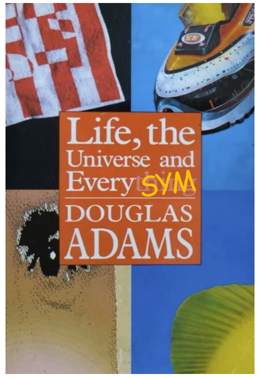
www.superheavies.de
duellmann@uni-mainz.de

Actinide samples from Mainz

or



Life, the Universe and Everysym

Christoph E. Düllmann

Johannes Gutenberg University Mainz, Mainz, Germany
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
Helmholtz Institute Mainz, Mainz, Germany

Radioactive Isotopes for Fundamental Physics Workshop
Oak Ridge National Laboratory, Oak Ridge, TN, USA
August 25-27, 2026

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Content of this presentation

- The (Oak Ridge &) Mainz (& ILL Grenoble) actinide program
- Application 1: Superheavy element research at GSI based on ORNL actinides
- Application 2: Laser++ experiments for nuclear and atomic physics and trace analytics
- Application 3: Samples for the fundamental symmetry community
- Summary

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Our program: actinides and superheavies

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

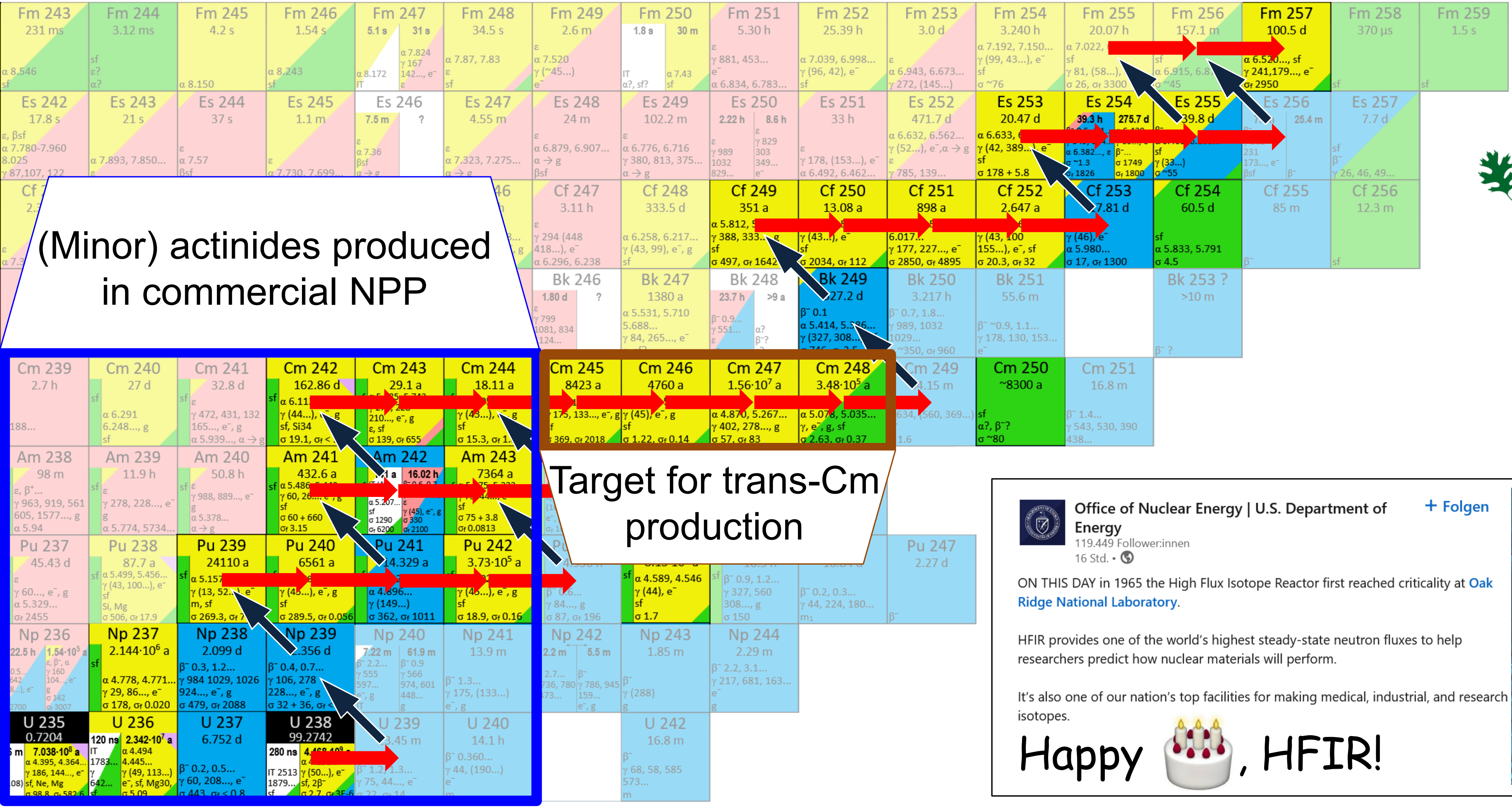
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

tons

mg / µg / pg

Production of transuranics

Production of transuranics



Oak Ridge National Laboratory

Office of Nuclear Energy | U.S. Department of Energy
+ Folgen
119.449 Follower:innen
16 Std. •

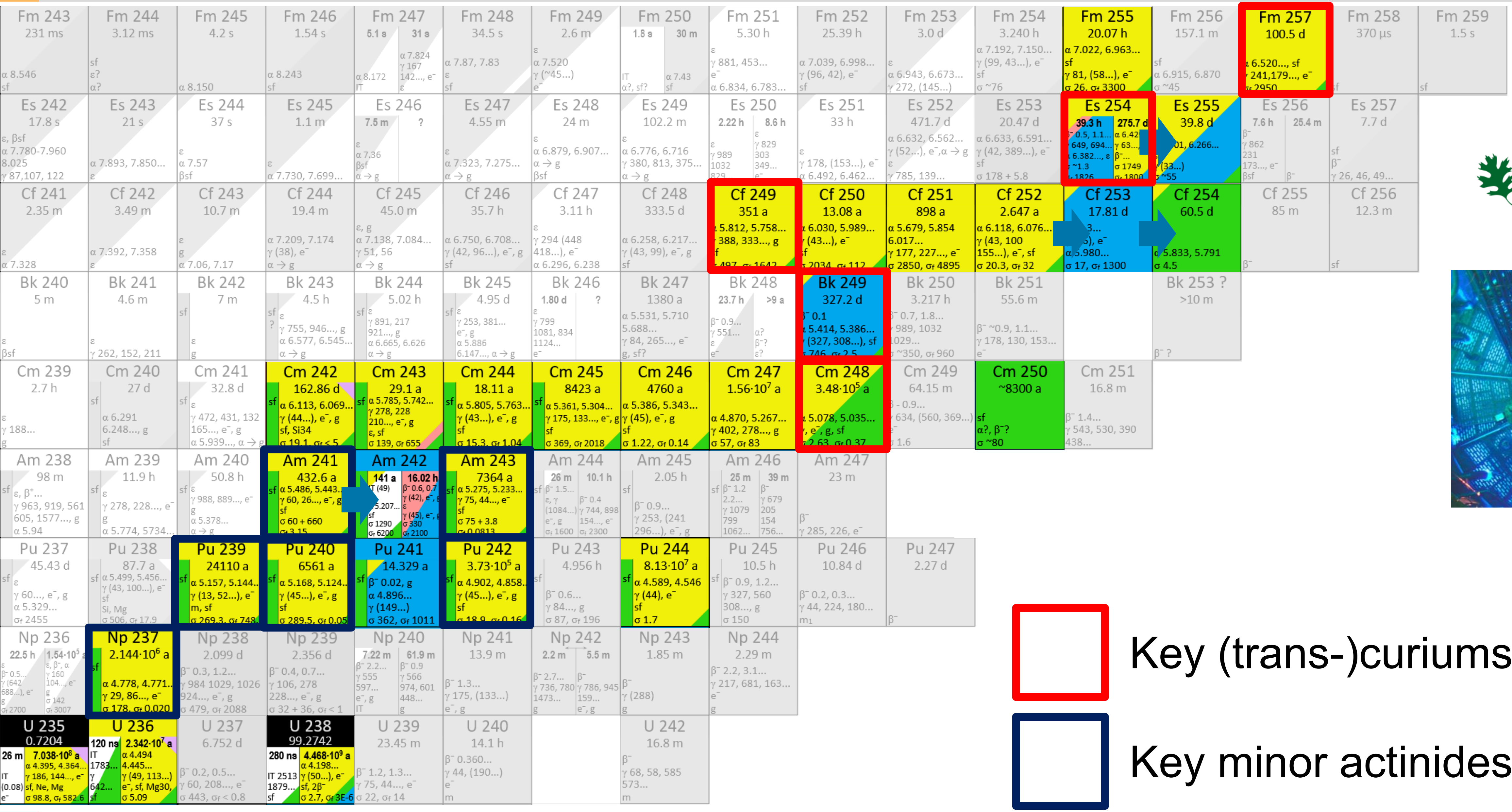
ON THIS DAY in 1965 the High Flux Isotope Reactor first reached criticality at Oak Ridge National Laboratory.

HFIR provides one of the world's highest steady-state neutron fluxes to help researchers predict how nuclear materials will perform.

It's also one of our nation's top facilities for making medical, industrial, and research isotopes.

Happy 🎂, HFIR!

Production of transuranics



OAK RIDGE
National Laboratory

Key (trans-)curiums (rare)

Key minor actinides (abundant)

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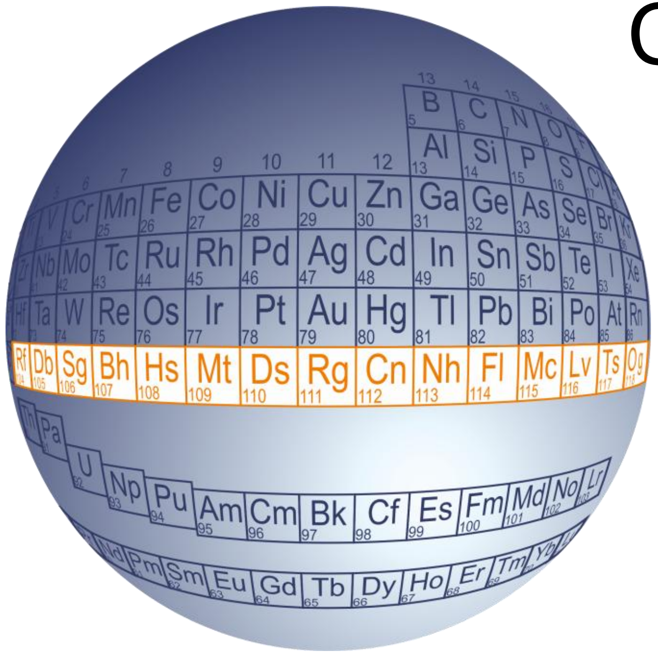
#1: Nuclear chemistry and physics studies on the Island of Stability



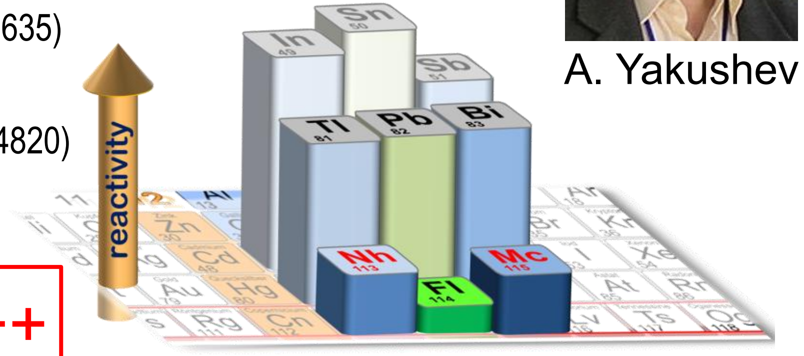
Chemical studies of the superheavy elements:

A. Yakushev

The heaviest chemically classified elements

- $_{114}$Fl (A. Yakushev *et al.*, Front. Chem. 10 (2022) 976635)
- $_{113}$Nh $_{115}$Mc (A. Yakushev *et al.*, Front Chem. 12 (2024) 1474820)

  Based on ^{244}Pu and ^{243}Am targets

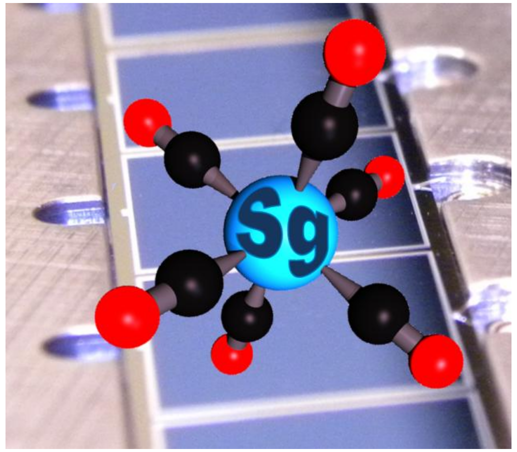


🙏 #1: 100 mg ^{248}Cm for $_{116}$Lv chem.++

Molecular studies of $_{106}Sg(CO)_6$

- **Volatility** and **reactivity**
- *Based on ^{248}Cm targets* (J. Even *et al.*, Science 345 (2014) 1491)
- **Reaction kinetics** and **bond strength**

  Based on ^{208}Pb targets (A. Yakushev *et al.*, pre-accepted in Nature)



J. Even

Charting the shore of the Island of Stability

- 60-ns ^{252}**Rf** marks the shoreline towards the Sea of fission Instability
- Detection possible thanks to longer-lived high-*K* state

