Production of actinide atomic and molecular ion beams at CERN-ISOLDE

LISA conference 2024

M. Au | CERN SY-STI-RBS

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

Outline: Actinide beams at CERN-ISOLDE

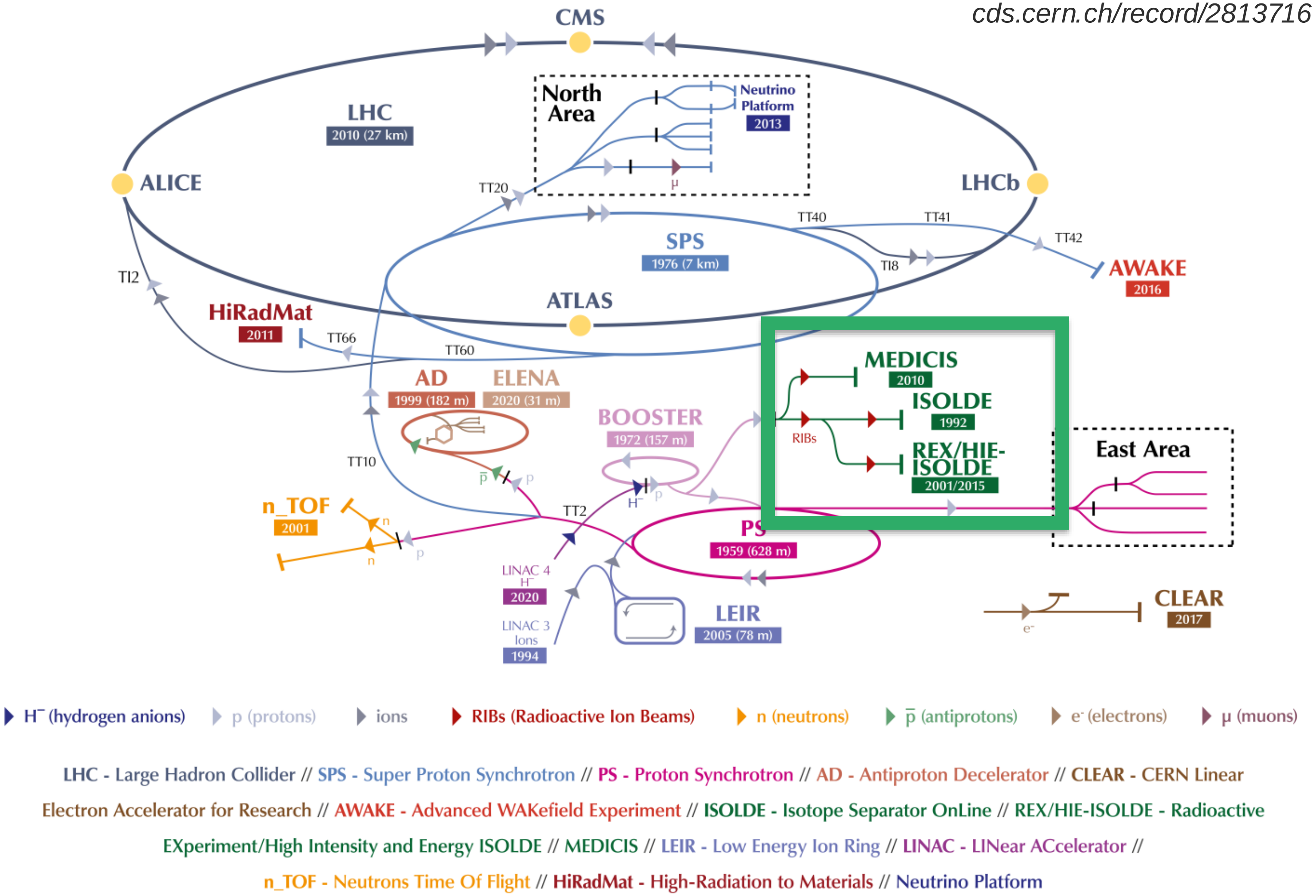
1 CERN-ISOLDE and ISOL

2 Atomic actinide beams

3 Radioactive molecules

4 Offline developments

CERN-PHOTO-202206-116
cds.cern.ch/record/2813716



The Isotope Separation On-Line (ISOL) method

1. Production
2. Release
3. Ionization
4. Mass separation
5. Delivery to experiments

$$Beam\ Intensity = \sigma \cdot j \cdot N_t \cdot \varepsilon$$

N_t – Number of target atoms
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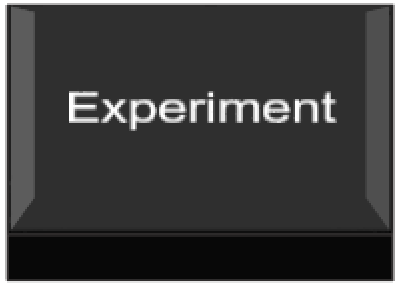

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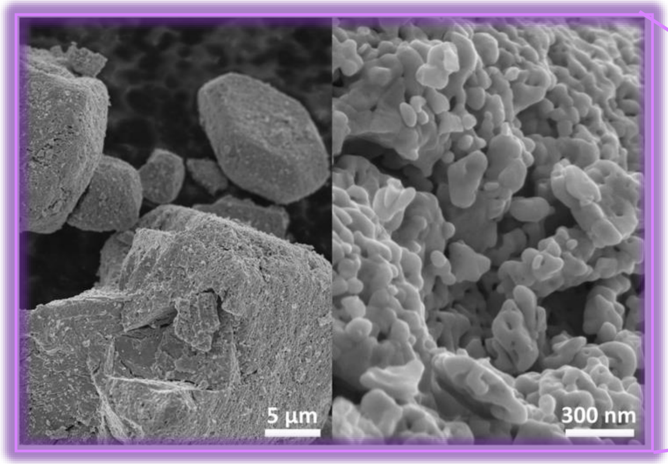
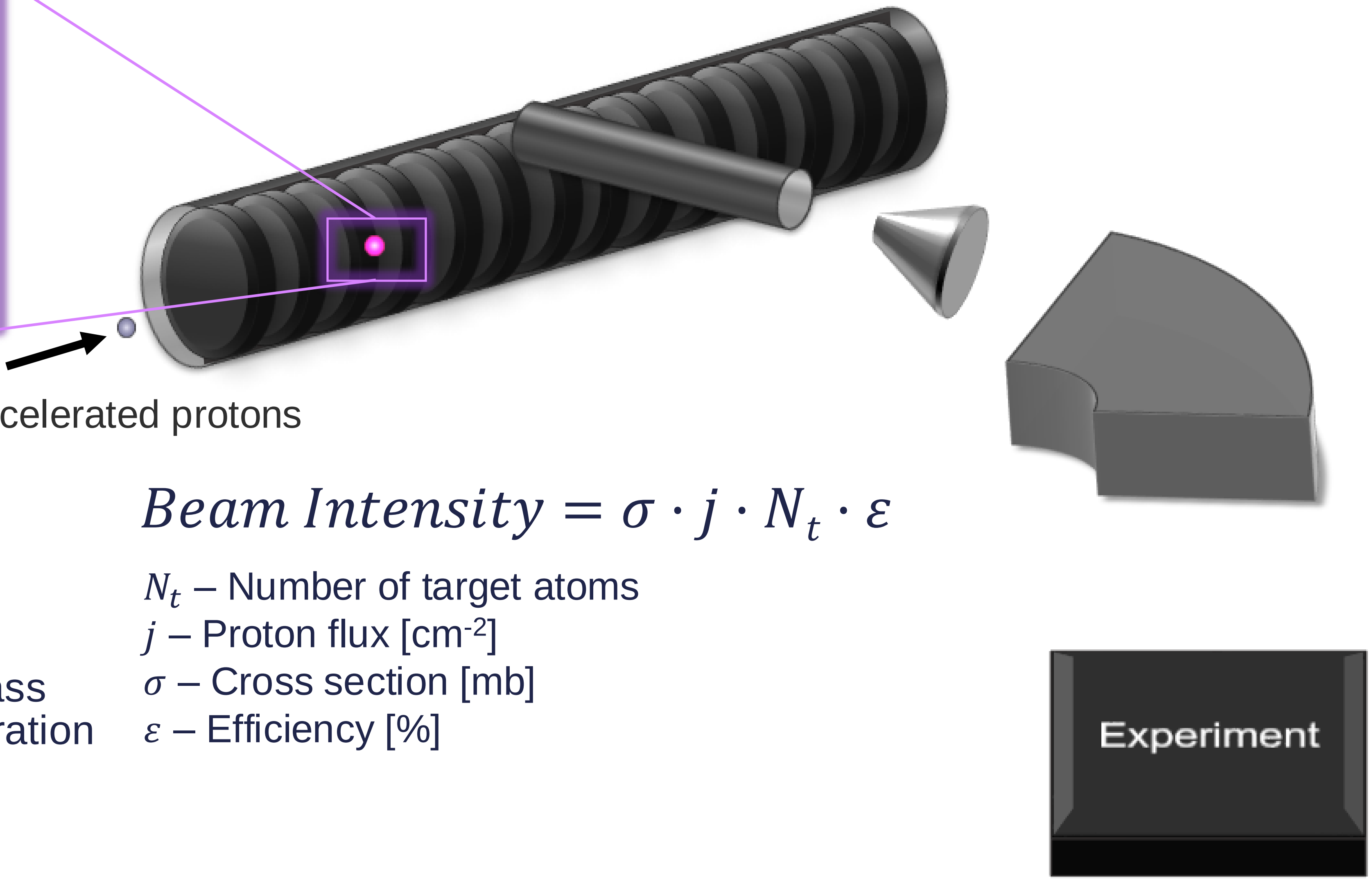


Figure published in Ramos *et al.*, (2020) *NIM B* **463**, 201



Accelerated protons

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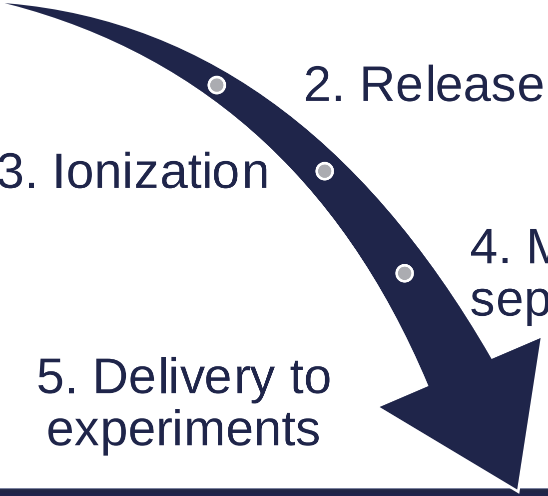

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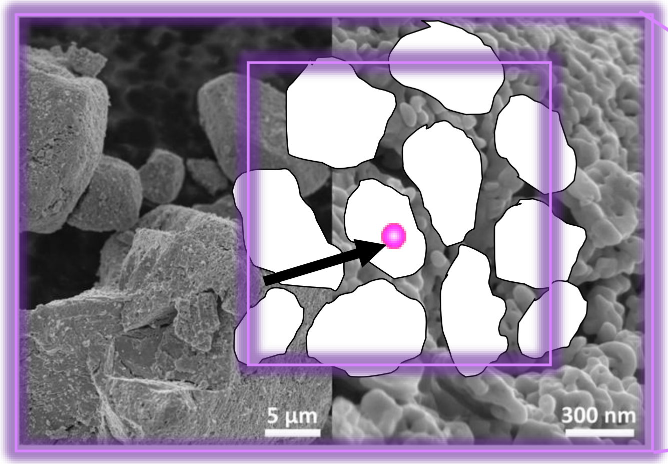

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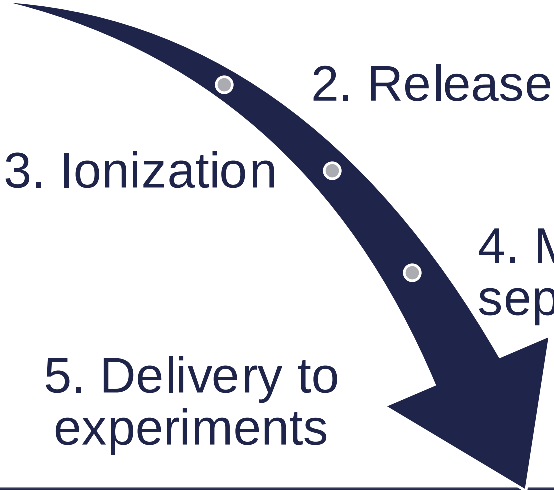

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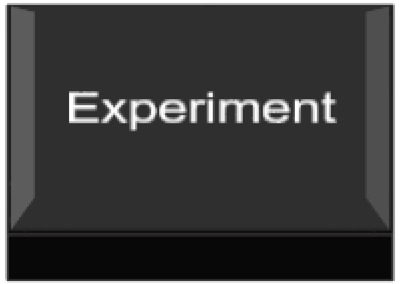

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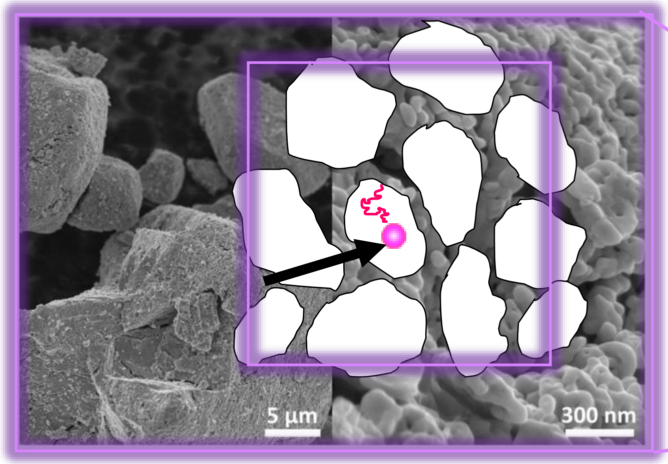

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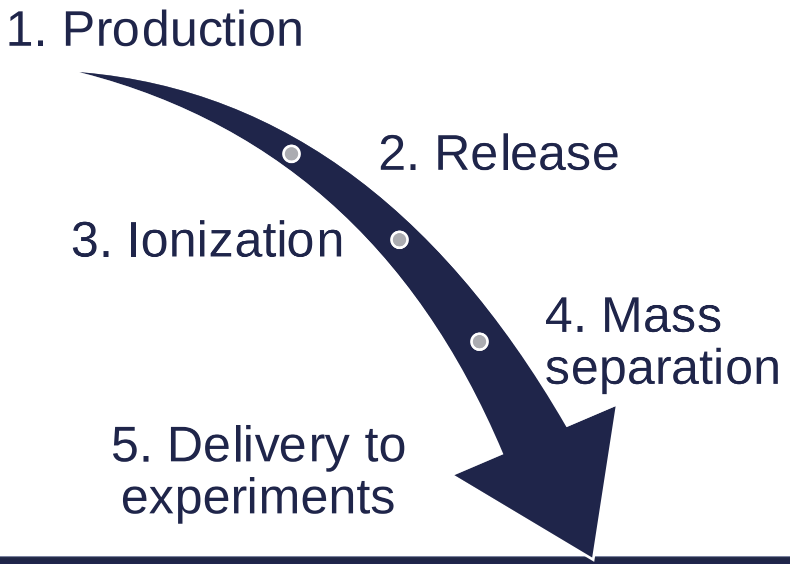

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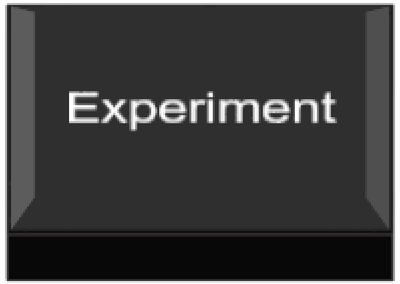

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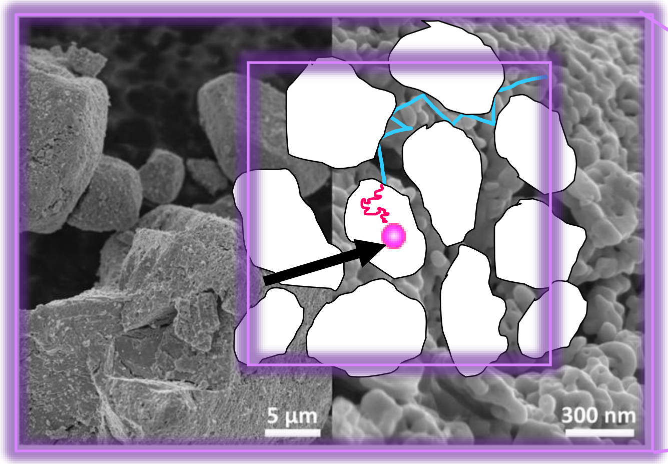

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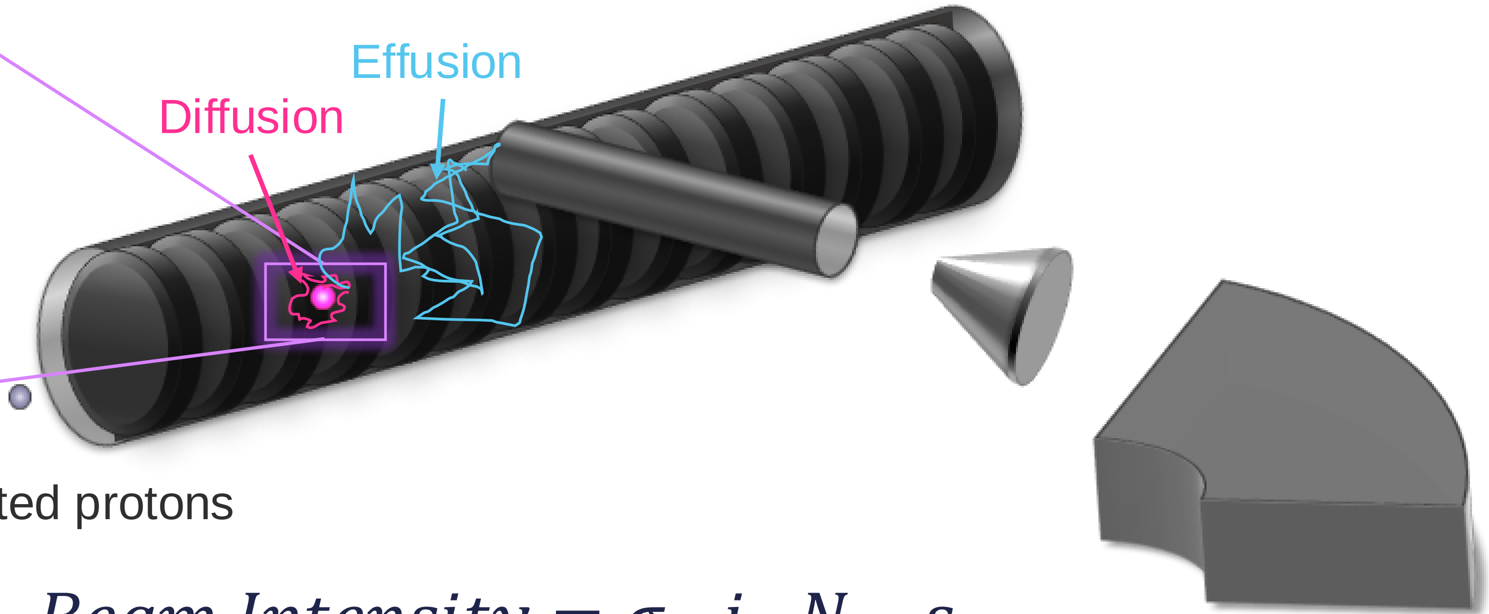

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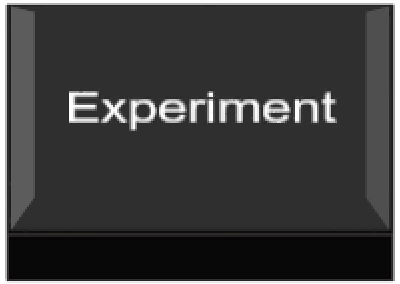

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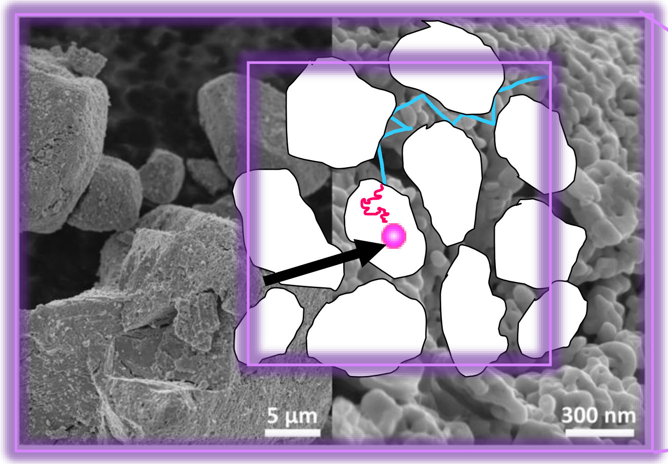

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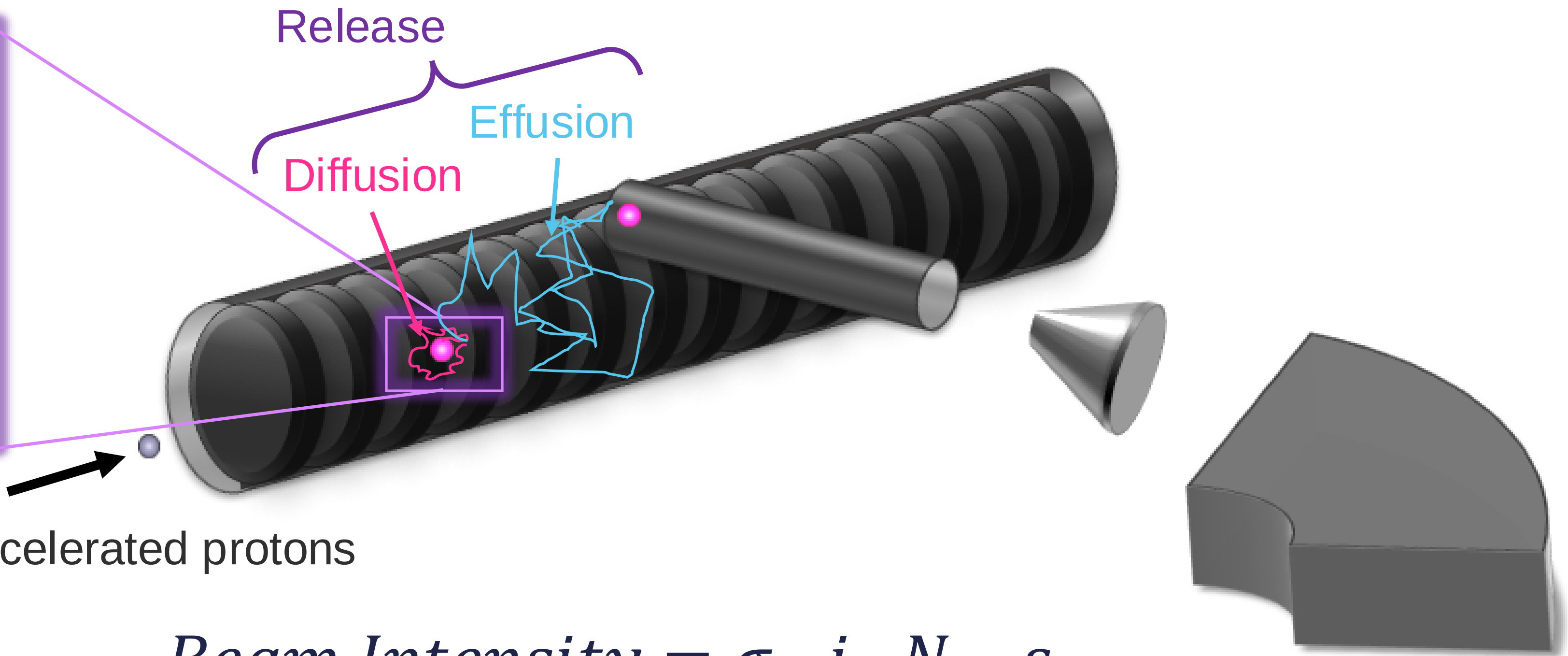

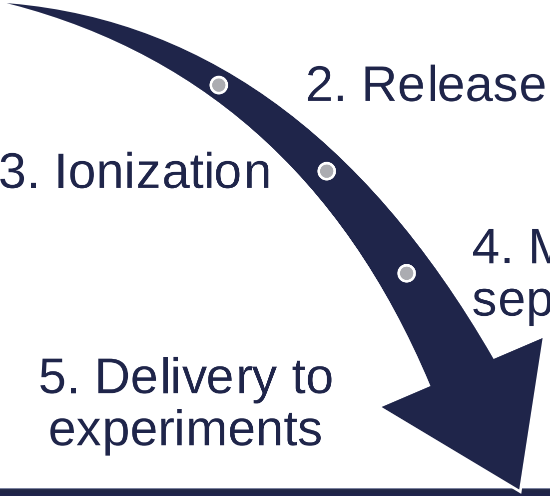

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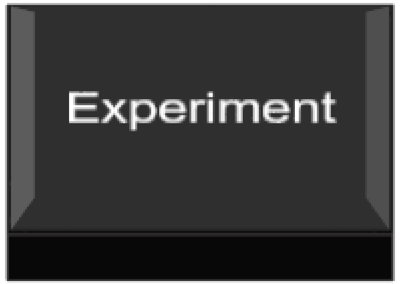

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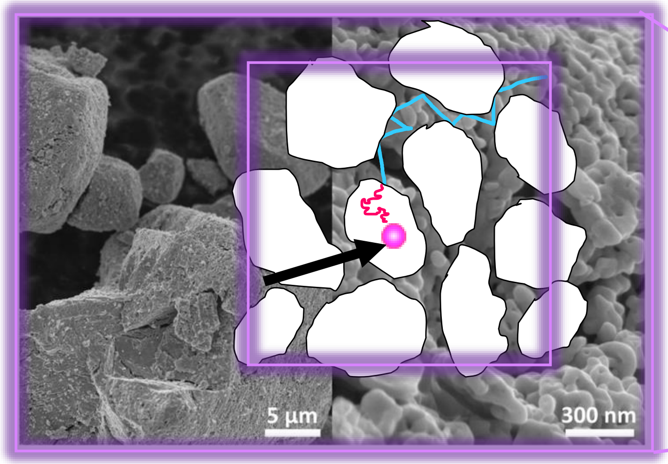

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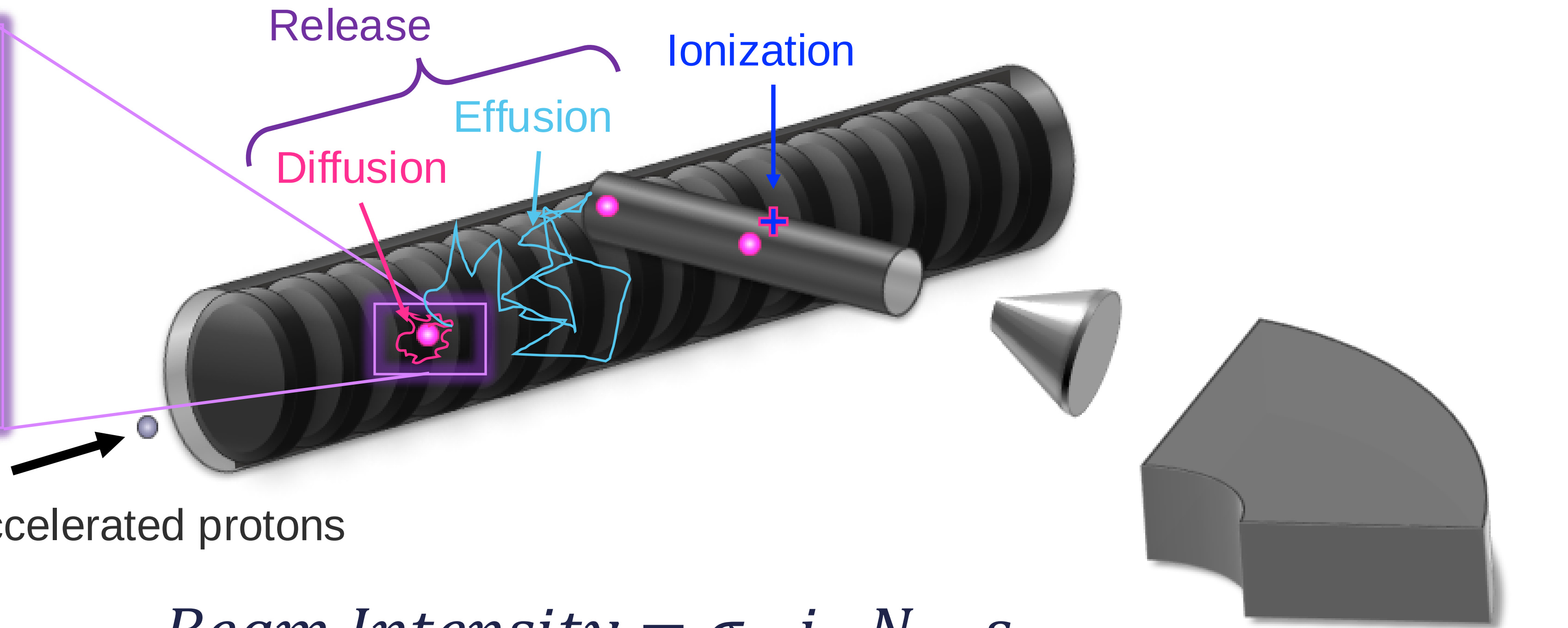

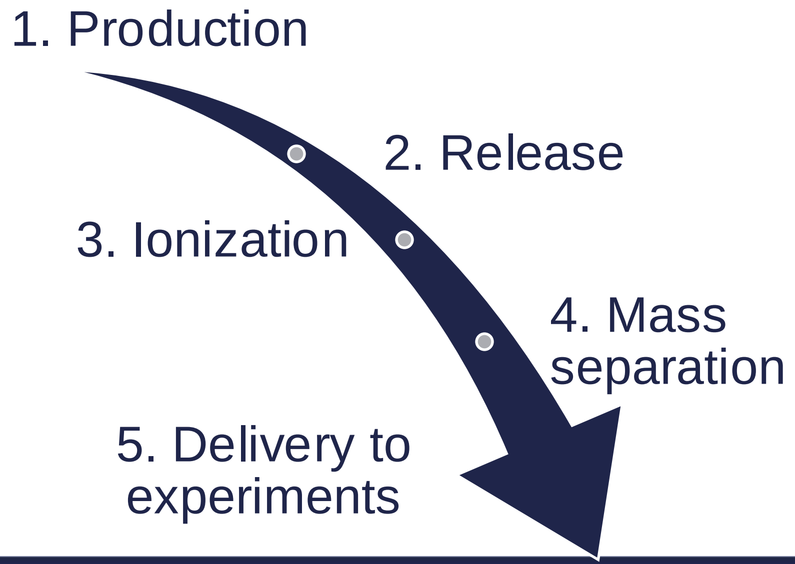

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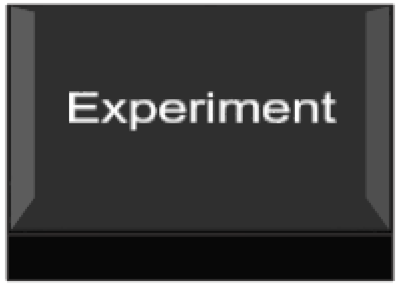

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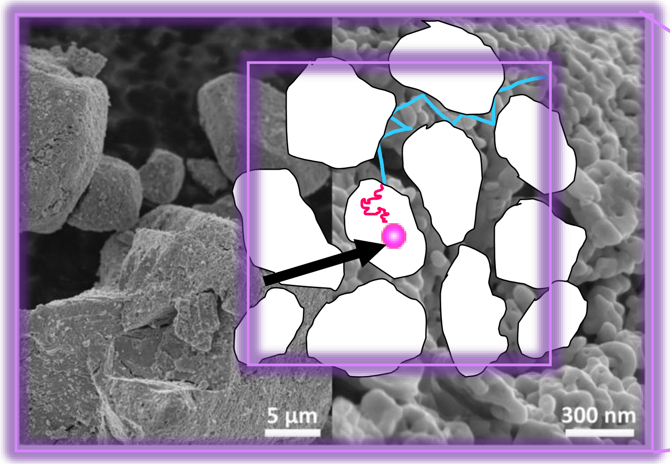

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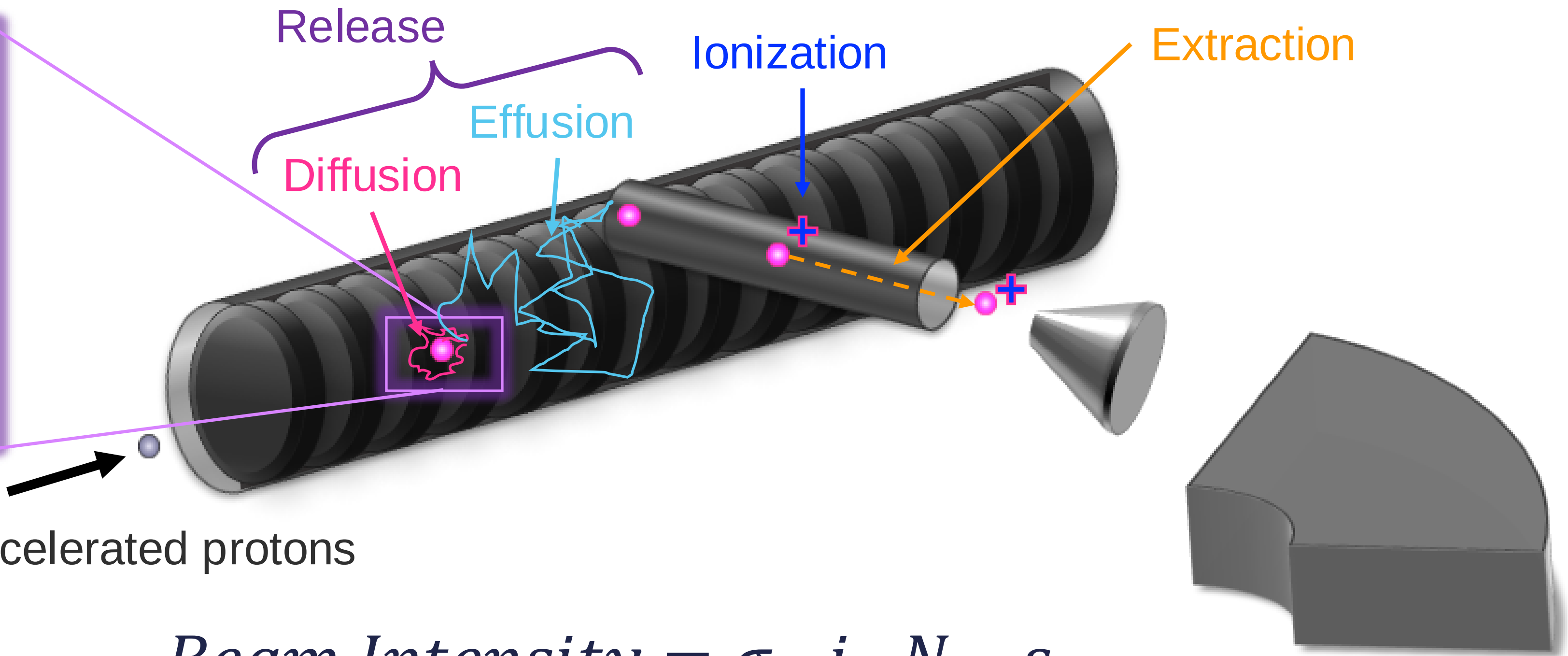

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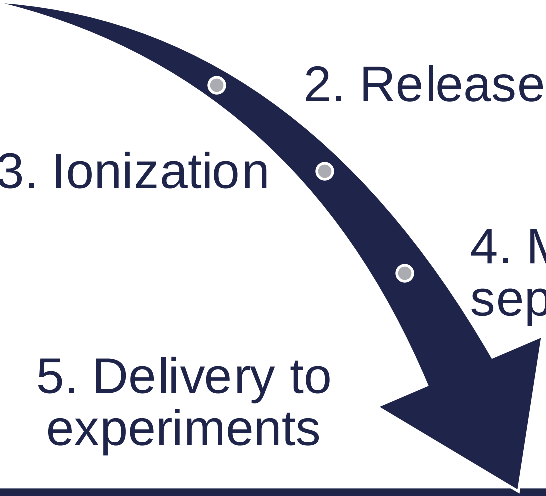

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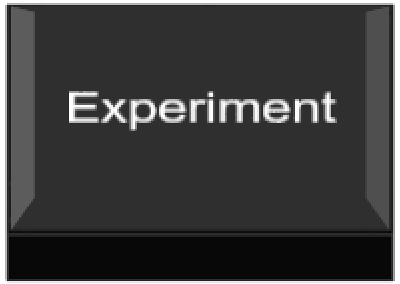

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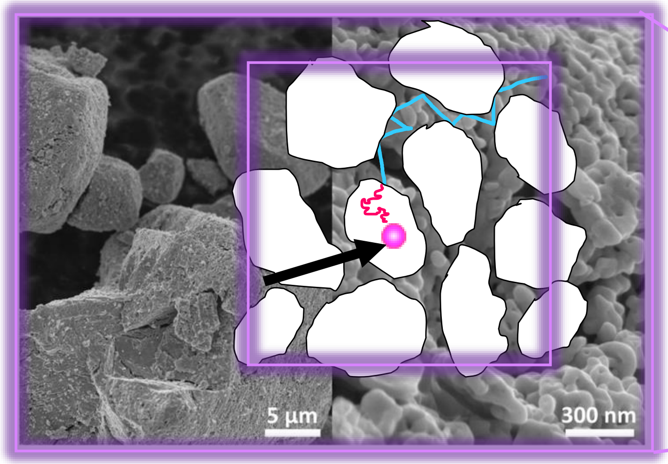

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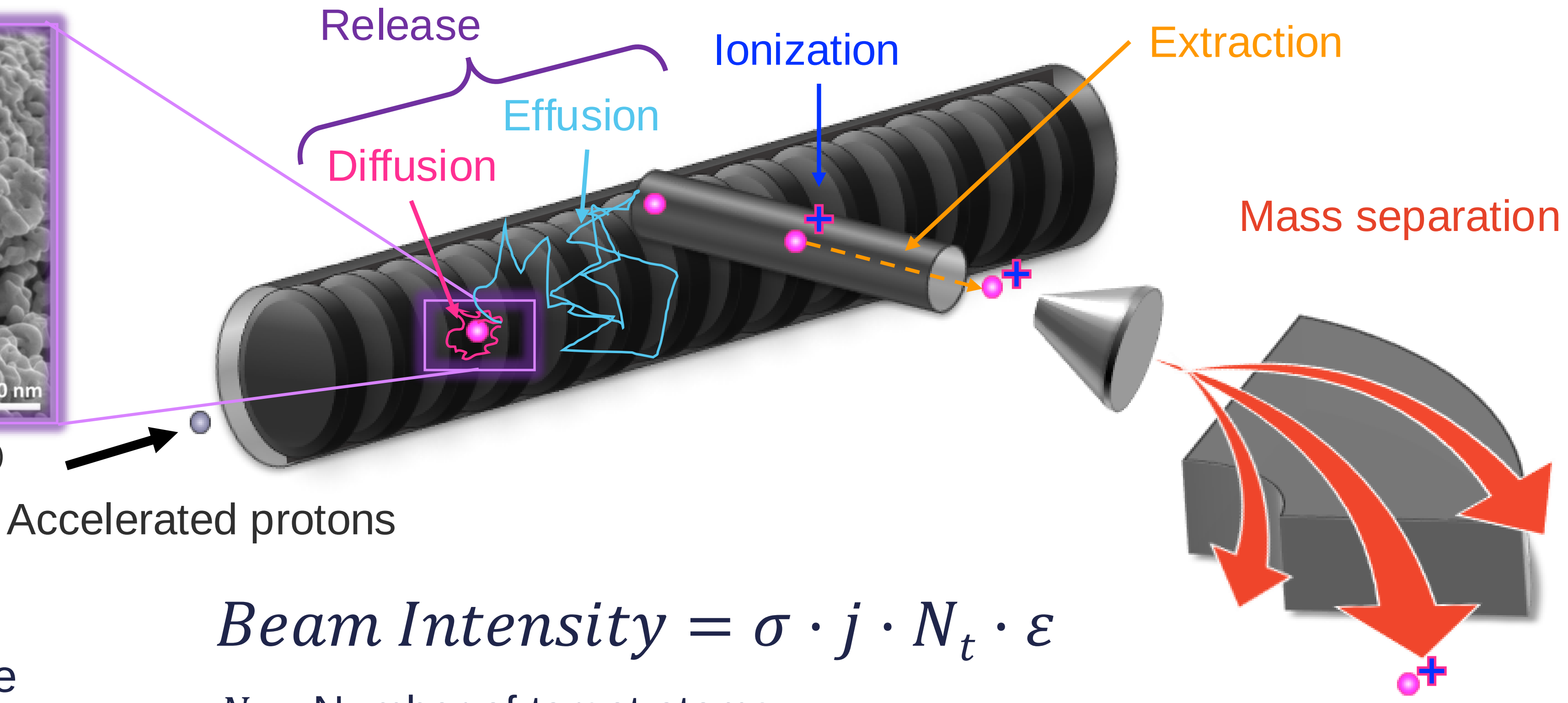

