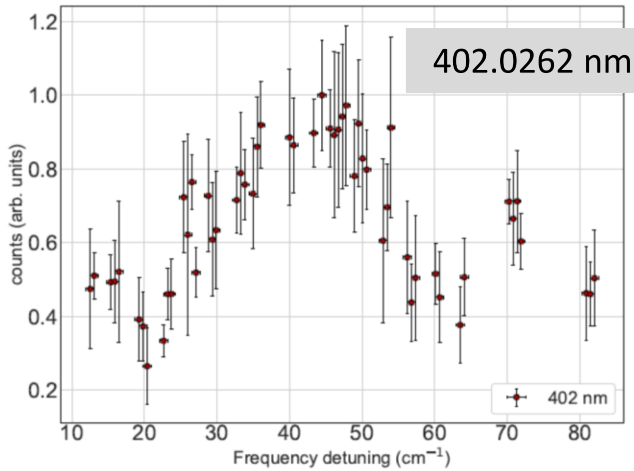
R. Ferrer *et al*.

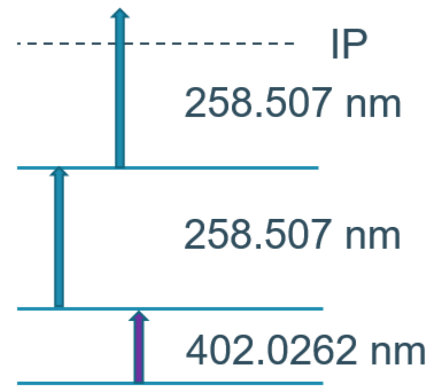
Two-color, three-step ionization of ^{232}Th

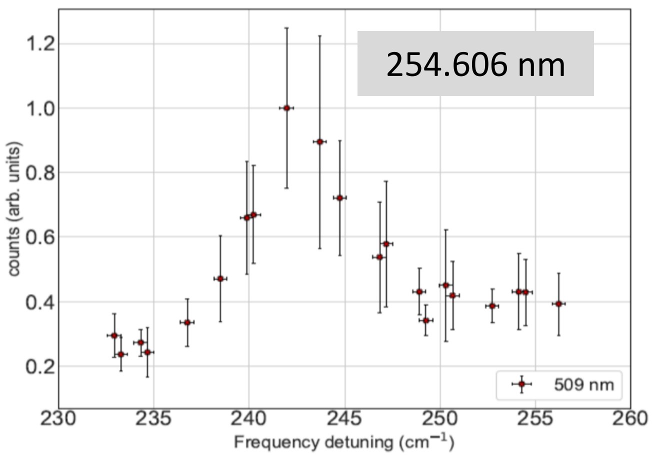
Task 2

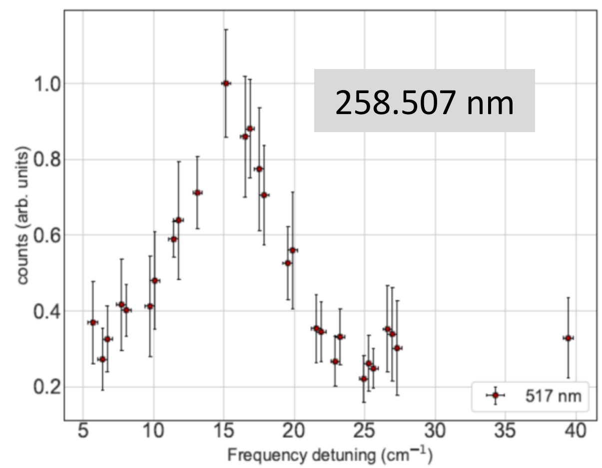
In-gas cell laser ionization











Low ionization efficiencies (~ 0.5%) for the two schemes tested.