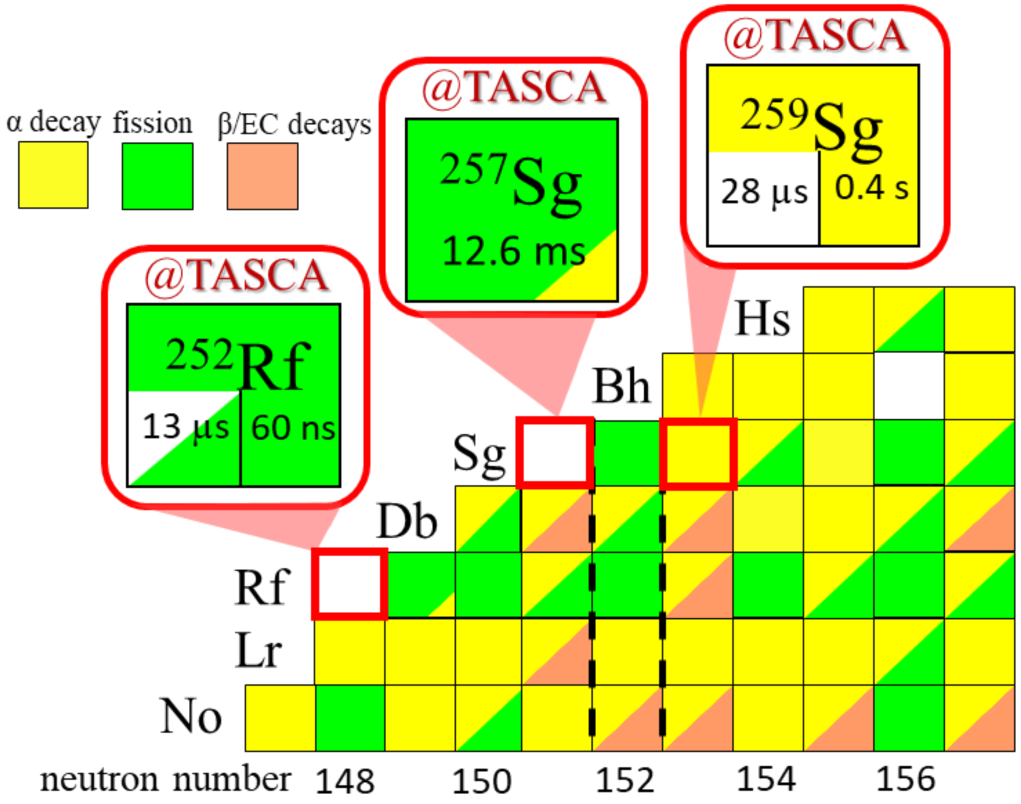
J. Khuyagbaatar *et al.*, Phys. Rev. Lett. 134 (2025) 022501

Editors' Suggestion / Featured in Physics

- New ^{257}**Sg**: Expands shoreline to Sg
- New ^{259m}**Sg**: First high-K state in Sg

P. Mosat *et al.*, Phys. Rev. Lett. 134 (2025) 232501

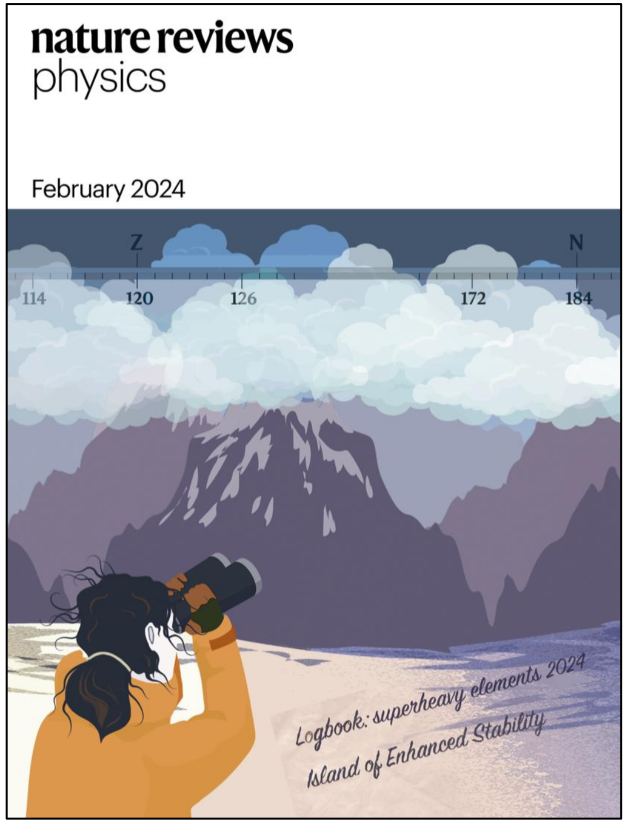
Editors' Suggestion



J. Khuyagbaatar

P. Mosat

2025 COLLECTION



O. Smits *et al.*, Nat. Rev. Phys. 6 (2024) 86

UNIVERSITY OF JYVÄSKYLÄ

भारतीय प्रौद्योगिकी संस्थान रूड़की
Indian Institute of Technology Roorkee

Breadth of SHE research @ GSI Darmstadt

Reaction studies toward Z=120 (ANU)
H.M. Albers *et al.*, Phys. Lett. B 808 (2020) 135626 (Z=120)
D.Y. Jeung *et al.*, Phys. Lett. B 837 (2023) 137641

Search beyond Z=118
J. Khuyagbaatar *et al.*, PRC 102 (2020) 064602 (Z=119&120)
S. Hofmann, Russ. Chem. Rev. 78 (2009) 1123 (Z=120)
S. Hofmann *et al.*, EPJA 52 (2016) 180 (Z=120)

Chemical studies
Ch.E. Düllmann *et al.*, Nature 418 (2002) 859 (Hassium)
J. Even *et al.*, Science 345 (2014) 1491 (Seaborgium)
A. Yakushev *et al.*, Front. Chem. 9 (2021) 753738 (Nihonium)
A. Yakushev *et al.*, Front. Chem. 10 (2022) 976635 (Flerovium)
A. Yakushev *et al.*, Front. Chem. 12 (2024) 1474820 (Moscovium)

Elements Lv&Ts confirmed
J. Khuyagbaatar *et al.*, PRL 112 (2014) 172501
S. Hofmann *et al.*, EPJA 48 (2012) 62

Nuclear structure in Fl/Mc chains
D. Rudolph *et al.*, PRL 111 (2013) 112502
A. Såmark-Roth *et al.*, PRL 126 (2021) 032503

High σ for ^{48}Ca + ^{244}Pu → ^{292}Fl*
Ch.E. Düllmann *et al.*, PRL 104 (2010) 252701

Proton number Z

114

108

Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts

GSI

Shore of Island of Stability in Rf & Sg
J. Khuyagbaatar *et al.*, PRL 134 (2025) 022501
P. Mosat *et al.*, PRL 134 (2025) 232501

Deformed doubly-magic $^{270}_{108}$Hs$_{162}$
J. Dvorak *et al.*, PRL 97 (2006) 242501
J. Dvorak *et al.*, PRL 100 (2008) 132503

Nuclear studies

Atomic & chemical

Green: articles based on actinide material

184

OAK RIDGE National Laboratory

^{244}Pu, ^{243}Am, ^{248}Cm, ^{249}Bk, ^{249}Cf, ^{254}Es, ^{257}Fm

Laser spectroscopy in Fm & No
M. Laatiaoui *et al.*, Nature 538 (2016) 495
S. Raeder *et al.*, PRL 120 (2018) 232503
P. Chhetri *et al.*, PRL 120 (2018) 263003
J. Warbinek *et al.*, Nature 634 (2024) 1075

High precision mass spec: mapping the N=152 shell closure
M. Block *et al.*, Nature 463 (2010) 785
E. Minaya Ramirez *et al.*, Science 337 (2012) 1207

Neutron number N

162

172

U.S. DEPARTMENT OF ENERGY

U.S. DOE Isotope Program, managed by Office of Science

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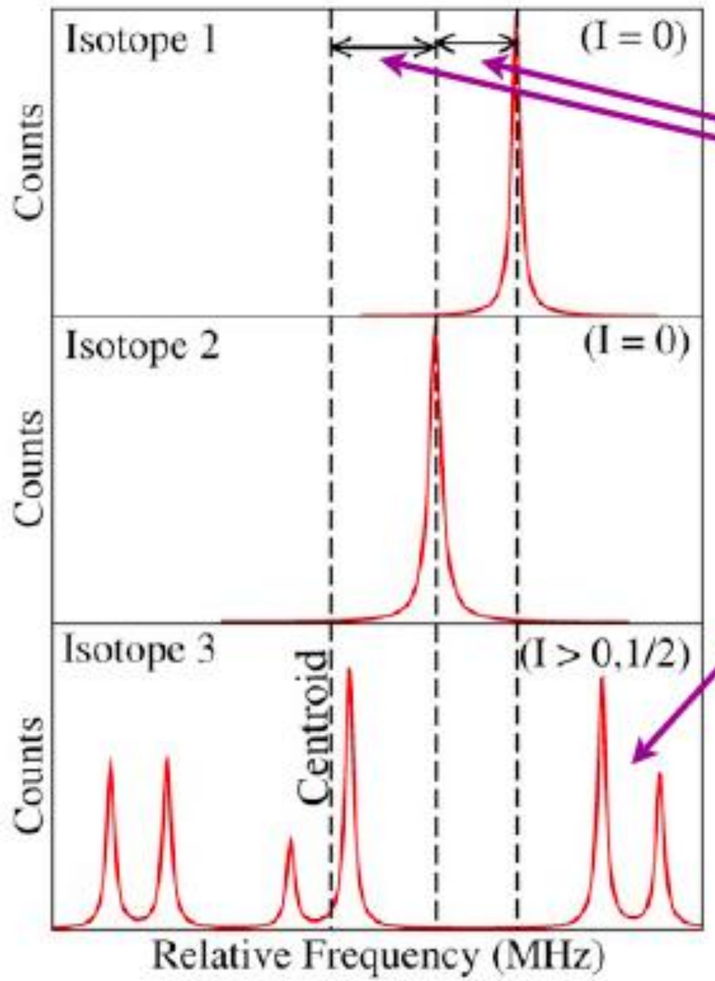
Production, purification, sample preparation and analytics of the **macroscopically available actinides** are a pillar of our research program

89	90	91	92	93	94	95	96	97	98	99	100
Ac	**Th**	**Pa**	**U**	**Np**	**Pu**	**Am**	**Cm**	**Bk**	**Cf**	**Es**	**Fm**

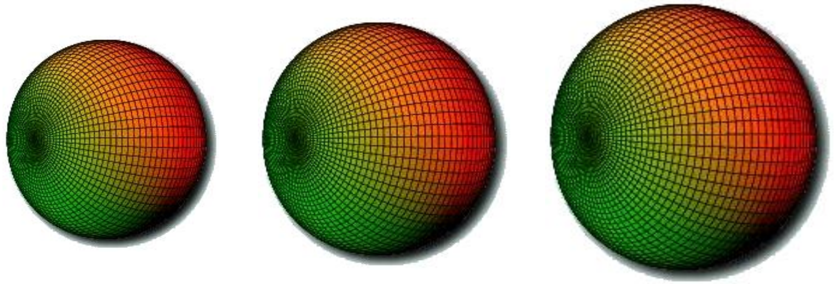
tons **mg / µg / pg**

Atomic and nuclear physics observables from laser spectroscopy



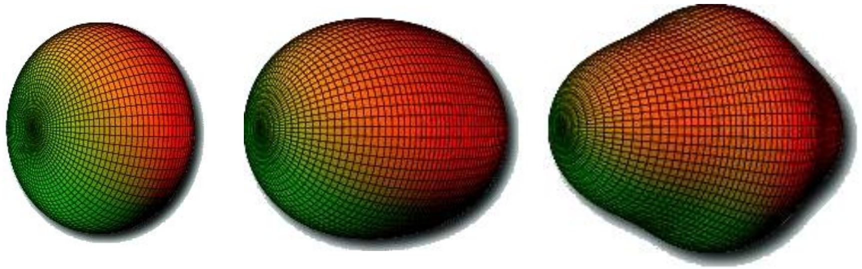
Isotope shifts in atomic level energies
reflect changes in mean square charge radii

→ **nuclear size**



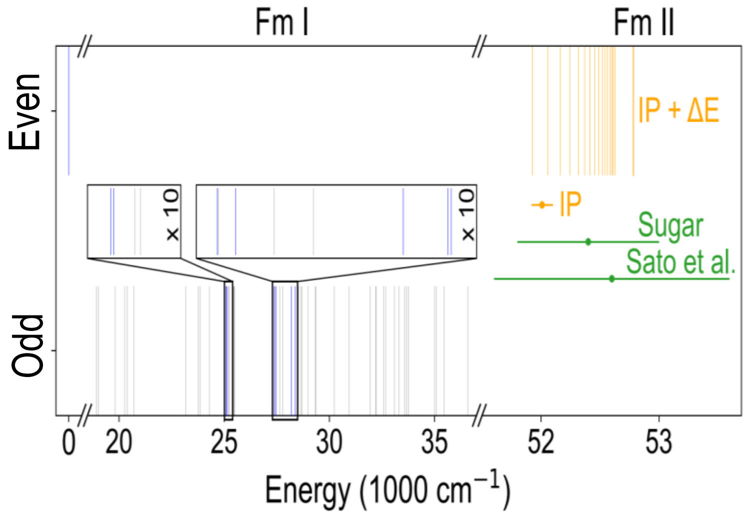
Hyperfine structure of individual lines in odd-A / odd-odd isotopes
reflects magnetic dipole moment
& spectroscopic quadrupole moment