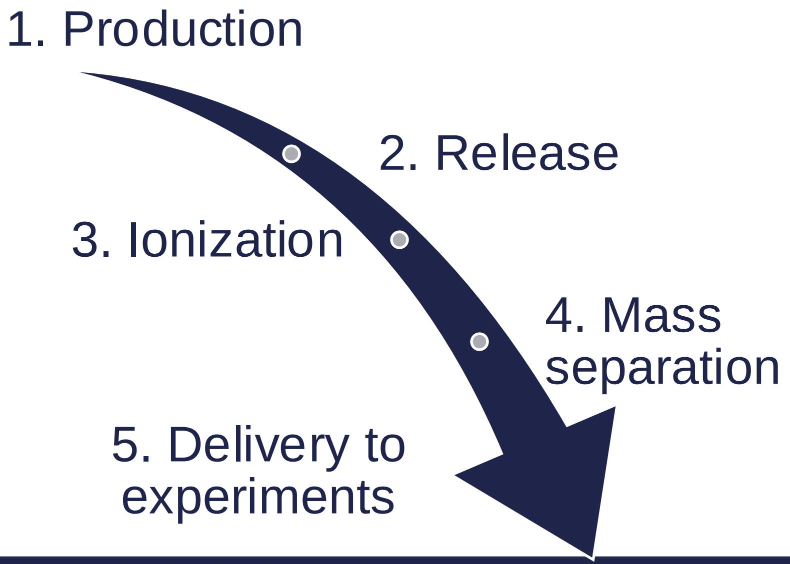

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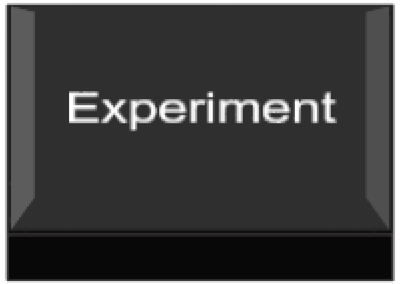

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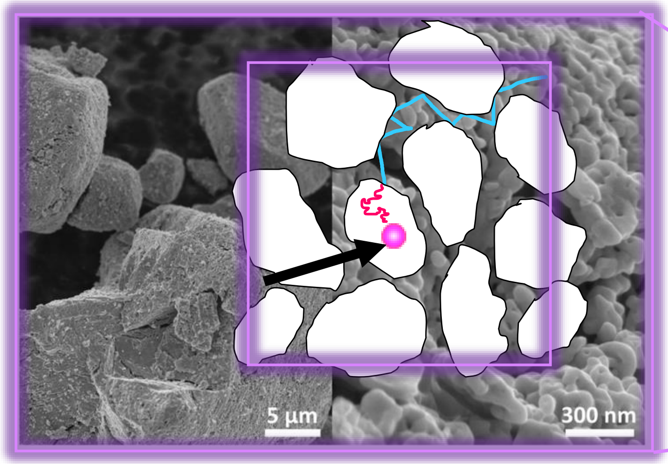

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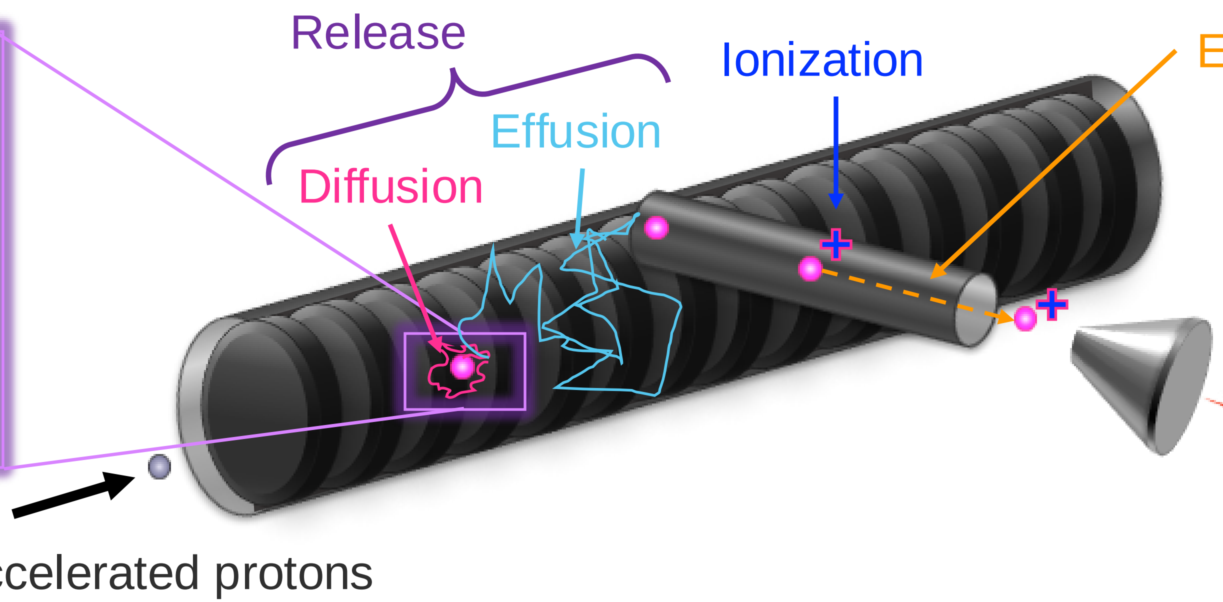

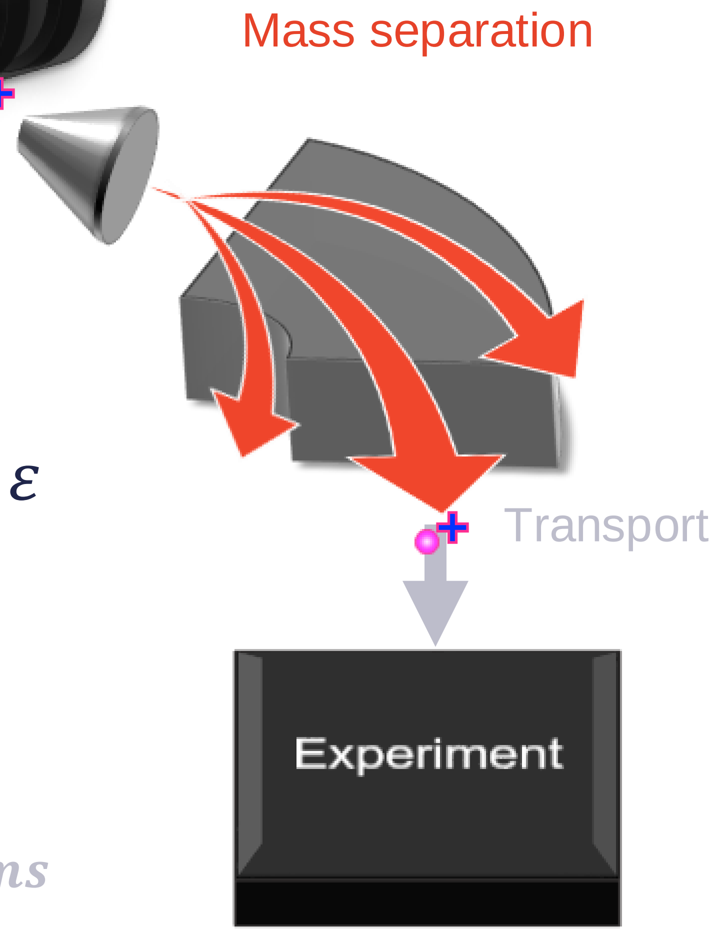

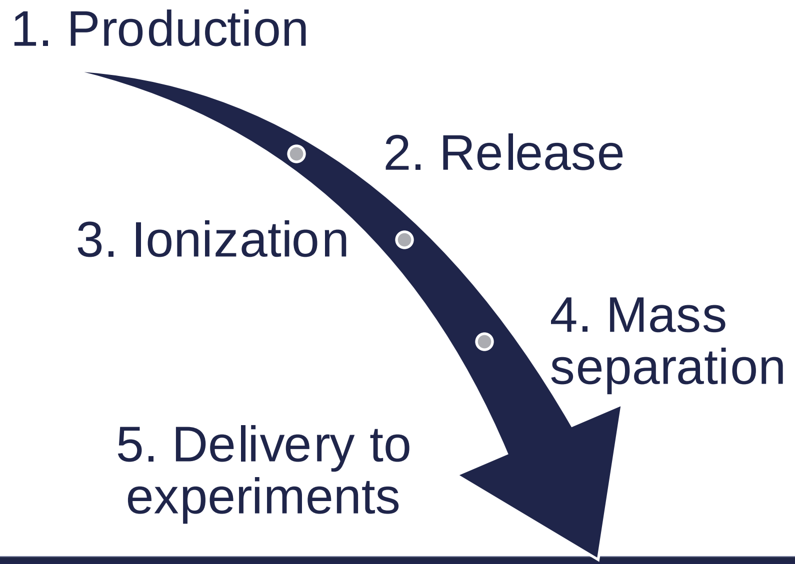

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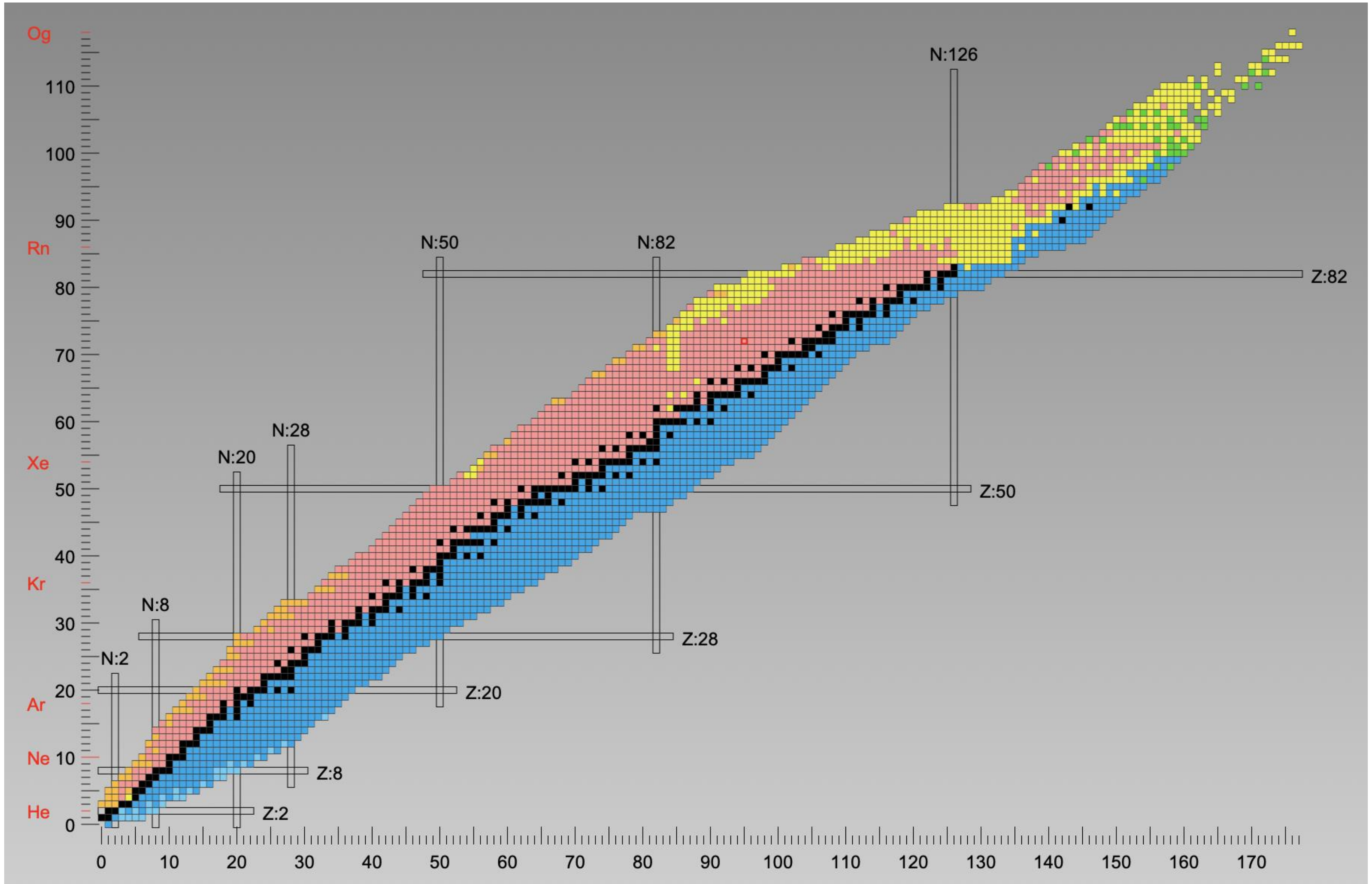
ISOL step 1: Production

Target selection

- Cross sections
- Bulk
- Half-lives

At ISOLDE

- 1.4-GeV p
- ^{232}Th, ^{238}U



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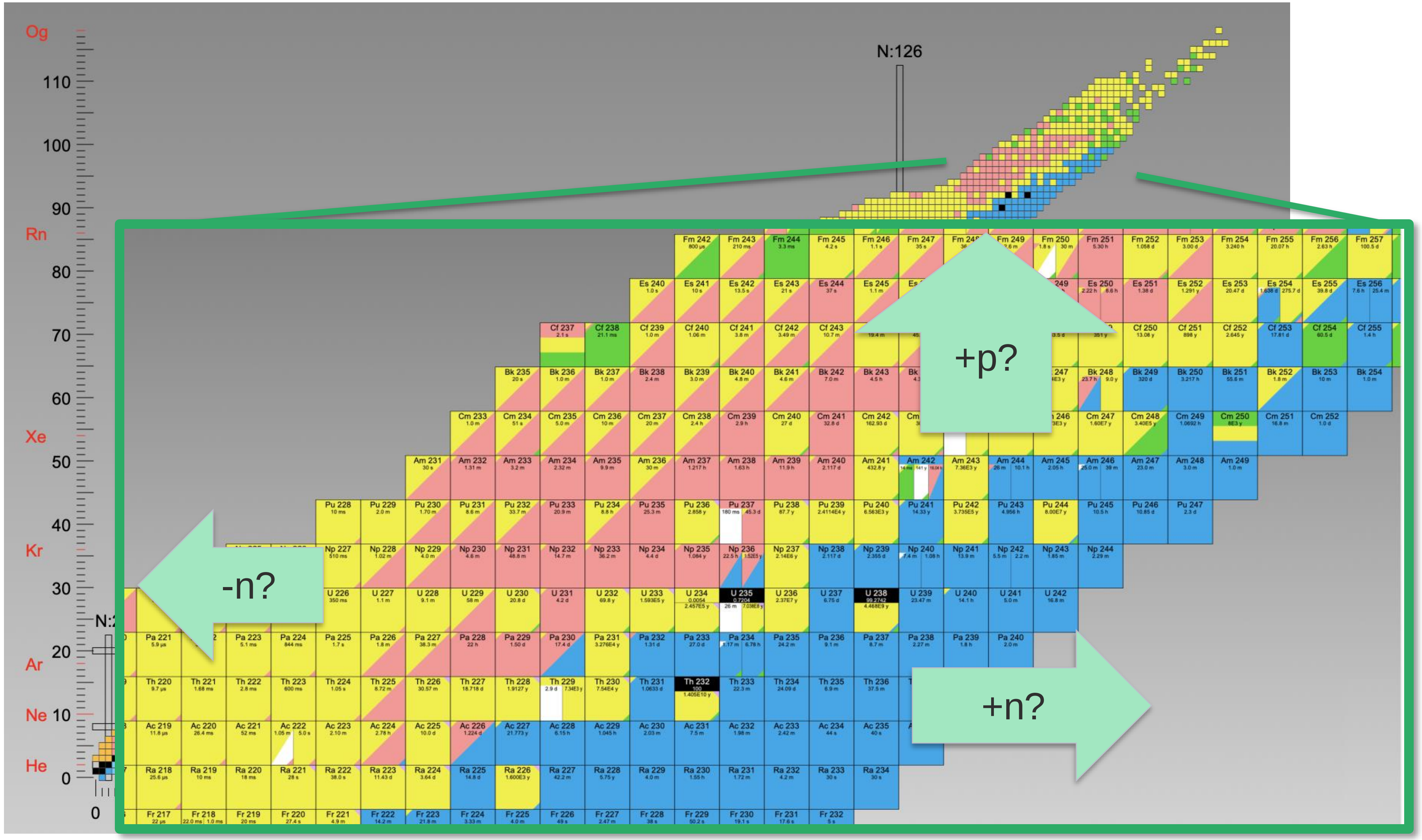

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Ballof et al. (2020) *NIM B* **463**, 211-215
cern.ch/isolde-yields

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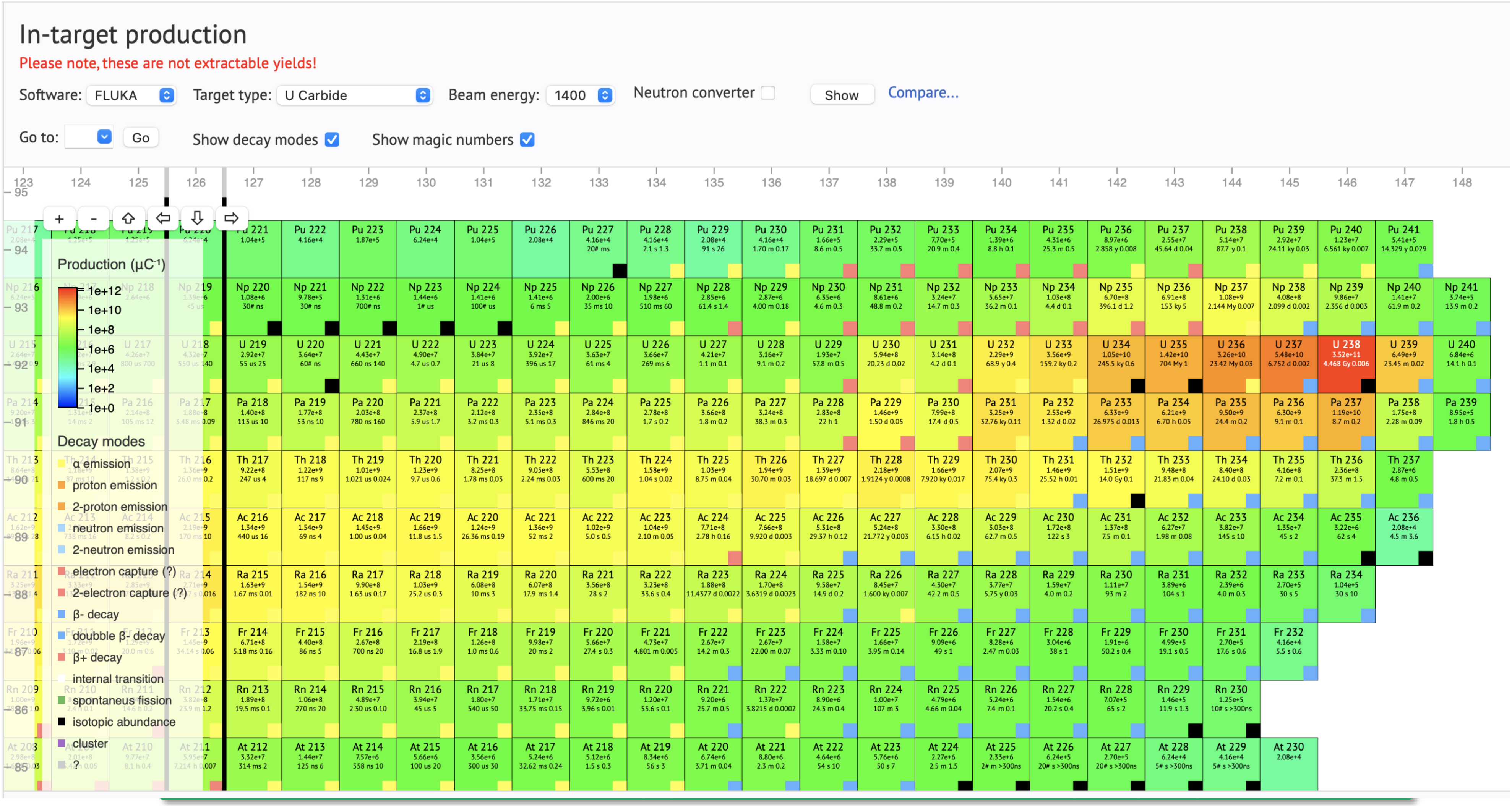

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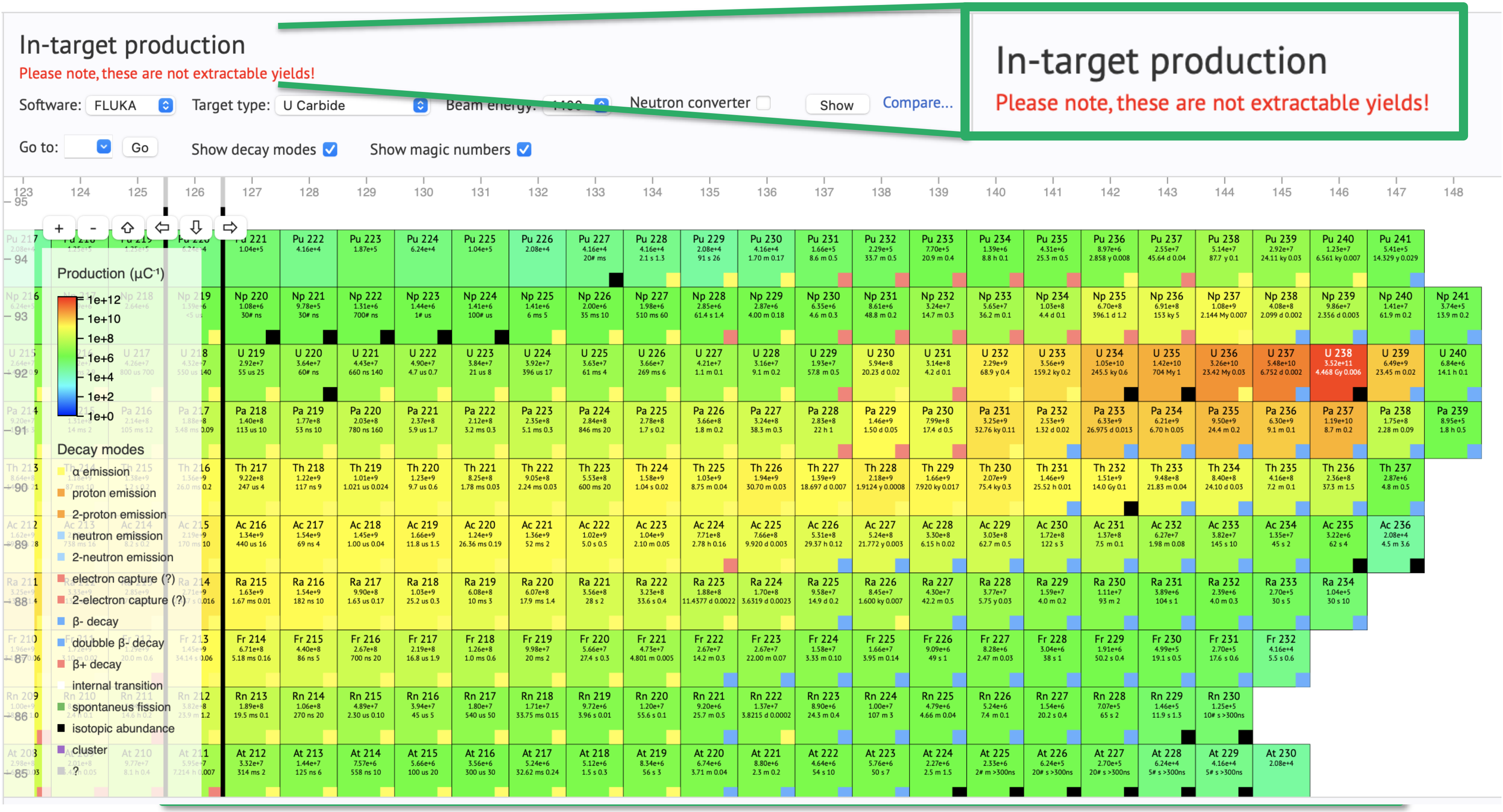

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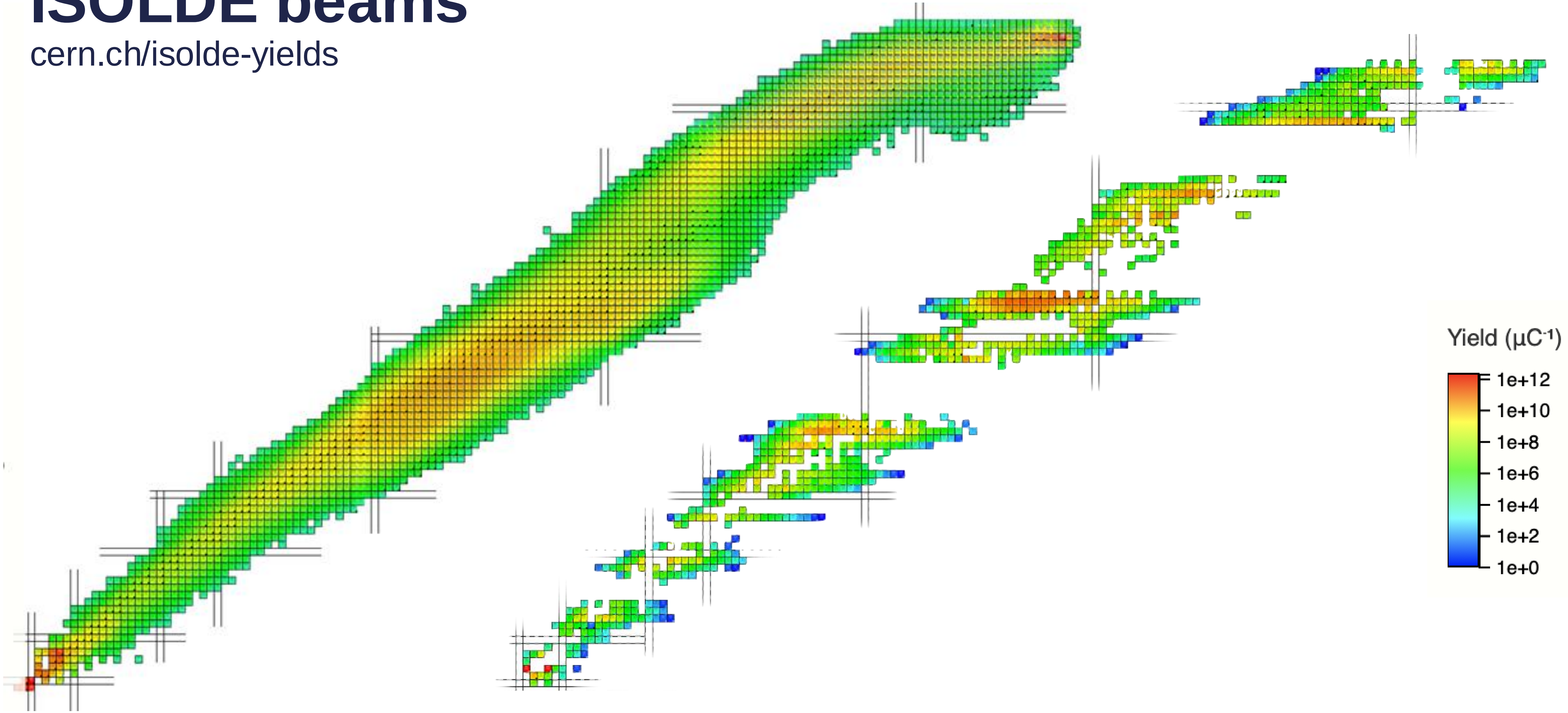
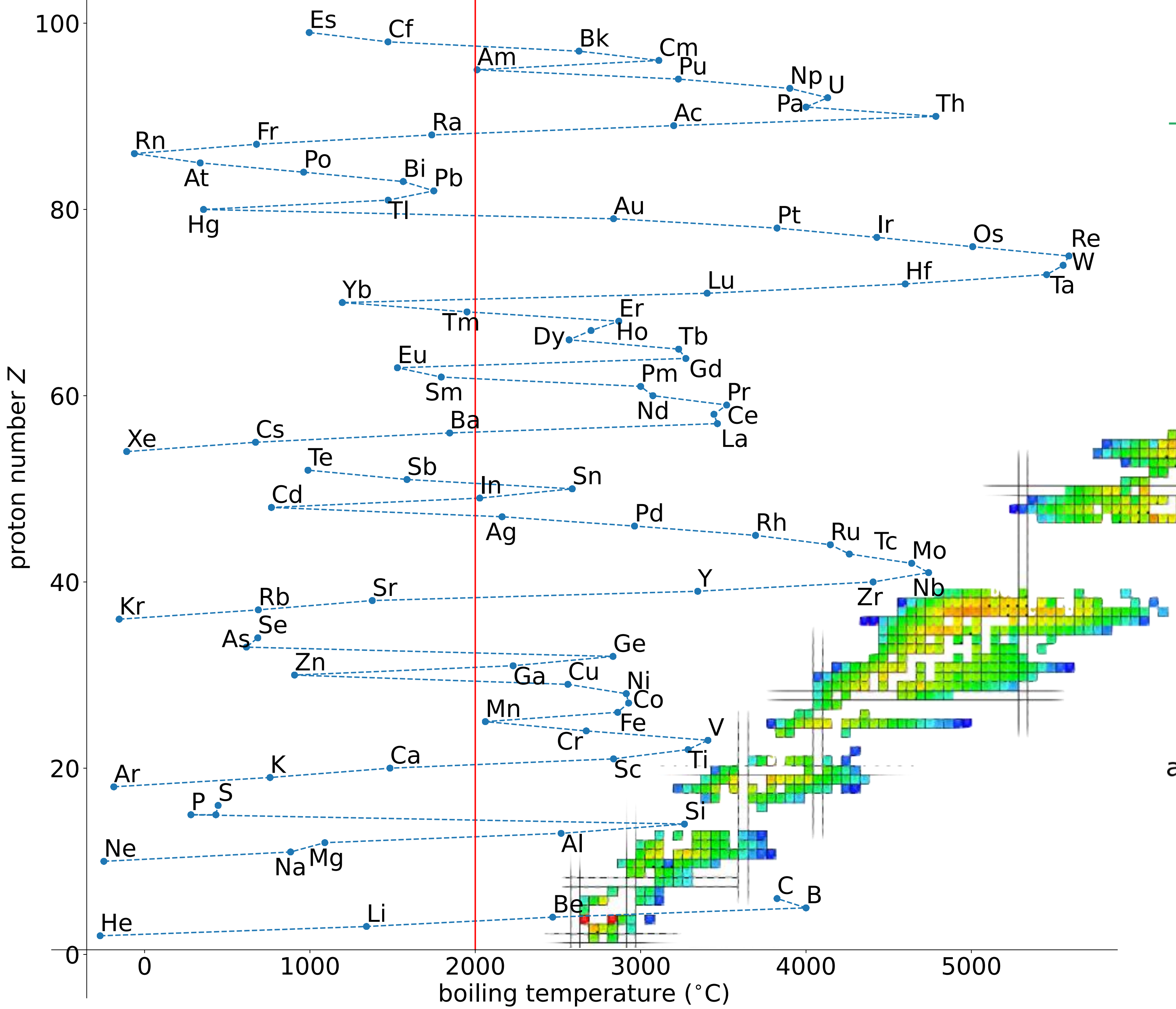
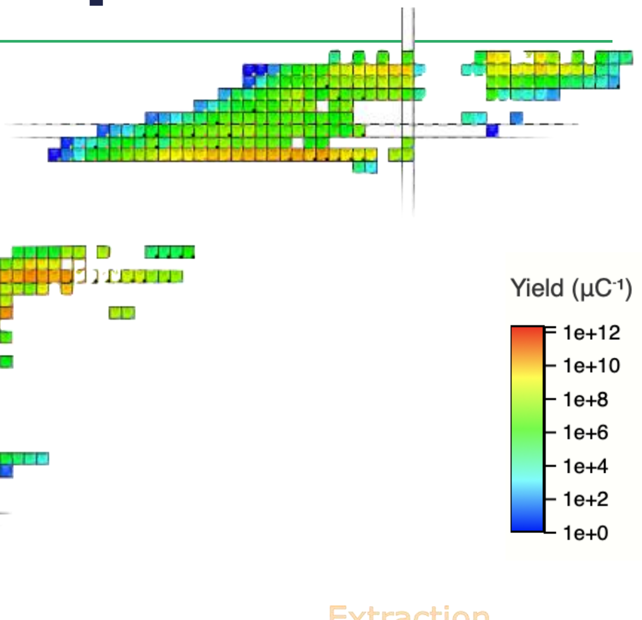
ISOLDE beams

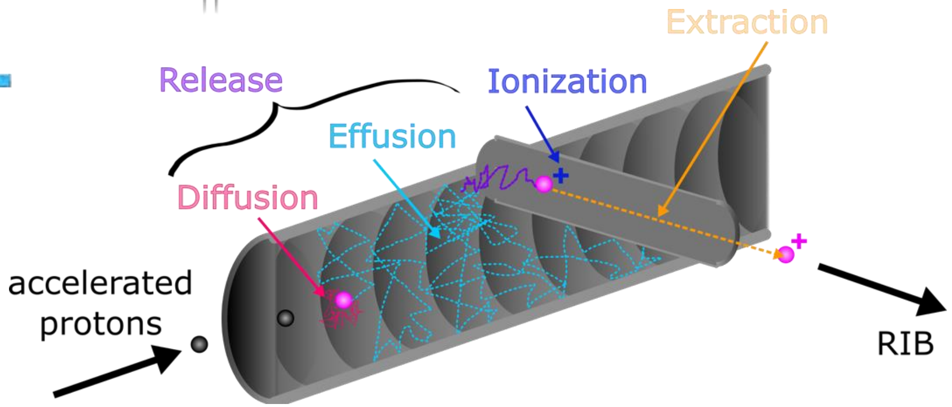
cern.ch/isolde-yields



ISOL Step 2: Release







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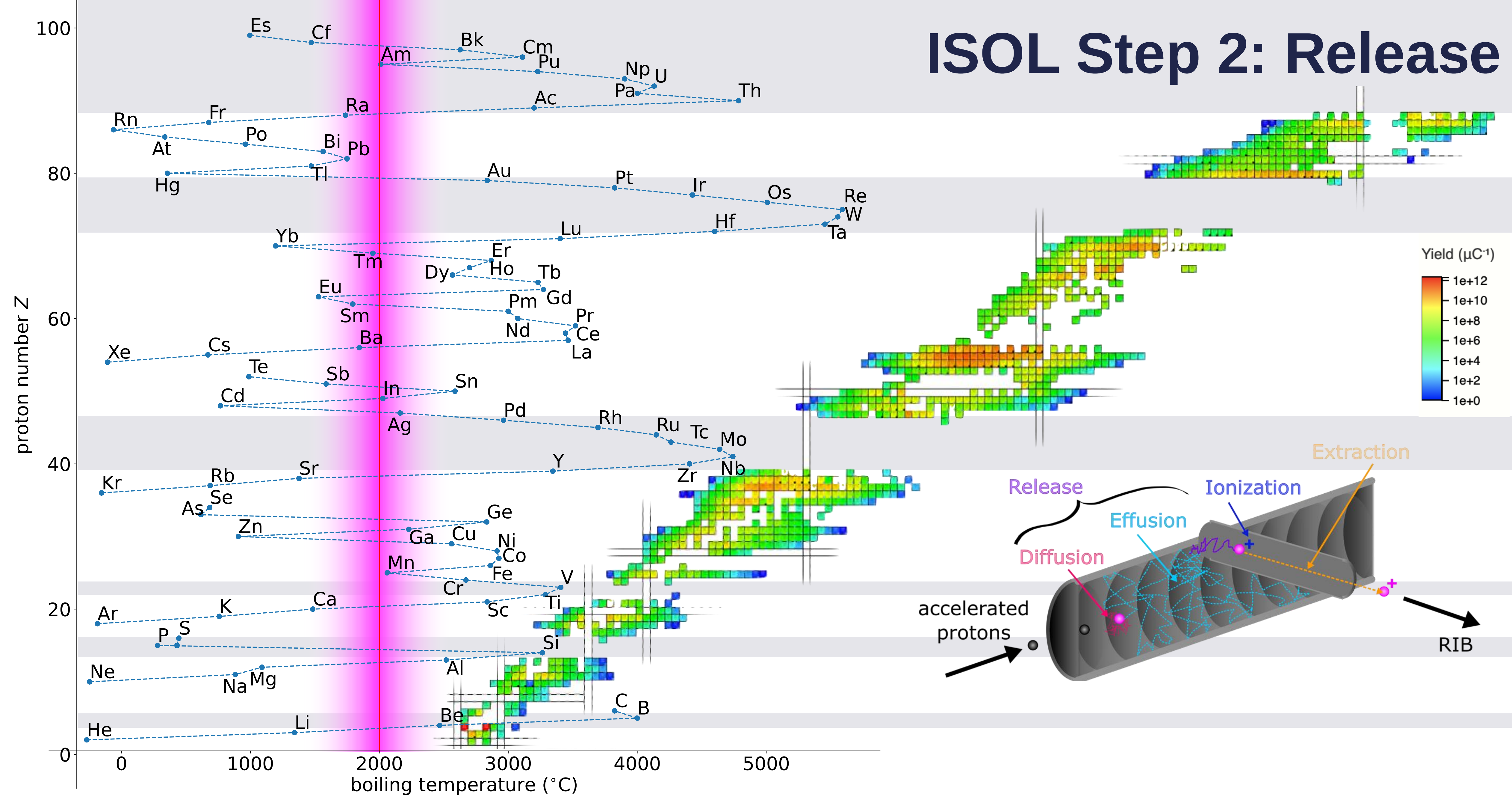

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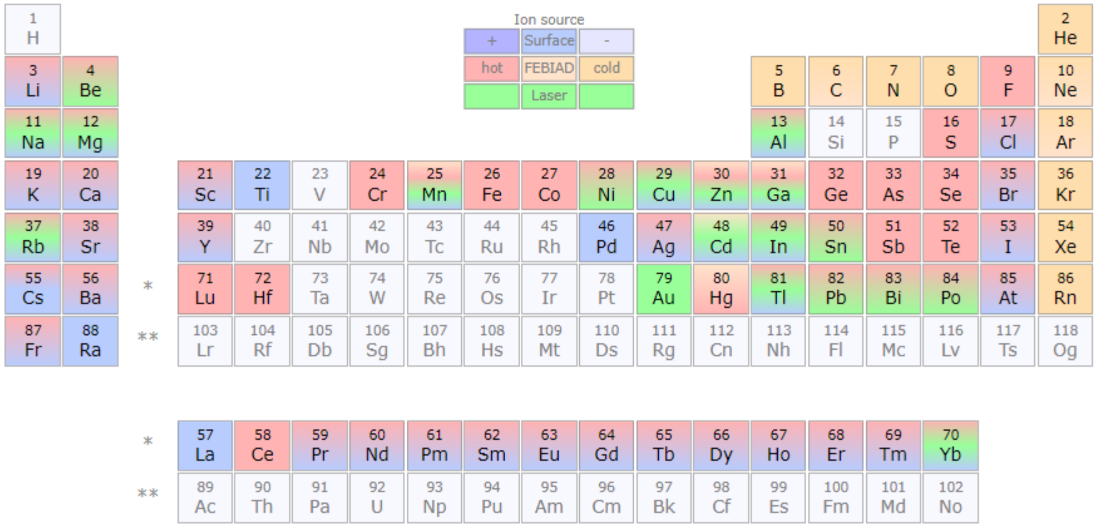