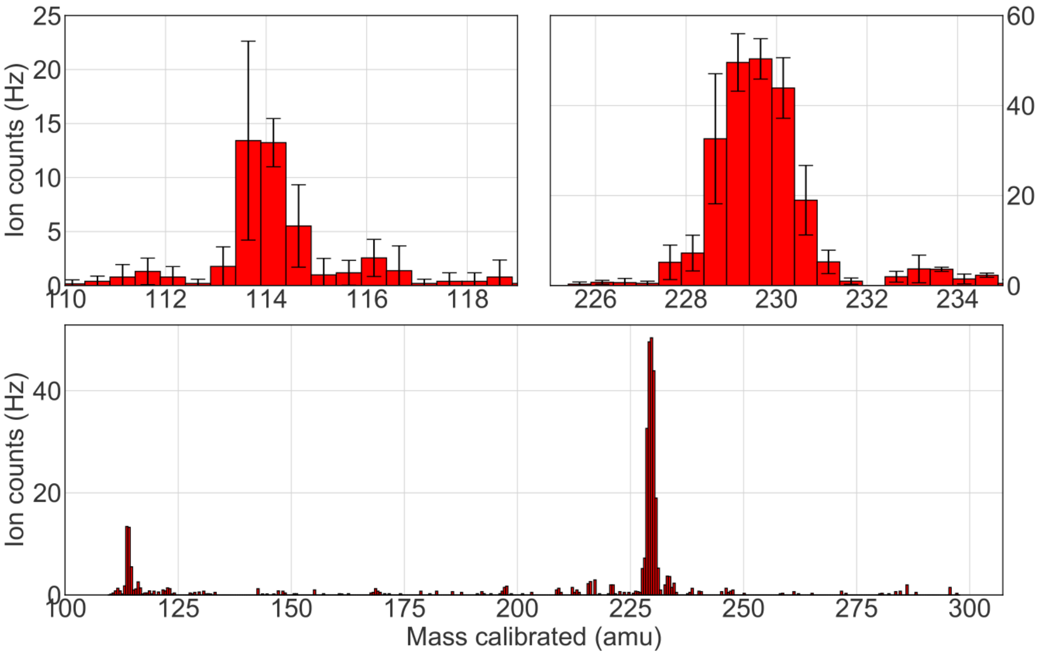
Search for autoionizing states will follow in the next months

R. Ferrer *et al.*

^{229}Th production

Task 2 & 6 (gas-jet developments)

- Produce ^{229g,m}Th with ^{233}U recoil source and transport through the IGLIS setup
- Thermalize and evacuate ^{229}Th to gas jet in ~1 ms



- Introduce tailor mode ^{233}U sources with 330 Bq (2π) recoil activity
- Design/construction/testing gas cell
- ^{229}Th II/III extraction and transport after purification studies IGLIS beam line

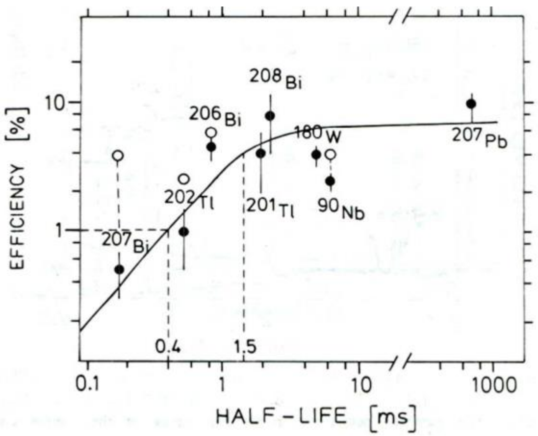
R. Ferrer *et al.*

On-line production of light actinides

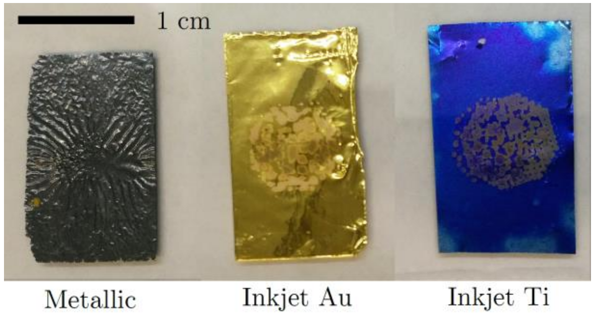
Proton-induced fusion-evaporation reactions at IGISOL