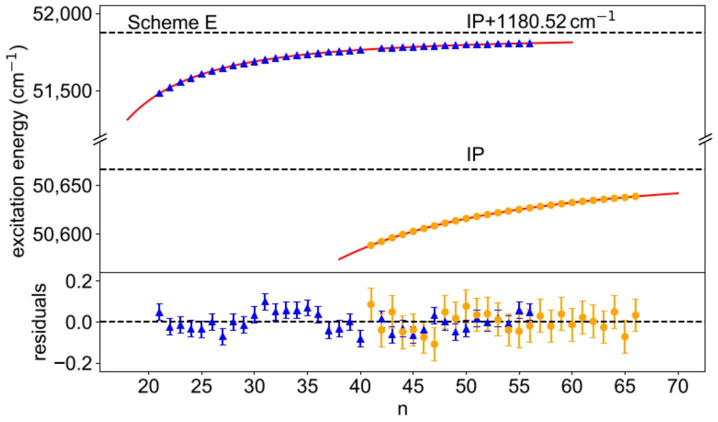
→ **nuclear shape**



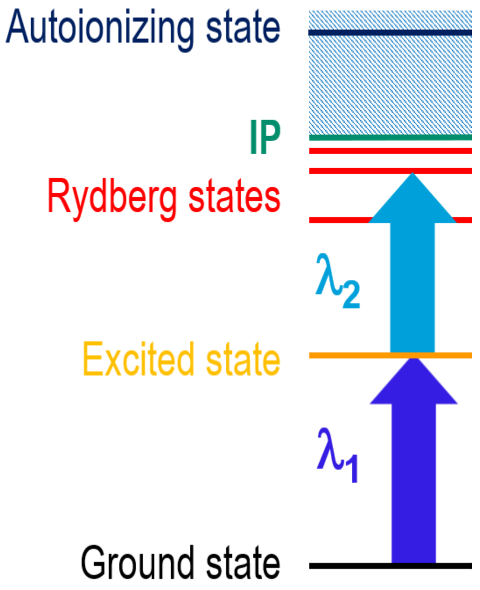
Rydberg spectroscopy

→ **ionization potential**

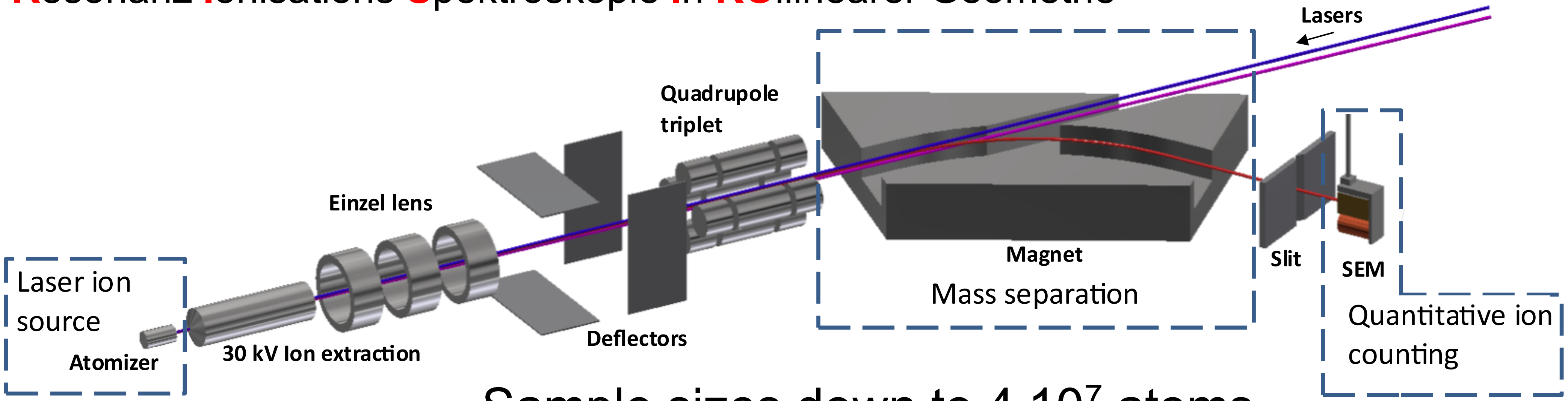




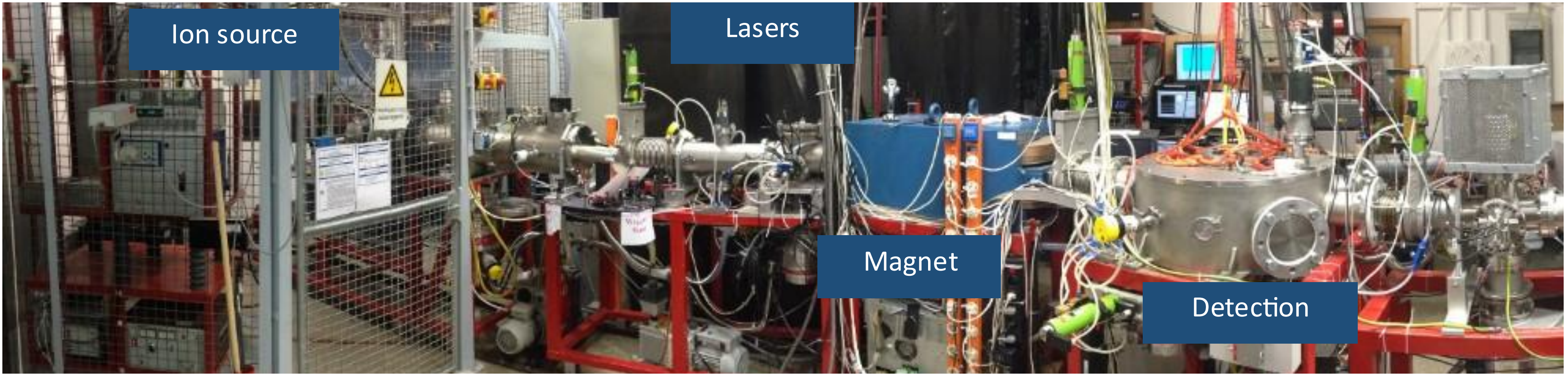
RISIKO Laser-Ionization Mass Spectrometer



Resonanz Ionisations Spektroskopie In KOllinearer Geometrie



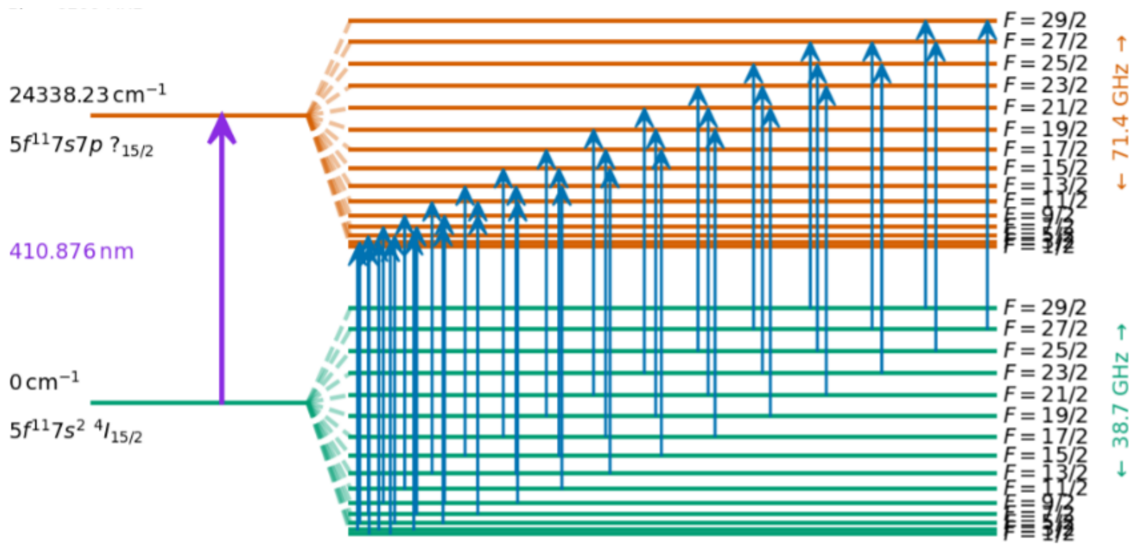
Sample sizes down to $4{\cdot}10^7$ atoms



Slide courtesy S. Berndt

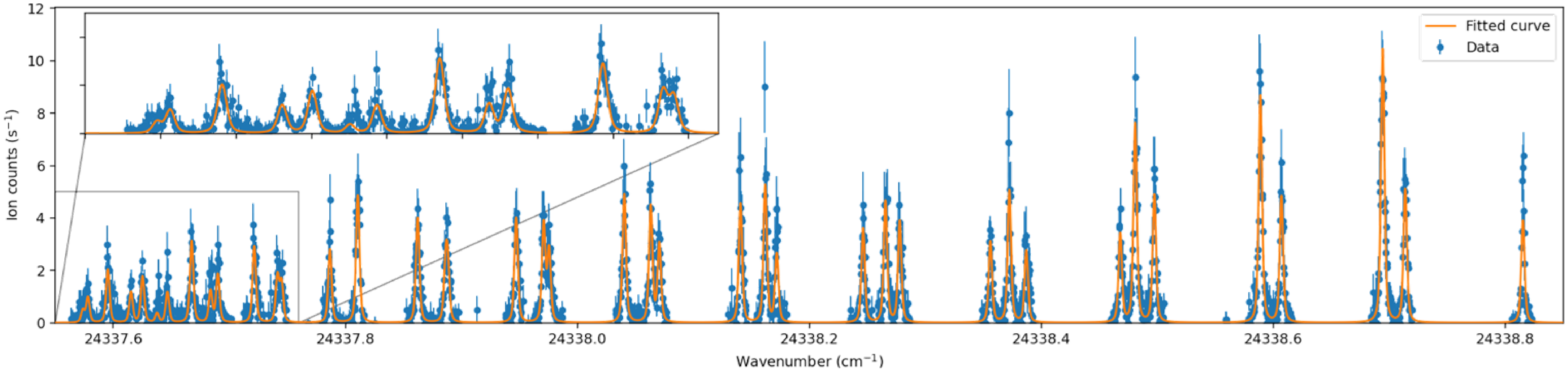
T. Kieck *et al.*, Nucl. Instrum. Meth. A 945 (2019) 162602

Example: hyperfine spectroscopy in ^{254}Es



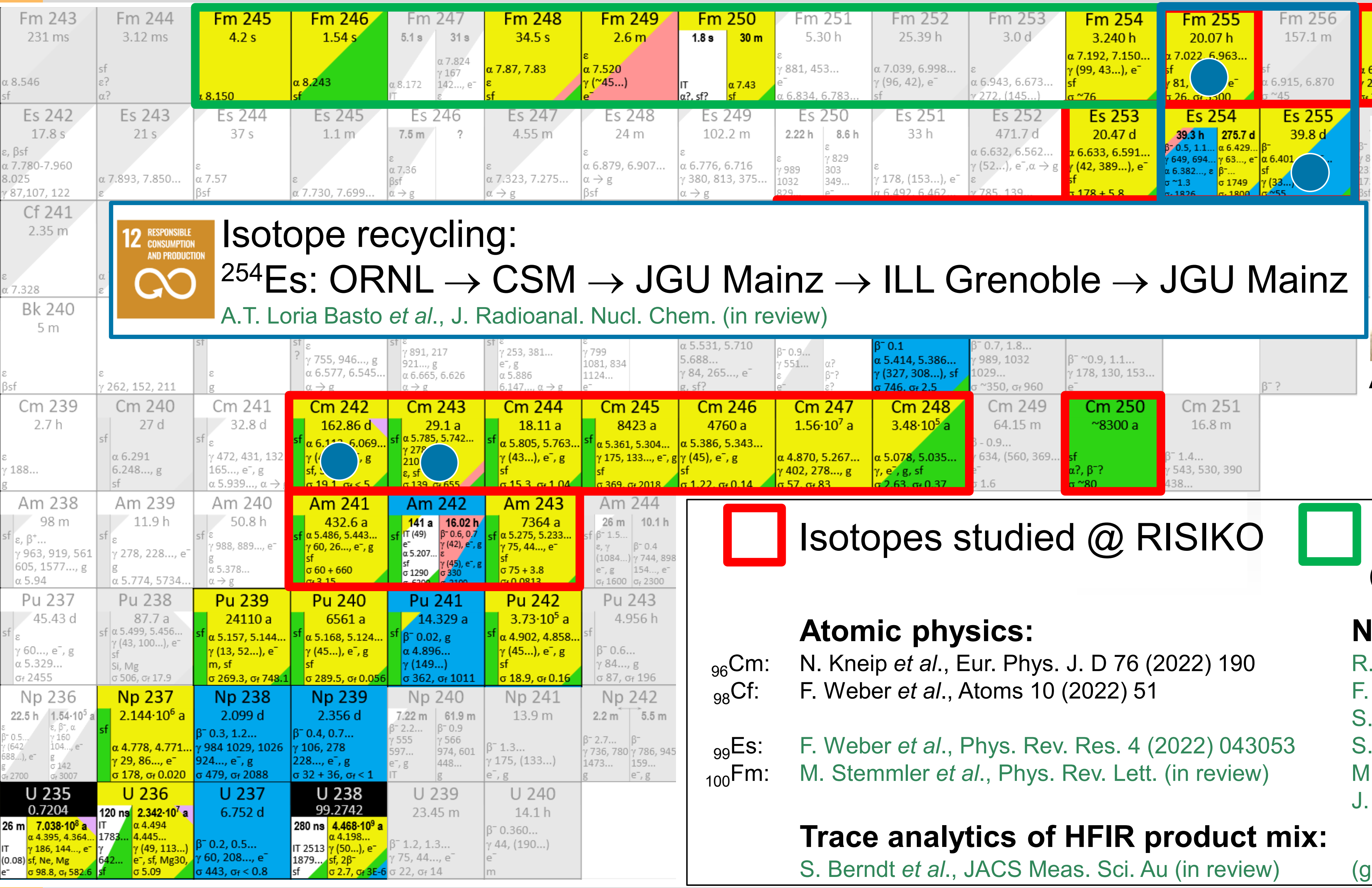
- Measured with PI-LIST ion source
- Spectral bandwidth of ~ 100 MHz
- Hyperfine coupling constants in agreement with low resolution (1-2 GHz) measurement

(S. Nothhelfer *et al.*, Phys. Rev. C 105 (2022) L021302)



Manuscript in preparation

Overview

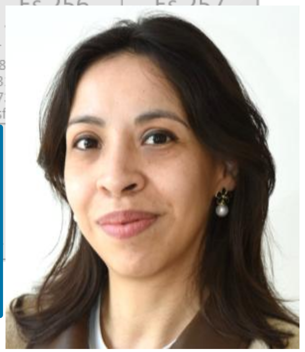


12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Isotope recycling:

^{254}Es: ORNL → CSM → JGU Mainz → ILL Grenoble → JGU Mainz

A.T. Loria Basto *et al.*, J. Radioanal. Nucl. Chem. (in review)



A.T. Loria Basto

After post-irradiation @ NEUTRONS FOR SOCIETY

Isotopes studied @ RISIKO

Isotopes studied online @ GSI (also on $_{102}$No isotopic chain, not shown)

Atomic physics:

$_{96}$Cm: N. Kneip *et al.*, Eur. Phys. J. D 76 (2022) 190

$_{98}$Cf: F. Weber *et al.*, Atoms 10 (2022) 51

$_{99}$Es: F. Weber *et al.*, Phys. Rev. Res. 4 (2022) 043053

$_{100}$Fm: M. Stemmler *et al.*, Phys. Rev. Lett. (in review)

Nuclear physics:

R. Hasse *et al.*, in prep.

F. Weber *et al.*, Phys. Rev. C 107 (2023) 034313

S. Berndt *et al.*, Phys. Rev. Lett. (in review)

S. Nothhelfer *et al.*, Phys. Rev. C 105 (2022) L021302

M. Urquiza *et al.*, Phys. Rev. Lett. 136 (2026) 192501

J. Warbinek *et al.*, Nature 634 (2024) 1075

Trace analytics of HFIR product mix:

S. Berndt *et al.*, JACS Meas. Sci. Au (in review)

(green entries: w/ ORNL co-authors & DOE Acknowl.)