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Ion sources

- Surface ionization
- Plasma / electron impact ionization
- Resonance laser ionization

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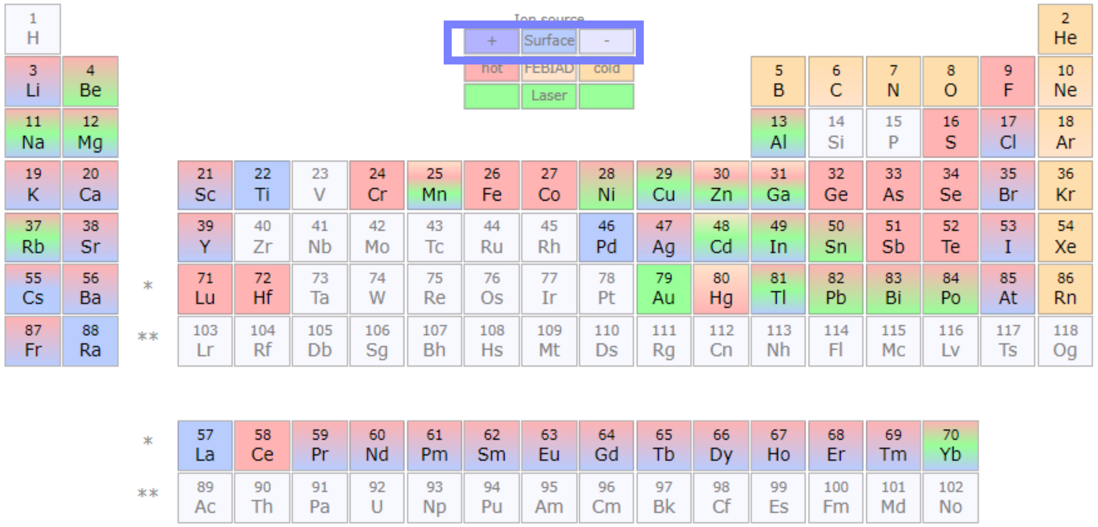

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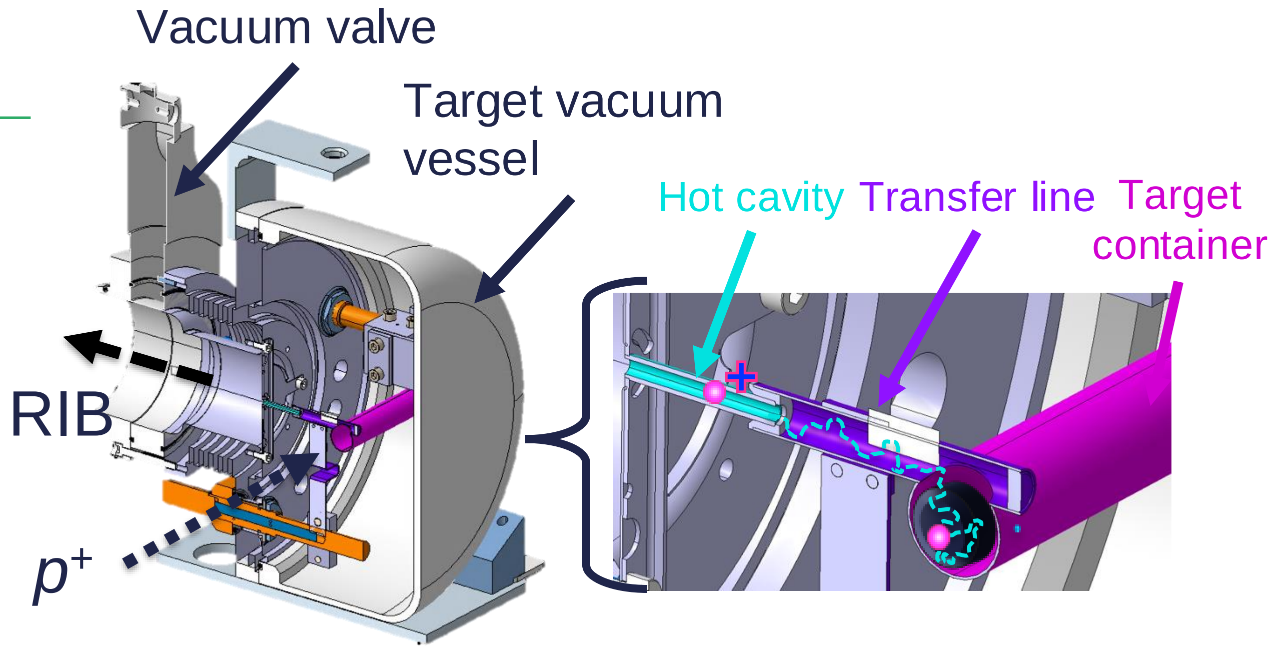

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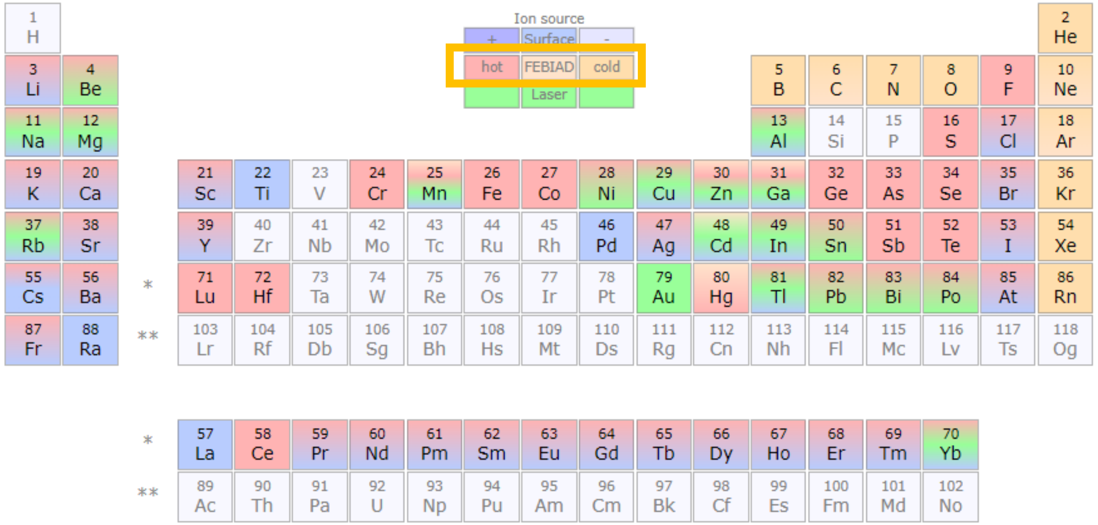

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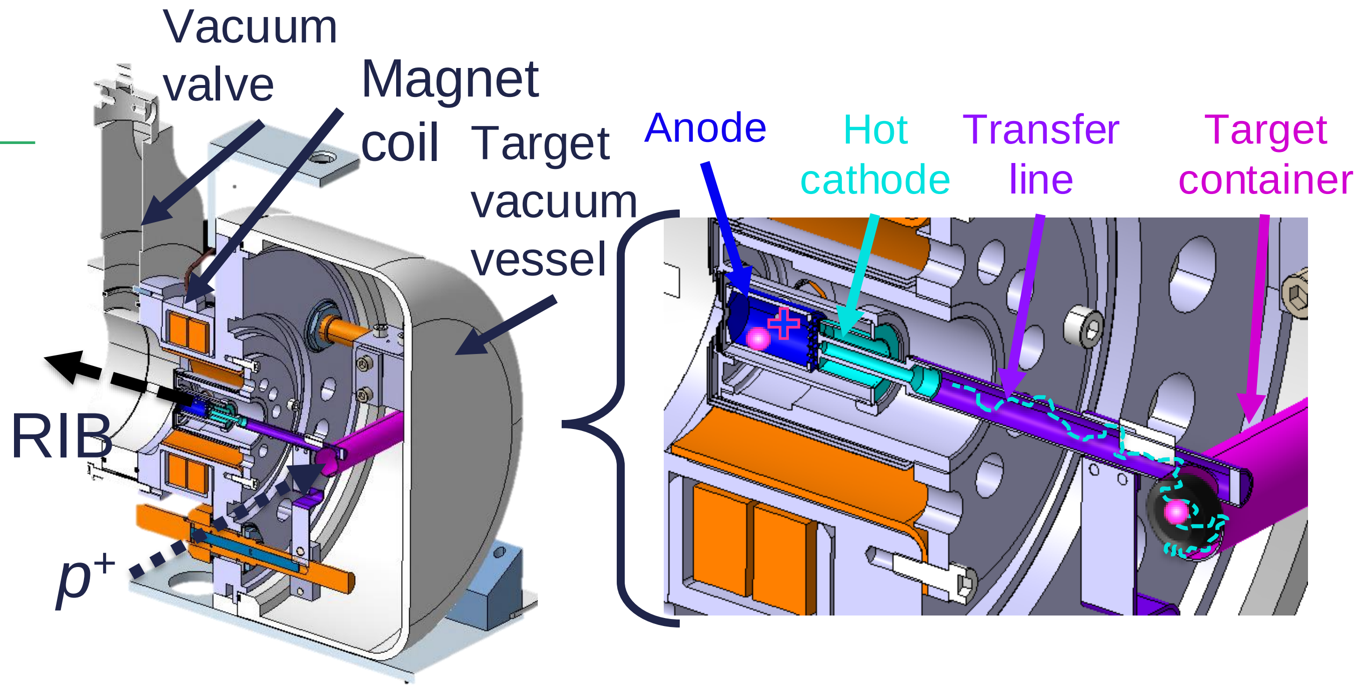

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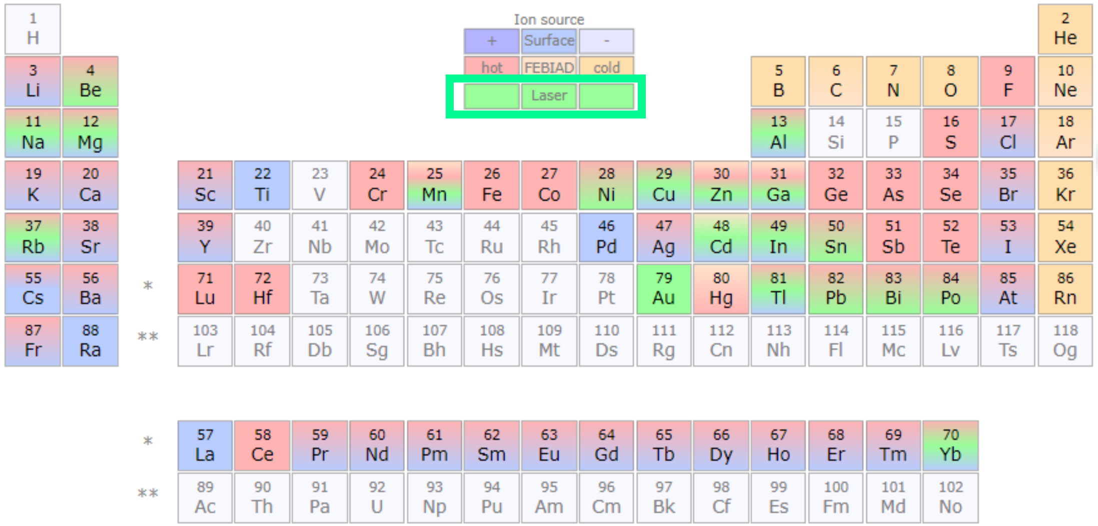

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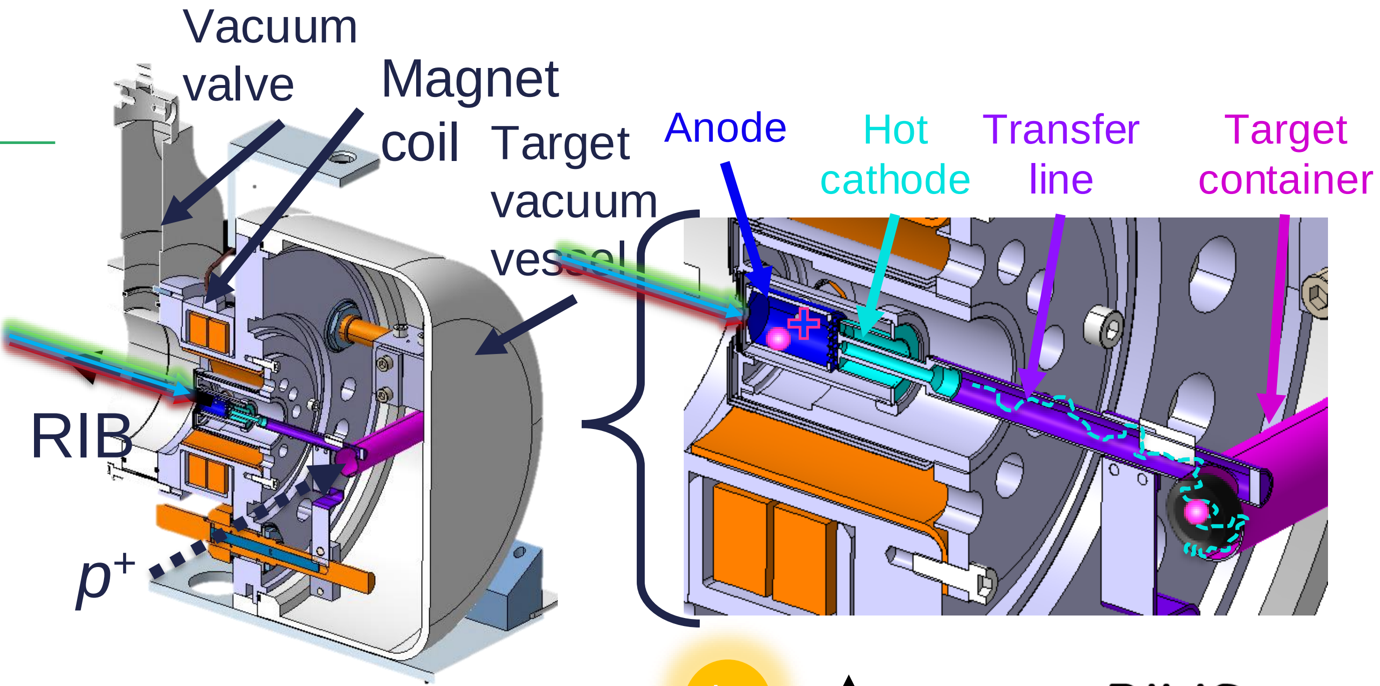

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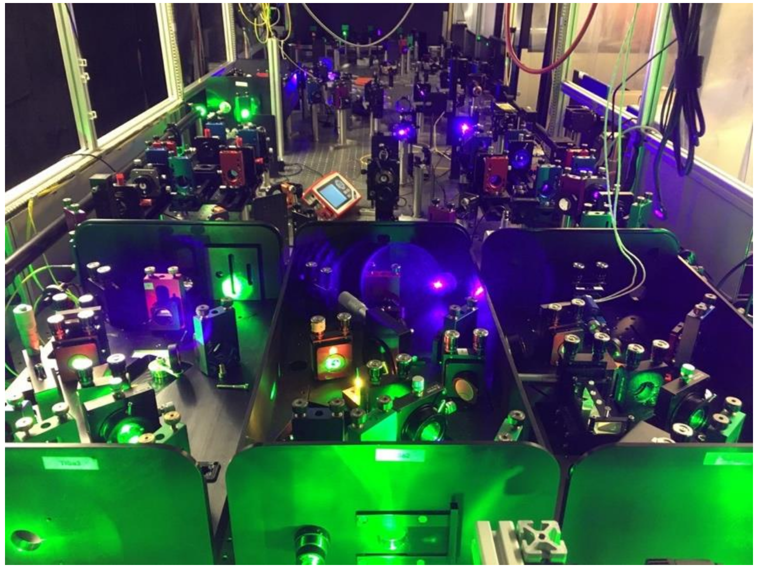
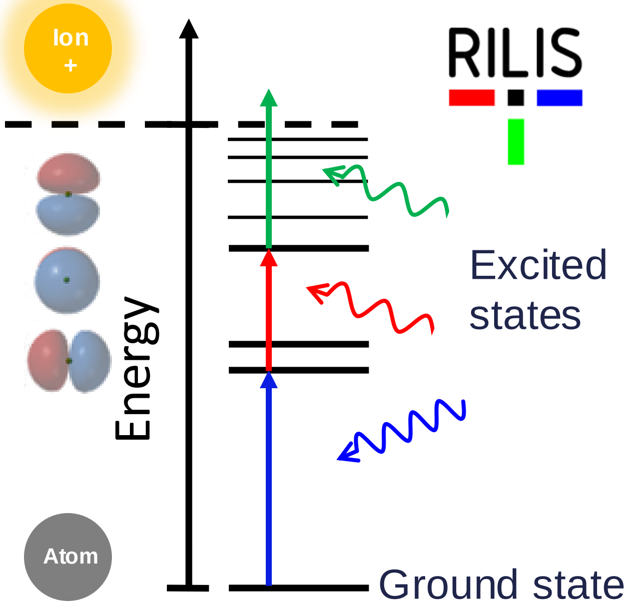
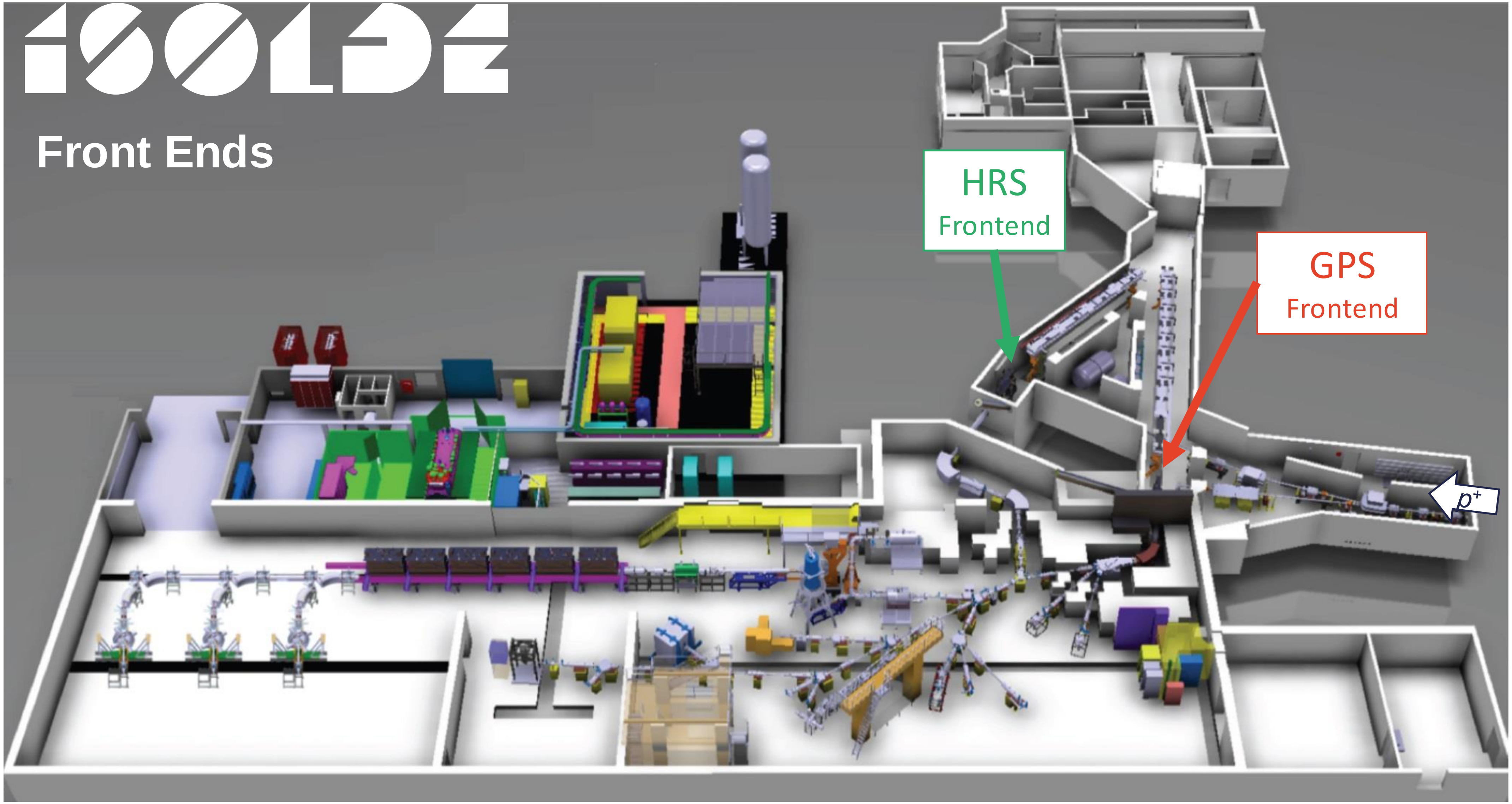




ISOL Step 4: Mass separation

Catherall et al. (2017) *J. Phys G* **44**, 094002
isolde.web.cern.ch



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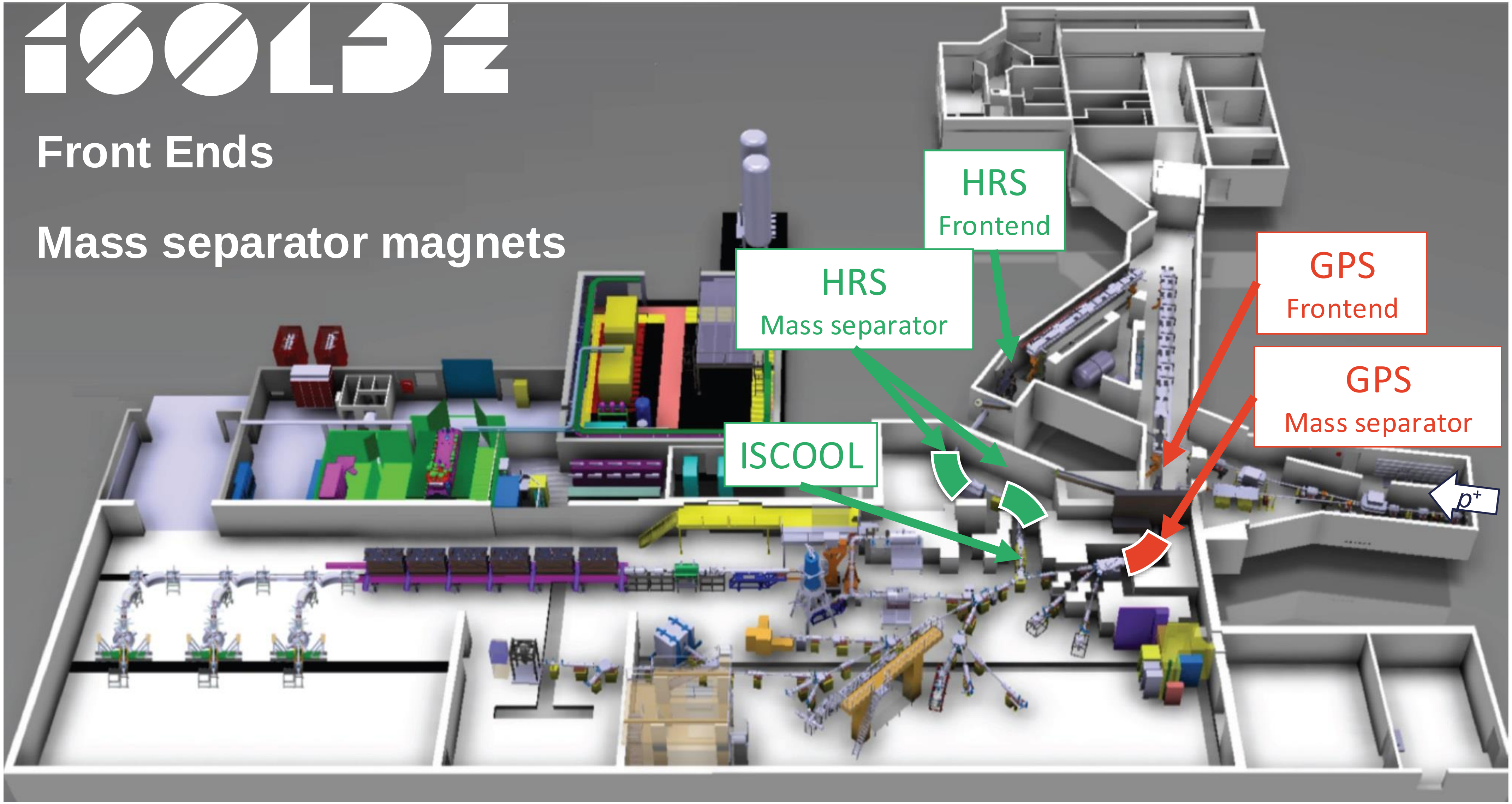

ISOL Step 5: Delivery to Experiments

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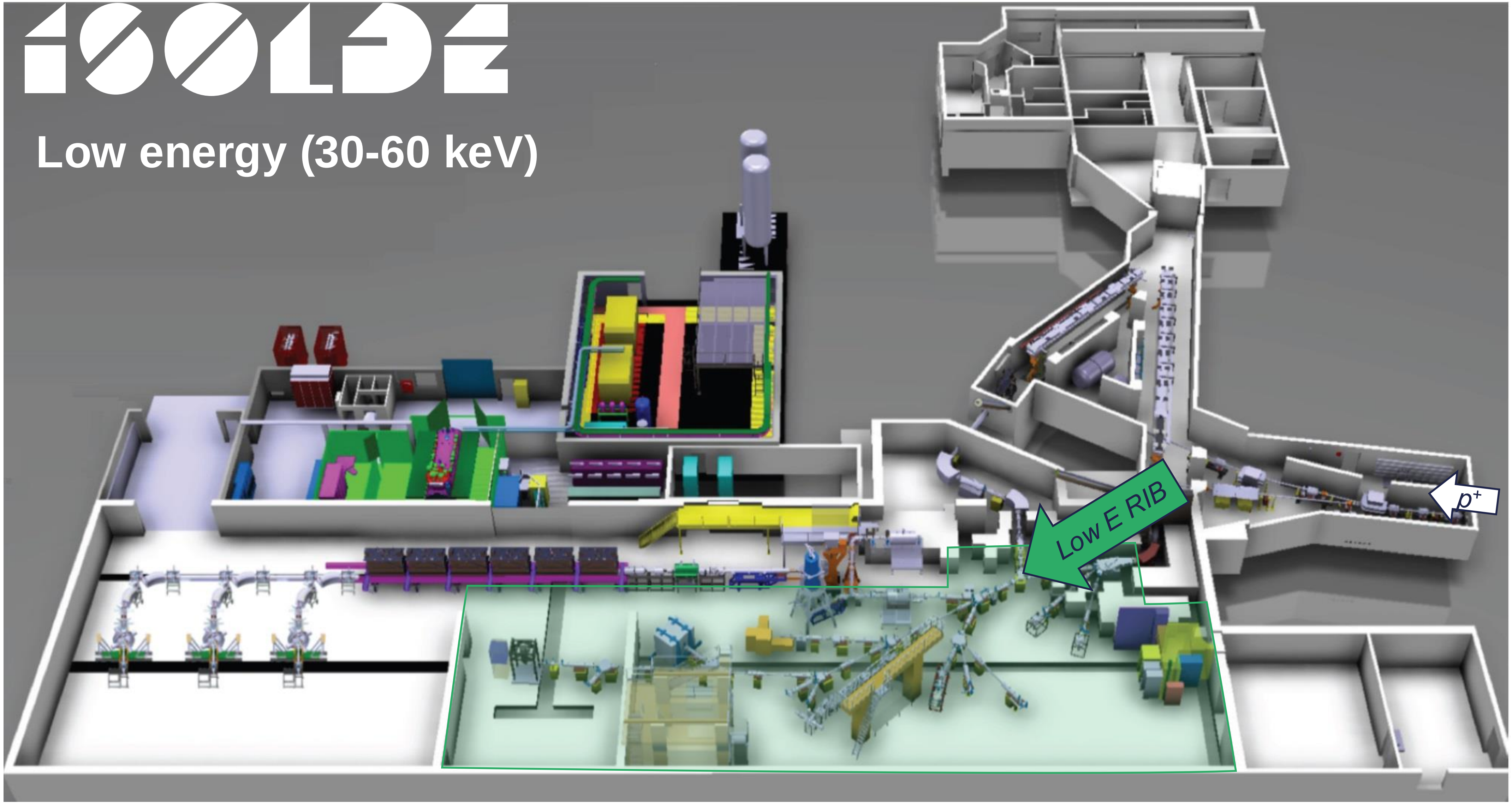

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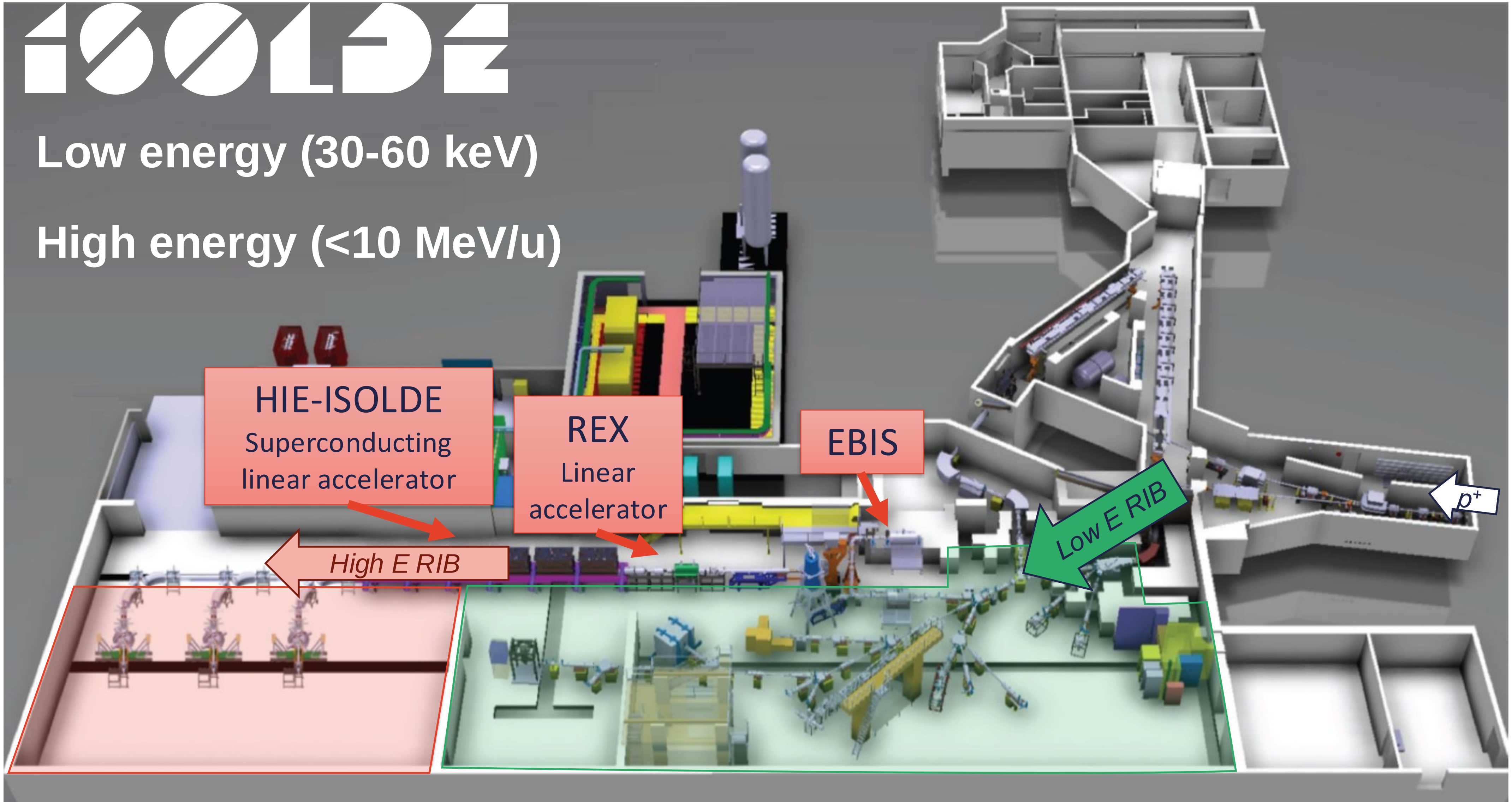

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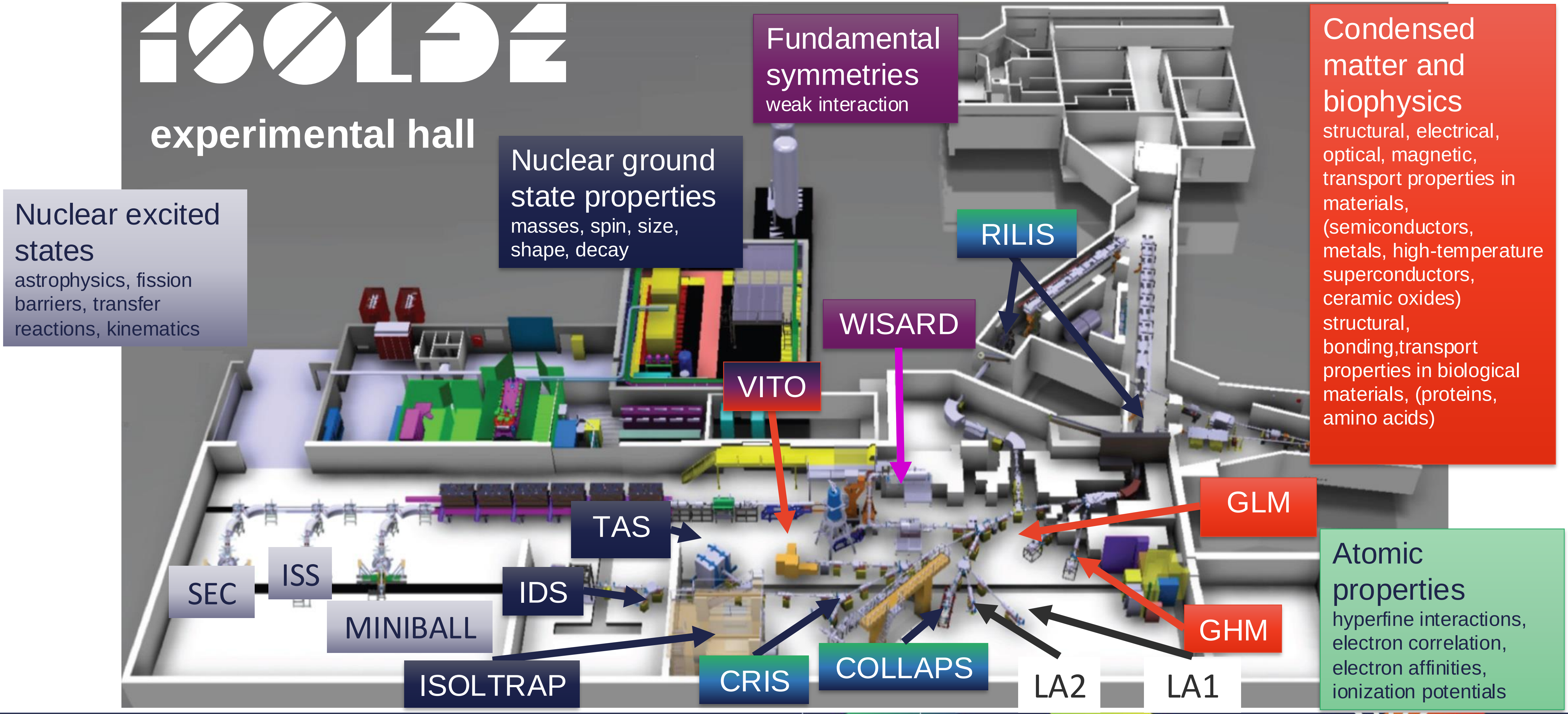
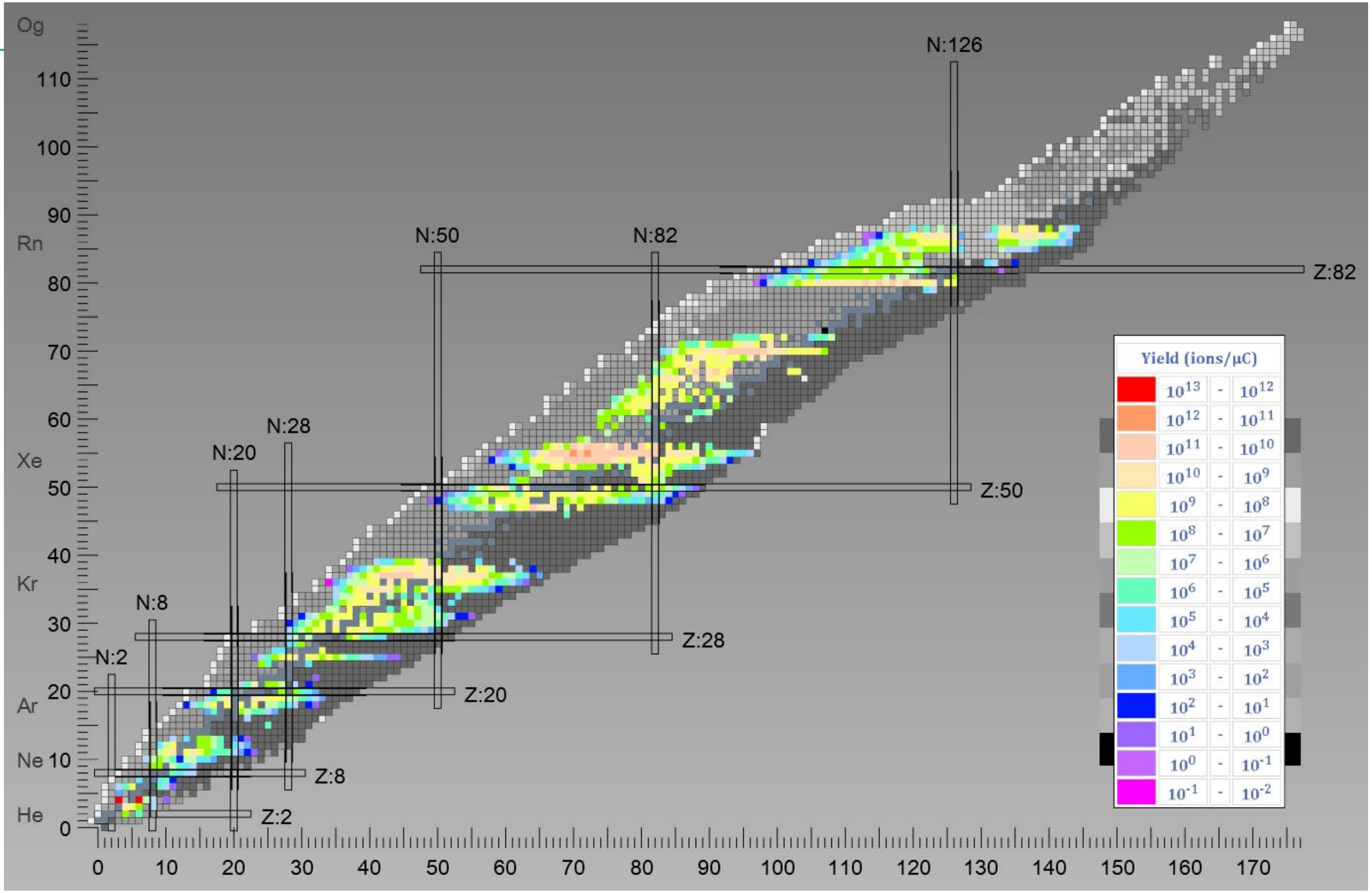