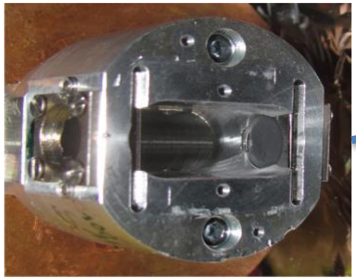
Task 4

J. Ärje, J. Äystö et al., Phys. Rev. Lett. 54 (1985) 99

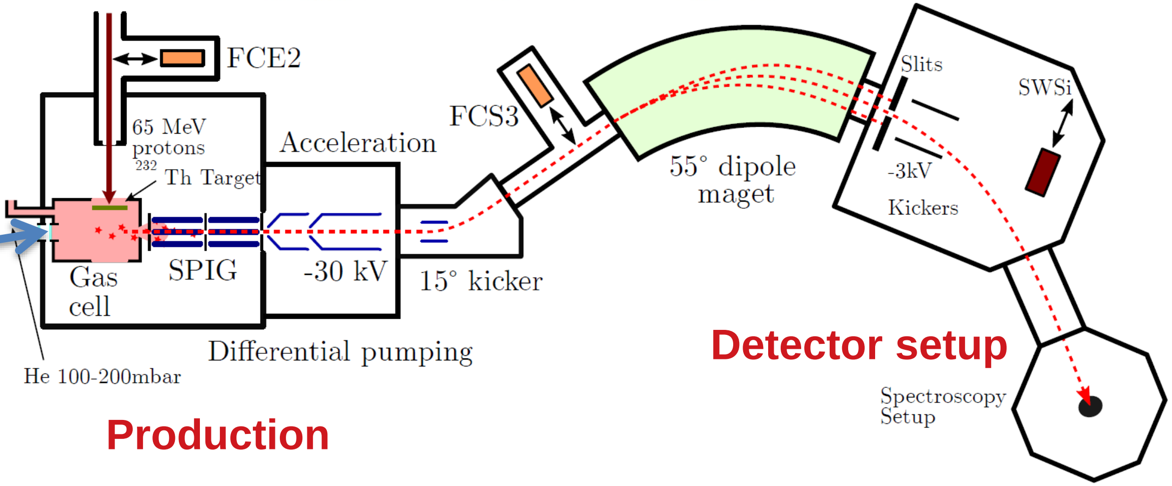


DoD targets provided from JGU





Small volume gas cell

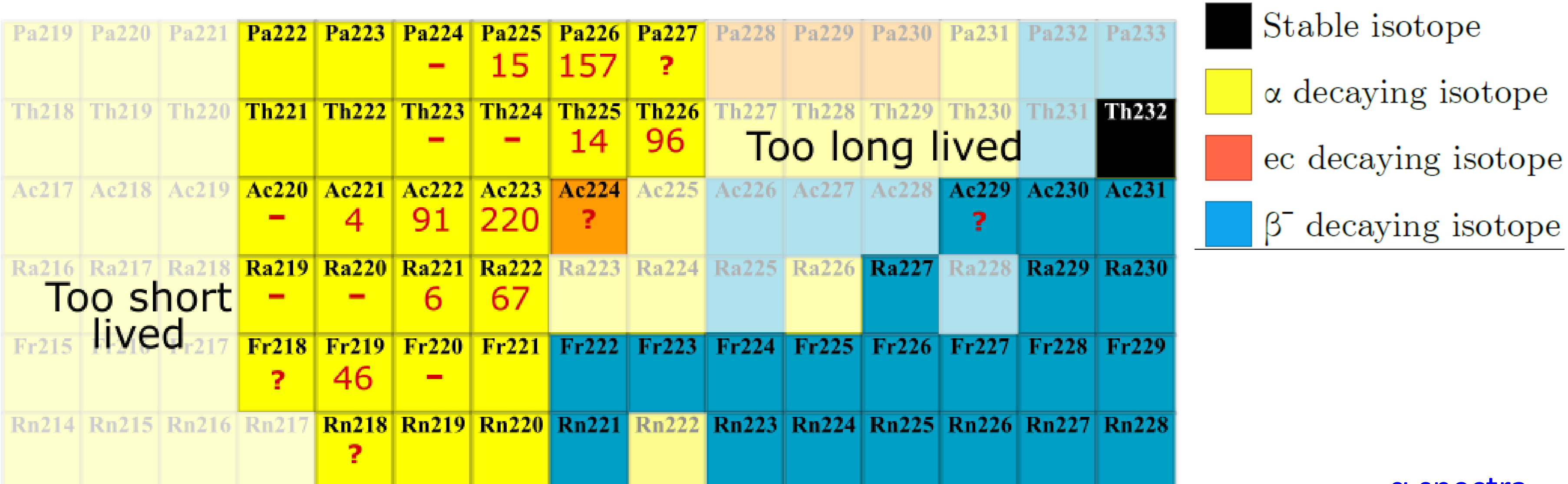


I.D. Moore, I. Pohjalainen *et al.*

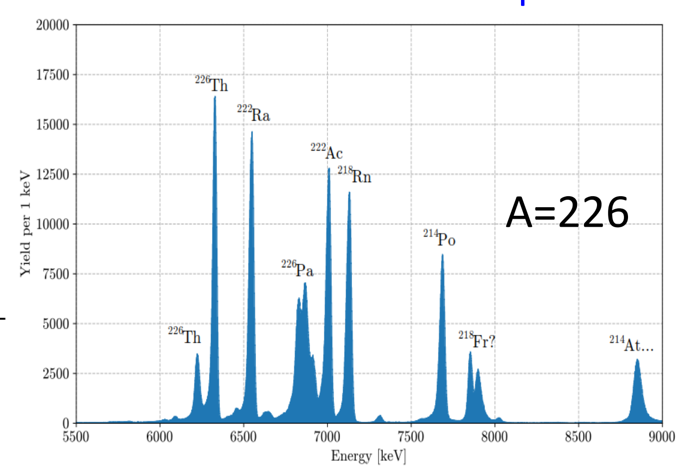
Proof-of-principal: ^{232}Th(p,X)Y

First test Nov. 2018; metallic ^{232}Th vs. DoD ^{232}Th

Task 4



α spectra

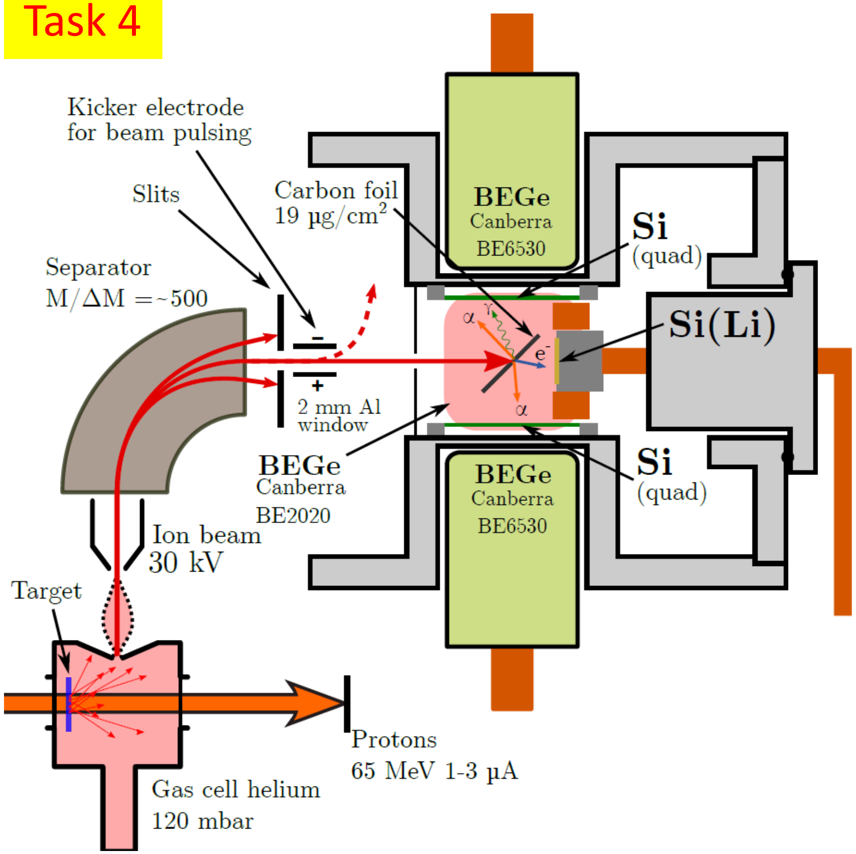


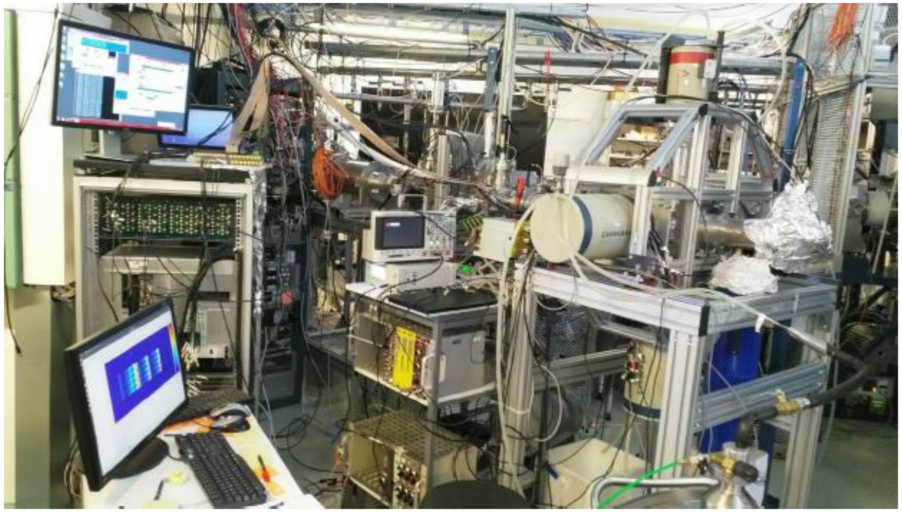
- Different reaction channels populate different isotopes