The fermium collaboration

Univ. Mainz
Julian Auler
Sebastian Berndt
Holger Dorrer
Christoph E. Düllmann
Vadim Gadelshin
Raphael Hasse
Magdalena A. Kaja
Nina Kneip
Mustapha Laatiaoui
Andrea T. Loria Basto
Christoph Mokry
Thorben Niemeyer
Dennis Renisch
Jörg Runke
Matou Stemmler
Petra Thörle
Norbert Trautmann
Felix Weber
Klaus Wendt

GSI Darmstadt
Michael Block
Manuel Gutiérrez-Torres
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Kenneth van Beek
Jessica Warbinek

ILL Grenoble
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FSU Tallahassee
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Alyssa Gaiser
Joseph Sperling

HÜBNER Photonics
Korbinian Hens
Volker Sonnenschein
Mitzi Urquiza-González

HIM Mainz
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Tom Kieck
Jeremy Lantis
Danny Münzberg
Steven Nothhelfer
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Kristian Mhyre
Samantha Schrell
Shelley Van Cleve

TU Darmstadt
Thomas Walther

Nagoya University
Hideki Tomita

CERN
Reinhard Heinke

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S. Karpuk

ILL Grenoble
ILL reactor team and health physics

Oak Ridge National Laboratory
Nate Sims, Radioisotope Laboratory Technician
Nonreactor Nuclear Facilities Division Hot Cell Staff

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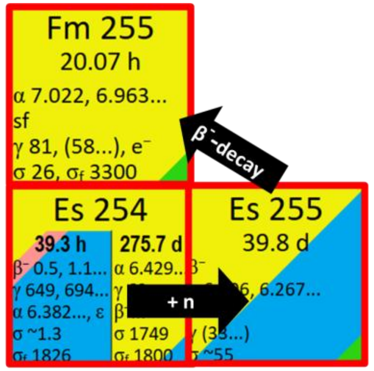
This research is supported by the U.S. DOE, Office of Science, BES Heavy Element Chemistry program. The isotopes used in this research were supplied by the U.S. DOE Isotope Program, managed by the Office of Science for Nuclear Physics.

2026/2027: Plans for the next ^{254}Es++ campaign



1) production of the sample / handling at Mines / shipment: Joe Sperling / Thomas Albrecht

2) considerations for the ILL irradiation: Ulli Köster

3) cross section (verification) measurements of Es-254, Es-255: Melanie Feucht

4) direct measurement of the ionization potential of Fm (Fm-255): Sebastian Berndt / Sebastian Raeder / Jana Weyrich

5) development of three-step ionization schemes for Fm (Fm-255): Sebastian Berndt / Sebastian Raeder / Jana Weyrich

6) biological effects of single 7-MeV alpha particles (Fm-255): Charlot Vandevoorde / Martina Benesova-Schäfer / Isabelle Miederer

7) development of three-step ionization schemes for Es (Es-254): Sebastian Berndt / Sebastian Raeder / Jana Weyrich

8) hyperfine structure studies in Bk-250 (from Es-254): Julian Hindermann

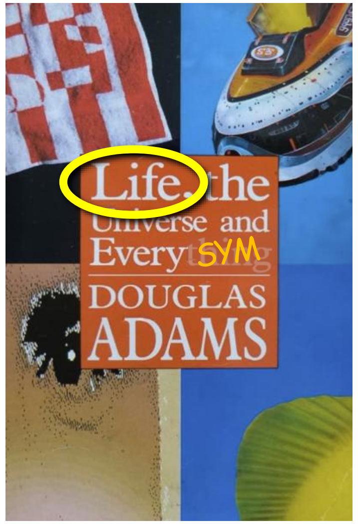
9) Penning trap high-precision mass measurement of Es-254: Tanvir Sayed

10) Bk-250 BDF search: Thomas Cocolios

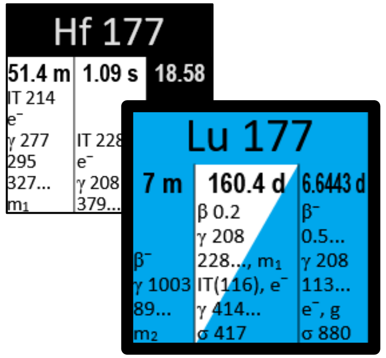
12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Sample size: 68 ng

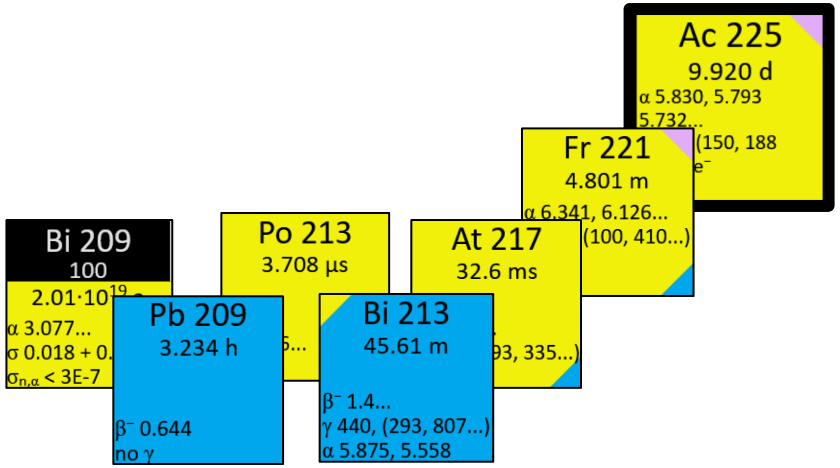
Next ^{254}Es sample – will serve multiple partners, including fundamental studies towards prostate cancer treatment



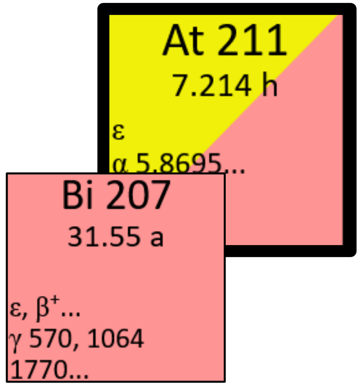
Current workhorse: Lu-177

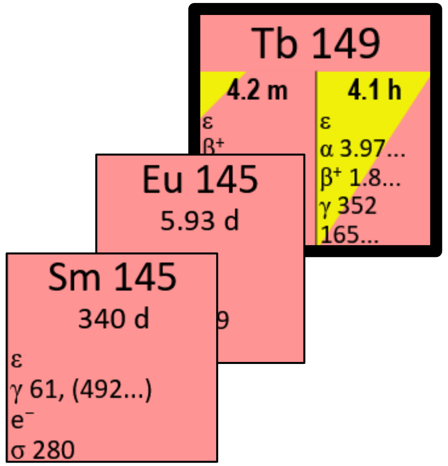


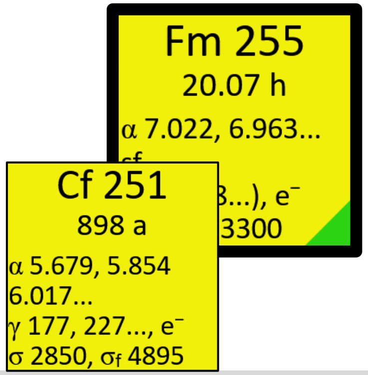
Future workhorse: Ac-225



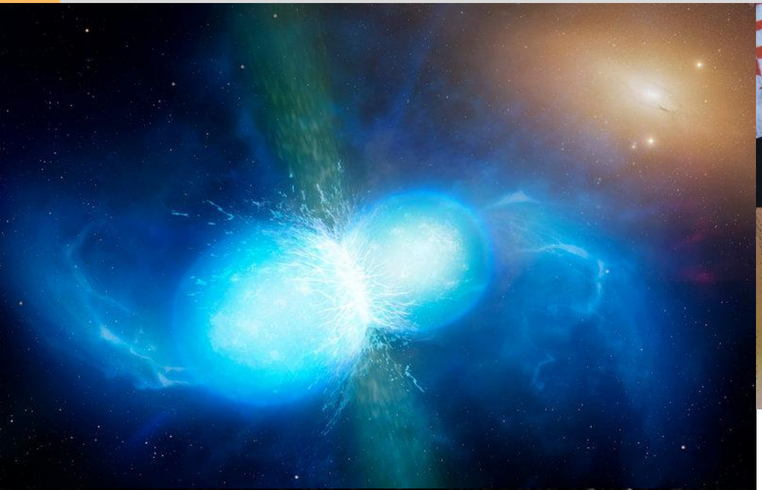
- Going towards targeted alpha-therapy
- But: Ac-chain emits multiple alphas over time that is sufficiently long for redistribution in human body
  - → How to disentangle the influence of different effects?
  - → Needs „single" α-emitter w/o decay chain
- **Example 1: At-211** → Chemistry is very different.
  - → Will DOTA work?
- **Example 2: Tb-149**
  - Low alpha energy
  - Low alpha branch (25%)
  - Hard to get
- **Example 3: Fm-255**
  - High alpha energy
  - 100% alpha branch
  - Almost impossible to get

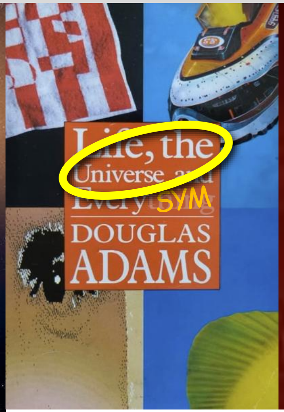






🙏 #2: 1 μg ^{254}Es for biomed++ research





How does the life of a neutron star end?

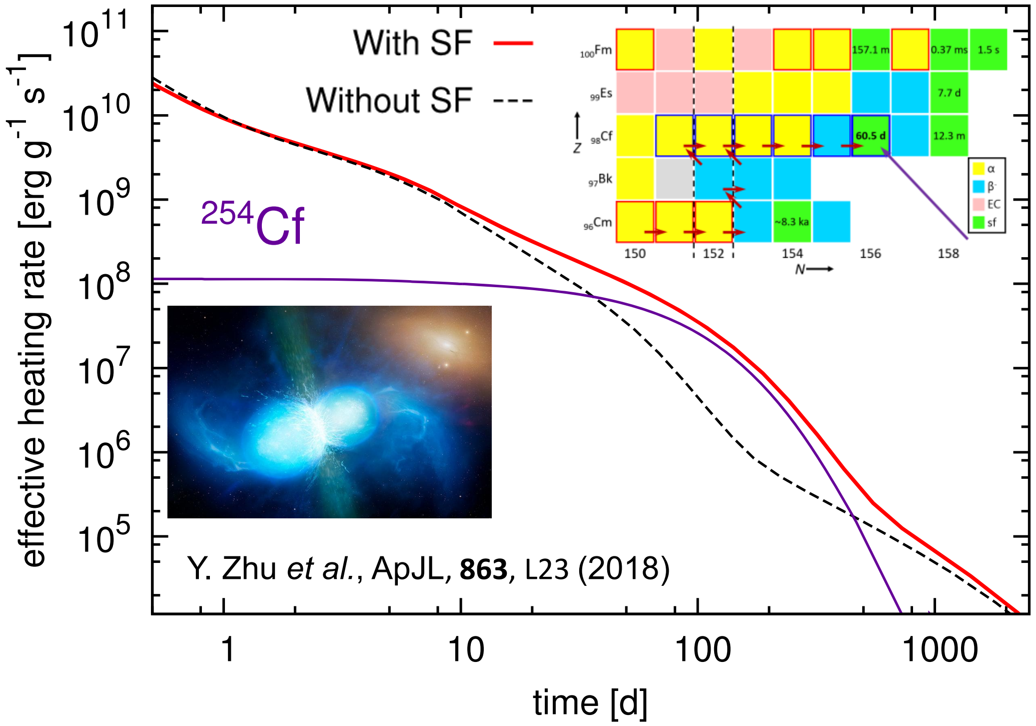
…and where do the heavy elements on Earth come from?