CERN-ISOLDE

>1000 isotopes and isomers

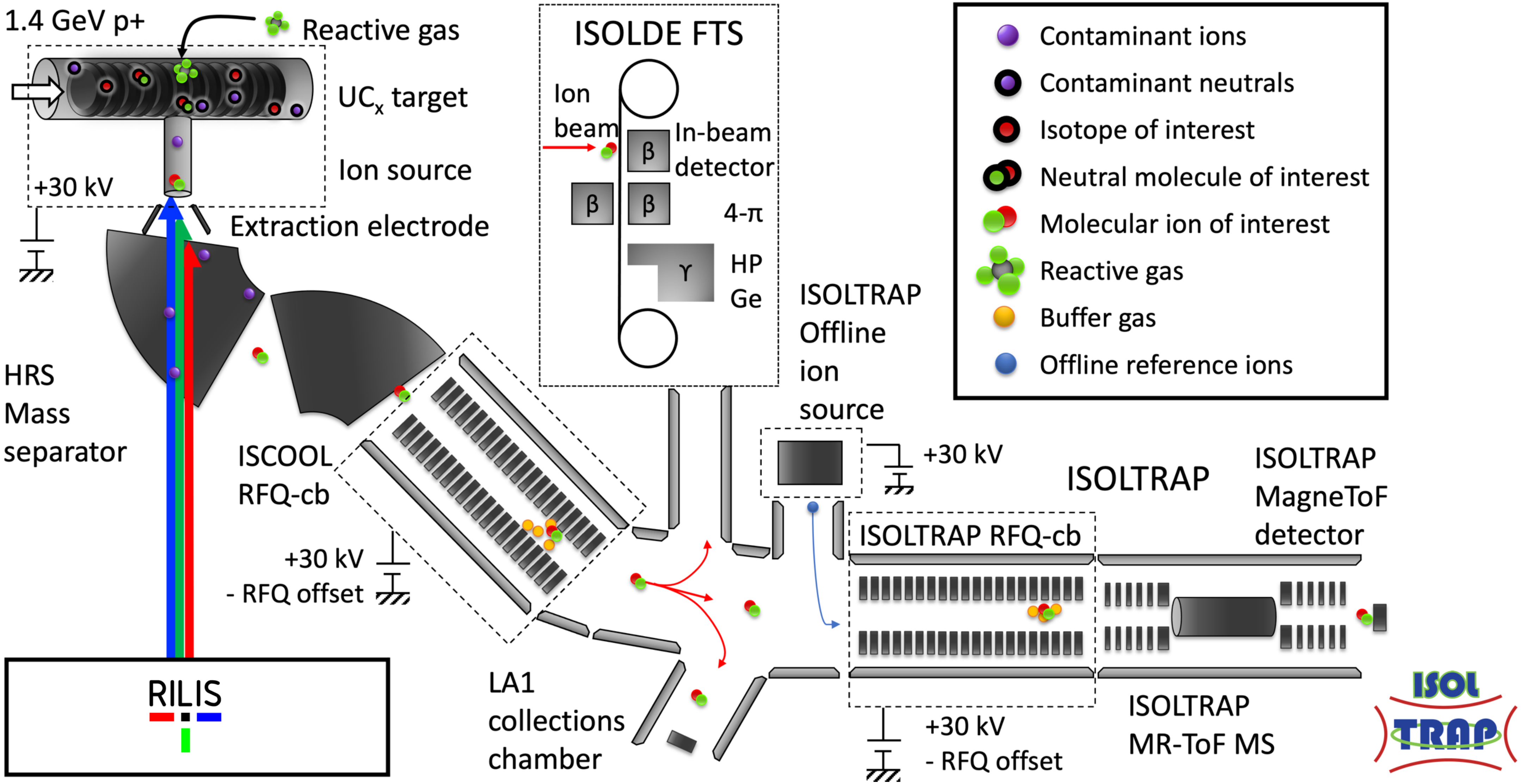
74 elements



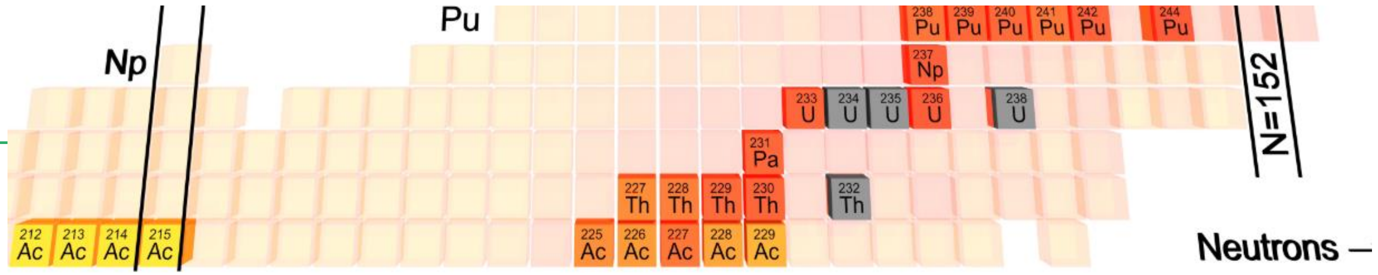
Ballof *et.al,* (2020) *NIM B* **463**, 211-215
cern.ch/isolde-yields

www.nucleonica.com
Dataset: JEFF-3.1 Nuclear Data Library, NEA (2023)

Beam development at ISOLDE



Atomic actinides



Original figure published in: Block, Laatiaoui Raeder, *Prog. Part. Nucl. Phys.* **116** 103834 (2021)

LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

Up to 2020

Actinium

- Delivered as Ra/Fr: ^{225}Ac [1]
- Laser-ionized: IS637 $^{222\text{-}231}$Ac [2]

Actinium

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Thorium

- From Ac/Ra/Fr: ^{229}Th [6]

Protactinium

- Laser-ionized: tried, failed

Uranium

- ^{234,235,238}U [7]

Neptunium

- Laser-ionized: $^{235\text{-}241}$Np

Plutonium

- Laser-ionized: $^{234\text{-}241}$Pu

[1] Guglielmetti et al, EPJA 12, 383-386 (2002)
[2] Jajčišinová, E., et al. Sci Rep 14, 11033 (2024).
[3] Andreyev et al, INTC-LOI-216 (2020)
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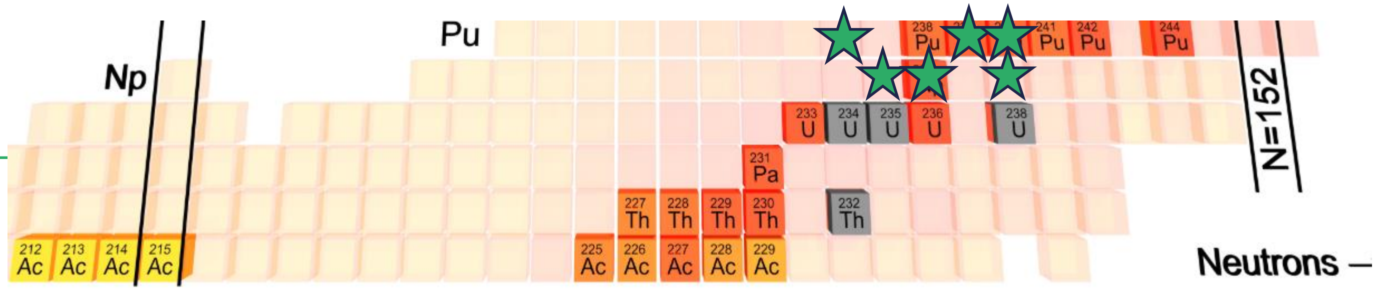

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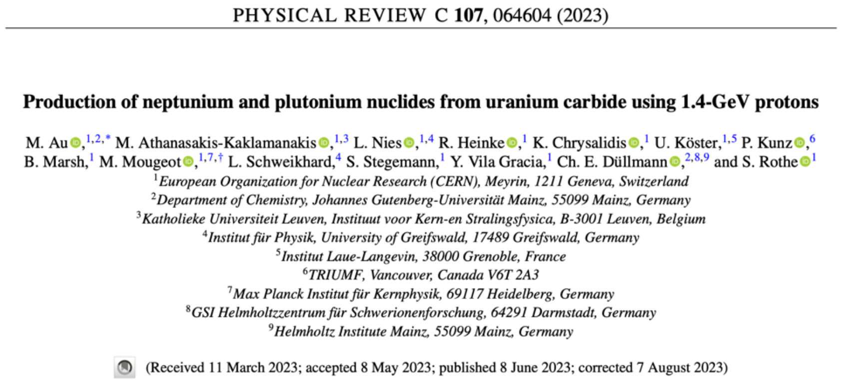

PHYSICAL REVIEW C **107**, 064604 (2023)

Production of neptunium and plutonium nuclides from uranium carbide using 1.4-GeV protons

M. Au,[1,2,*] M. Athanasakis-Kaklamanakis,[1,3] L. Nies,[1,4] R. Heinke,[1] K. Chrysalidis,[1] U. Köster,[1,5] P. Kunz,[6] B. Marsh,[1] M. Mougeot,[1,7,†] L. Schweikhard,[4] S. Stegemann,[1] Y. Vila Gracia,[1] Ch. E. Düllmann,[2,8,9] and S. Rothe[1]

[1]*European Organization for Nuclear Research (CERN), Meyrin, 1211 Geneva, Switzerland*
[2]*Department of Chemistry, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[3]*Katholieke Universiteit Leuven, Instituut voor Kern-en Stralingsfysica, B-3001 Leuven, Belgium*
[4]*Institut für Physik, University of Greifswald, 17489 Greifswald, Germany*
[5]*Institut Laue-Langevin, 38000 Grenoble, France*
[6]*TRIUMF, Vancouver, Canada V6T 2A3*
[7]*Max Planck Institut für Kernphysik, 69117 Heidelberg, Germany*
[8]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[9]*Helmholtz Institute Mainz, 55099 Mainz, Germany*

(Received 11 March 2023; accepted 8 May 2023; published 8 June 2023; corrected 7 August 2023)

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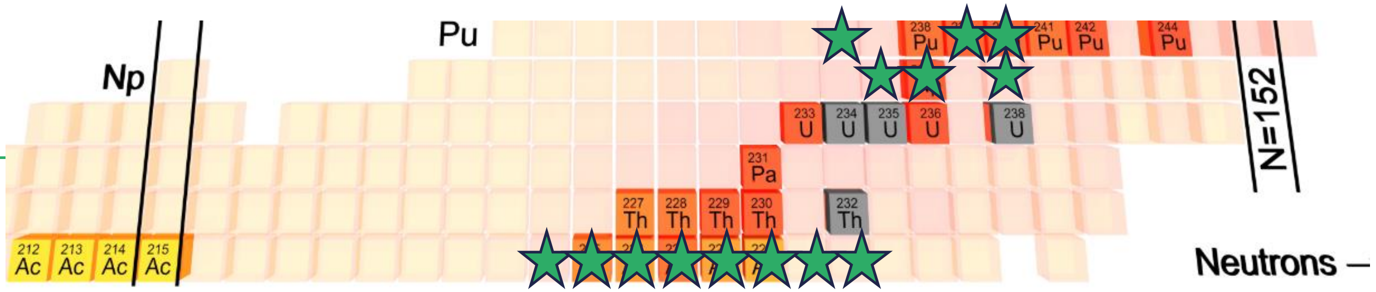

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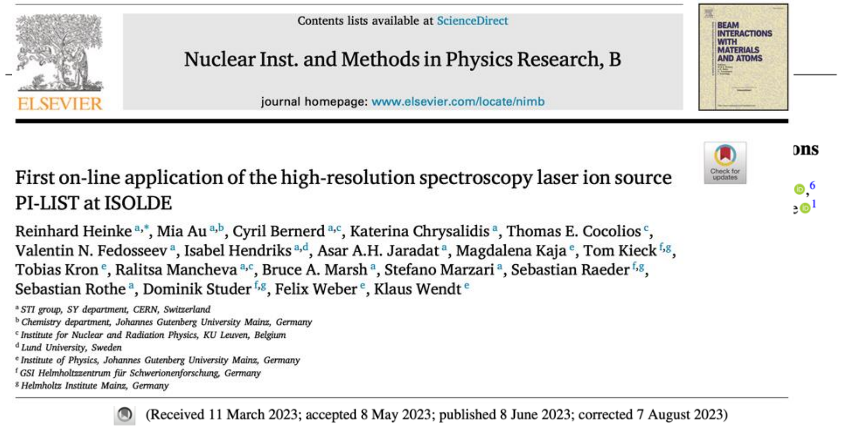

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, B

journal homepage: www.elsevier.com/locate/nimb

ELSEVIER

First on-line application of the high-resolution spectroscopy laser ion source PI-LIST at ISOLDE

Reinhard Heinke [a,*], Mia Au [a,b], Cyril Bernerd [a,c], Katerina Chrysalidis [a], Thomas E. Cocolios [c], Valentin N. Fedosseev [a], Isabel Hendriks [a,d], Asar A.H. Jaradat [a], Magdalena Kaja [e], Tom Kieck [f,g], Tobias Kron [e], Ralitsa Mancheva [a,c], Bruce A. Marsh [a], Stefano Marzari [a], Sebastian Raeder [f,g], Sebastian Rothe [a], Dominik Studer [f,g], Felix Weber [e], Klaus Wendt [e]

[a] STI group, SY department, CERN, Switzerland
[b] Chemistry department, Johannes Gutenberg University Mainz, Germany
[c] Institute for Nuclear and Radiation Physics, KU Leuven, Belgium
[d] Lund University, Sweden
[e] Institute of Physics, Johannes Gutenberg University Mainz, Germany
[f] GSI Helmholtzzentrum für Schwerionenforschung, Germany
[g] Helmholtz Institute Mainz, Germany

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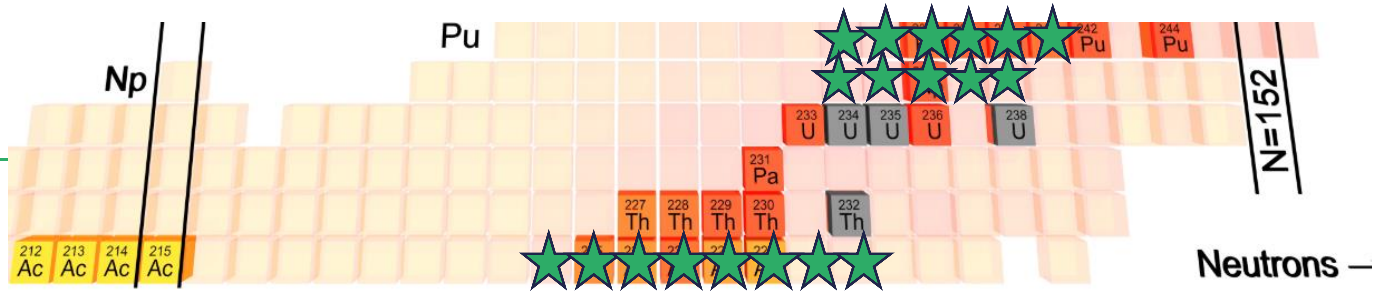

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Magdalena Anna Kaja

14:45 - 15:15

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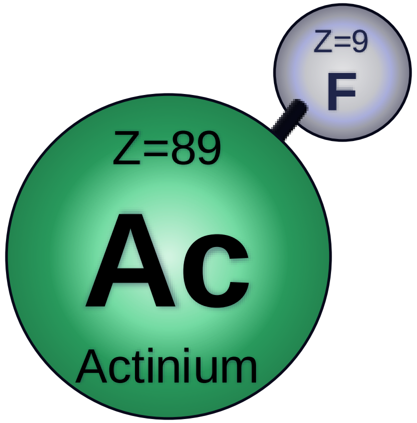
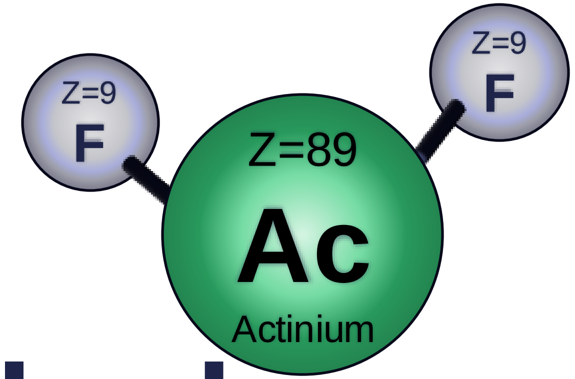
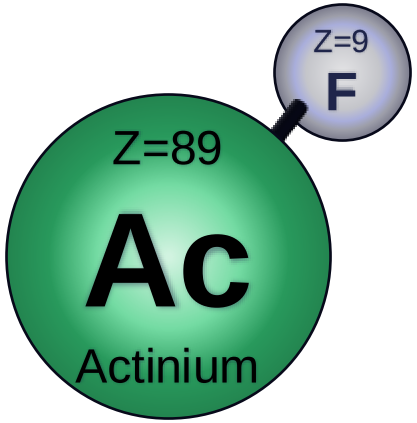
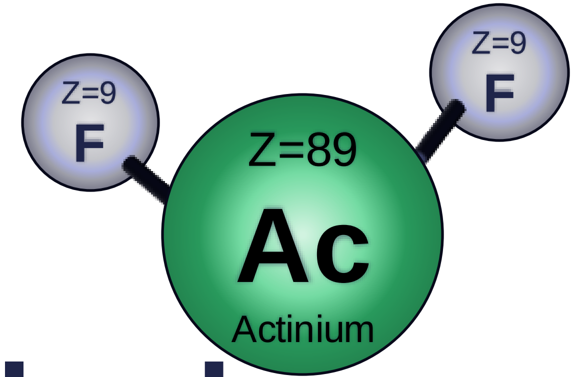


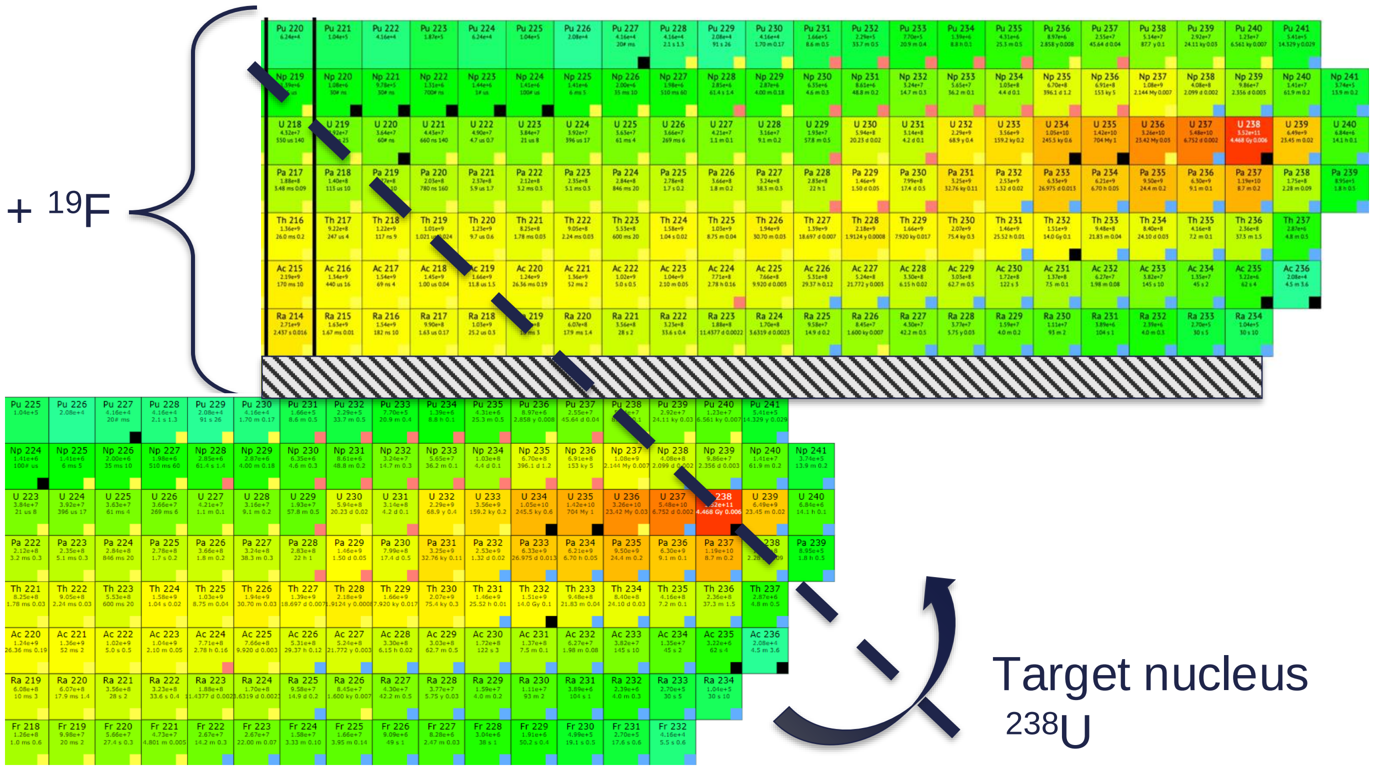


Molecular beams

Image published in EP Newsletter, CERN (2020)



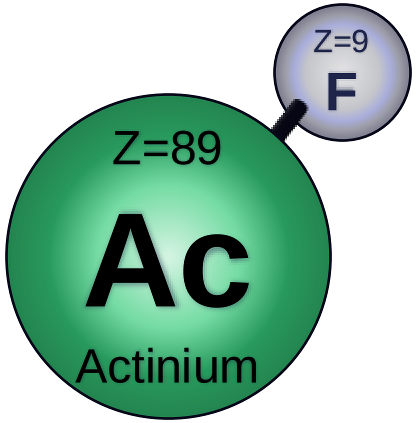


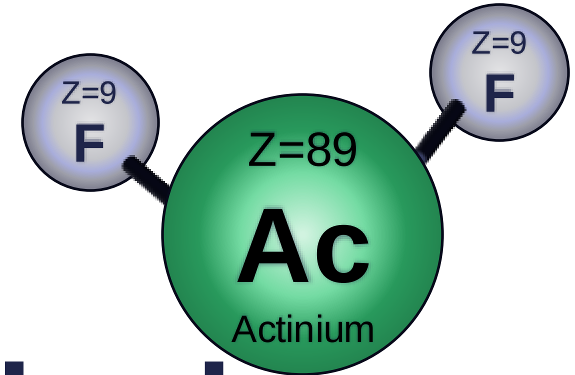


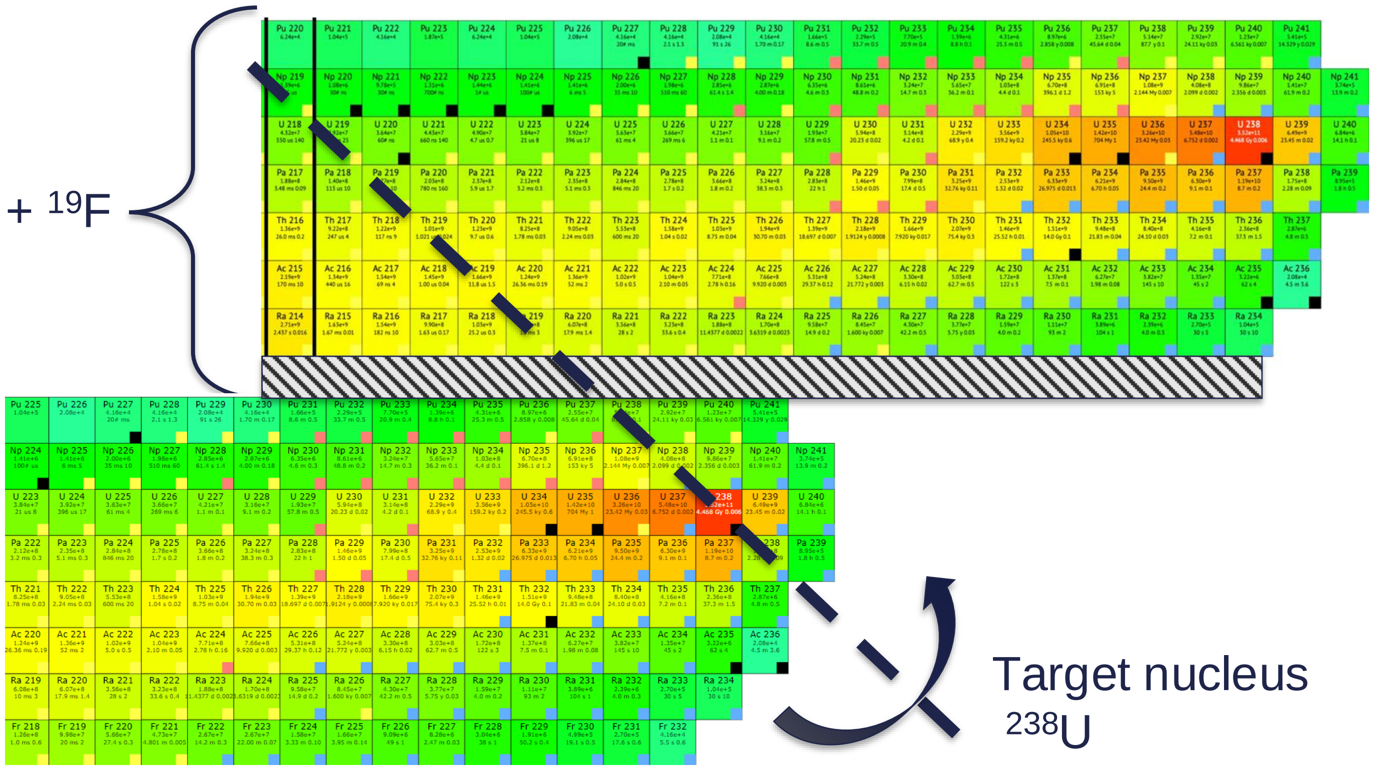
Molecular beams

Sideband extraction

Image published in EP Newsletter, CERN (2020)





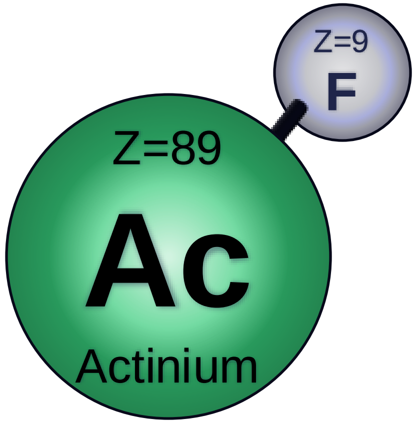


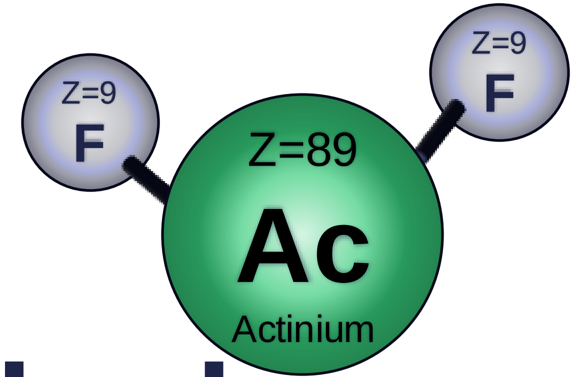
Molecular beams

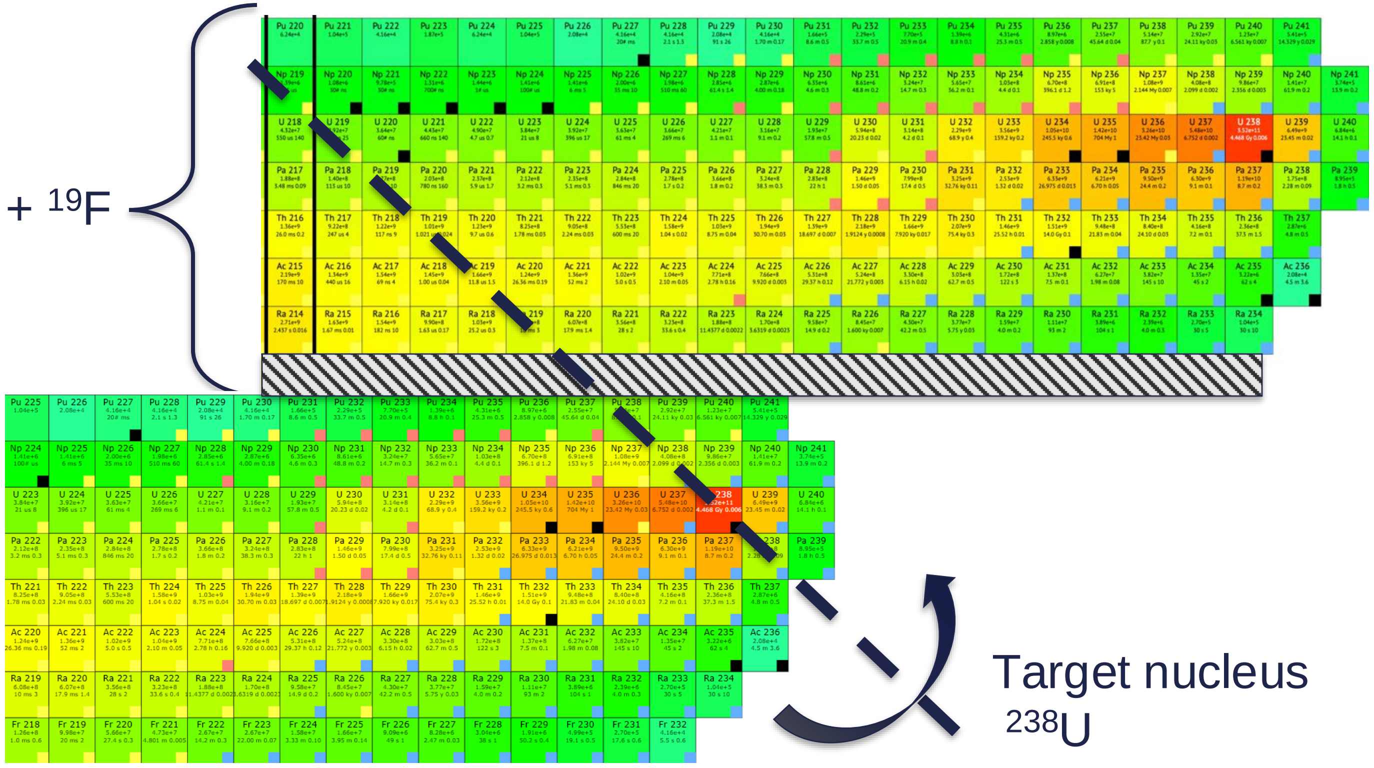
Sideband extraction

Volatilization

Image published in EP Newsletter, CERN (2020)







Molecular beams

Sideband extraction

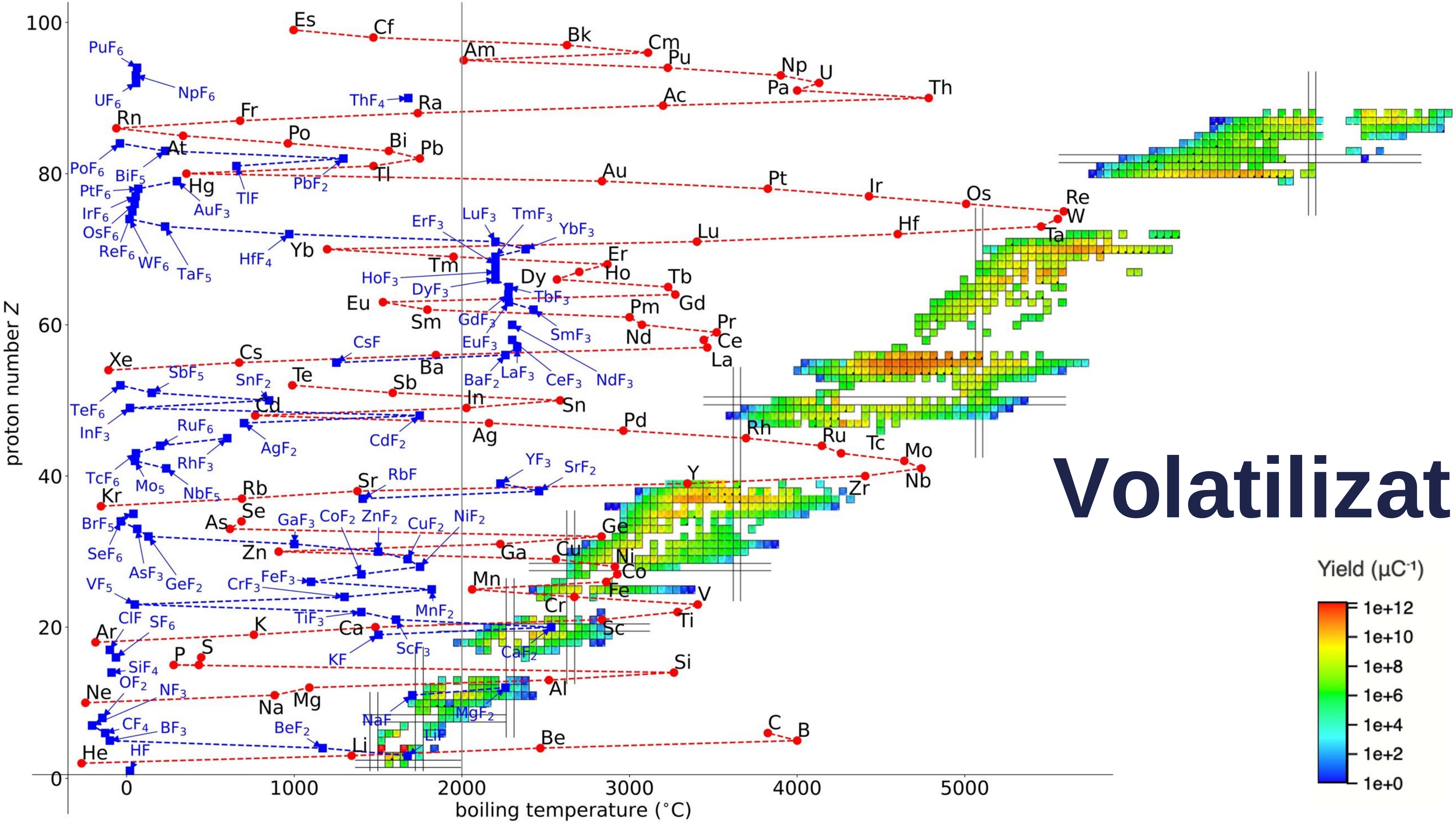
Volatilization

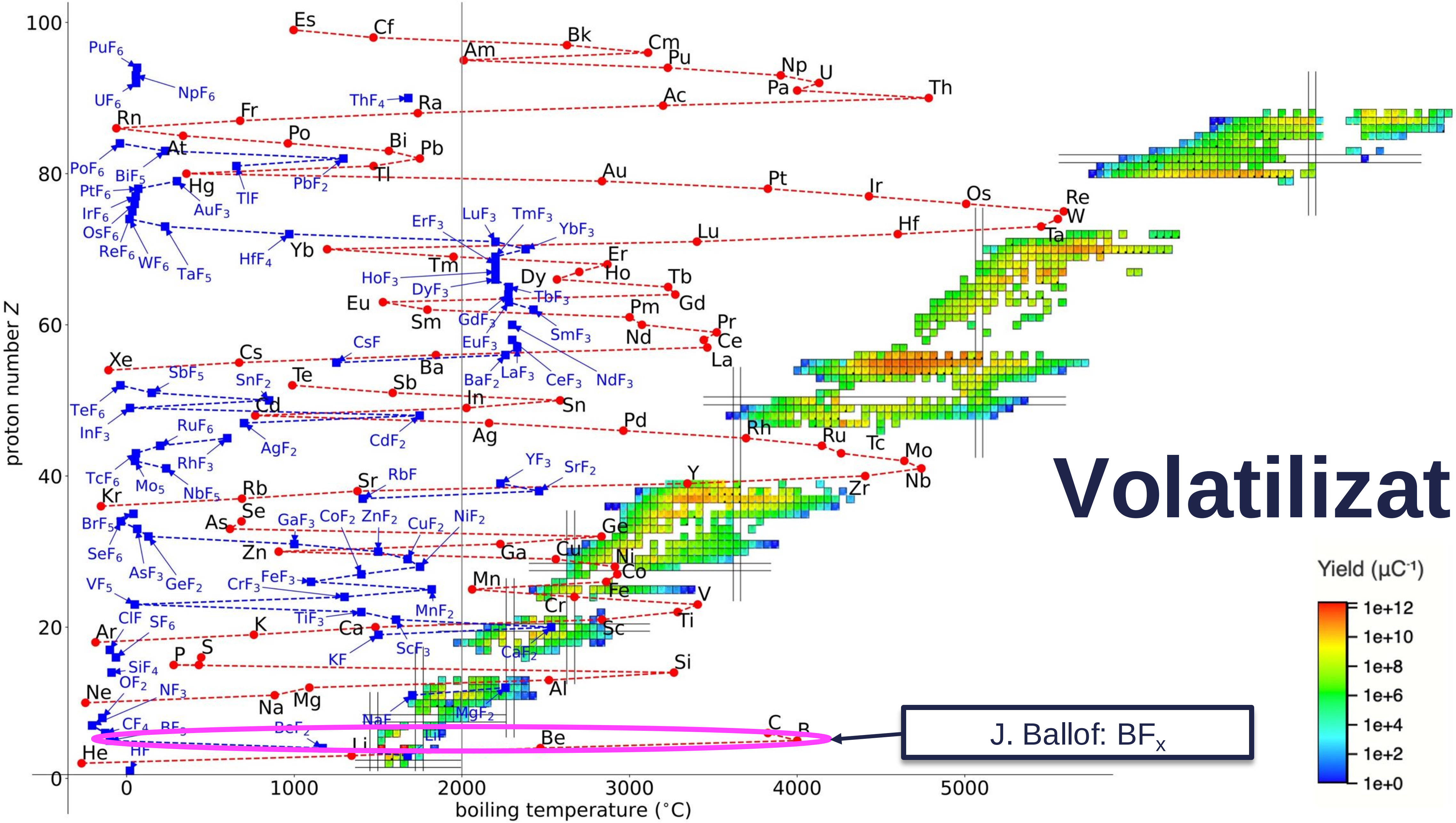
Research opportunities

Opportunities for Fundamental Physics Research with Radioactive Molecules, PMID: 38215499
DOI: 10.1088/1361-6633/ad1e39 (2024)