- Identification via alpha & gamma spectroscopy
- Build up of alpha recoils in the target
- Production of ^{229}Th?
- Explore available yields (at 60 MeV)

I.D. Moore, I. Pohjalainen *et al.*

New experiment – summer 2020

Task 4





- Optimized decay spectroscopy station (α, γ, conversion electrons)
- Pulsing of mass-separated beam (lifetimes)
- Higher beam energy (= more exotic isotopes)
- Data analysis Andrea Raggio (ESR 4)

Accepted proposal for ^{233}U targets (access to Np isotopes)

I. Pohjalainen, A. Raggio, IM *et al.*

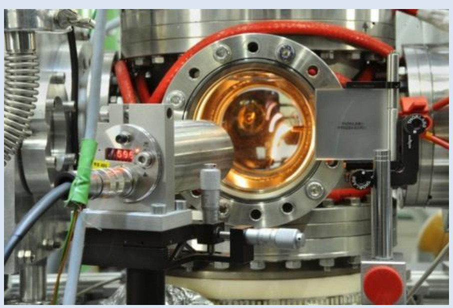
Laser spectroscopy of heavy elements

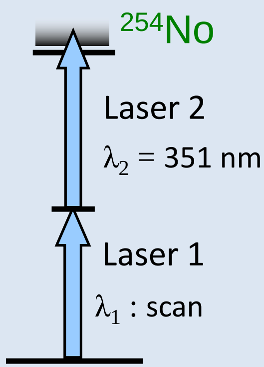
Task 5

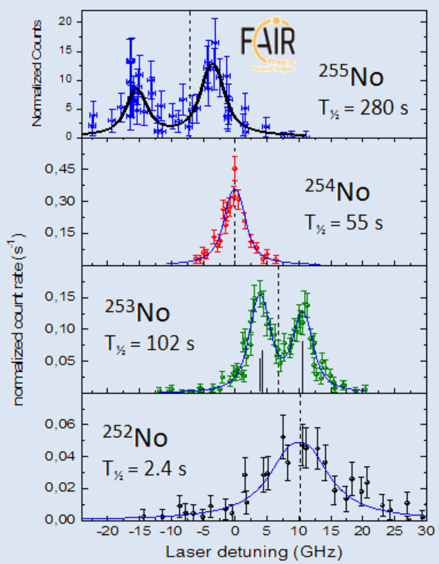
Nobelium and Fermium isotopes produced in on-line fusion reactions at GSI

– Sensitive gas-cell laser spectroscopy
– Atomic levels identified for the first time for $Z > 100$
– Isotopes $^{252-255}$No investigated

[1] *M. Laatiaoui et al., Nature 538 (2016) 7626*
[2] *S. Raeder et al., Phys. Rev. Lett.* ***120*** *(2018) 232503*
[3] *P. Chhetri et al., Phys. Rev. Lett.* ***120*** *(2018) 263003*