Heavy elements from neutron-star mergers

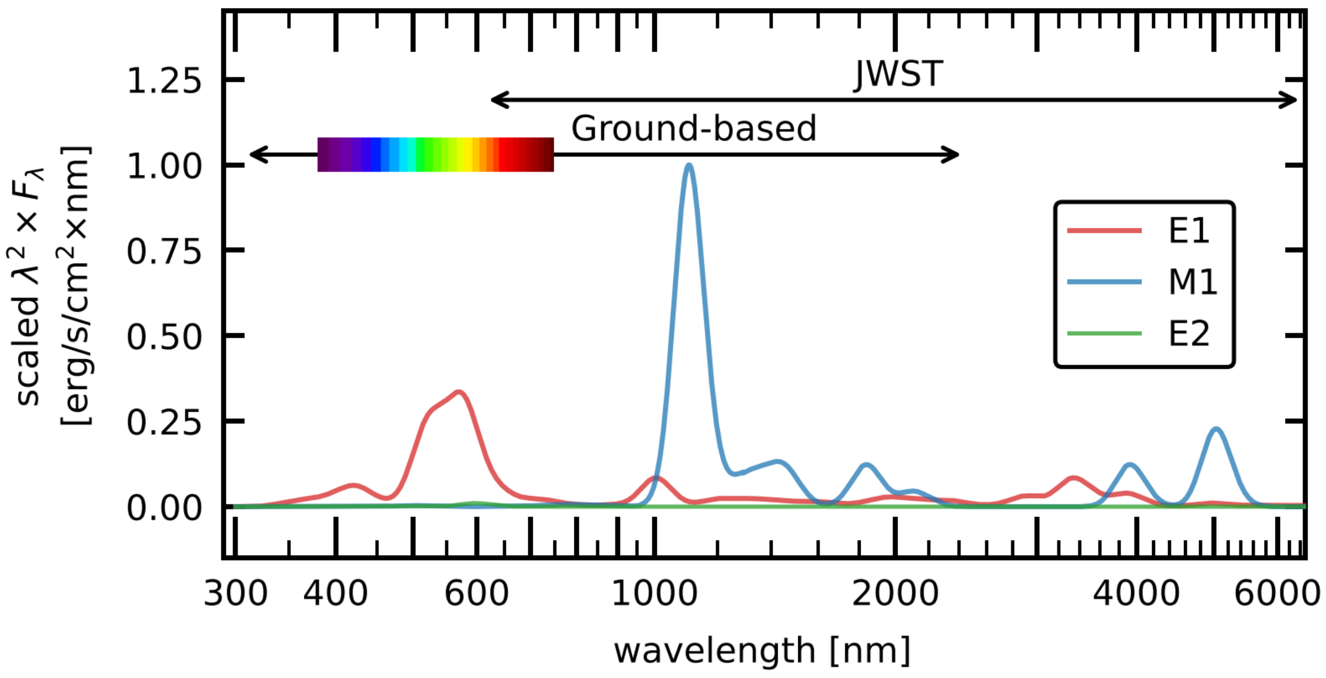
Two merging neutron stars create a luminous event called “kilonova“

To date: exactly one kilonova was observed, ever (2017, LIGO collaboration et al.)

Predicted light-curve after 30 days is dominated by 60-d SF isotope ^{254}Cf



Y. Zhu *et al.*, ApJL, **863**, L23 (2018)

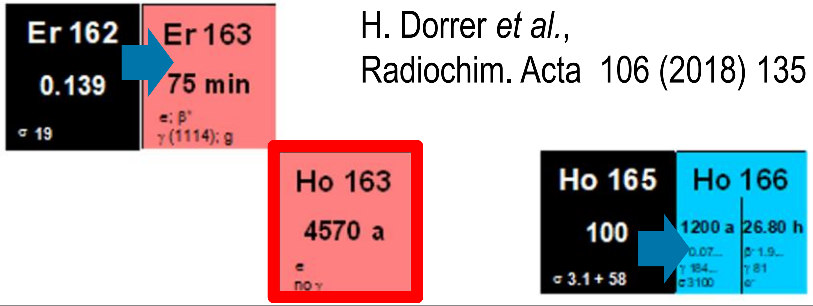


→ production fo $4{\cdot}10^7$ atoms of ^{254}Cf from ^{252}Cf-impurity in ORNL’s ^{254}Es sample

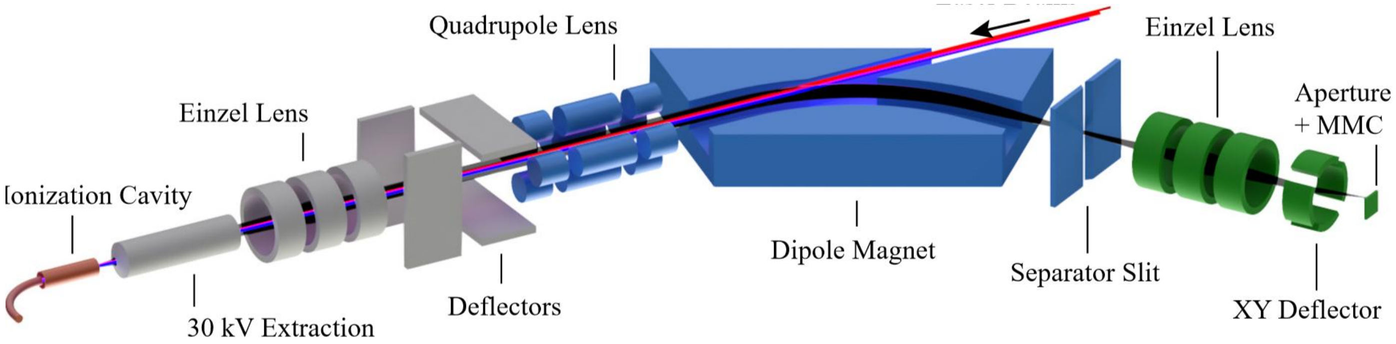
Measurement of two atomic transitions; calculation of Cf I emission spectrum

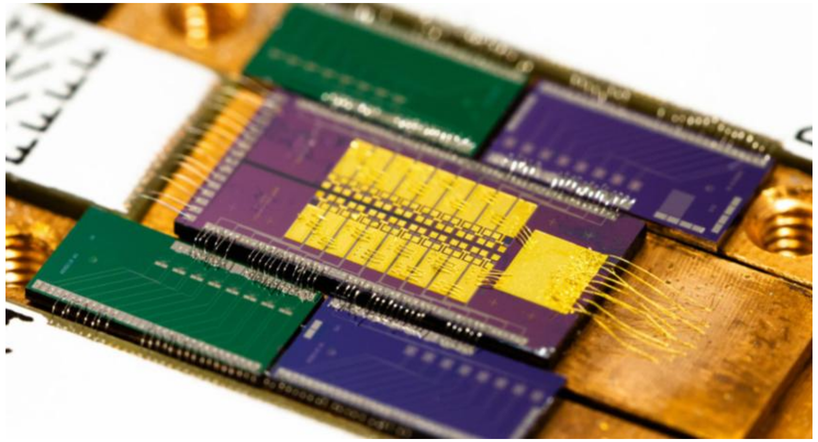
S. Berndt *et al.*, under review w/ Phys. Rev. Lett.

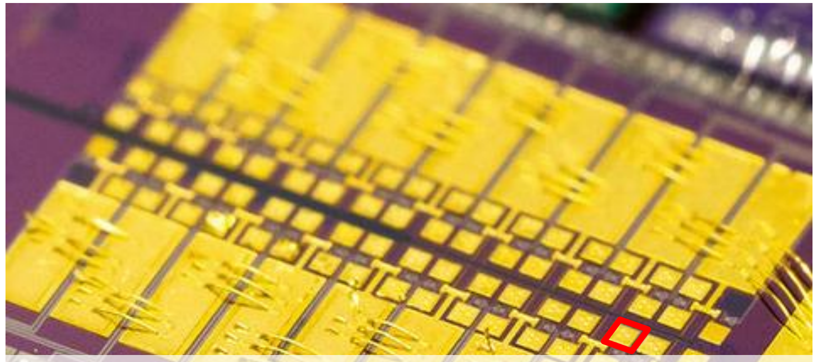
RISIKO as an ion implantor for neutrino physics



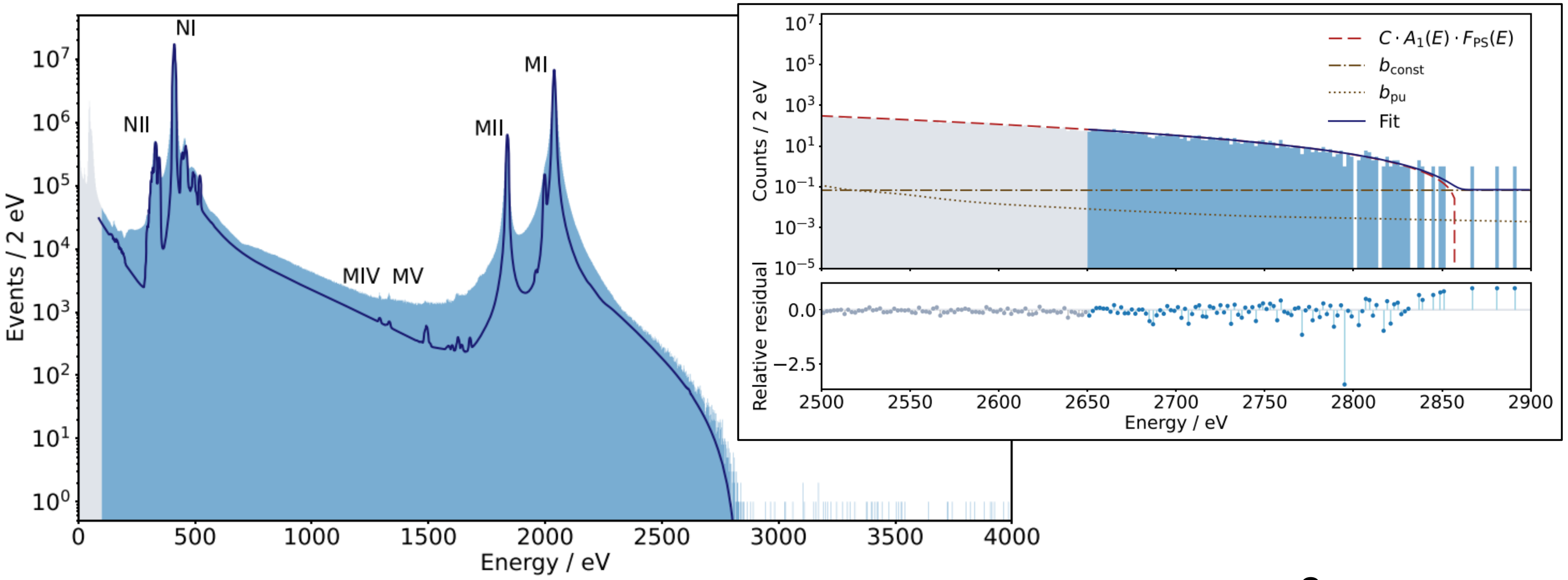
H. Dorrer *et al.*,
Radiochim. Acta 106 (2018) 135







180 x 180 µm^2 microcalorimeters



$m(\nu_e) < 15$ eV/c^2 (90% c.l.)

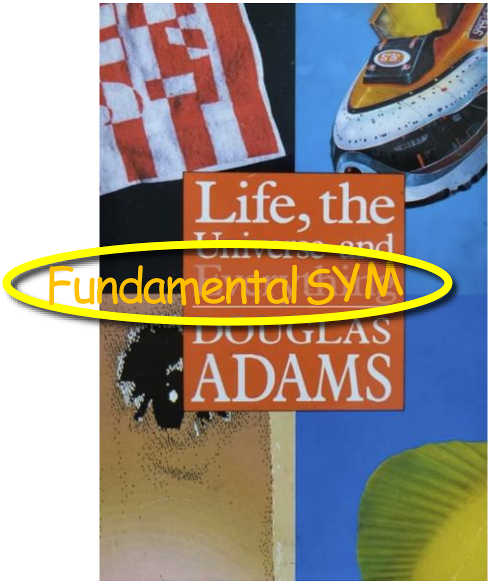
F. Adam *et al.*, Phys. Rev. Lett. 136 (2026) 121801

https://press.uni-mainz.de/hunting-for-the-neutrino-mass-with-cool-detectors/

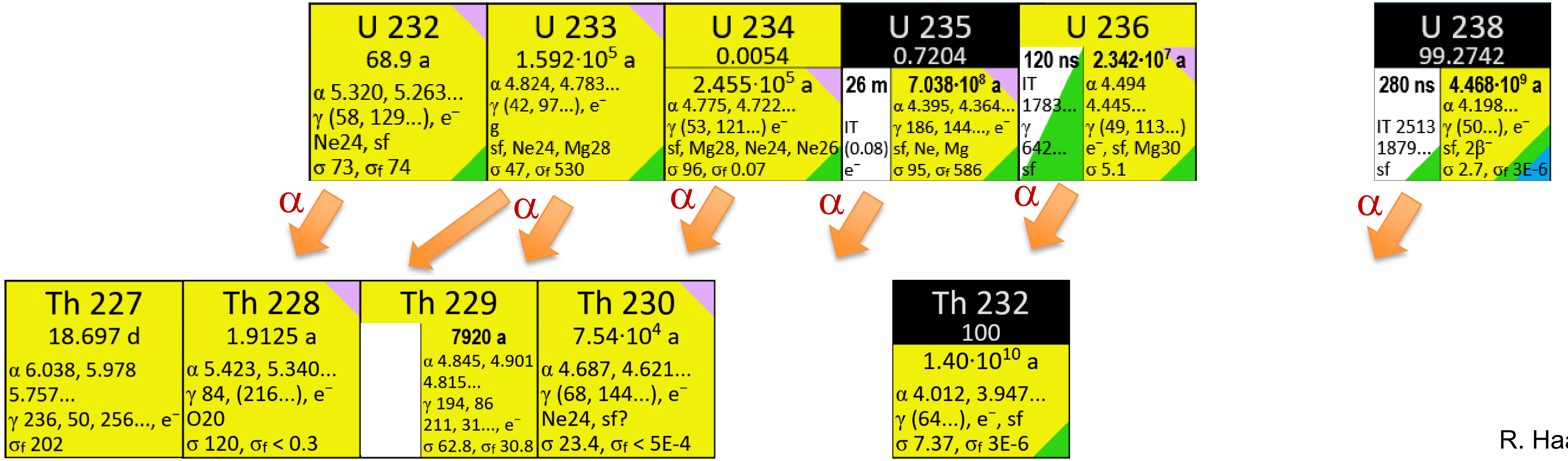
cf. Talk by Justin Griswold

Content of this presentation

- The (Oak Ridge &) Mainz (& ILL Grenoble) actinide program
- Application 1: Superheavy element research at GSI based on ORNL actinides
- Application 2: Laser++ experiments for nuclear and atomic physics and trace analytics
- Application 3: Samples for the fundamental symmetry community
- Summary