- Symmetry violations
- Nuclear structure
- Astrophysics
- Quantum chemistry

Volatilization

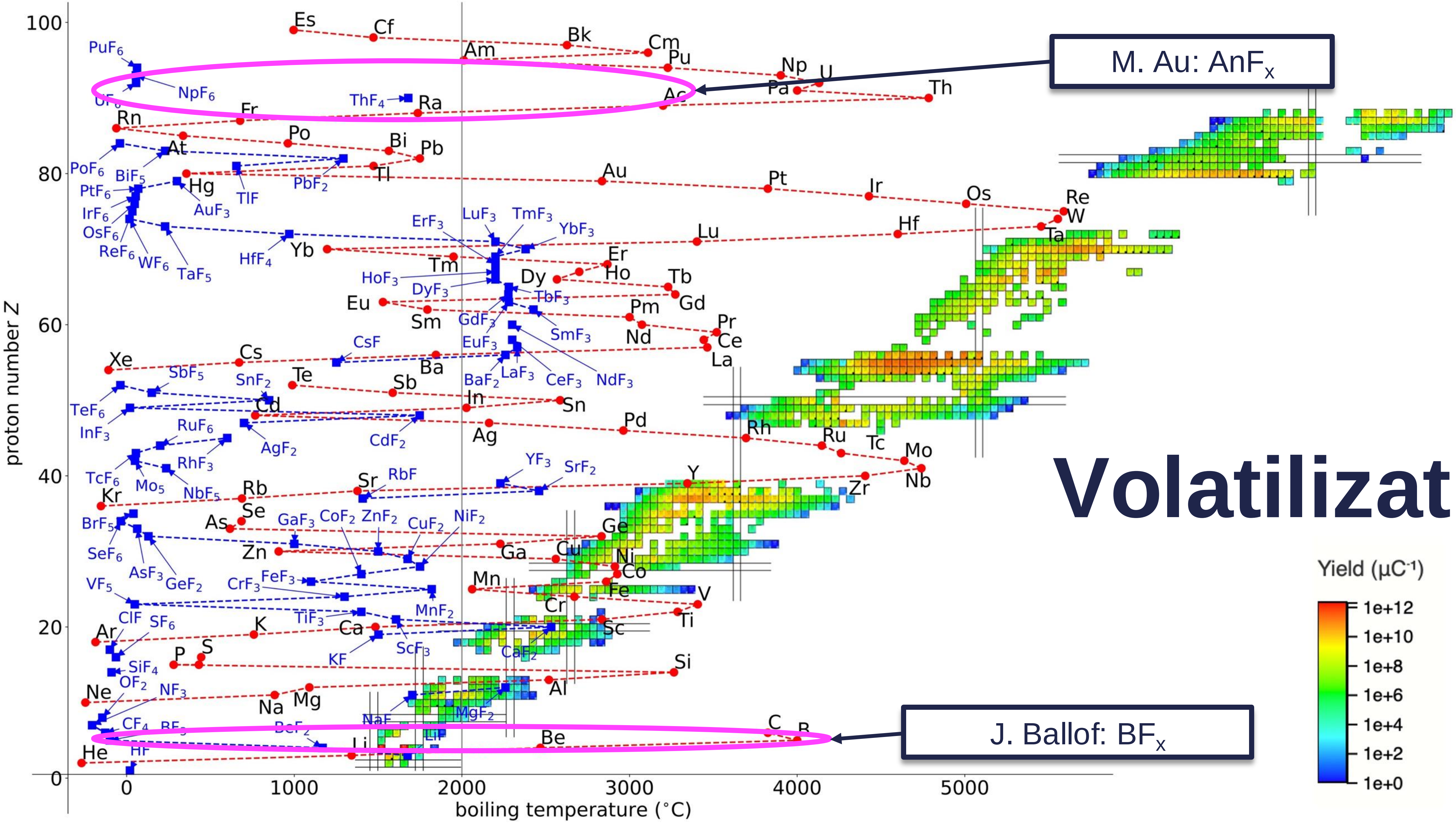




Volatilization

J. Ballof: BF_x

Volatilization



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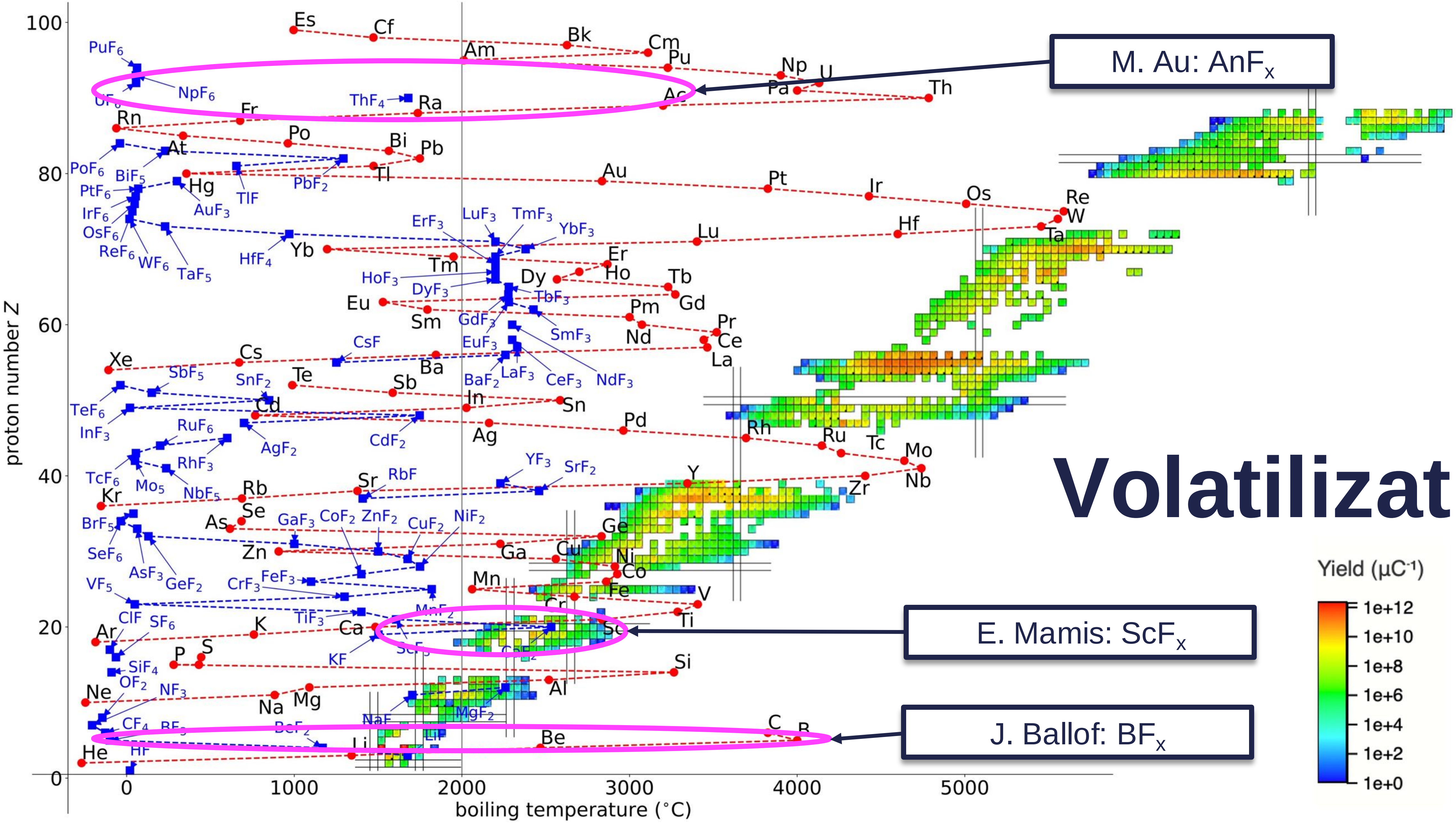
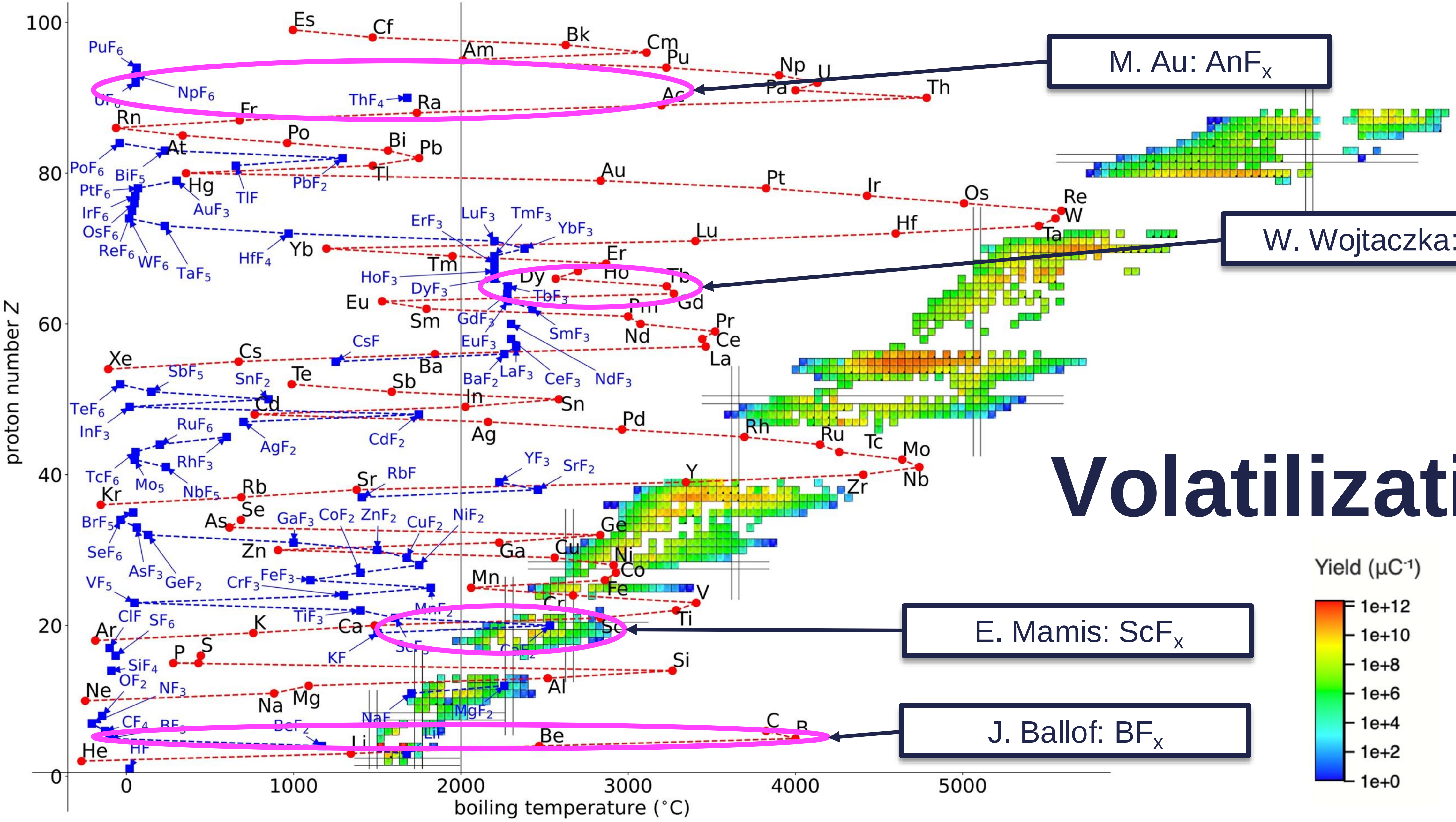


M. Au: AnF_x

E. Mamis: ScF_x

J. Ballof: BF_x

Volatilization



Research opportunities: a small detour

Matter-antimatter asymmetry

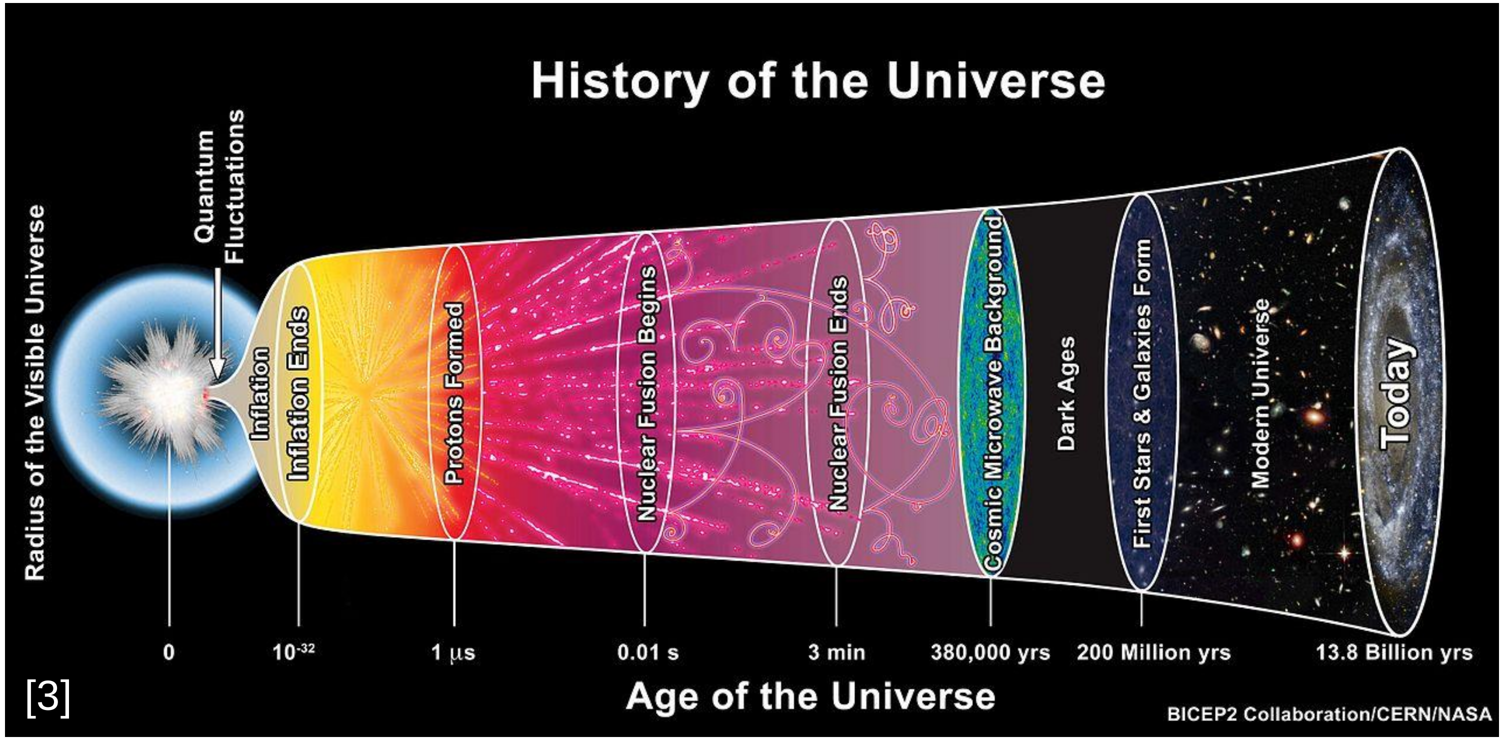
- Initial conditions of expanding universe

Sakharov's conditions [1]

- CP violation for baryogenesis

CPV in the Standard Model

- CKM phase δ_{CKM} (order 1)
- Strong CP-phase $\bar{\theta}$ (tiny)
- Unconfirmed: PMNS matrix, Majorana neutrinos, other operator?
- *Required: Evaluation from complementary sources [2]*



[3]

"… the occurrence of *C* asymmetry is the consequence of violation of *CP* invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed" – [1]

[1] Sakharov (1991) *Sov. Phys. Usp.* **34** 392
[2] Alarcon *et al*., (2022) *arXiV* 2203.08103
[3] The BICEP2 Collaboration CERN-NASA (1991) https://home.cern/news/series/lhc-physics-ten/recreating-big-bang-matter-earth

Research opportunities

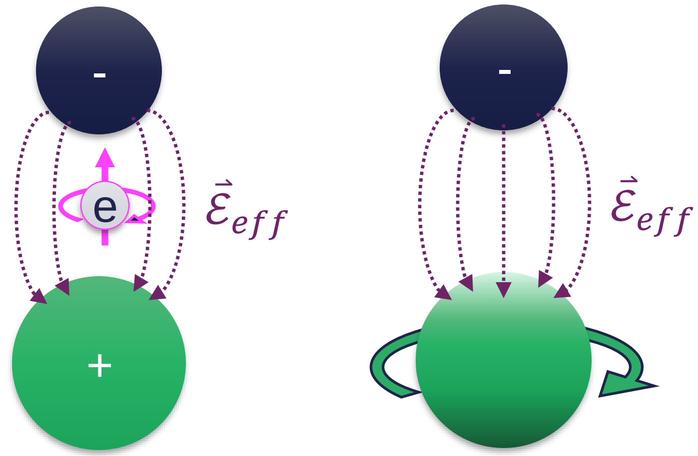
- Low energy observables for physics beyond the Standard Model

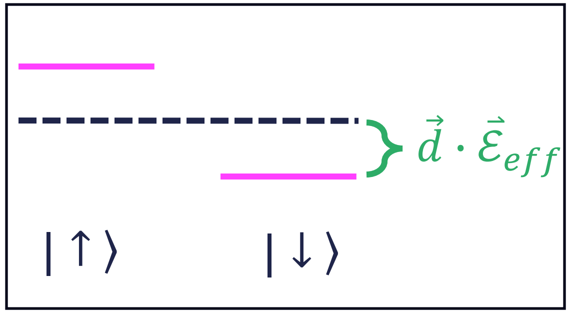
eEDM

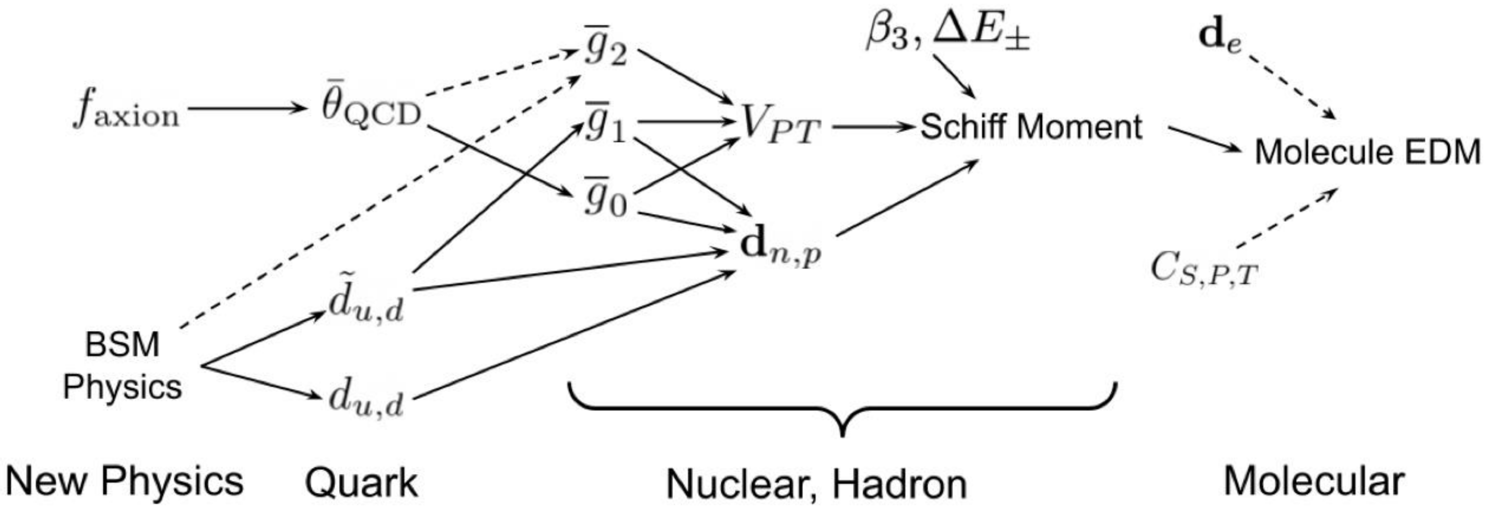
- Sensitive to electron-coupled CPV

Hadronic CPV

- Enhanced in heavy, deformed nuclei







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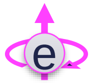
eEDM 

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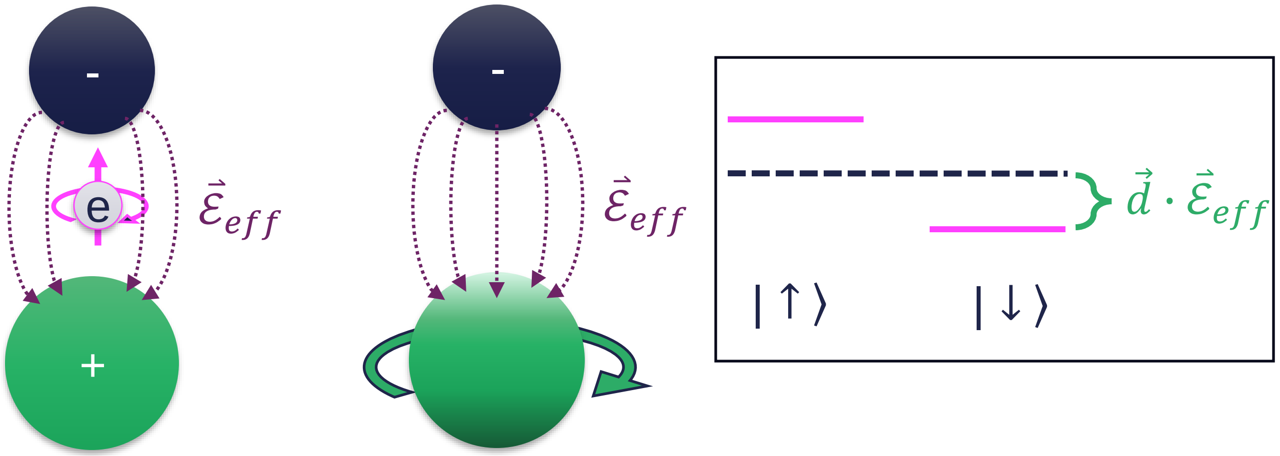

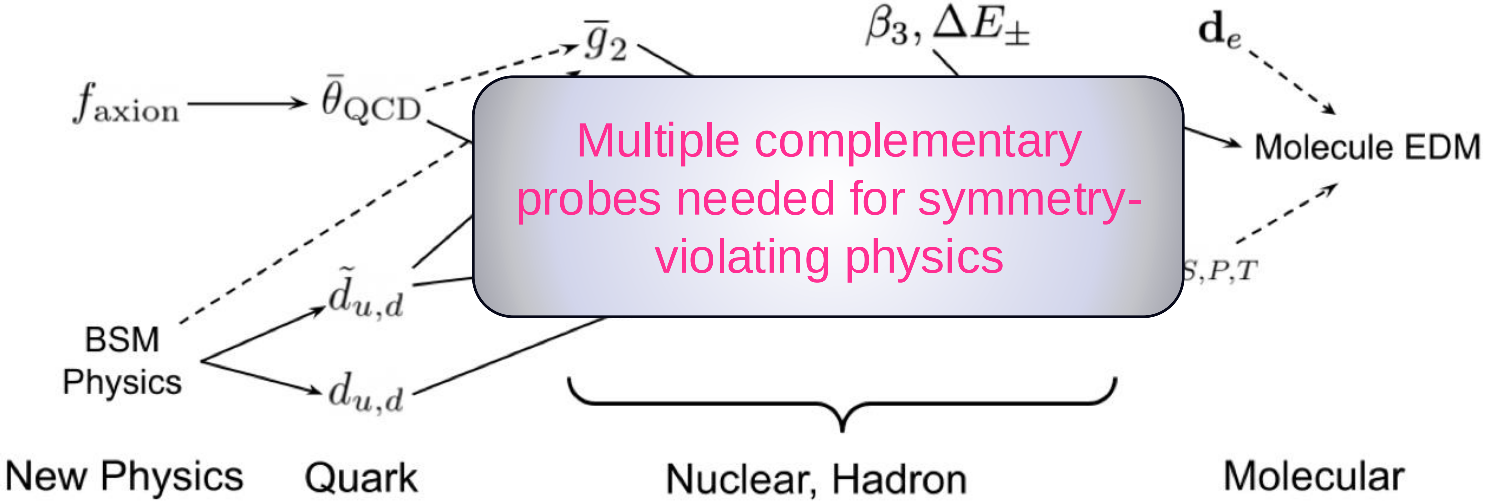

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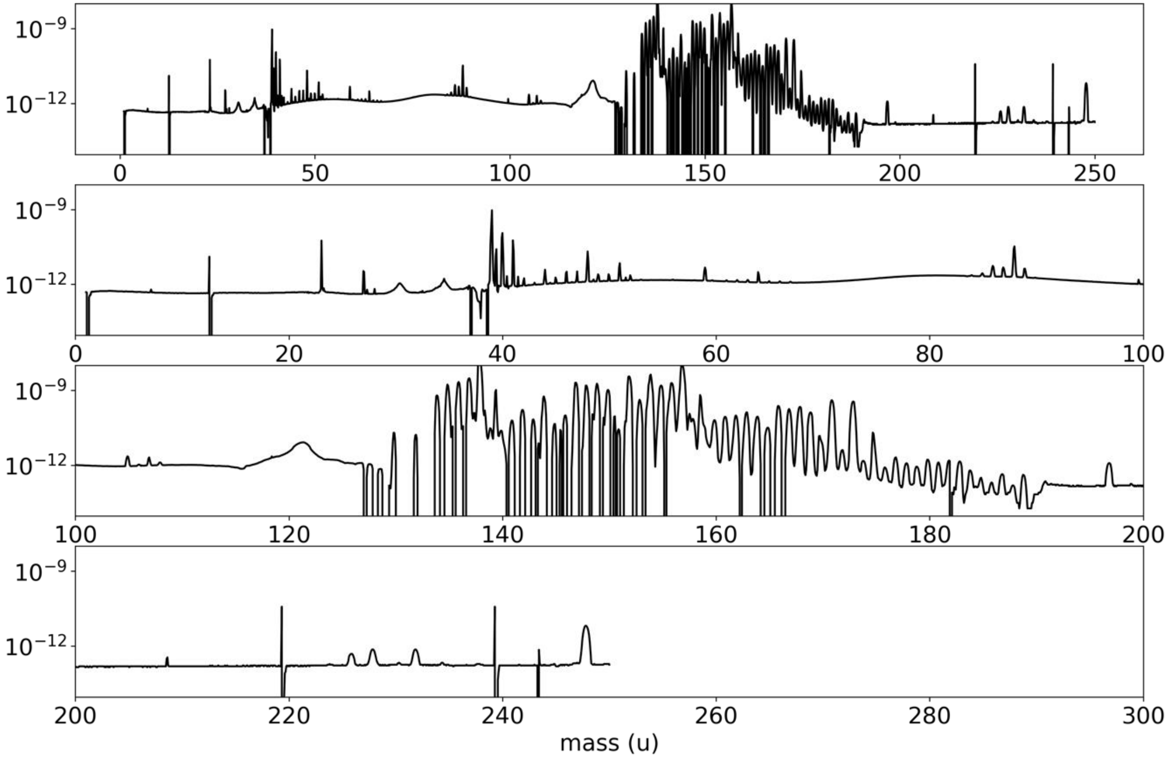
Molecular beam production: Ion sources and effects

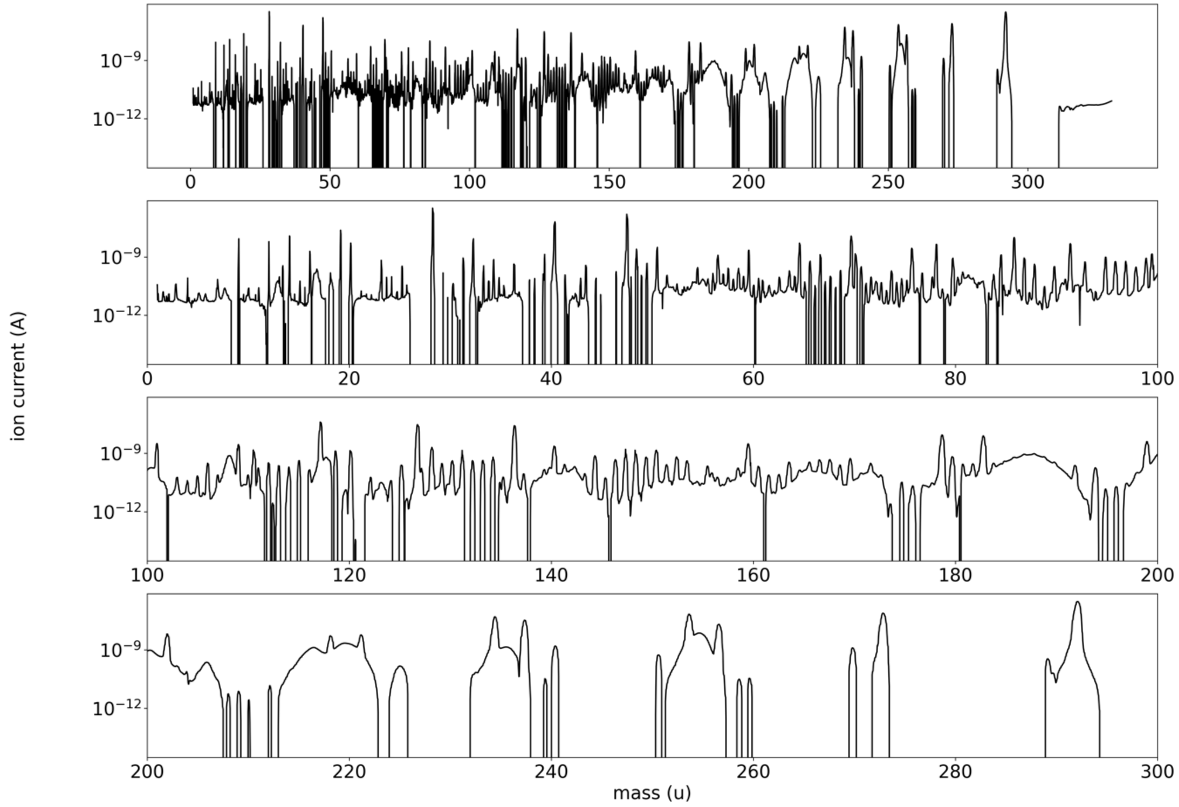
Surface

- Low IPs
- Surface ionization efficiency



FEBIAD

- High/unknown IPs
- High efficiency



[1] Wilkins et al., arXiv:2408.14673 (2024)

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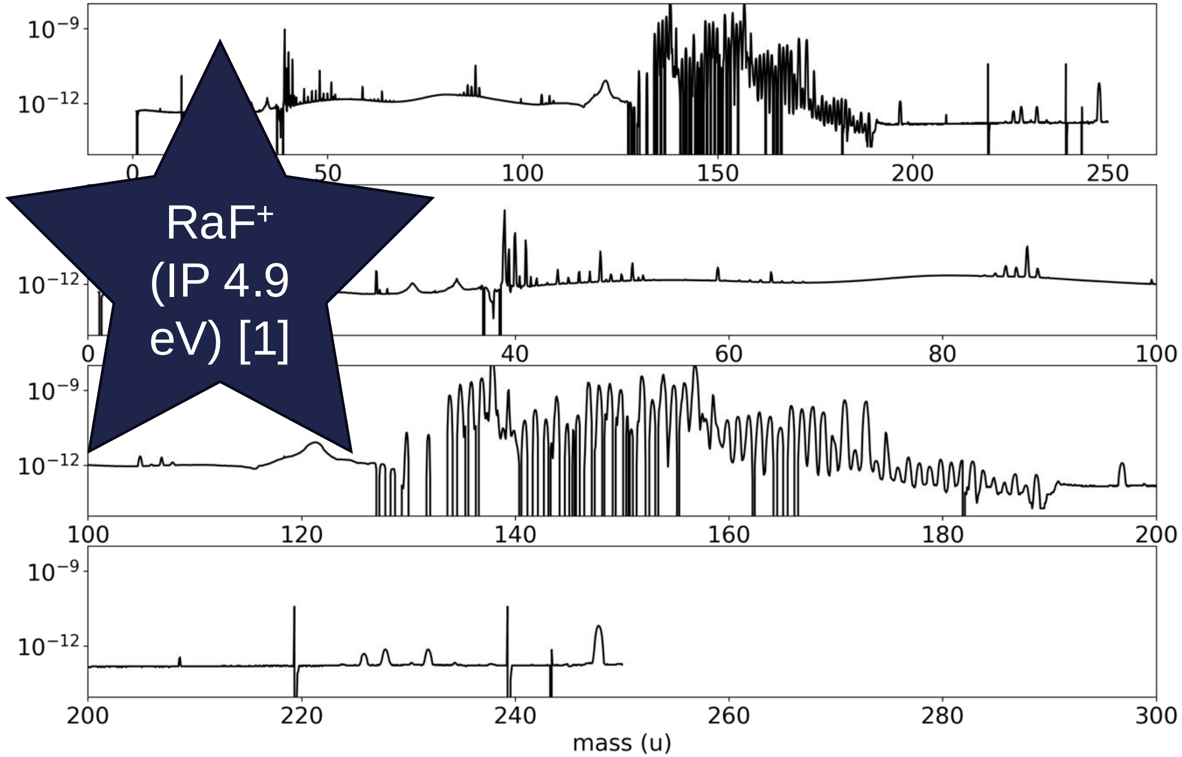

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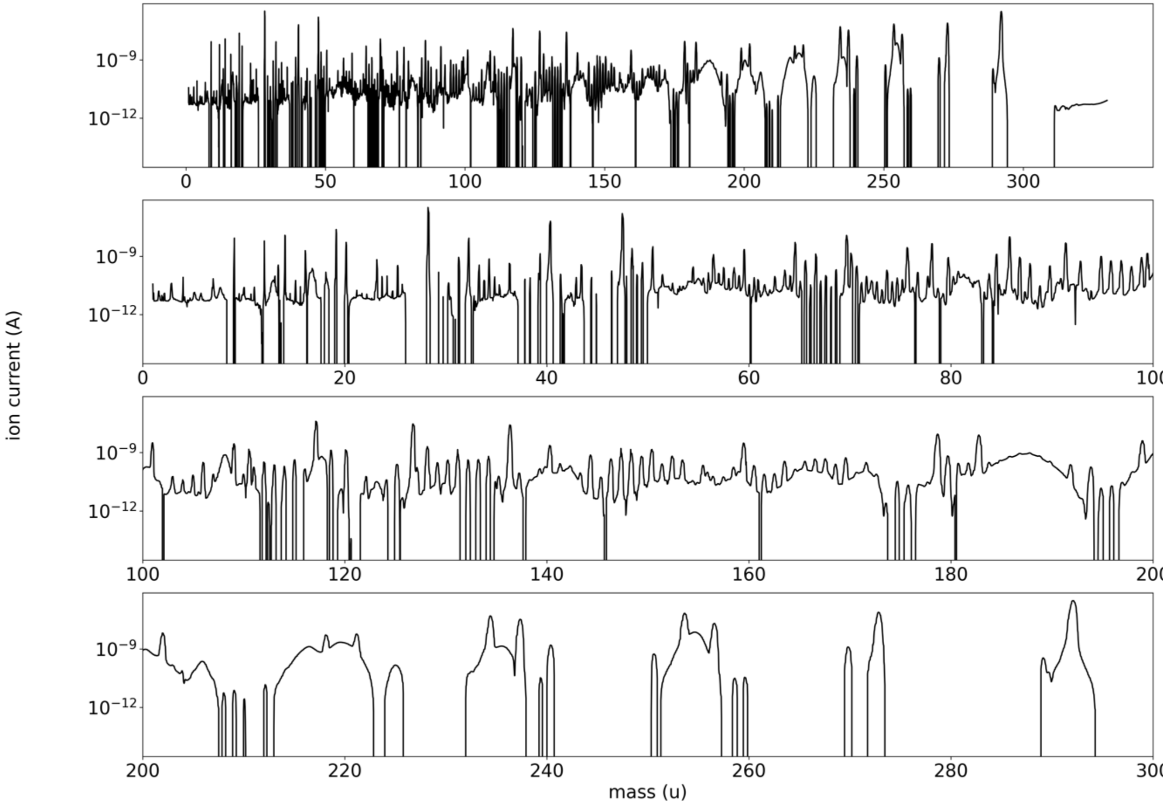

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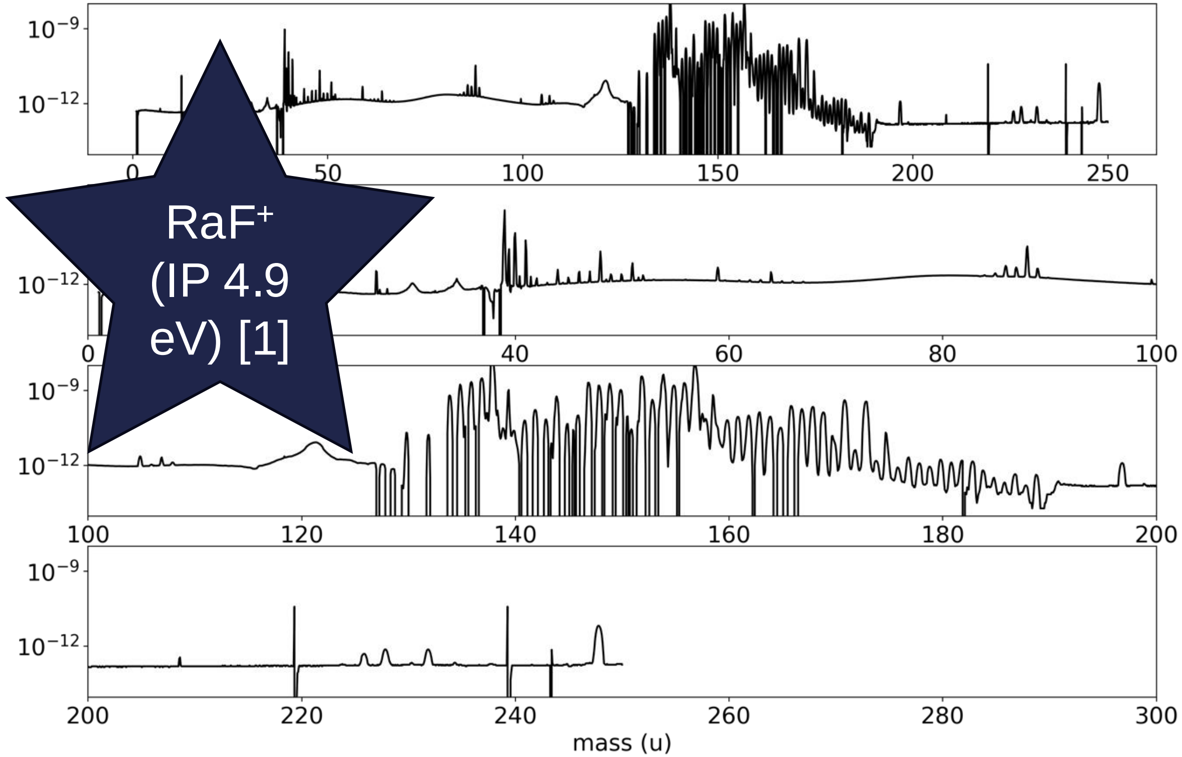
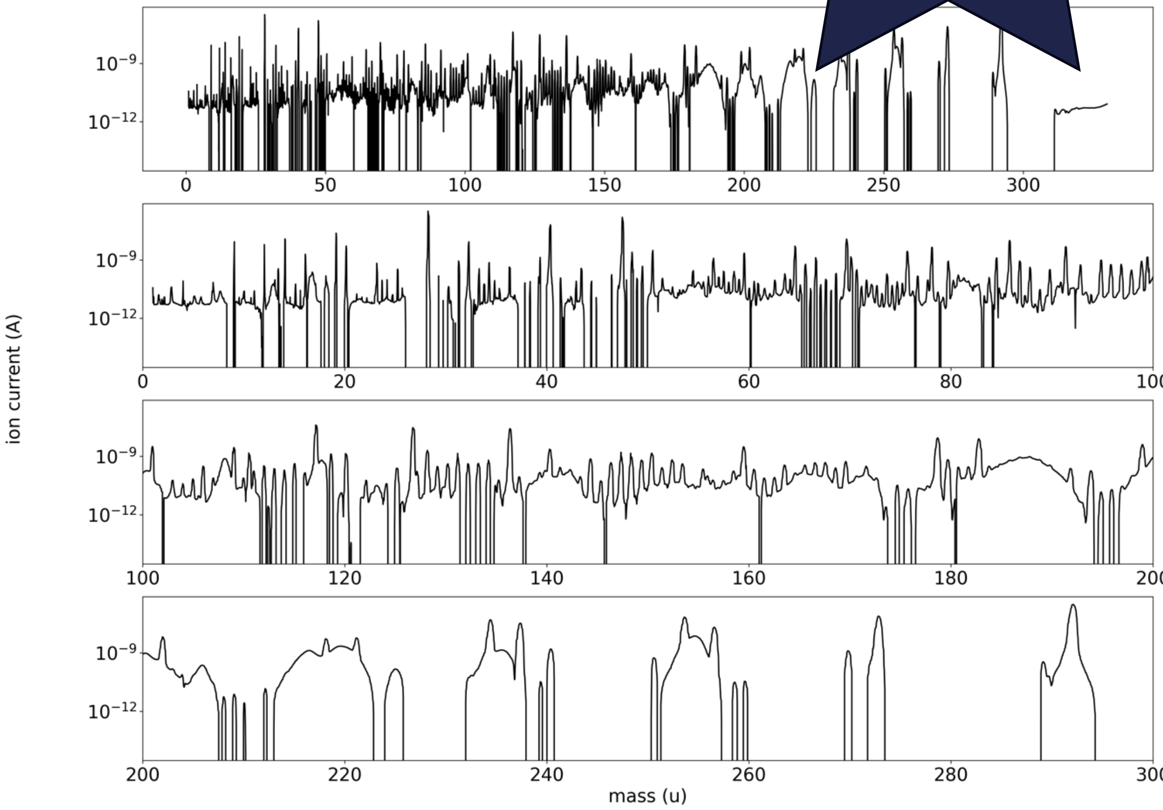


RaF+
(IP 4.9 eV) [1]

FEBIAD

- High/unknown IPs
- High efficiency

AcF+
AcF_2^+
(IP ?)