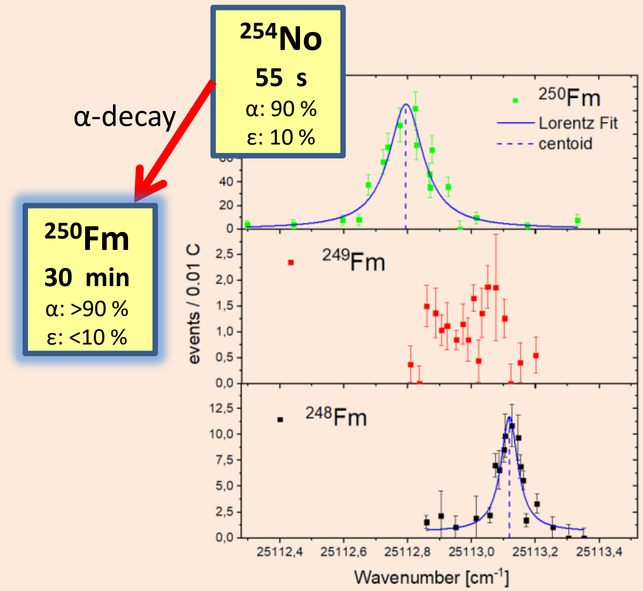






2020 – NEW: Fm (Z=100)

– First laser spectroscopy of $^{248-250}$Fm
– Available from decay of nobelium



M. Block, S. Raeder, M. Laatiaoui *et al.*

Laser spectroscopy of heavy elements

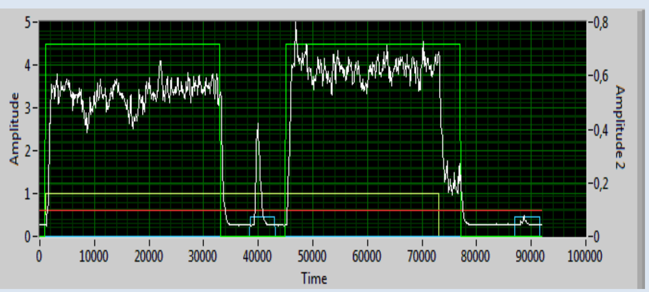
Task 5

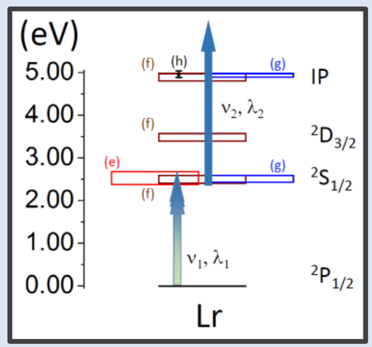
Next steps: GSI and JGU

Tackling the next heavier element - lawrencium (Z=103)

Challenges:
- Atomic structure only known from theory
- Production rate 3 x lower compared to No
- Lower ionization potential

MS21





Off-line studies of the filament for desorption of Lu/Lr

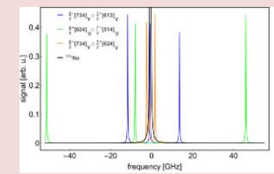
→ Hf is the best filament

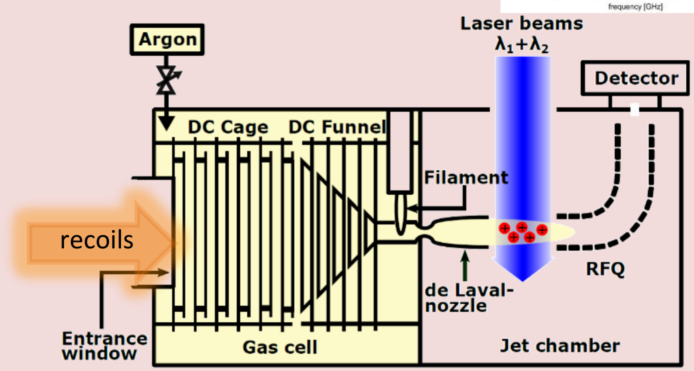
T. Murböck et al., Hyp. In. 241 (2020) 35

Improved resolution for nobelium

- Development of gas-jet spectroscopy
- Implementation of a new laser system

Science cases: e.g. K isomer in No-254; $T_{1/2}$=266 ms





M. Block, S. Raeder, M. Laatiaoui *et al.*

GSI HIM HELMHOLTZ Helmholtz-Institut Mainz

Conclusions

- Despite the effect of COVID, WP-5 is generally moving ahead according to plan.
- Small adjustments expected for the secondments to account for the different starting dates of our ESRs.
- All beneficiaries of WP-5 are active in related actinide developments required to realize our objectives.
- Our ESR’s will get a truly multidisciplinary training within LISA!