Uranium and thorium nuclei



R. Haas *et al.*, Hyp. Int. 241 (2020) 241

- ^{228,229g,230,232}Th are available as long-lived macroscopic samples; ^{227}Th via dedicated effort
- Alpha-decays of long-lived U isotopes populate a long Th isotopic chain, including ^{229m}Th
- Nuclear decay leads ions to recoil from sample with 70-100 keV kinetic energy
- For trapping, slowed-down ions are required

Our 1.6 mg ^{229}Th comes from a 2017 chemical separation from 9.0 g legacy ^{233}U certified 08/27/1965 $^{(*)}$

(*) cf. backup slides

Providing molecular reagents in the Th target

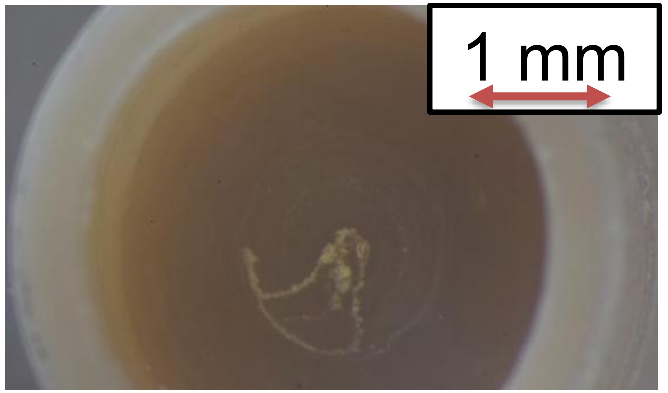
- Most actinide isotopes are not available in metallic form → ablation of salt-targets
- Adding foreign elements as a component of the salt
- Optimize species and charge state by laser spot size / laser beam power
- Analysis of produced species via ToF-MS

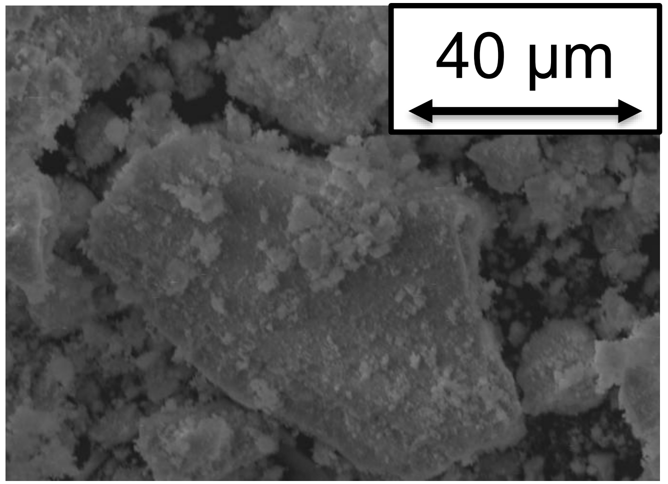
J. Stricker,
Master's thesis
University *of* Mainz (2023)

J. Stricker *et al.*,
Phys. Rev. A 112 (2025) 012821

J. Stricker

Synthesis of a ThF_4 ablation target





- Synthesis of $^{232}ThF_4$ in microgram scale:
- Reaction of 10 µg $Th(NO_3)_4$ with hydrofluoric acid:

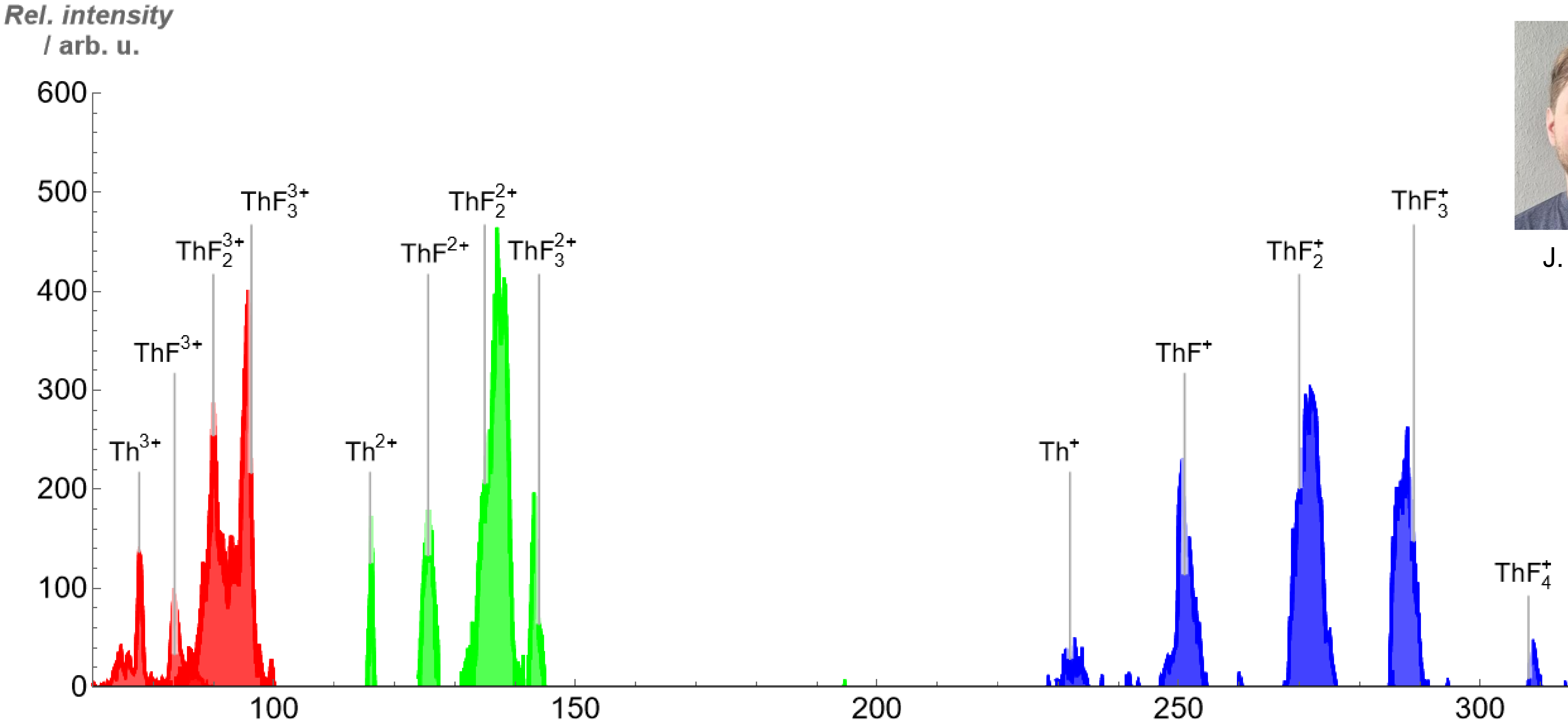
$$Th(NO_3)_4\,(s) + 4\,HF\,(aq.) \rightarrow ThF_4\,(s) + 4\,HNO_3\,(g)\uparrow$$

- Direct synthesis on target holder
  -Thorium fluoride is inert
  -Reduce loss of product
- Quantitative reaction and oxygen free product
  Analyzed by:
  - scanning electron microscopy
  - energy dispersive X-ray spectroscopy
  - X-ray diffraction (by O. Walter @ JRC Karlsruhe)

Slide courtesy Jonas Stricker

J. Stricker *et al.*, Phys. Rev. A 112 (2025) 012821

Synthesis of a 10 μg $^{232}ThF_4$ ablation target



J. Stricker

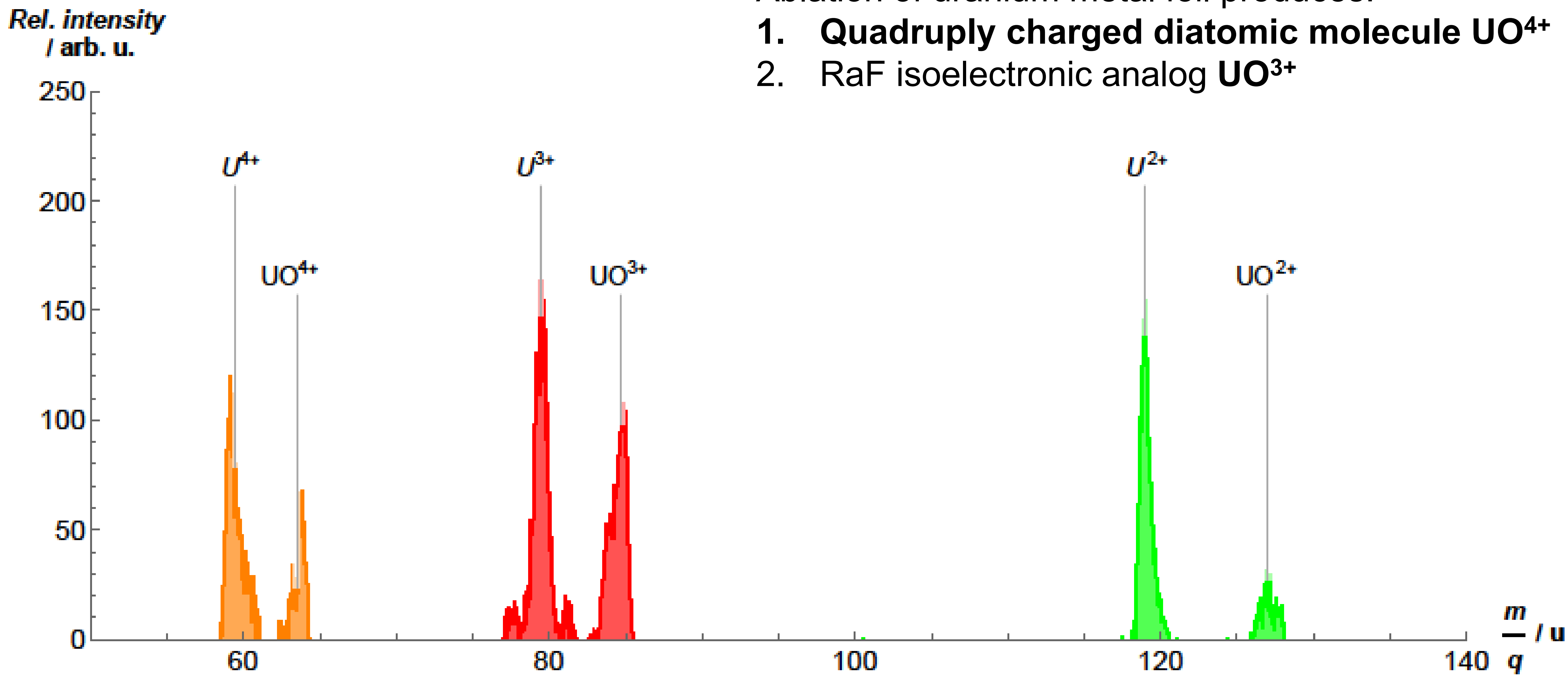
Relative abundance of species depends on laser power

J. Stricker *et al.*, Phys. Rev. A 112 (2025) 012821

From Th to U: Ablation of U metal foil

Ablation of uranium metal foil produces:

1. **Quadruply charged diatomic molecule UO^{4+}**
2. RaF isoelectronic analog **UO^{3+}**

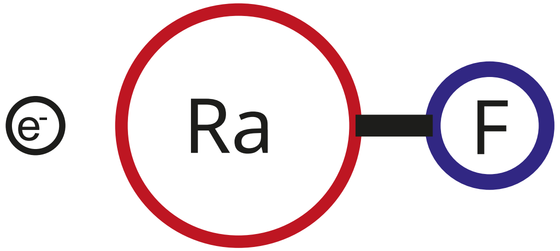


J. Stricker *et al.*, submitted (2025), https://arxiv.org/abs/2512.14924

Multiply charged actinide molecules

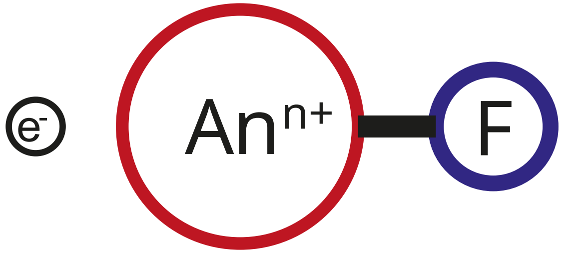
[RaF]^0 :

- One unpaired electron
  → Enhanced polarity in molecule
  → Better chances to detect CP-violations