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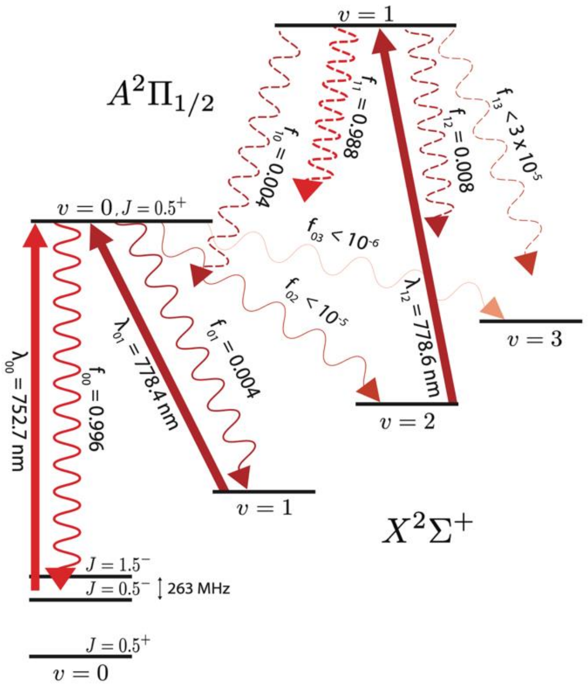
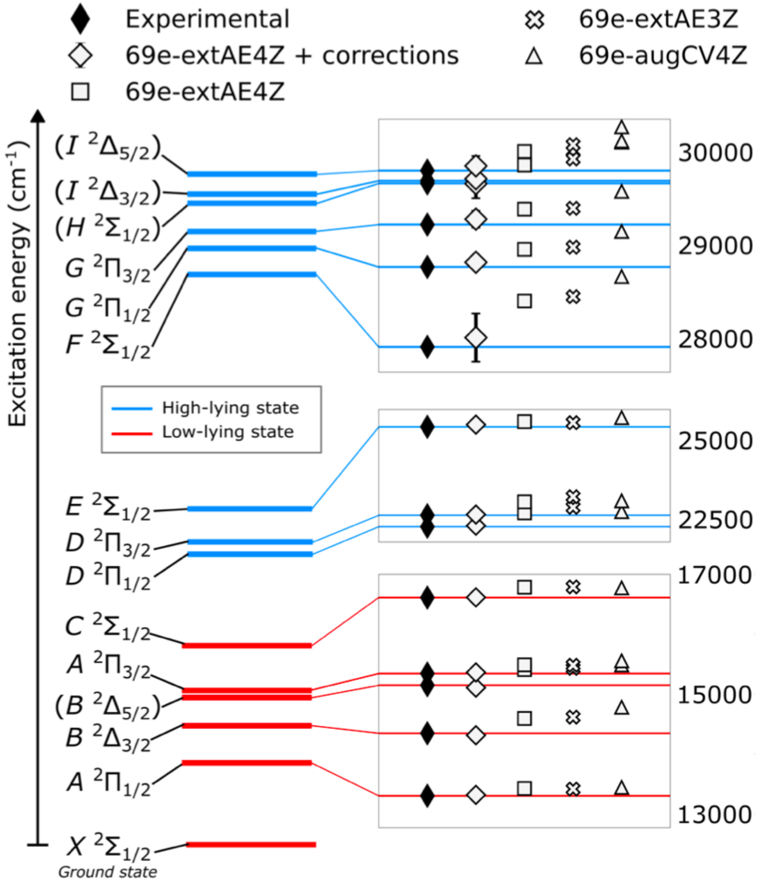
Production of RaF

Laser cooling [1]



Excited states [2]

- agreement ≥ 99.64% (~12 meV)

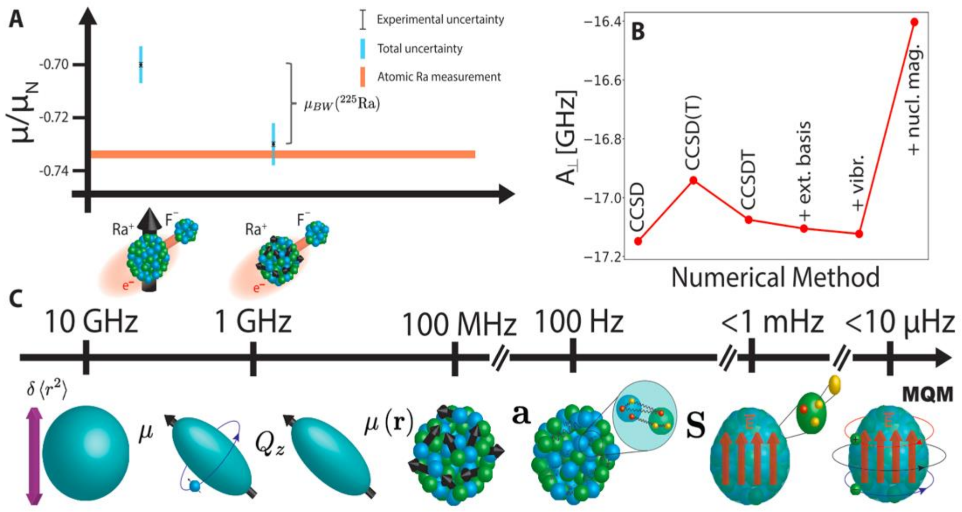


State lifetimes [3]

- Radiative lifetime of A $^2\Pi_{1/2}$ state

Nuclear magnetization effect [4]

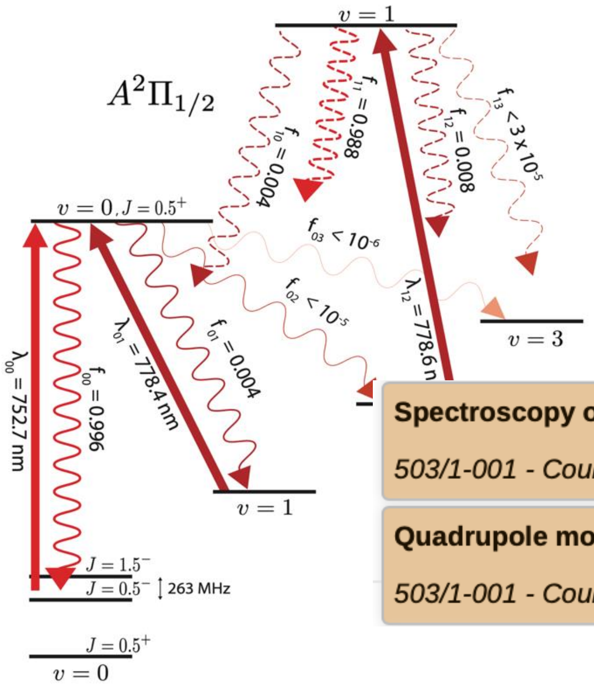
- $\mu(^{225}Ra)$



[1] Udrescu *et al.*, Nat. Phys. 20, 202 (2024)
[2] Athanasakis-Kaklamanakis *et al.*, arXiv 2308.14862 submitted (2024)
[3] Athanasakis-Kaklamanakis *et al.*, PRA 110, L010802 (2024)
[4] Wilkins *et al.*, arXiV 2311.04121 in review (2024)

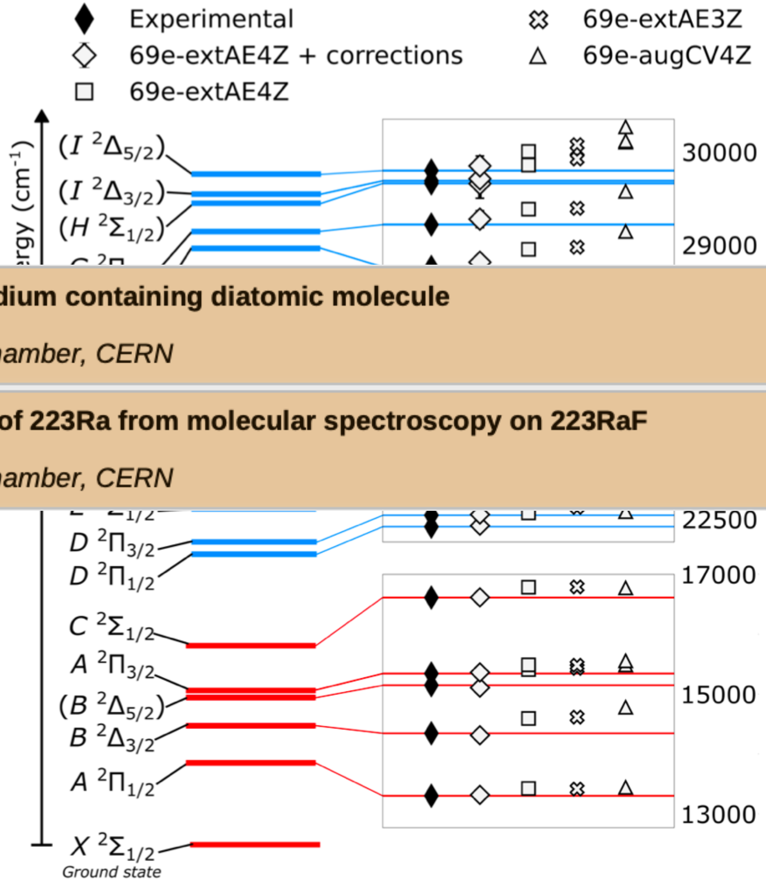
Production of RaF

Laser cooling [1]



Excited states [2]

- agreement ≥ 99.64% (~12 meV)



Spectroscopy of a radium containing diatomic molecule — *Justus Berbalk*

503/1-001 - Council Chamber, CERN — 11:25 - 11:45

Quadrupole moment of 223Ra from molecular spectroscopy on 223RaF — *Carlos Mario Fajardo Zambrano et al.*

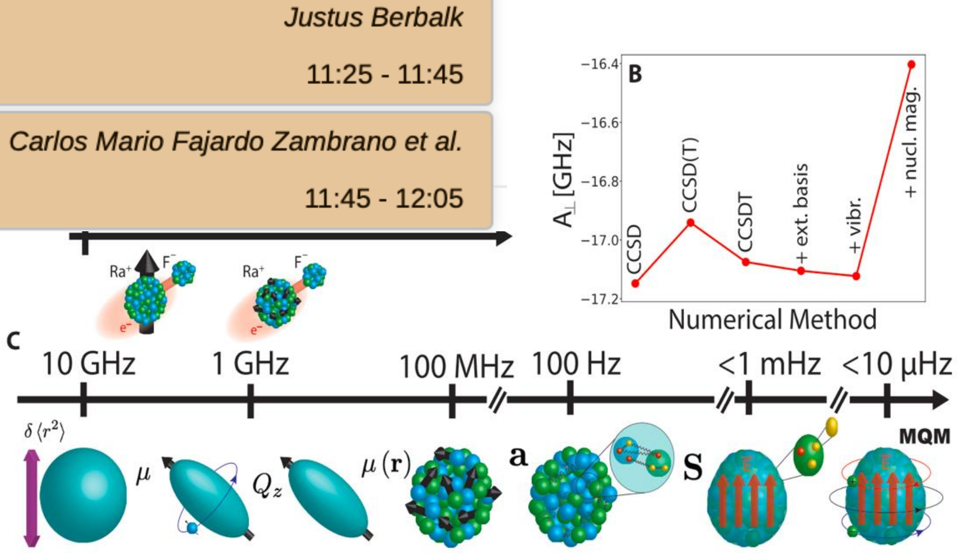
503/1-001 - Council Chamber, CERN — 11:45 - 12:05

State lifetimes [3]

- Radiative lifetime of A $^2\Pi_{1/2}$ state

Nuclear magnetization effect [4]

- $\mu(^{225}Ra)$



[1] Udrescu *et al.*, Nat. Phys. 20, 202 (2024)
[2] Athanasakis-Kaklamanakis *et al.*, arXiv 2308.14862 submitted (2024)
[3] Athanasakis-Kaklamanakis *et al.*, PRA 110, L010802 (2024)
[4] Wilkins *et al.*, arXiV 2311.04121 in review (2024)

Motivation: Actinium

Ac: Nuclear properties

- Octupole deformation
- Low-lying opposite parity states
- Schiff moment enhancement

[4]

TABLE IV. Schiff moments (S) and EDMs (d_A) of some atoms in terms of the QCD θ-term constant $\bar{\theta}$. We remind the reader that the current experimental limit is $|\bar{\theta}| < 10^{-10}$.

Z	Atom	S $[e\,\mathrm{fm}^3\bar{\theta}]$	$d_A[e\,\mathrm{cm}]$ $10^{-17}S[e\,\mathrm{fm}^3]$	$10^{-17}\bar{\theta}$
63	^{153}Eu	−3.7	−1.63	6
63	^{153}Eu^{3+}	−3.7	0.33	−1.2
66	^{161}Dy	$\lesssim 4$	−2.23	$\lesssim 9$
80	^{199}Hg	0.005	−2.50	−0.013
81	^{205,203}Tl^{+}	0.02	−2.79	−0.06
82	^{207}Pb^{2+}	0.005	−2.99	−0.015
86	^{223}Rn	−3	3.3	−10
87	^{223}Fr^{+}	1.6	2.87	4.6
88	^{225}Ra	−1	−8.25	8
89	^{227}Ac	−6	−10.1	60
89	^{227}Ac^{+}	−6	−9.8	60
90	^{229}Th^{2+}	$\lesssim 2$	−6.93	$\lesssim 14$
91	^{229}Pa[a]	−40	−11.4	460
92	^{233}U	$\lesssim 2$	−12.1	$\lesssim 20$
93	^{237}Np	−4	−7.5	30
94	^{239}Pu	$\lesssim 0.1$	−9.2	$\lesssim 1$

[a] Estimates for ^{229}Pa are presented assuming that the existence of a very close nuclear doublet level will be confirmed.

[1] Verstraelen et al., Phys. Rev. C. 100, 044321 (2019)
[2] Heinke et al., CERN-INTC-2020-029, INTC-P-556 (2020)
[3] Flambaum, Feldmeier, Phys. Rev. C. 101, 015502 (2020)
[4] Flambaum, Dzuba, Phys. Rev. A. 101, 042504 (2020)

Motivation: Actinium Fluoride

Ac: Nuclear properties

- Octupole deformation
- Low-lying opposite parity states
- Schiff moment enhancement

AcF: molecular enhancement

- Enhanced sensitivity to CP-violating observables?

[4]

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[3]

The interaction constant W_S for the effective T,P-violating interaction in ^{227}Ac-containing molecules is

$$W_S \approx 46000 \text{ a.u.} \quad (55)$$

The energy shift is

$$2W_S S = 5 \times 10^7 \bar{\theta}\, h\,\mathrm{Hz}. \quad (56)$$

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Motivation: Actinium Fluoride

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- Enhanced sensitivity to CP-violating observables?

Production

- IP: ? D_e: ?

[4]

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[4] Flambaum, Dzuba, Phys. Rev. A. 101, 042504 (2020)

Motivation: Actinium-225

9-10 MBq

T-αT (targeted alpha therapy)

- **Damage to cancer cells**
  - DNA double strand breaks, membrane, mRNA damage
  - Ionization through free radicals
- High linear energy transfer

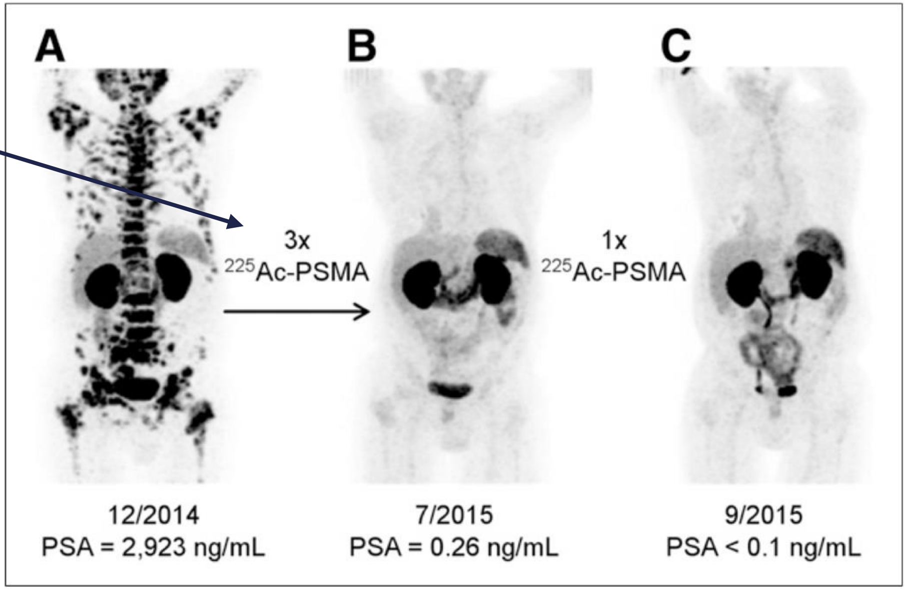

Figure published in: Kratchowil *et al.* (2016) J. Nucl. Med. **57** 1941-1944

Production routes

- **^{226}Ra**
  - ^{226}Ra(p,2n)^{225}Ac

^{225}Ra (generator)

  - ^{226}Ra(γ,n)^{225}Ra → ^{225}Ac
  - ^{226}Ra(n,2n)^{225}Ra → ^{225}Ac

Actinide

  - ^{nat}Th(p,x)^{225}Ac, ^{225}Ra (^{nat}Th(p,x)^{227}Ac, ^{227}Ra)
  - $^{nat/dep}$U(p,x)^{225}Ac, ^{225}Ra ($^{Nat/dep}$U(p,x)^{227}Ac, ^{227}Ra)

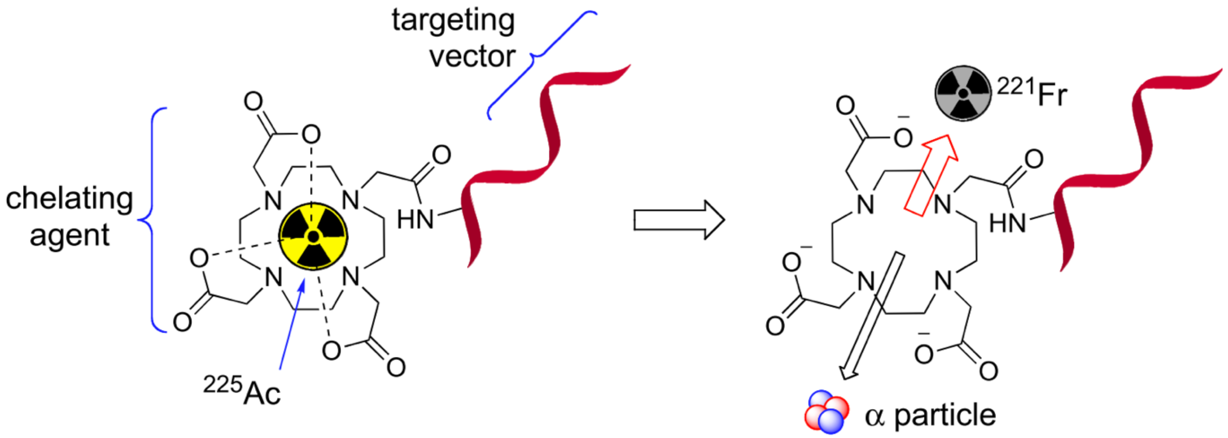

Figure published in: Robertson *et al.* (2018) Current Radiopharmaceuticals. **11** 156-172

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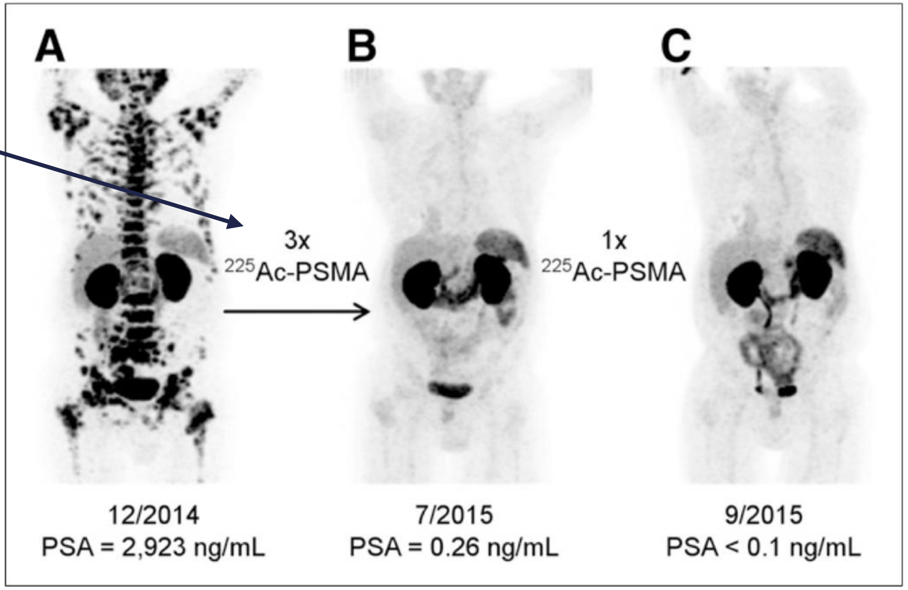

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Jake David Johnson et al.
11:35 - 12:05

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Actinide

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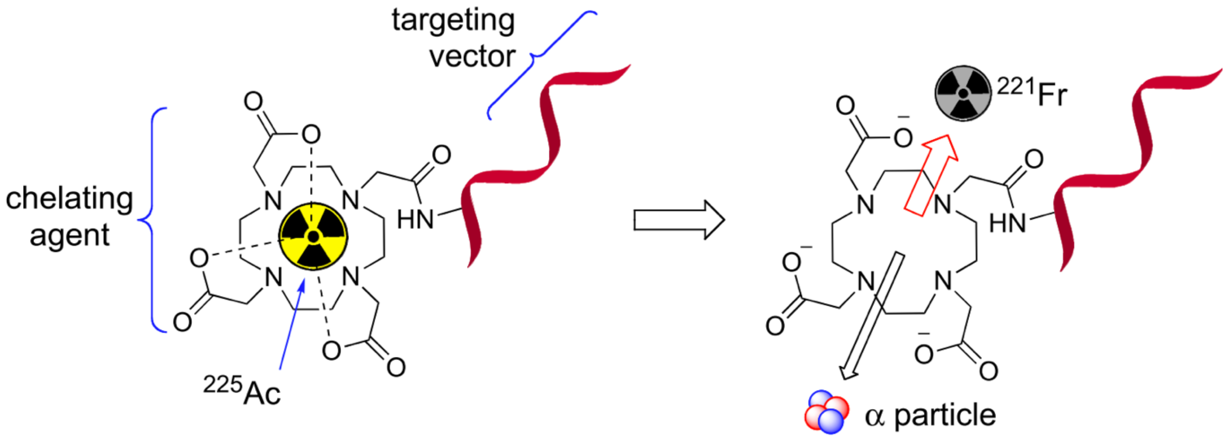

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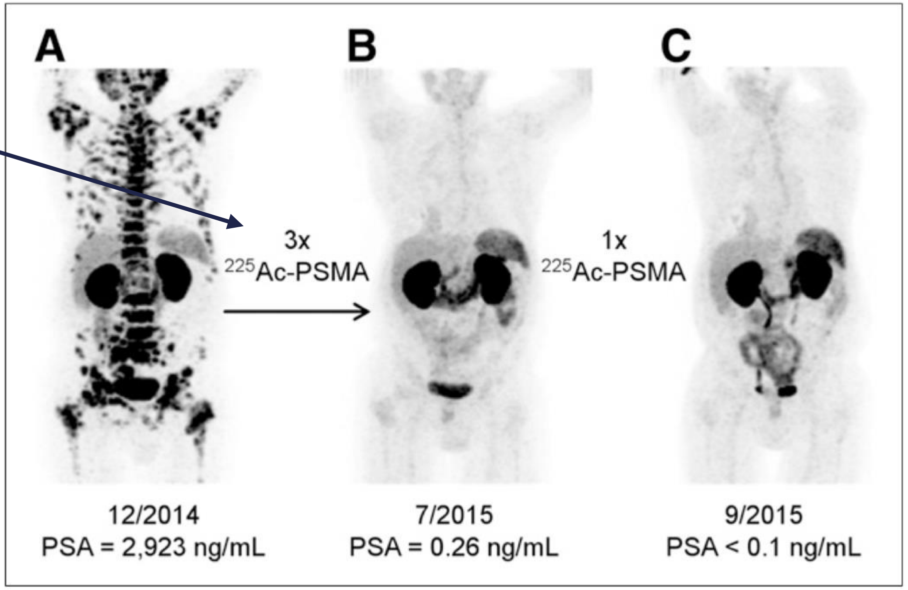

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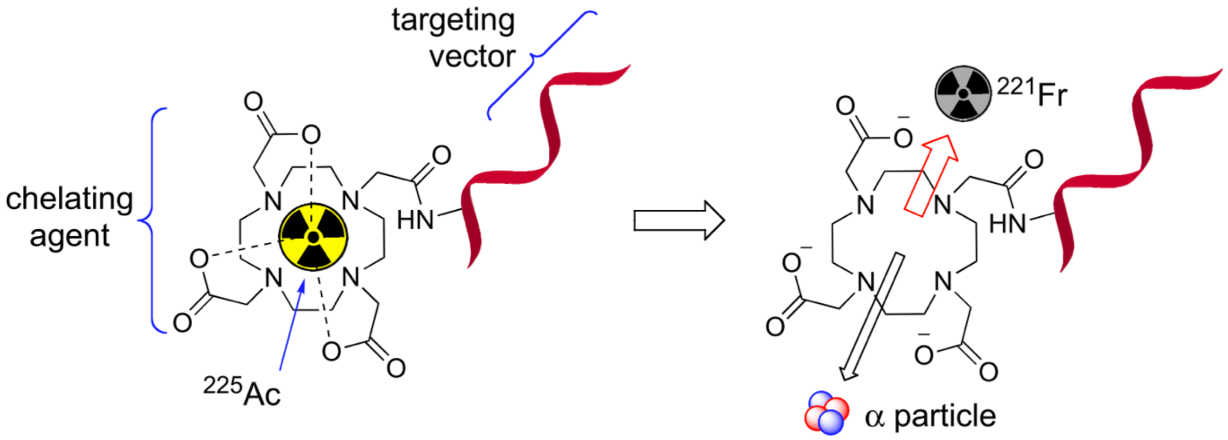

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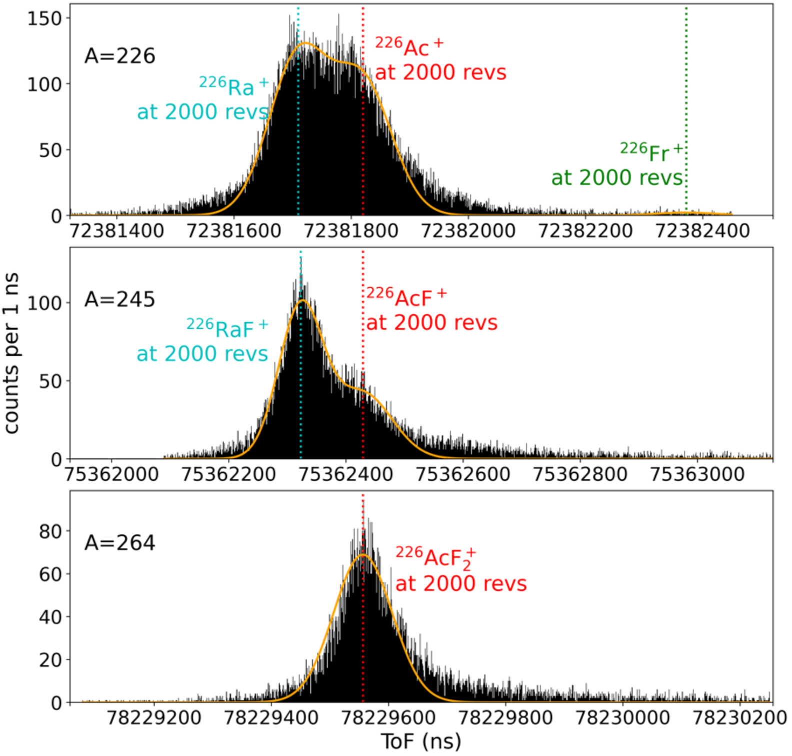
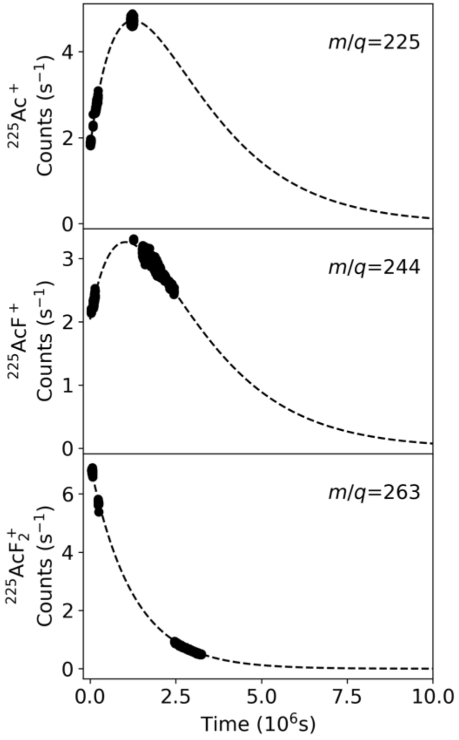
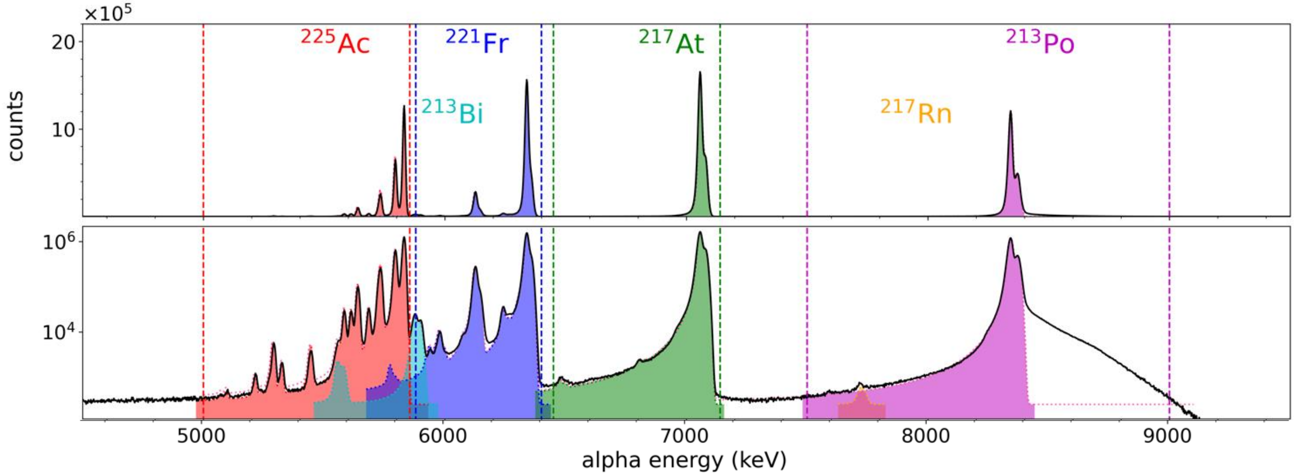
Production of AcF_x^+

- AcF spectroscopy - characterization
- ^{225}Ac: Targeted-alpha therapy
- Ac: enhanced extraction







[1] Au, *PhD thesis* (2023)
[2] Au et al., *in review* (2024)

AcF spectroscopy: characterization

Proposal [1]

Production

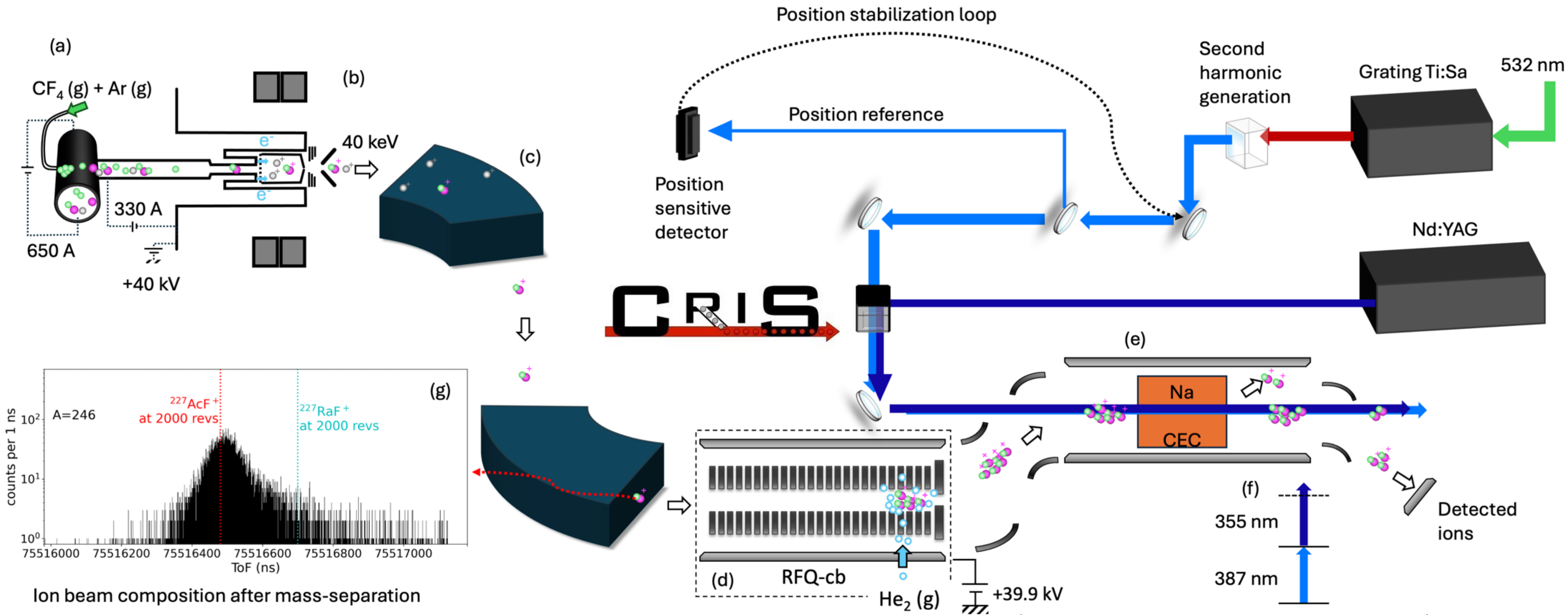
- 1 year proposal to experiment

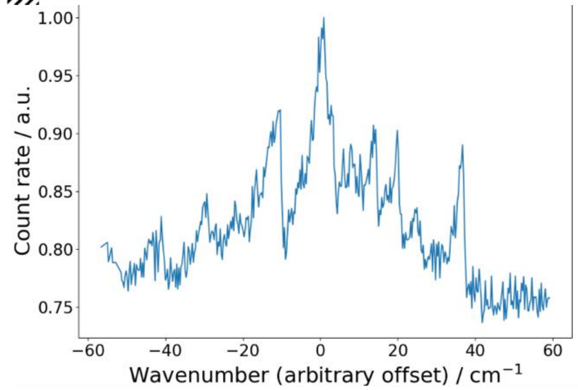
Experiment

- CRIS

Molecular theory

- IH-FS-RCCSD [3]
- IP = 48,866 cm^{-1}
- D_e = 57,214 cm^{-1}





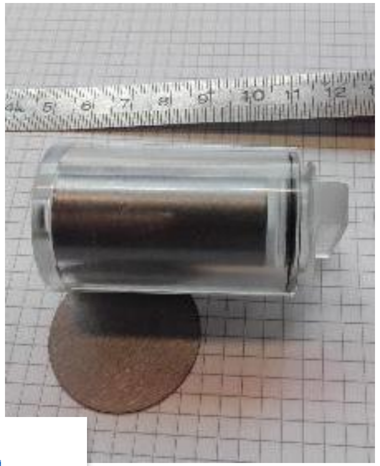
[1] Athanasakis-Kaklamanakis et al, INTC-P-615 (2021)
[2] Athanasakis-Kaklamanakis et al, *in preparation* (2024)
[3] Oleynichenko et al., *J. Chem. Phys*. 159, 12 (2023)
[4] CERN EP newsletter (2023) *https://ep-news.web.cern.ch/content/isolde-lays-ground-cp-violation-tests-radioactive-molecules*

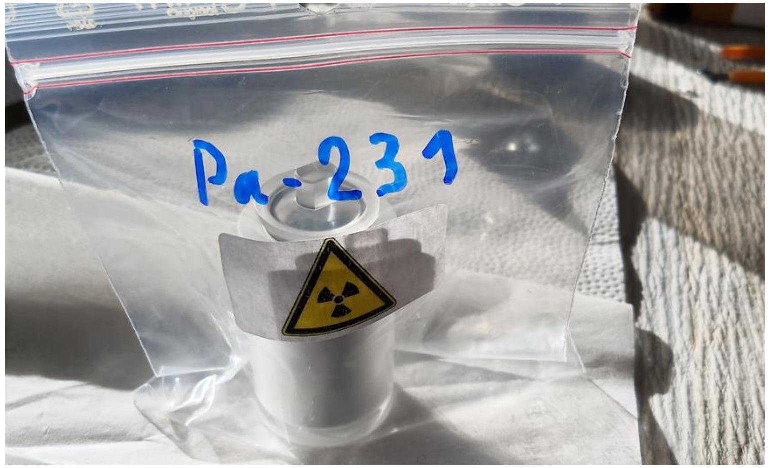
The challenging case: protactinium

Protactinium

- Laser-ionized: tried, failed

950 Bq 231-Pa (1.417e+15 atoms)





Protactinium chemistry at ISOLDE from external sources

September 22, 2023

M. Au[1,2], M. Athanasakis-Kaklamanakis[1,3], L. Nies[1], K. Blaum[4] C. Duchemin[1], Ch.E. Düllmann[2,5,6], C. M. Fajardo-Zambrano[3], P. F. Giesel[7], M. Heaven[8], L. Lambert[1], D. Lange[4], U. Köster[9], G. Neyens[3], D. Renisch[2,6], S. Rothe[1], Ch. Schweiger[4], L. Schweikhard[7], J. Stricker[2,6], W. Wojtaczka[3]

Protactinium results: preliminary

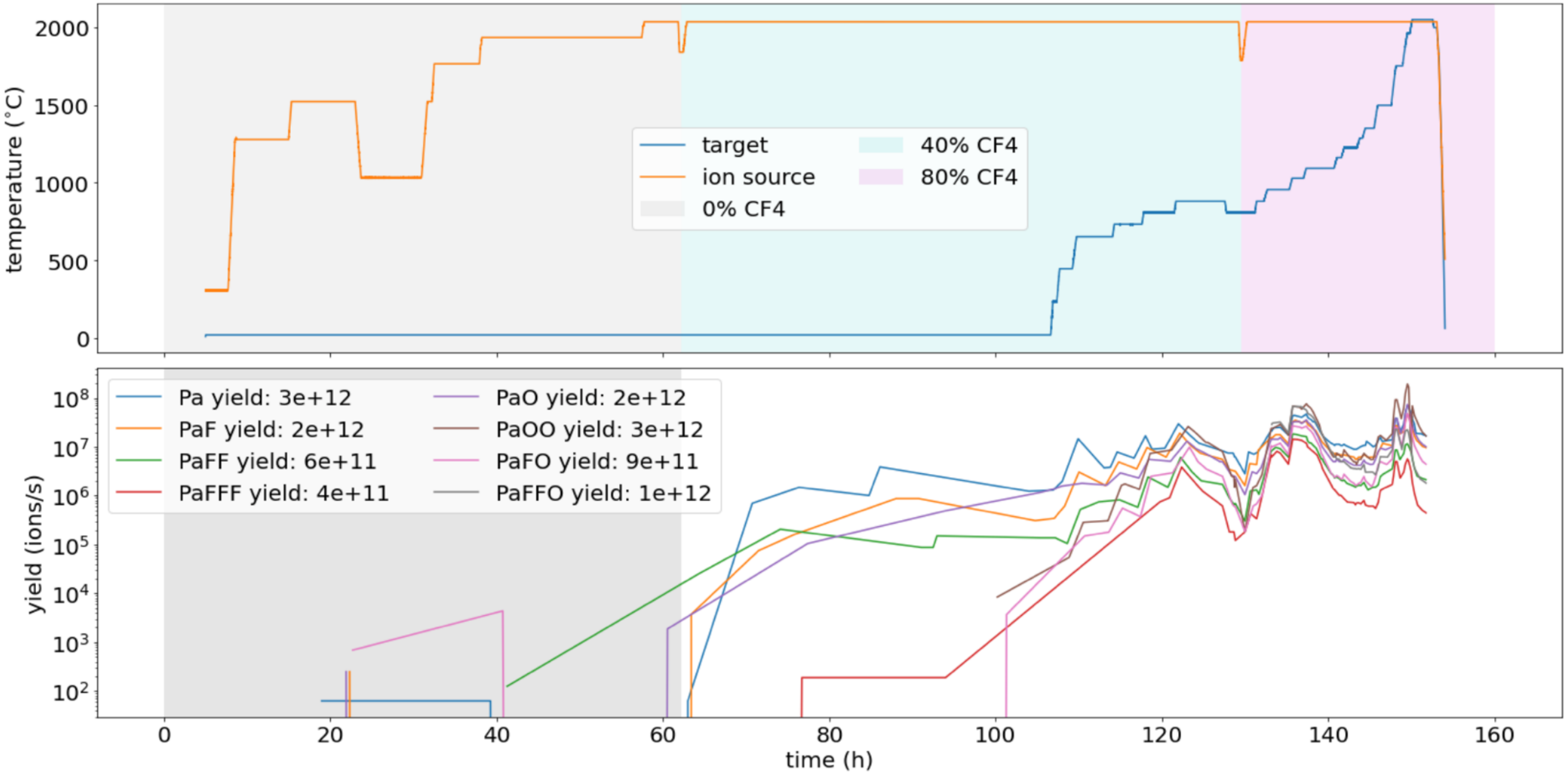
Preliminary yield across all measured sidebands: 1.2e+13 / 1.417e+15 = 0.8%