Beyond Standard Model

RaF	AcF	ThF	PaF	UF	NpF	PuF
	1+	2+	3+	4+	5+	6+



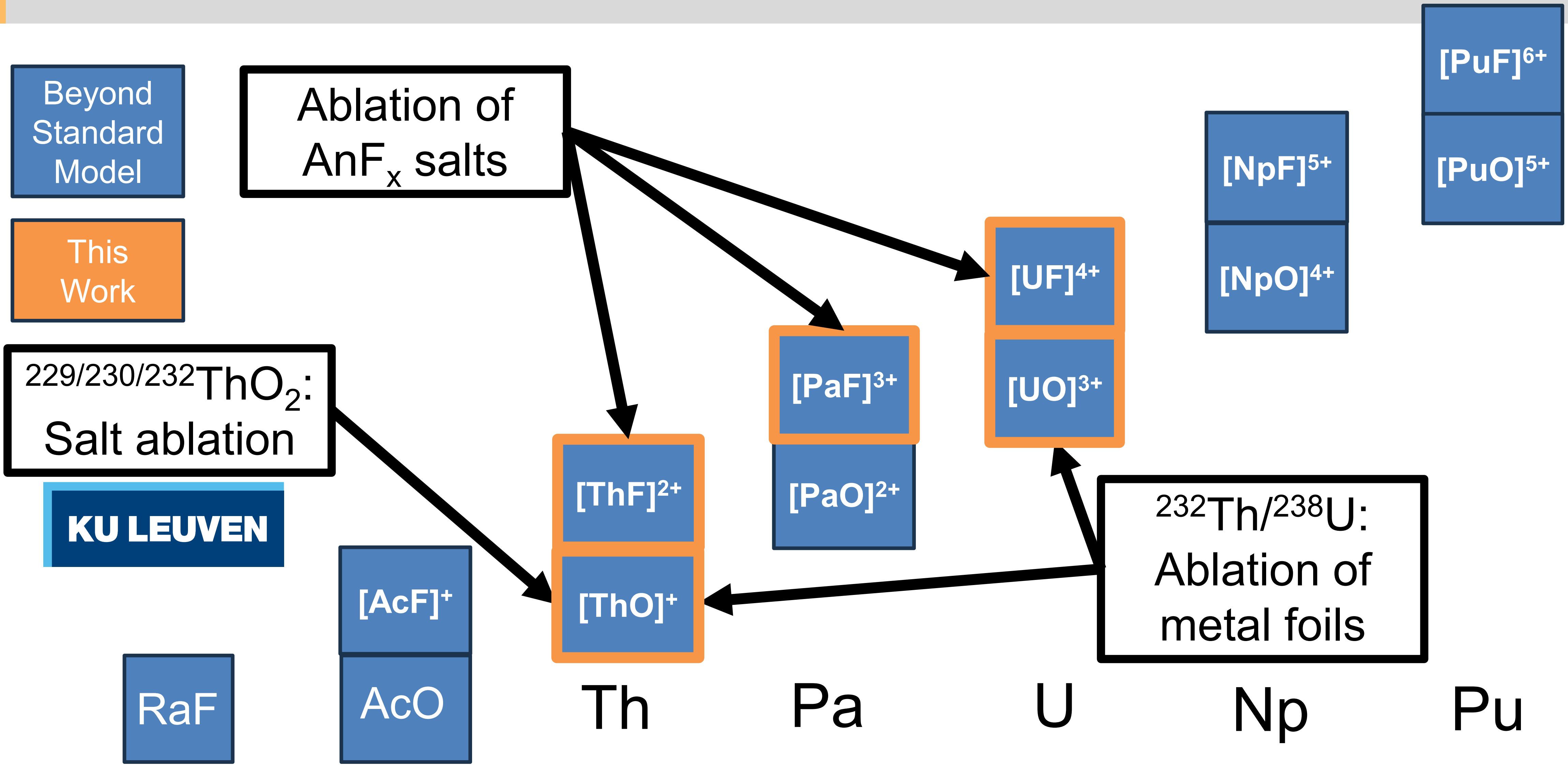
[AnF]$^{n+}$:

- Isoelectronic to **[RaF]^0**
- Trappable inside ion traps
- Variety of isotopes available
- Deformed nuclei ideal to study nuclear structure

Slide courtesy Jonas Stricker

C. Zülch, et al., arXiv physics.chem-ph, 2203.10333371 (2022).
R. F. Garcia Ruiz et al., Nature 581, 396 (2020).

Overview molecular actinides for BSM



Slide courtesy Jonas Stricker

J. Stricker *et al.*, Phys. Rev. A 113 (2025) 012821
S. B. Diewald, B.Sc. thesis (2025), JGU Mainz.
P. Fischer *et al.*, Eur. Phys. J. D (2025) 79 :30
J. Stricker *et al.*, https://arxiv.org/abs/2512.14924

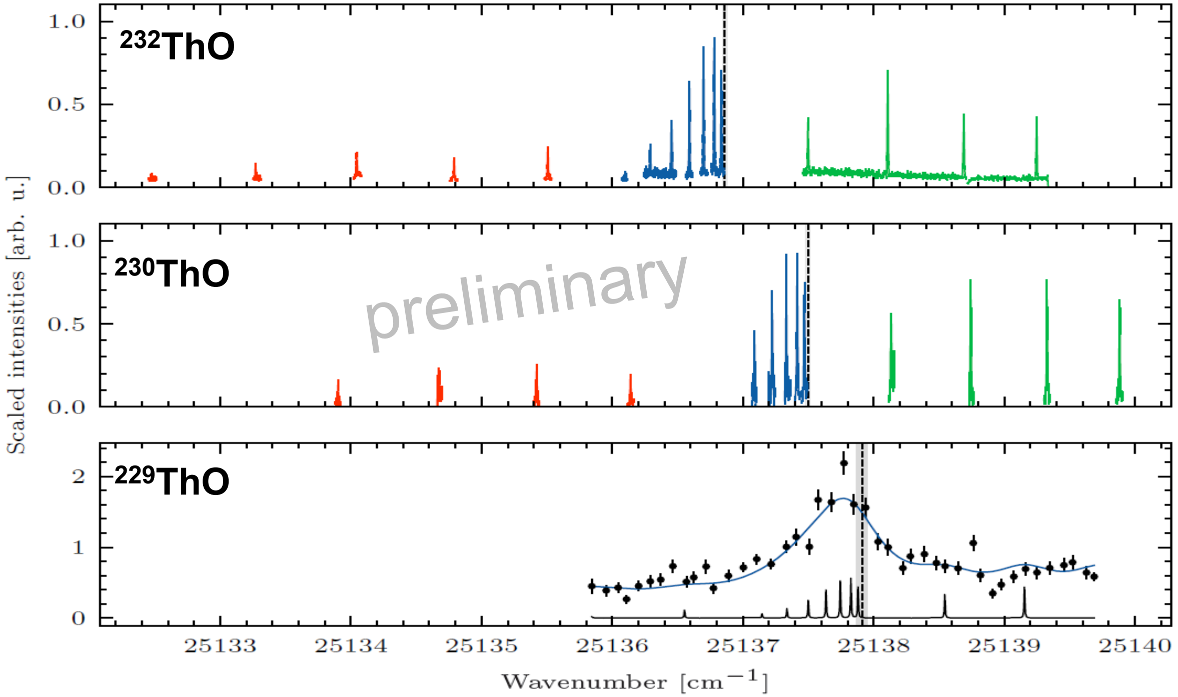
Isopologue shifts from Th-triflate ablation sources

Th ablation targets

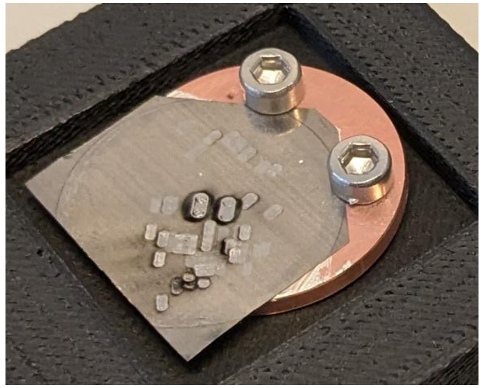
Isotopes	Mass (mg)	A (kBq)	Dia. (cm)	Thickness (μm)
Th-230, 232	1.95	20	2.5	1.8 ± 0.4
Th-230, 232	1.32	19	2.5	2.0 ± 0.4
Th-229, 232	0.67	20	1.0	8.56±12
Th-229, 232	2.67	11	1.0	14.07±18
Th-229, 232	0.34	5	1.0	18.53±21

Targets by L. Arndt
(Student assistant @ JGU)

IGLIS on U–X transition ^{232}ThO vs ^{230}ThO vs ^{229}ThO



- Two transitions (U-X and B' -X) studied in broad- and narrowband
- Full studies done with a fraction of one 20 kBq (10^{16} atoms) target →



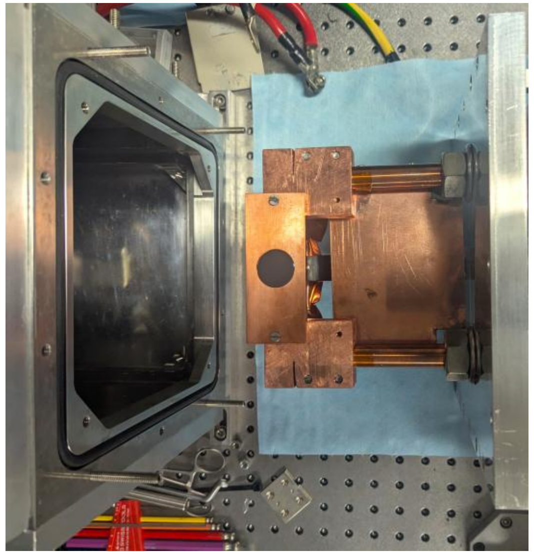
Slide courtesy R. Ferrer and A. Claessens
Cf. talk by Shane Wilkins

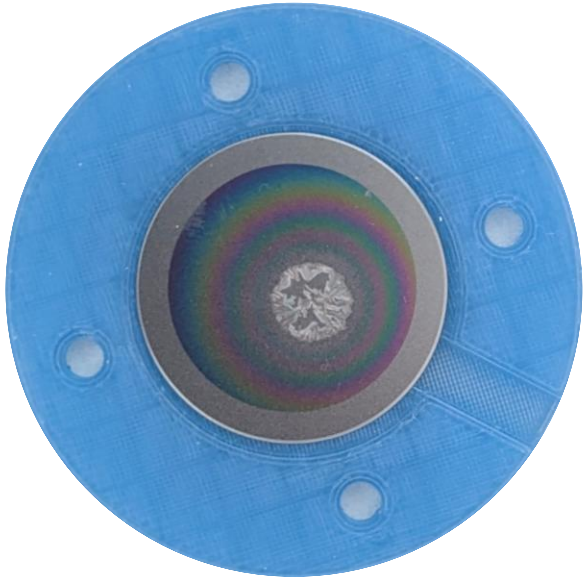
Th fluoride thin films (CERN ISOLDE and TU Vienna)

1. VUV beamtime at CERN ISOLDE

2. Cooperation with TU Vienna: Preparation of ThF_4 powder

3. Thin layers for University of Vienna





Targets by S.B. Diewald
(Student assistant @ JGU)

The Stricker target mail-order business

🙏 #3: 1 mg ^{229}Th for fundamental physics

(locations are approximate)

Summary

- The (Oak Ridge &) Mainz (& ILL Grenoble) actinide program
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U.S. DEPARTMENT OF ENERGY | Office of Science

🙏 #1: 100 mg ^{248}Cm for $_{116}$Lv chem.++

🙏 #2: 1 µg ^{254}Es for biomed++ research

🙏 #3: 1 mg ^{229}Th for fundamental physics

Thank you for the opportunity to be a part of this workshop!

Backup

^{229}Th at Institute of Nuclear Chemistry in Mainz

Our isotope inventory includes:

9.0 g ^{233}U, certified 27. Aug. 1965.

Isotopic composition

232	233	234	235	236	238
10.8 ppm	87.87%	0.83%	0.09%	<0.03%	11.21%

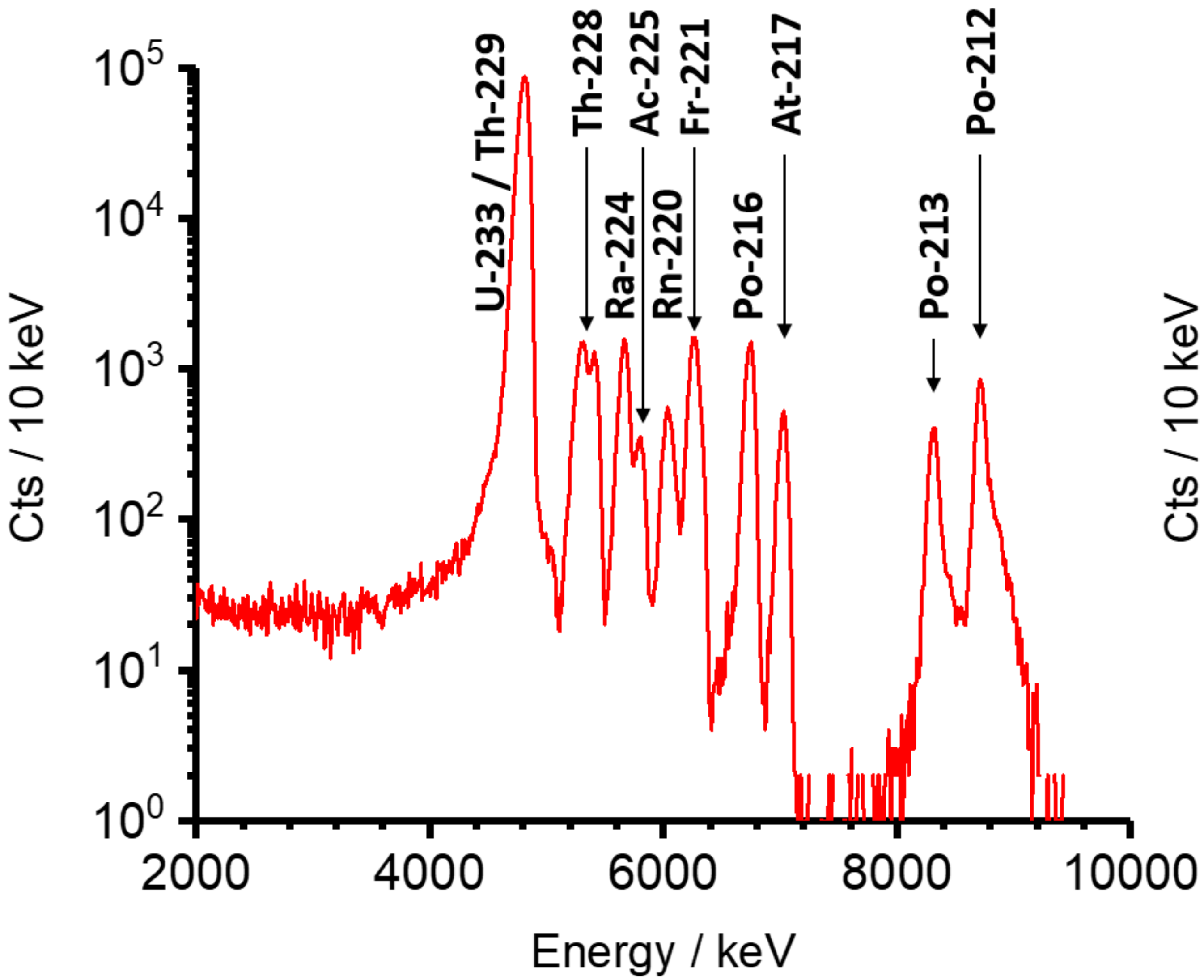
Chemical separation of in-grown (>50 yrs) ^{229}Th in June 2017

Dissolve U in ~100 ml 8 M HCl, make four ~25 ml batches

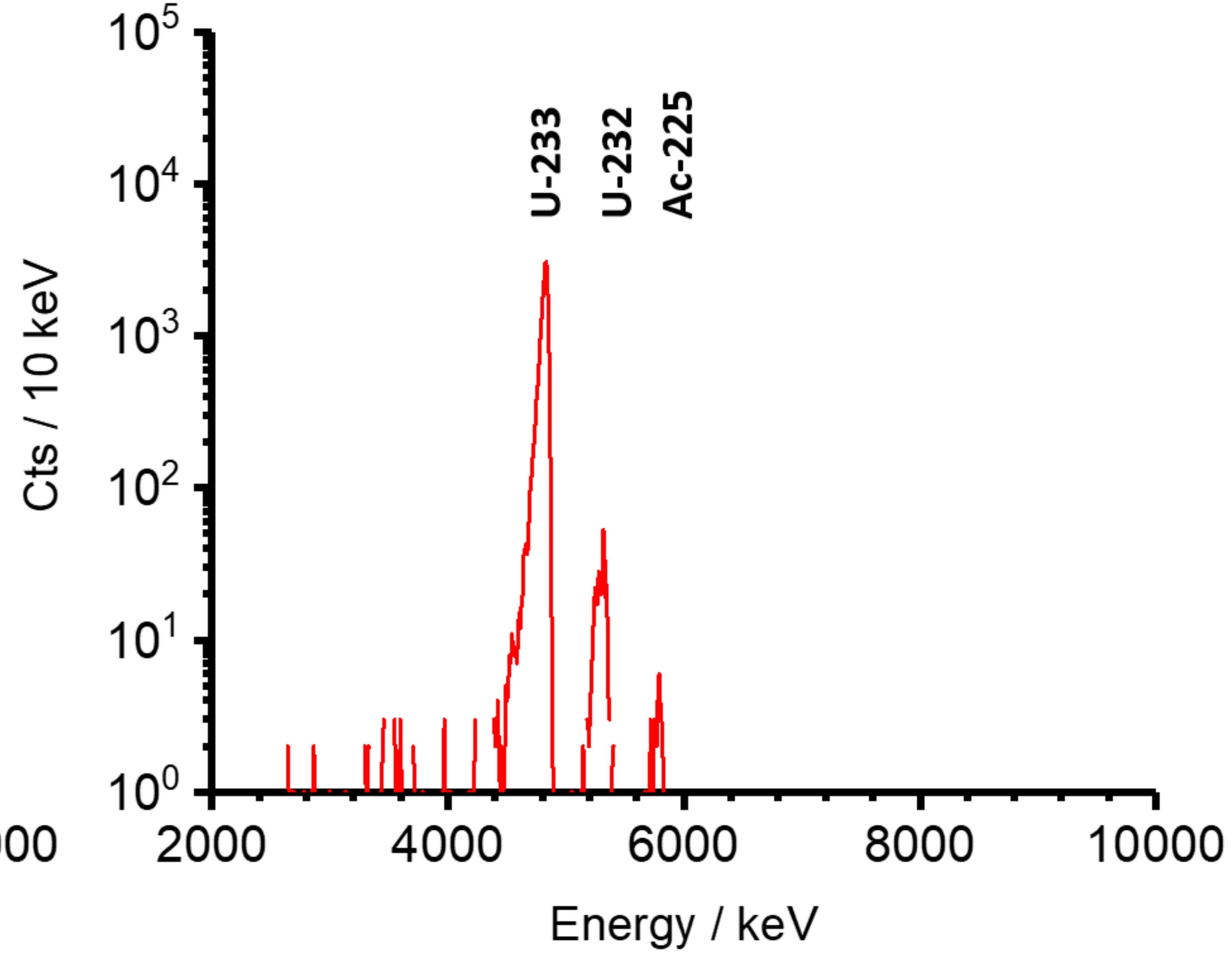
Anion exchange chromatography (resin AG 1X8)
Column length: 500 mm
Column diameter: 8 mm

^{233}U α spectra before and after chemical purification

Before separation



After separation

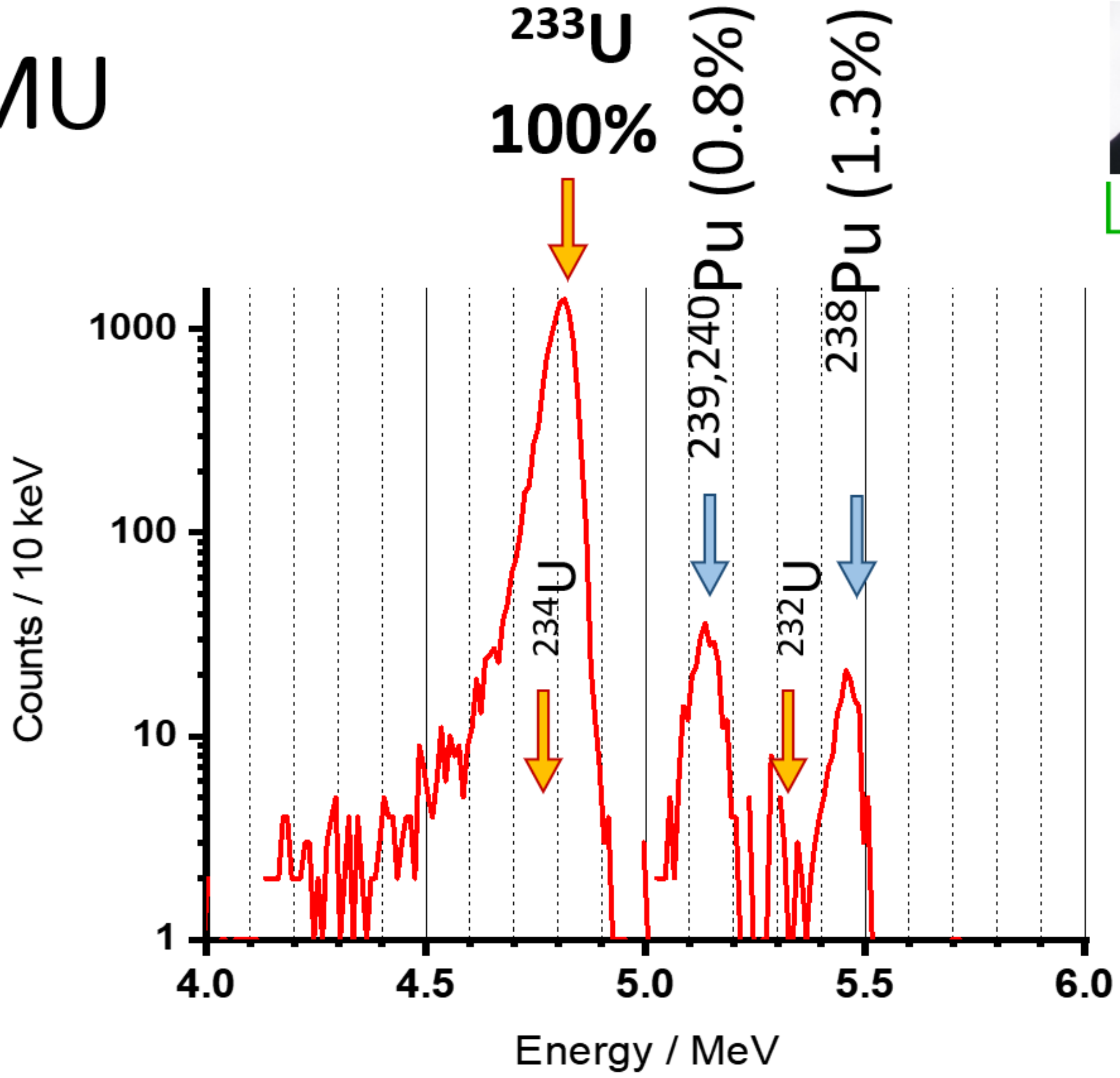


^{233}U recoil sources for LMU

Chemical purification:
removal of in-grown daughters

1) Dissolution of U in 8 M HCl
2) Anion exchange chromatography
   (resin AG1X8)
   → U remains on column
   → Th and daughters are eluted
3) Elution of Uranium with 0.5 M HCl

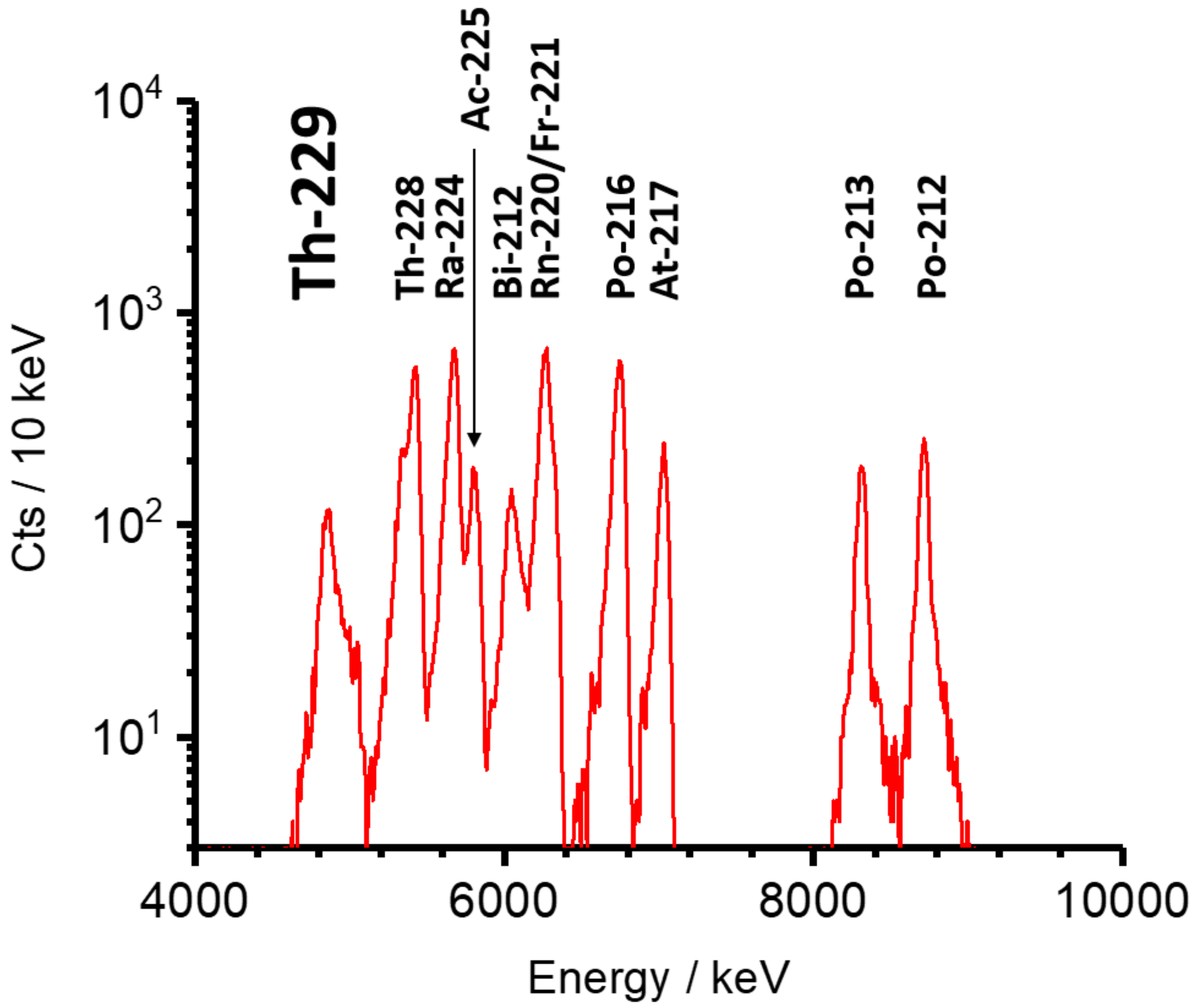
Relative purification factor: >250
(γ spectra before/after purification)



Atom content from α and γ spectrometry

U-233: ≈ 1 U-232: $6\cdot10^{-7}$ U-234: $2\cdot10^{-2}$
Pu-238: $4\cdot10^{-6}$ Pu-239: $2\cdot10^{-3}$

^{229}Th eluate α spectrum



Full sample (currently w/ daughters):

^{229}Th: 12.22 MBq (1.67 mg)

(amount confirmed via ^{217}At daughter in secular equilibrium: 11.97 MBq)

^{228}Th: 38.4 MBq (1.27 μg)

(amount confirmed via ^{224}Ra daughter in secular equilibrium: 38.0 MBq)

Content in atom numbers:

^{229}Th: 0.99924

^{228}Th: 0.00076

Available for nuclock