Pa molecules

- $^{231}Pa^+$, $^{231}PaO^+$, $^{231}PaO_2^+$, $^{231}PaF^+$, $^{231}PaF_2^+$, $^{231}PaF_3^+$, $^{231}PaFO^+$, $^{231}PaF_2O^+$

- Formed in RFQ:
  - From $^{231}Pa^+$: $^{231}PaO^+$, $^{231}PaO_2^+$
  - From $^{231}PaF^+$: $^{231}PaFO^+$, $^{231}PaFOH_2^+$
  - From $^{231}PaF_2^+$: $^{231}PaF_2O^+$,
  - From $^{231}PaO^+$: $^{231}PaO_2^+$,

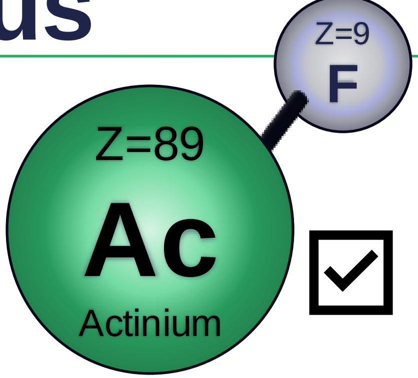
- Checked but not seen:
  - PaN^+, PaC^+, $PaFO_2^+$, $PaNO^+$

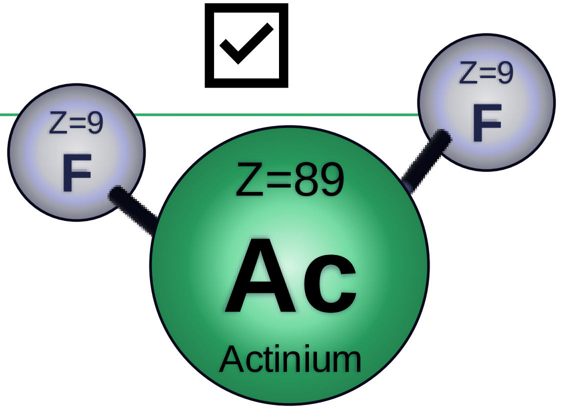


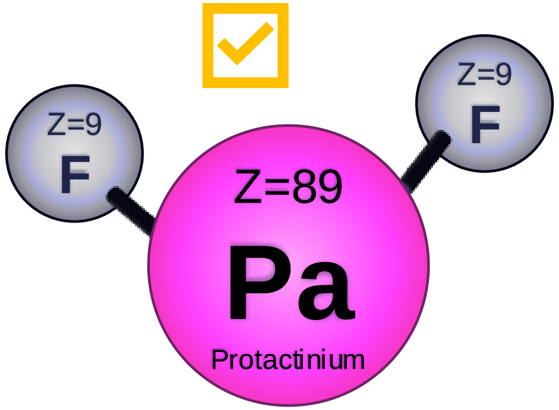
Fluoride beams current status

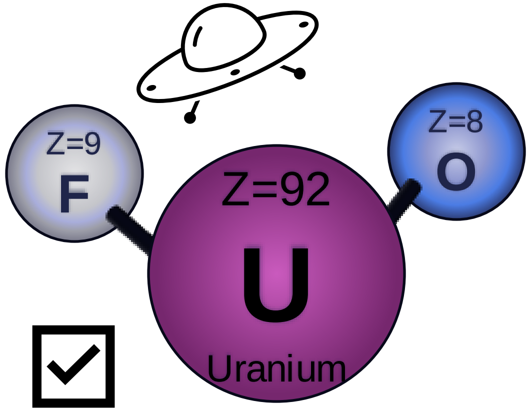
- RaF_x: developed, available*
- AcF_x: developed, available*
- NpF_x, PuF_x: observed
- PaF_x, PaO_x: external sources, development
- ThF_x, UF_x: not observed
- ScF_x, TbF_x: ongoing development
- VF_x: requested

Image published in EP Newsletter, CERN (2020)





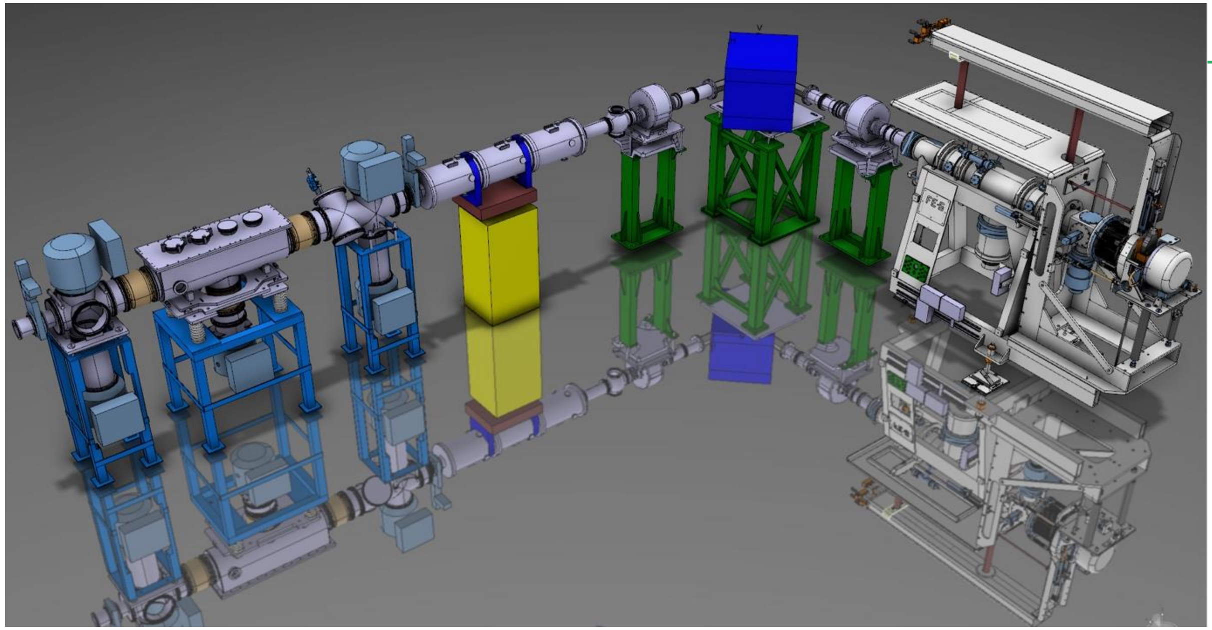


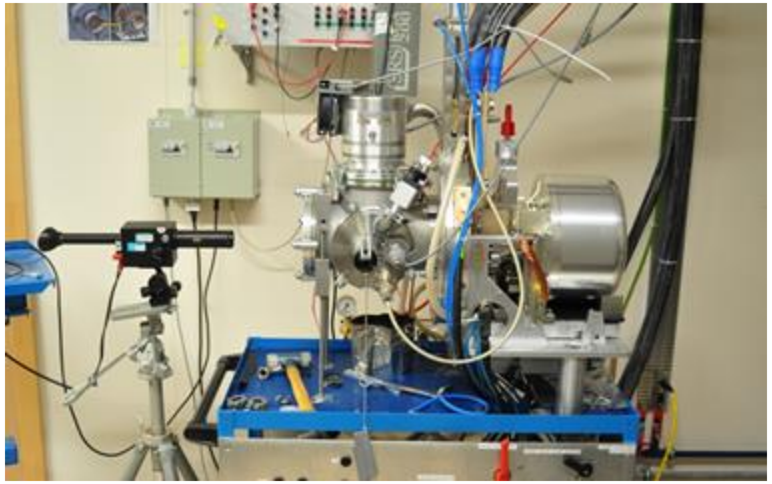


Next steps

- Characterization
- Target developments

*Yield publication in progress





ISOLDE OFFLINE 1
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ISOLDE PUMP STAND
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ISOLDE OFFLINE 2
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Behind the scenes: Offline developments

Next steps

Molecular formation

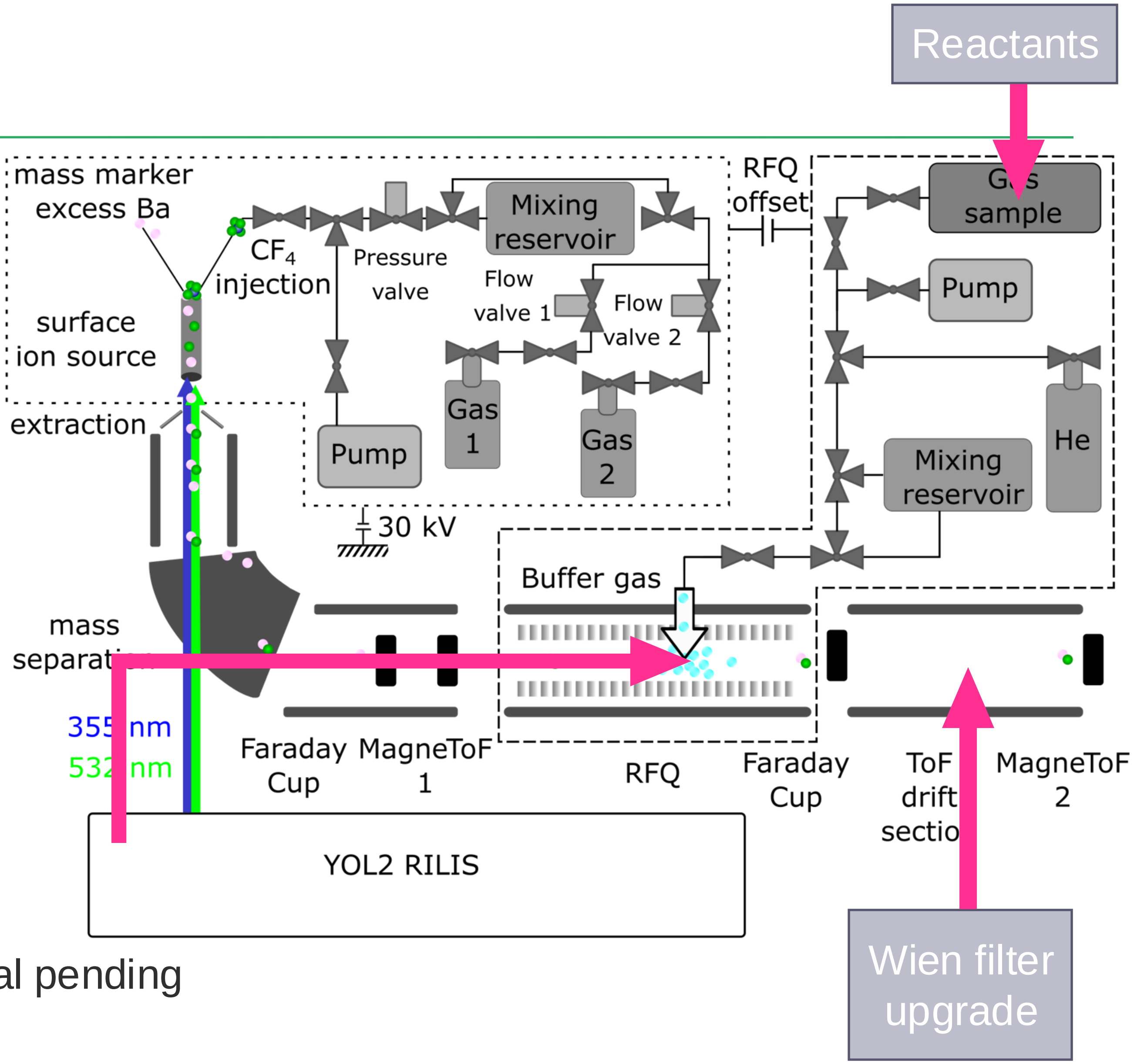
- Ion source developments
- RFQ gas mixing and injection tests
- Implantation/ablation

Laser setup

- New end of beamline
- Laser path to RFQ

Characterization / spectroscopy

- In-source: Offline LIST – fluorides, oxides
- In-trap: molecular formation studies – polyatomics
- Towards high precision radioactive studies: proposal pending



Acknowledgements

Michail Athanasakis-Kaklamanakis, Jochen Ballof, Ermanno Barbero, Mathieu Bovigny, Katerina Chrysalidis, Bernard Crepieux, Charlotte Duchemin, Christoph Düllmann, Paul Florian Giesel, Paul Fischer, Simone Gilardoni, Reinhard Heinke, Jake Johnson, Ulli Köster, Laura Lambert, Daniel Lange, Bruce Marsh, Maxime Mougeot, Lukas Nies, Bianca Reich, Jordan Reilly, Edgar Reis, Sebastian Rothe, Moritz Schlaich, Christoph Schweiger, Simon Stegemann, Jonas Stricker, Yago Nel Vila Gracia, Julius Wessolek, Frank Wienholtz, Shane Wilkins, Wiktoria Wojtaczka,

ISOLDE operations team, ISOLDE RILIS, CRIS, and ISOLTRAP teams
ISOLDE targets and ion sources team

This project has received funding from the European's Union Horizon 2020 Research and Innovation Programme under grant agreement number 861198 project 'LISA' (Laser Ionization and Spectroscopy of Actinides) Marie Sklodowska-Curie Innovative Training Network (ITN)

CERN
LISA – LASER IONISATION AND SPECTROSCOPY OF ACTINIDES
ISOLDE
RILIS
ISOL TRAP
CRIS
FRIB
ILL – NEUTRONS FOR SOCIETY
UNIVERSITÄT GREIFSWALD – Wissen lockt. Seit 1456
TECHNISCHE UNIVERSITÄT DARMSTADT
JG|U
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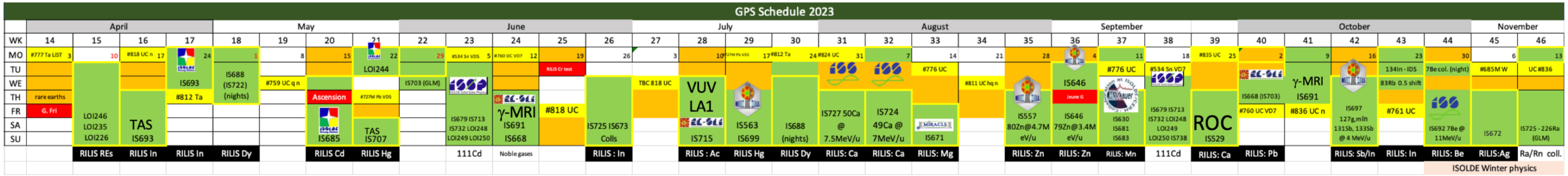
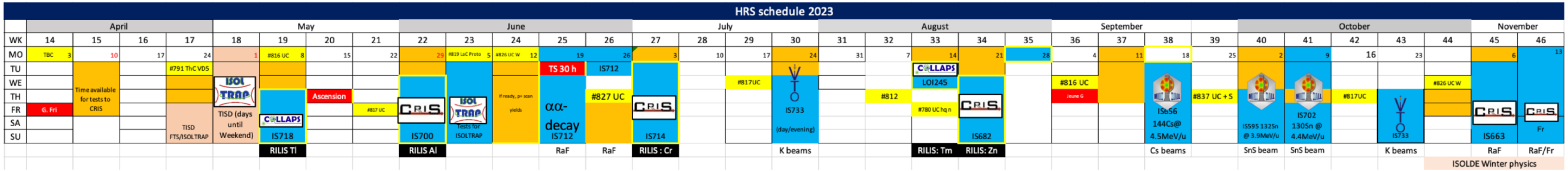
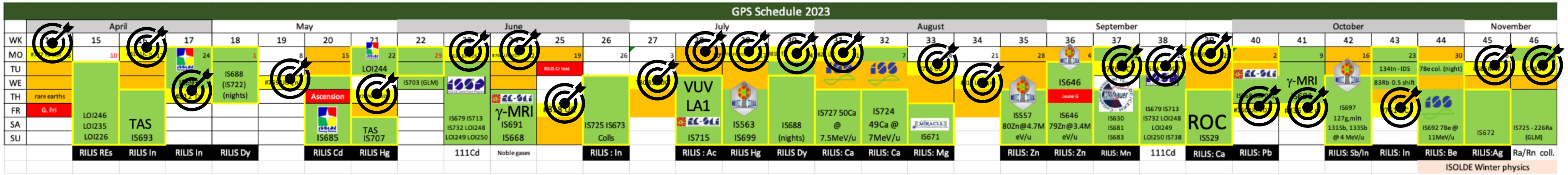


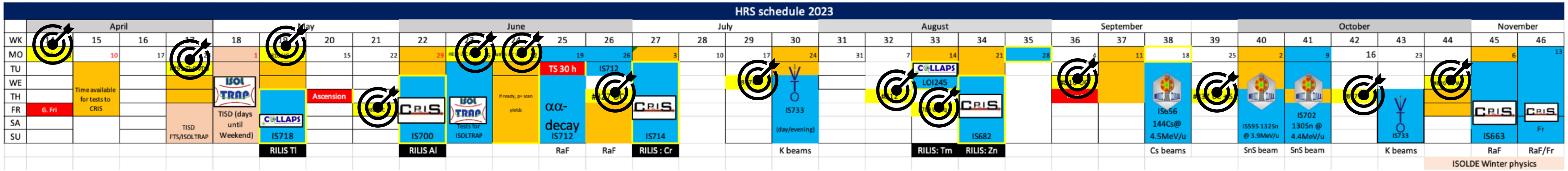


= Yield measurements, proton scans, setup

RILIS 23 : U, Np, Pu, Dy, Tm, Pm, Er, Gd, Yb, In, Cd, Hg, Al, Cr, Ac, Ca, Mg, Zn, Mn, Pb, Sb, Be, Ag

TISD 2023





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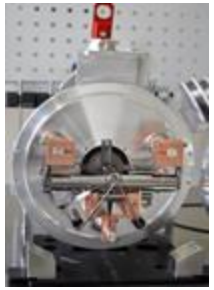

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RILIS

23 : U, Np, Pu, Dy, Tm, Pm, Er, Gd, Yb, In, Cd, Hg, Al, Cr, Ac, Ca, Mg, Zn, Mn, Pb, Sb, Be, Ag

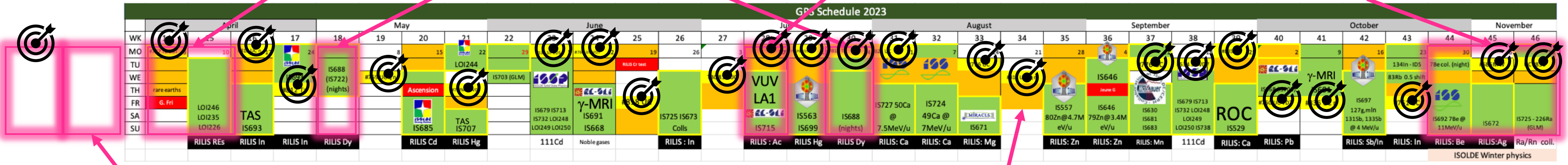
TISD 2023

Back-of-line heating: Dy collections

Batch mode: Ra → Ac

LIST: lanthanides

Winter physics: long-lived isotopes + external samples

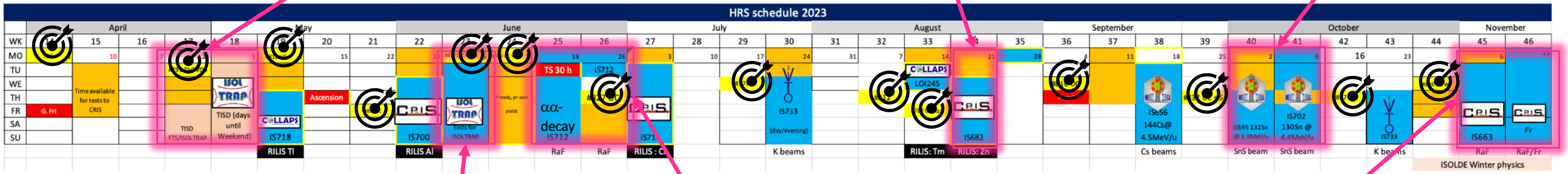


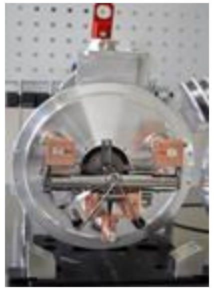
LIST: actinides

ThC_x VD5+CF_4

hot quartz

Molecular beams: SnS





= Prototype target + prototype ion source

Molecular beams: RaF

Winter physics: molecular beams

= Yield measurements, proton scans, setup

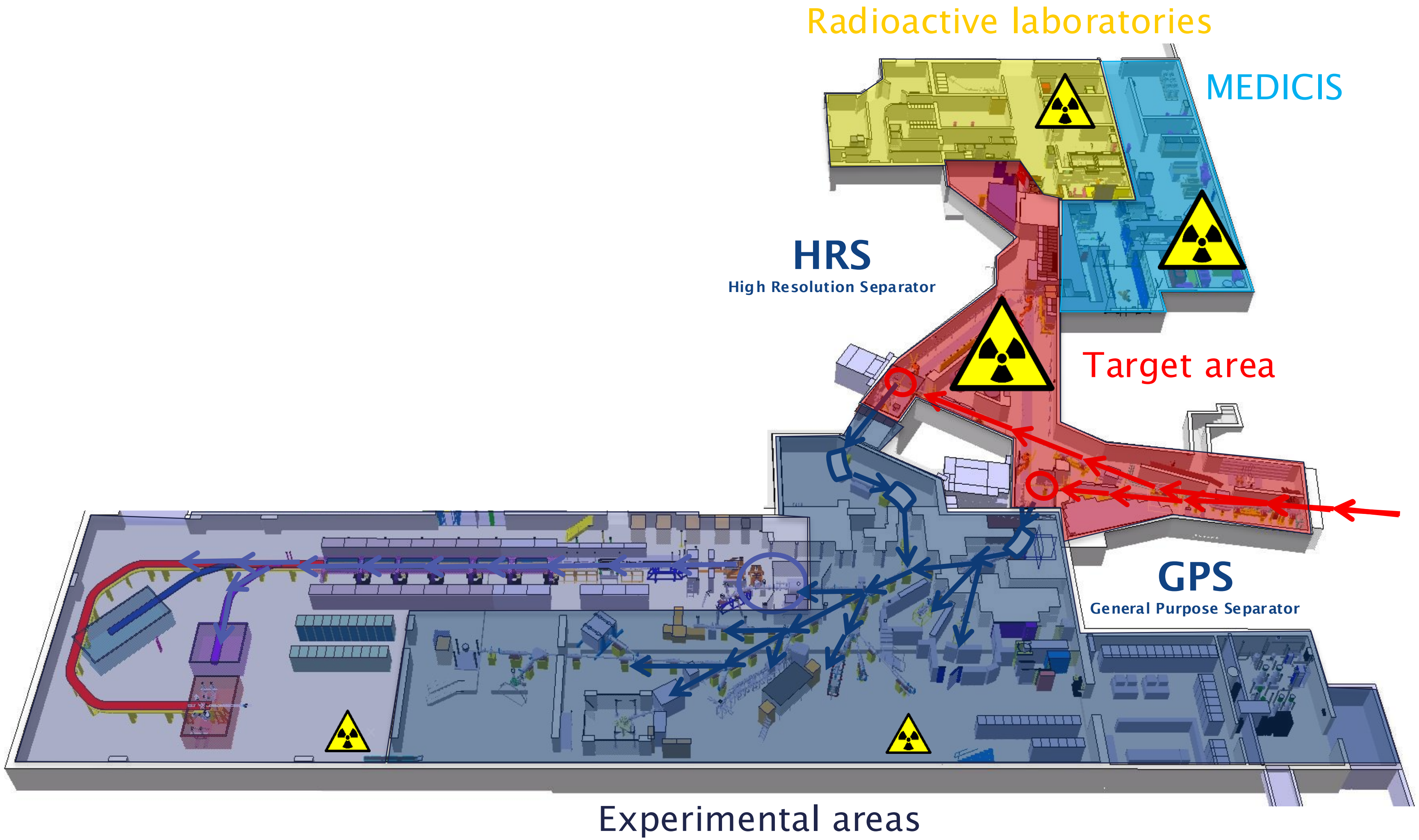
RILIS 23 : U, Np, Pu, Dy, Tm, Pm, Er, Gd, Yb, In, Cd, Hg, Al, Cr, Ac, Ca, Mg, Zn, Mn, Pb, Sb, Be, Ag

ISOL

Catherall et al. (2017) *J. Phys G* **44**, 094002
isolde.web.cern.ch

"On-Line":

- Production
- Release
- Ionization
- Extraction



Catherall et al. (2017) *J. Phys G* **44**, 094002
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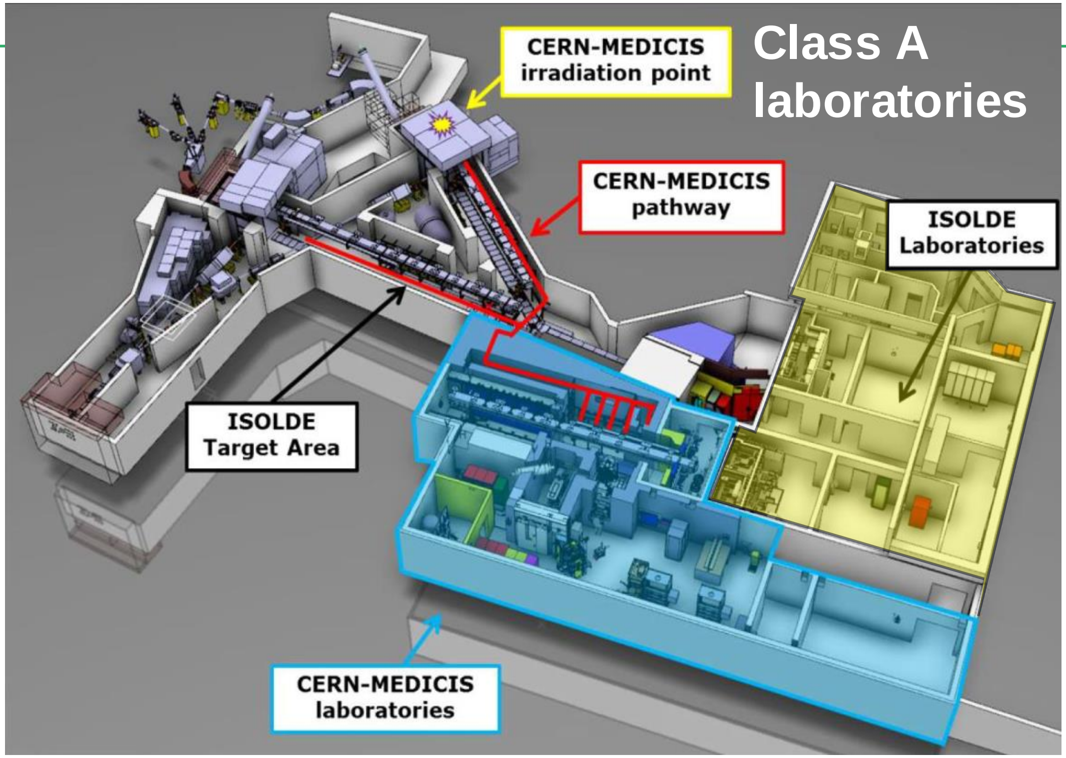

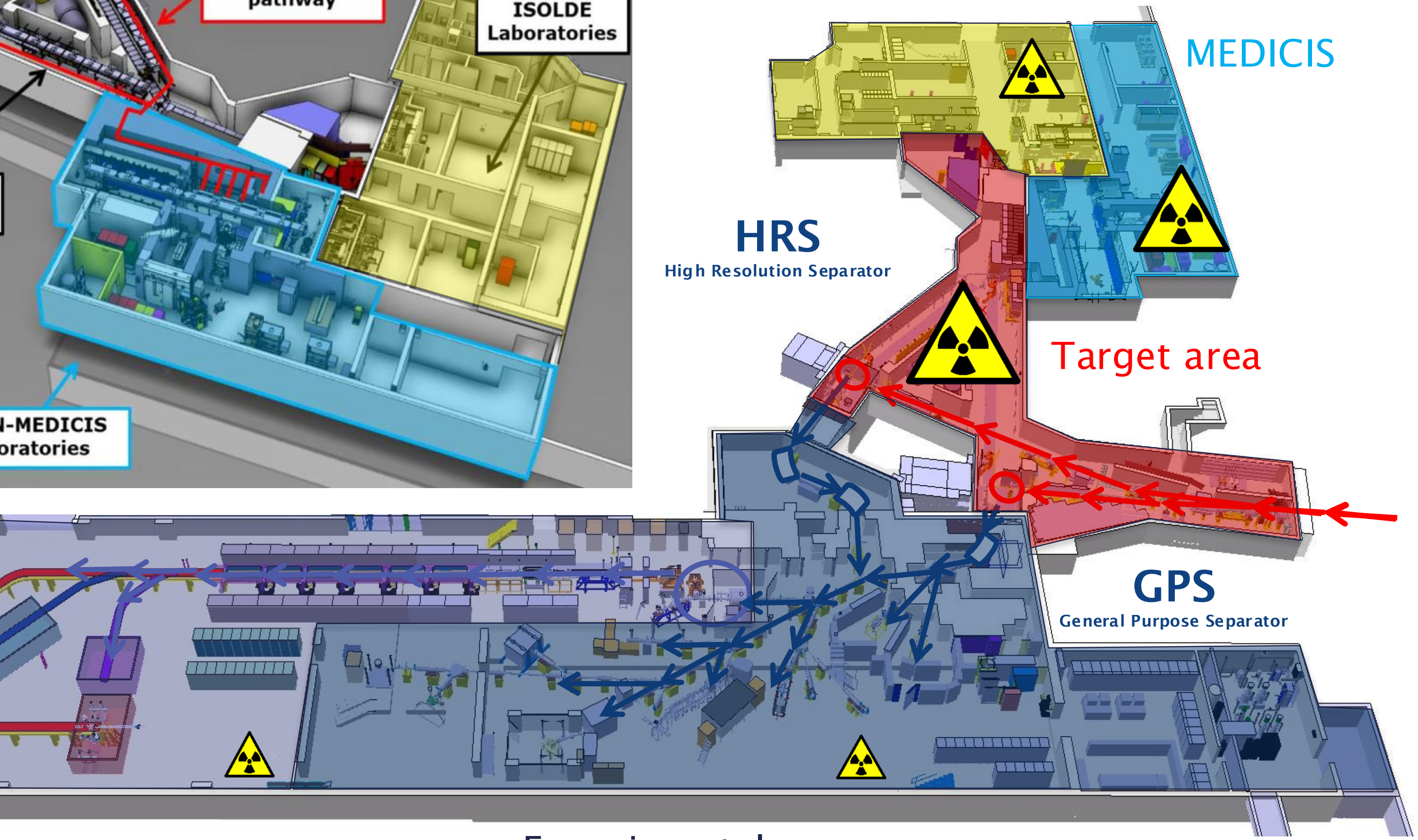

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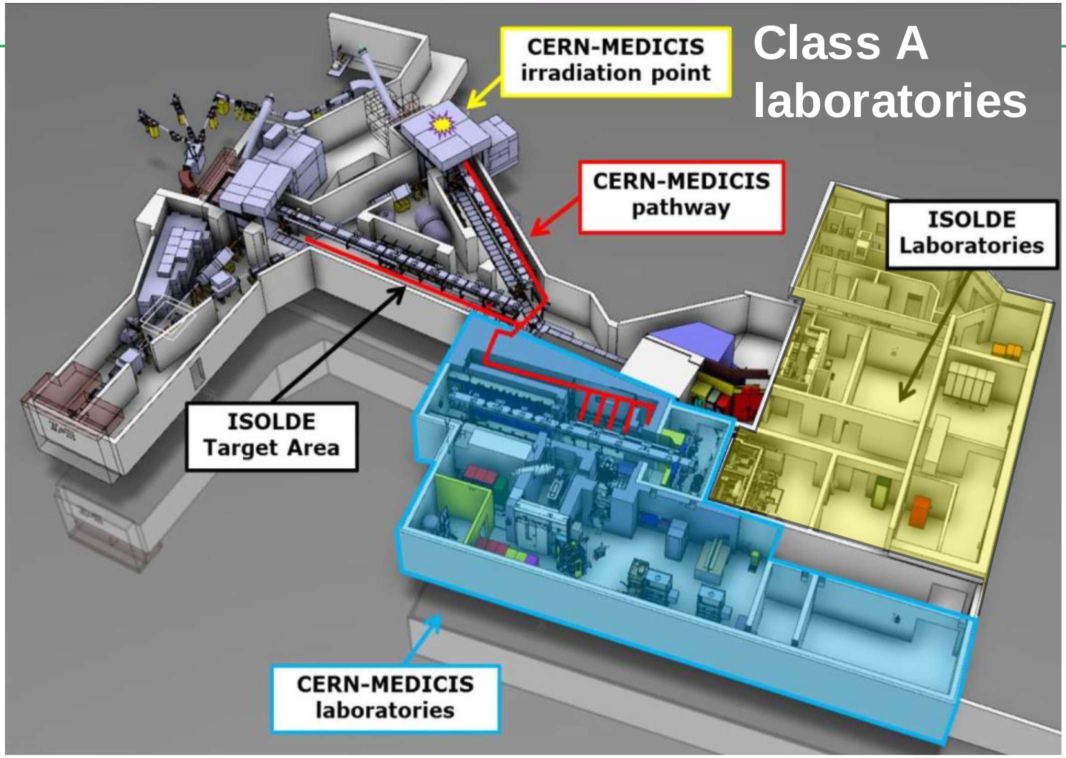
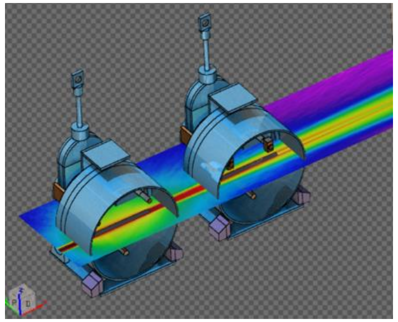
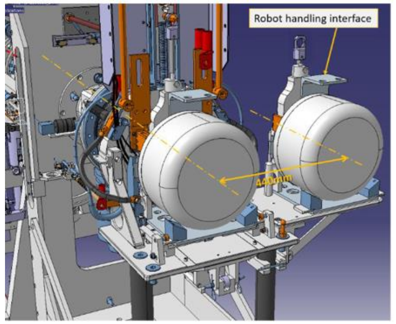
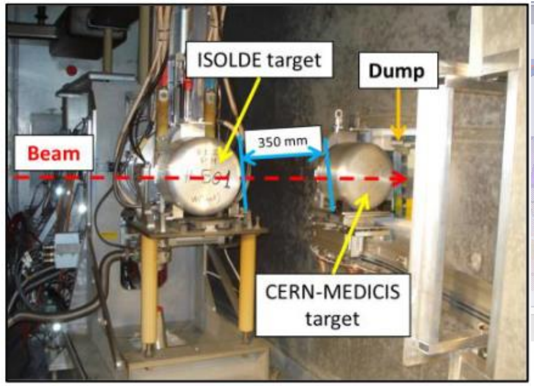
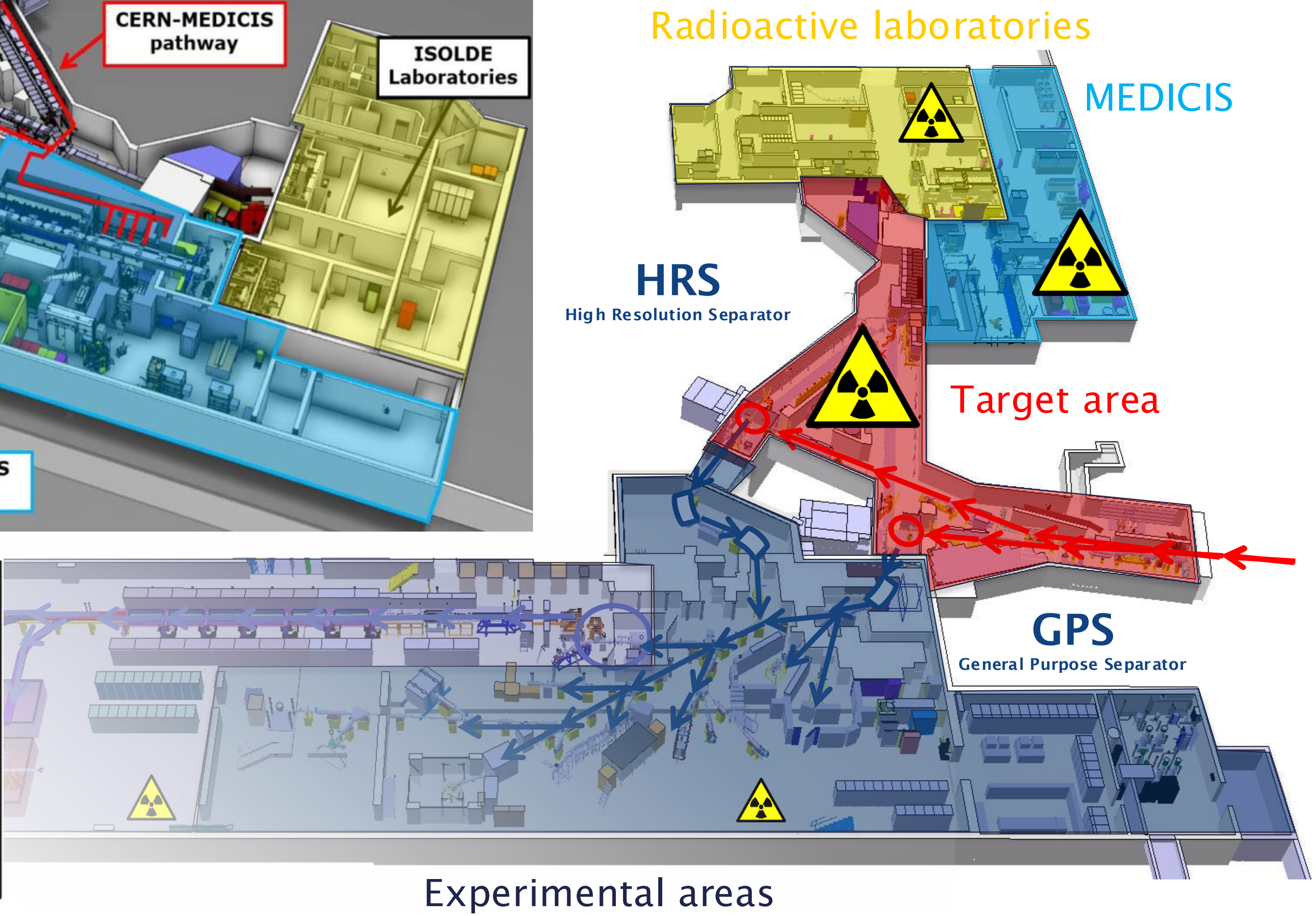




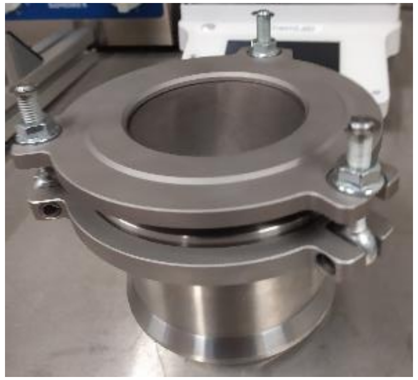






Non-actinide development and characterization lab

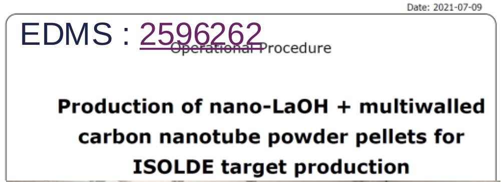
Planetary ball mill – Powder particle size reduction



Laser diffraction **particle size analyzer**

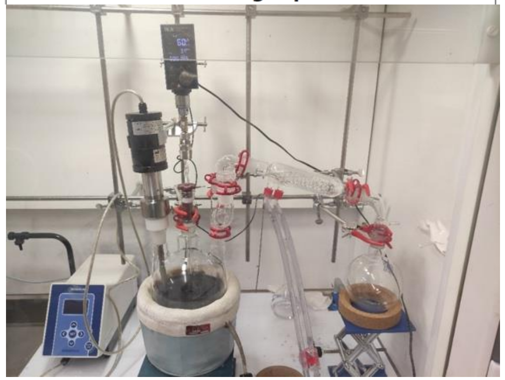
Gas sorption – Pore size distribution (BET)

EDMS : 2596262


Date: 2021-07-09

Operational Procedure

Production of nano-LaOH + multiwalled carbon nanotube powder pellets for ISOLDE target production



Reactor setup

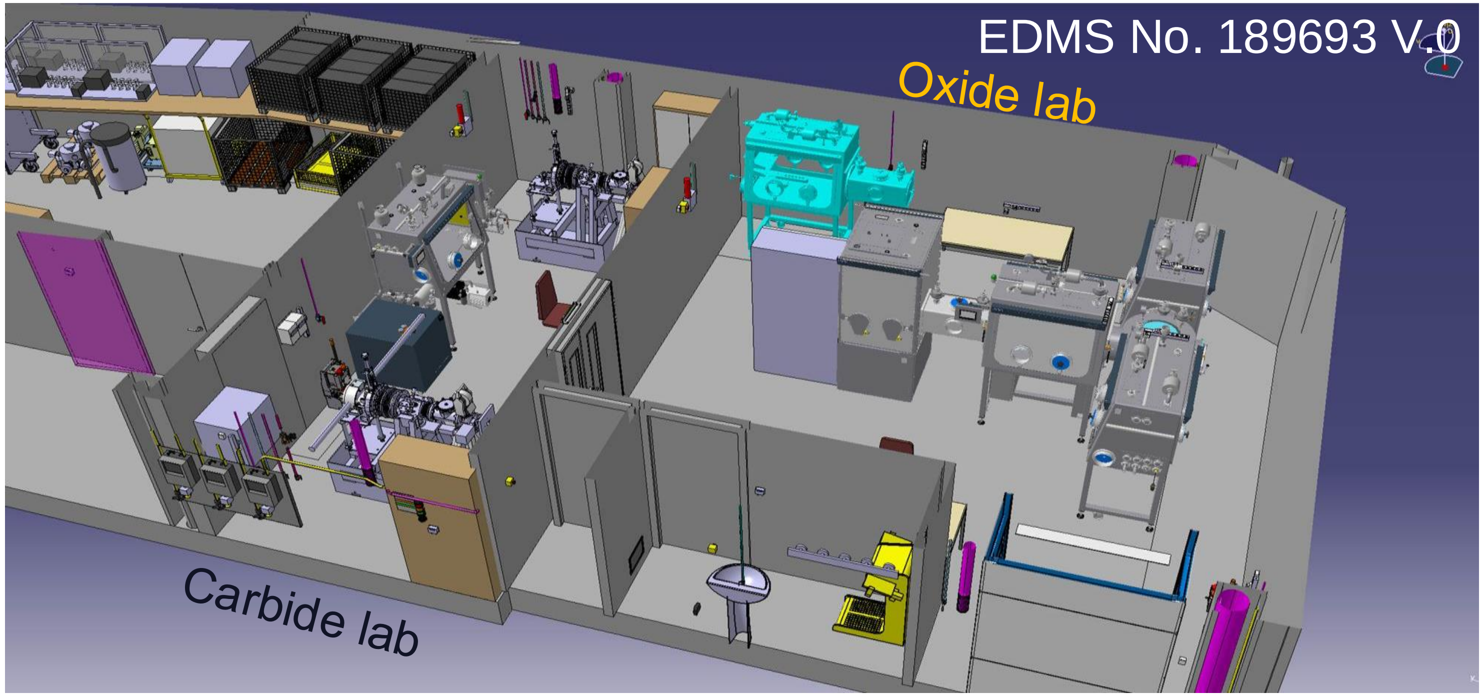
Carburization pumpstand
Target development, sintering studies

Gas pycnometry
Apparent density determination

TGA-MS – Reaction kinetics

Photos courtesy of V. Berlin, E. Reis, L. Lambert, S. Rothe

The Nanolab: Production and Research



Carbide lab

Oxide lab

5 Glove boxes
- 4 connected in T shape: non-pyrophoric
- 1 inert atmosphere: carbides

Production alternating with development

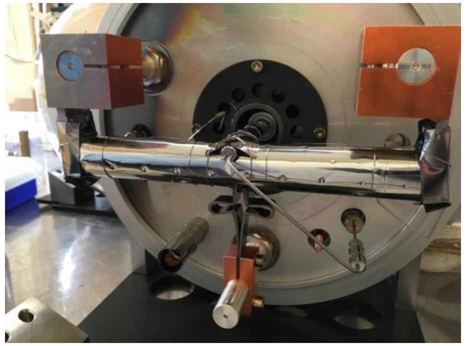
Storage capsules

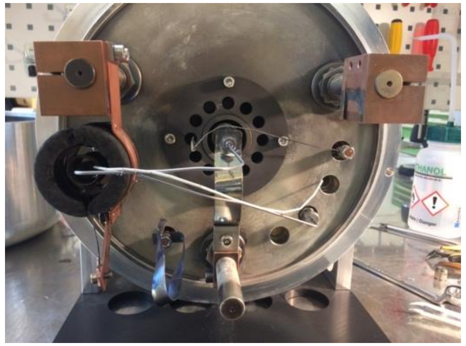
Photos courtesy of L. Lambert

Material developments

Gas injection

- Reactive/corrosive gases





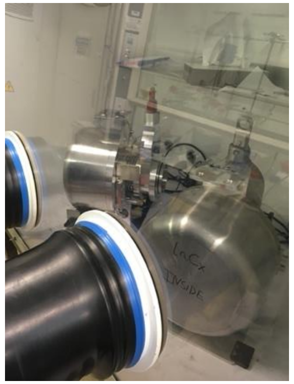
Reactants

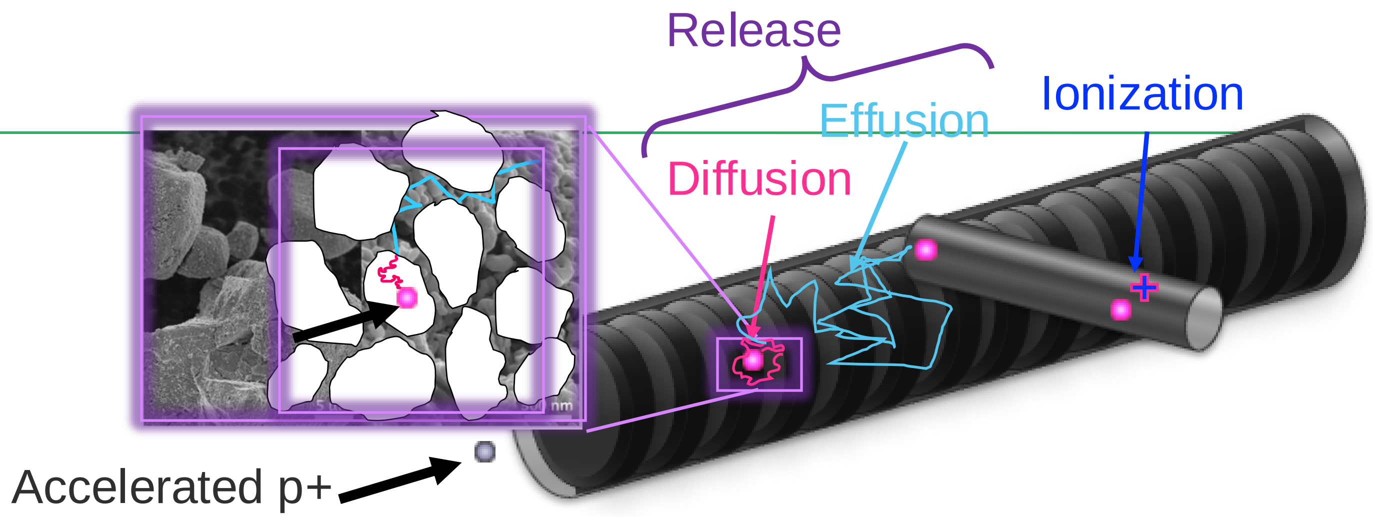
Mass markers

Target materials

Particle size

Open porosity





$$Beam\ Intensity = \sigma \cdot j \cdot N_t \cdot \varepsilon$$

N_t – Number of target atoms
j – Proton flux [cm^{-2}]
σ – Cross section [mb]
ε – Efficiency [%]

$$\varepsilon = \varepsilon_{diff}\varepsilon_{eff}\varepsilon_{is}\varepsilon_{ext}\varepsilon_{sep}\varepsilon_{trans}$$

Adapted from:
J.P. Ramos. EMIS XIII, CERN, Geneva, 2018.

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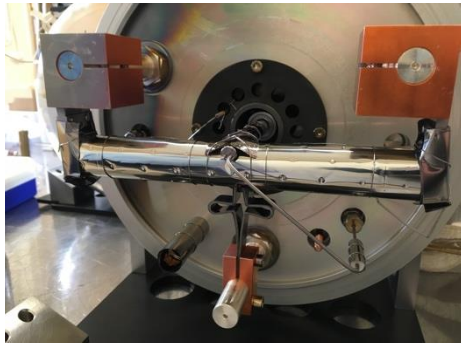

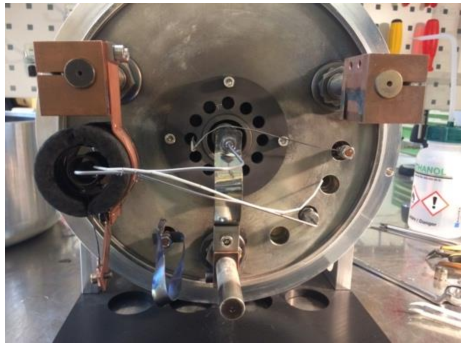

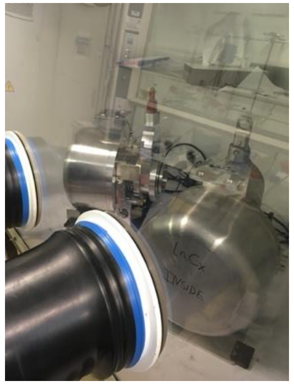

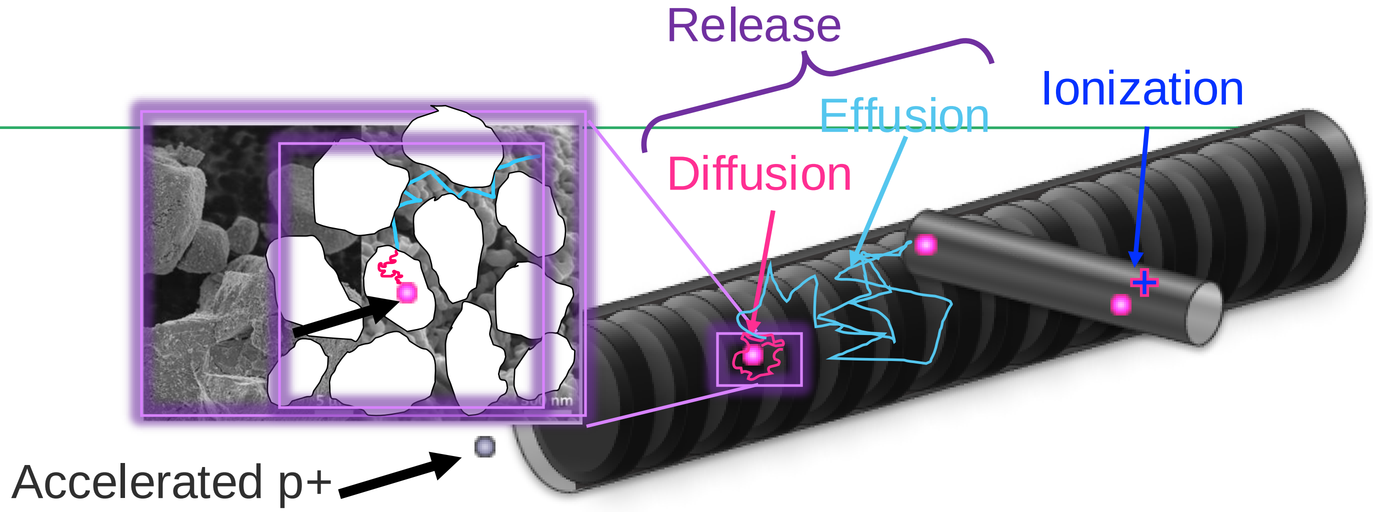

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$$\varepsilon_{\mathrm{diff}} \propto \sqrt{\mu \cdot T_{1/2}} \propto \frac{1}{G}$$

$$\mu = \frac{\pi^2 D}{G^2}$$

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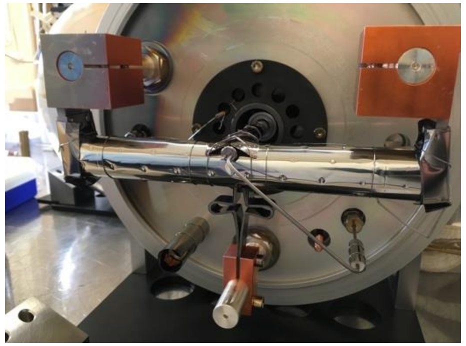

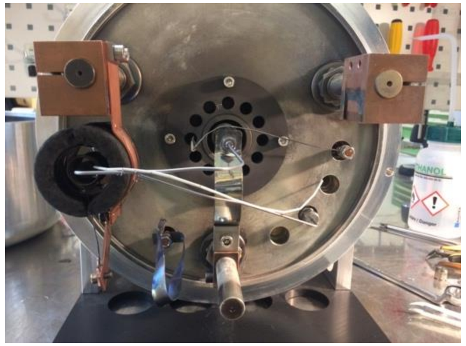

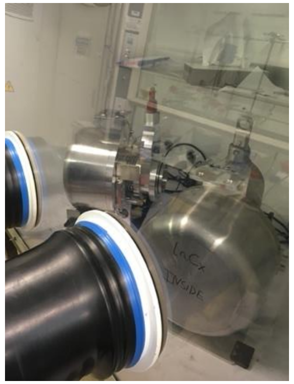

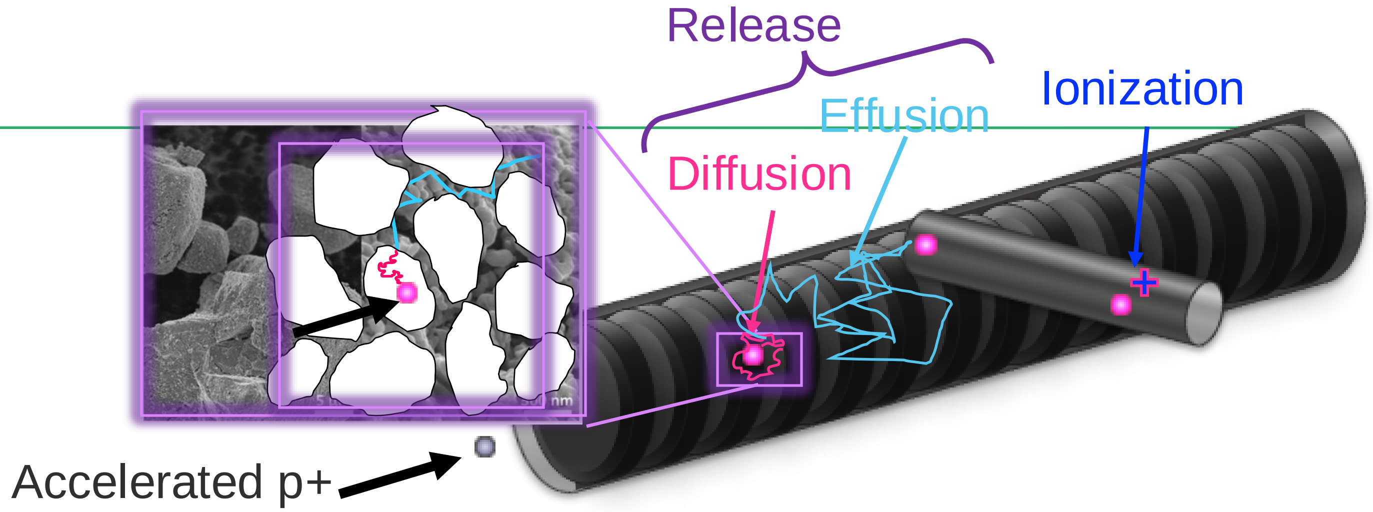

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$$\mu = \frac{\pi^2 D}{G^2}$$

Small G, high T ⇨ Increased $\varepsilon_{\mathrm{diff}}$

Increased $\varepsilon_{\mathrm{diff}}$ ⟺ Increased sintering and grain growth

Adapted from:
J.P. Ramos. EMIS XIII, CERN, Geneva, 2018.

Ion source developments

Molecular breakup and characterization studies

- FEBIAD-type ion sources [1,2]
- Electron energy and source optimization
- Ion source systematics

Photocathode ion sources [3]

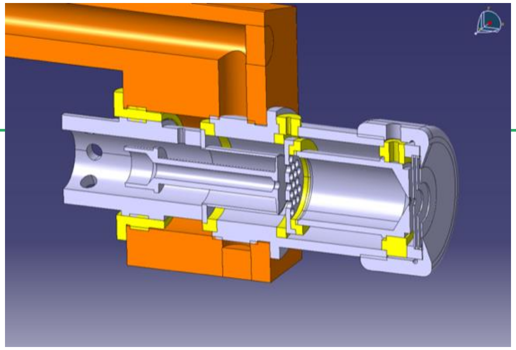
- Cold (room-temperature) environments

In-source spectroscopy [4]

- PI-LIST: sub-Doppler hot-cavity in-source spectroscopy
- CERN-ISOLDE implementation

[1] Maldonado (2023) PhD thesis
[2] Martinez Palenzuela (2020) PhD thesis
[3] Ballof . et al., 2022) *J. Phys.: Conf. Ser.* **2244** 012072
[4] Heinke et al. (2023) *NIM B.* **541** (8-12)

Ion source developments



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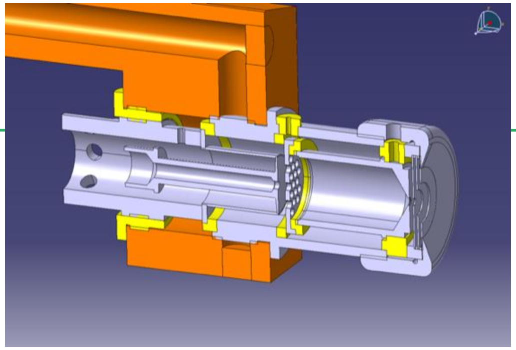

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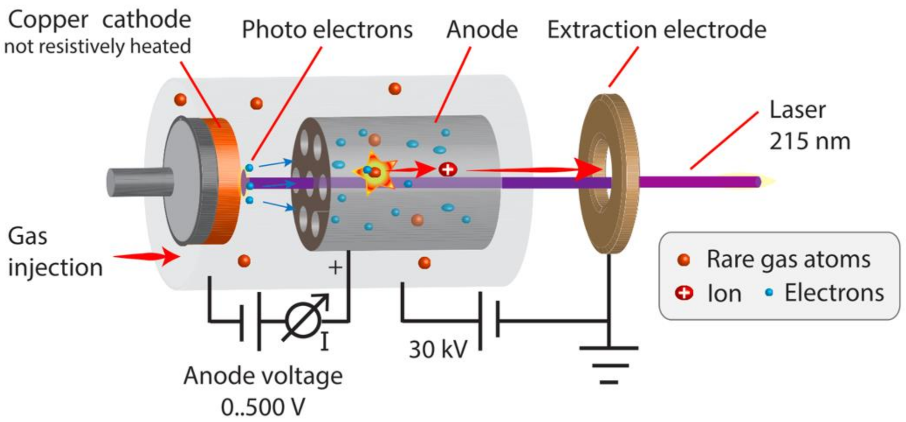

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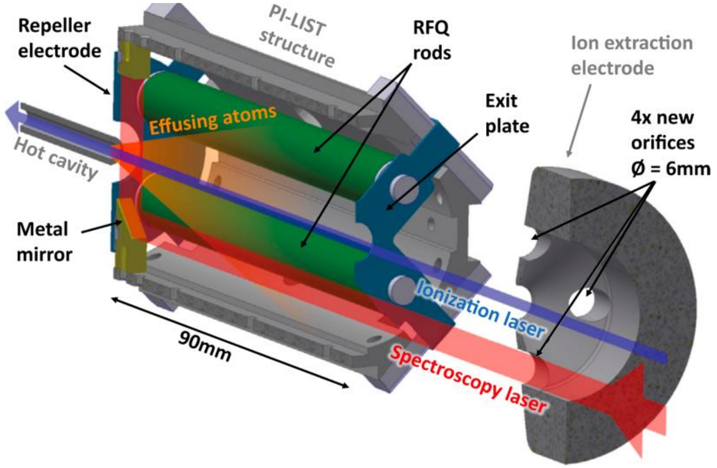

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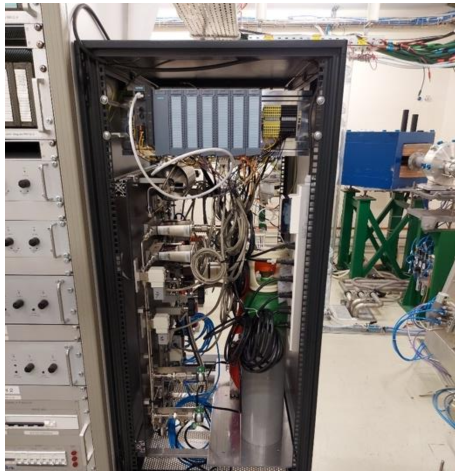
Offline upgrades for molecular beam development

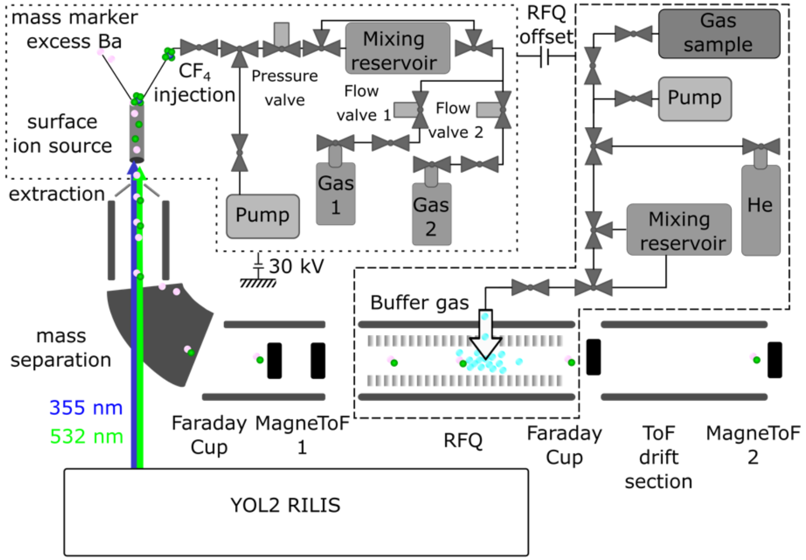
Detection, implantation, ion counting

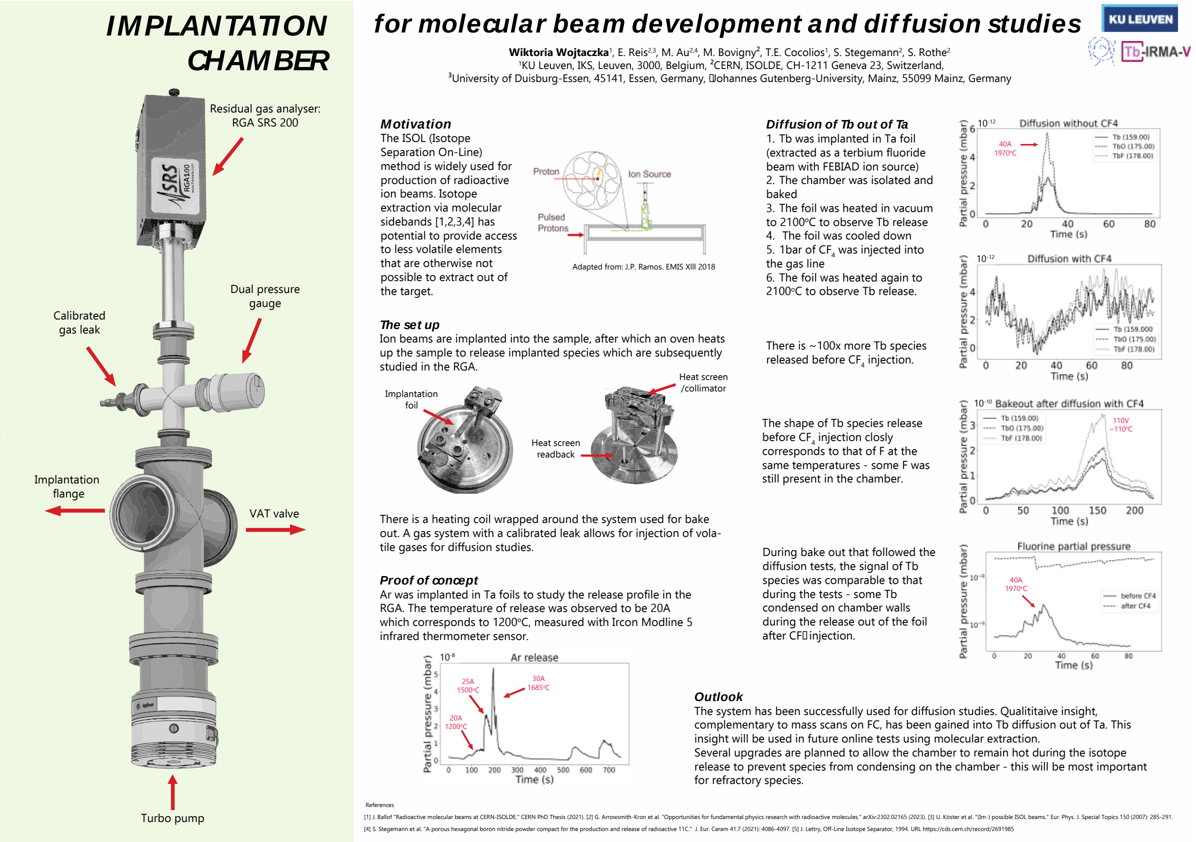
RILIS for molecules

Gas injection and mixing

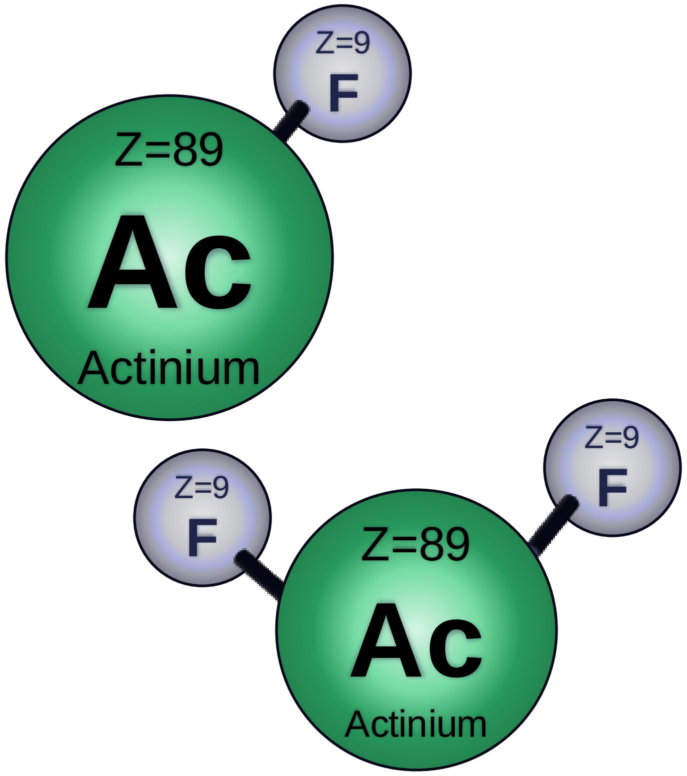
- Remote control of HV gas systems and partial pressures

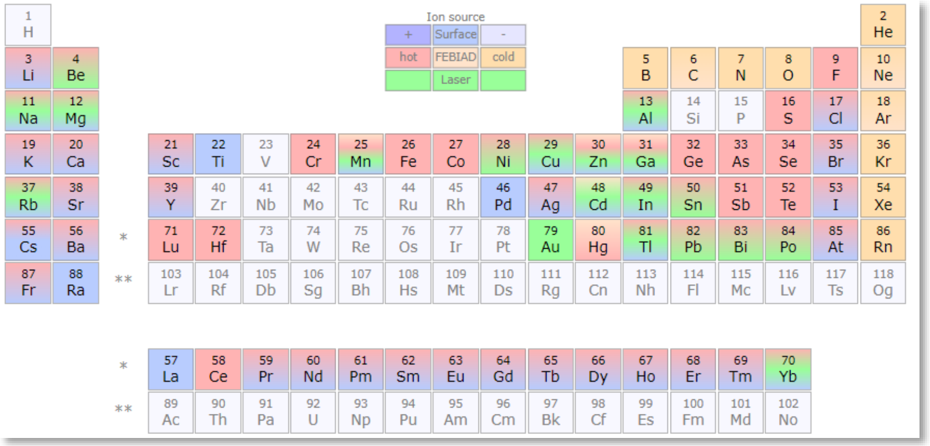


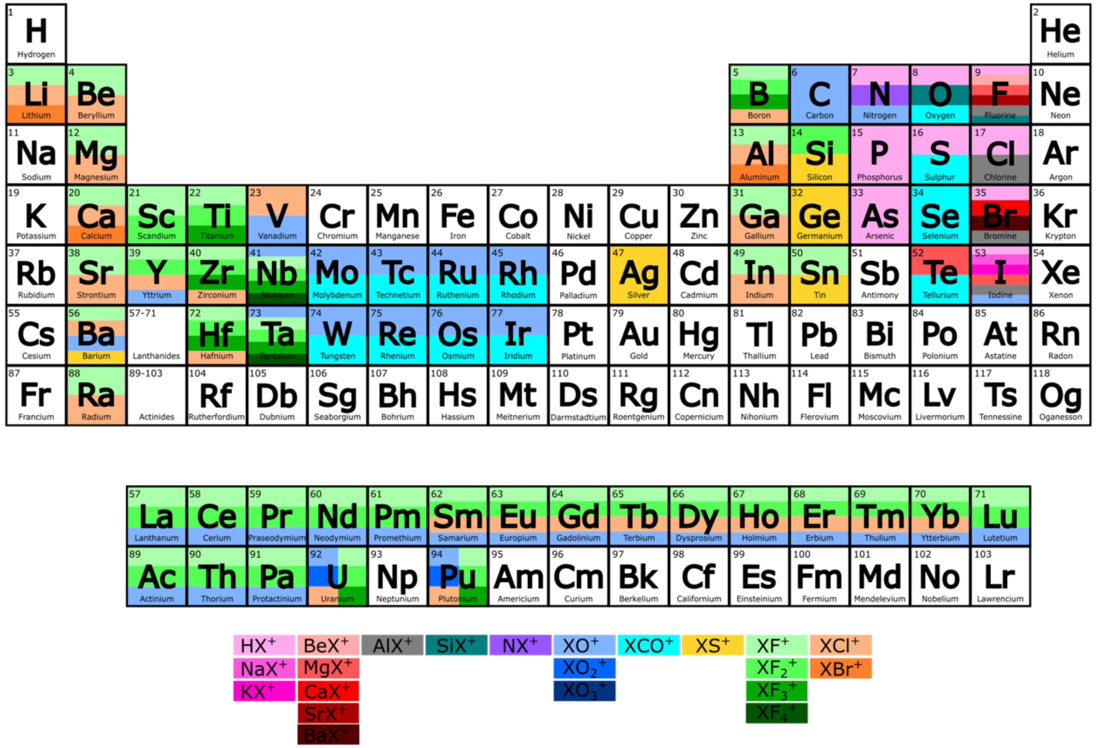




[1] Au et al. (2023) *NIM B.* **541** (144-147)
[2] Wojtaczka et al. (2023) *ICIS'23,* Victoria, Canada







Molecular beams

Formation

Detection and identification

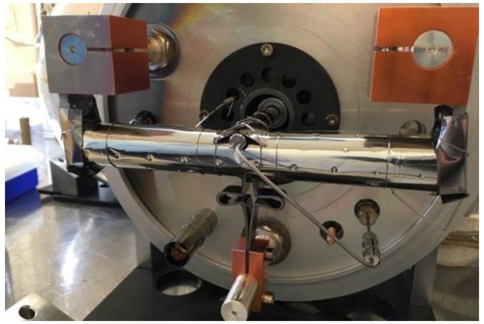
Characterization

Au and Ballof, (2022) *Zenodo* 10.5281/zenodo.6884293 DOI 10.5281/zenodo.6884293

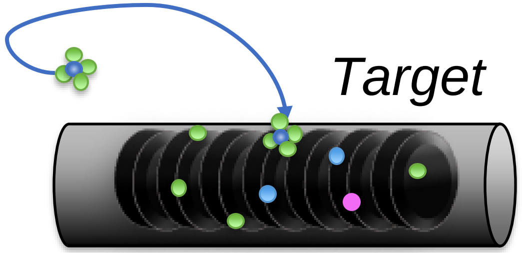
Formation: how do we make molecules?

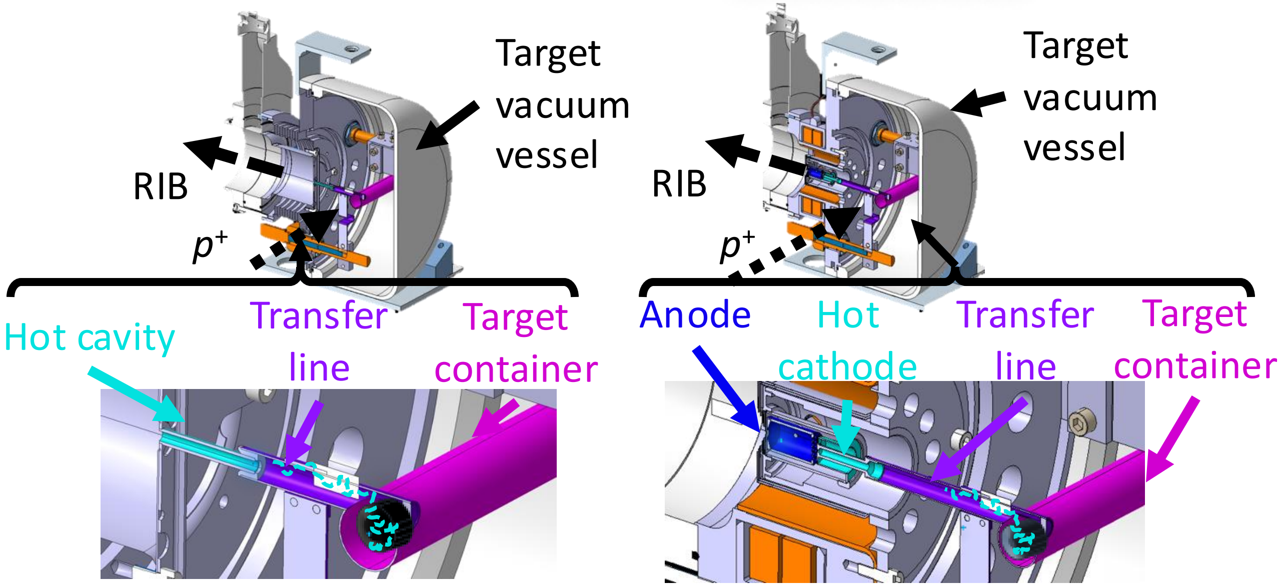
In-source

- Reactive gas



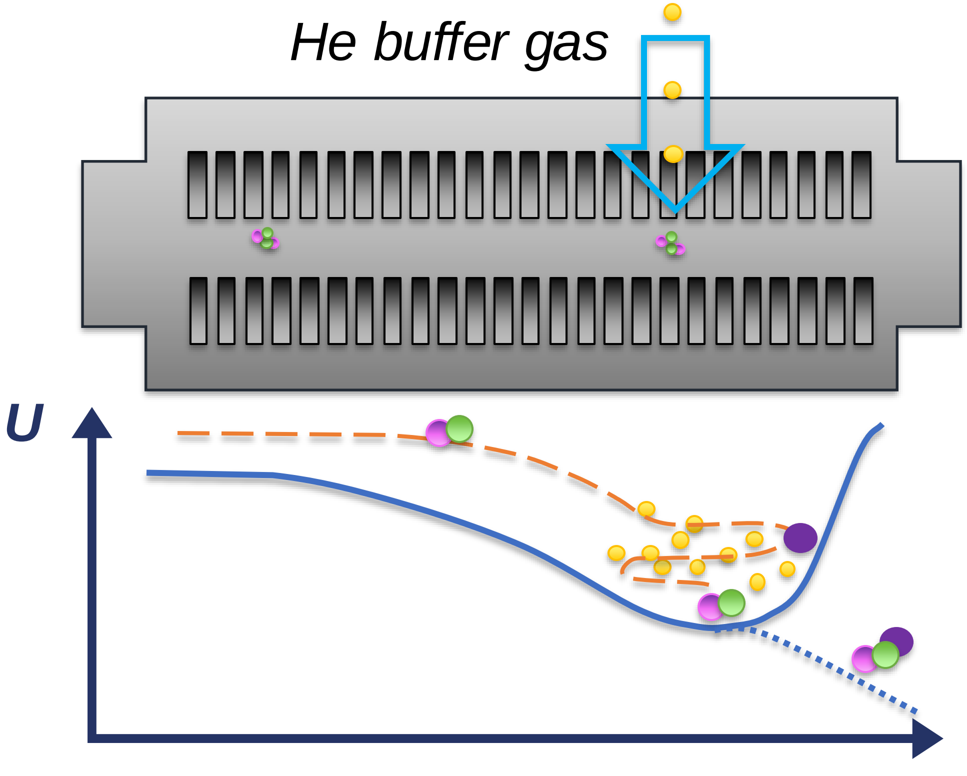
CF_4, NF_3, SF_6





In-trap

- Radio-frequency quadrupole cooler-buncher (RFQ-cb)

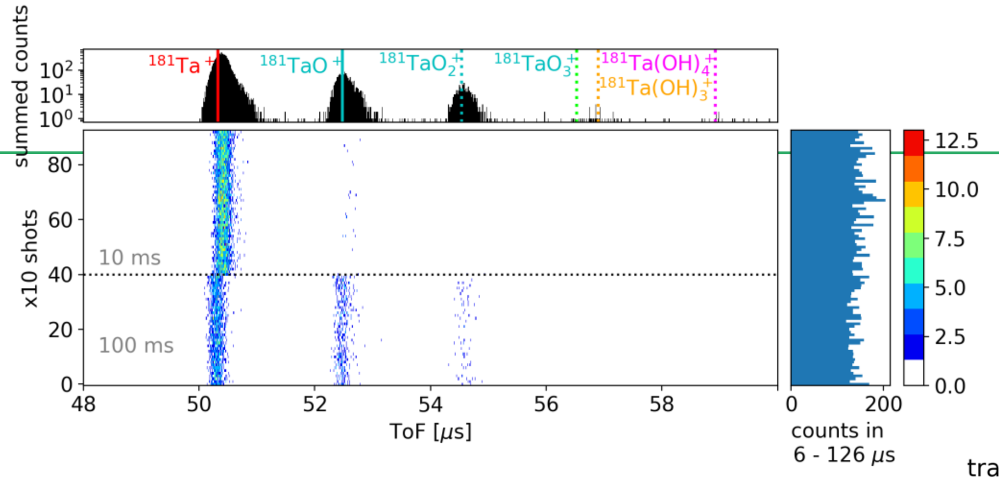


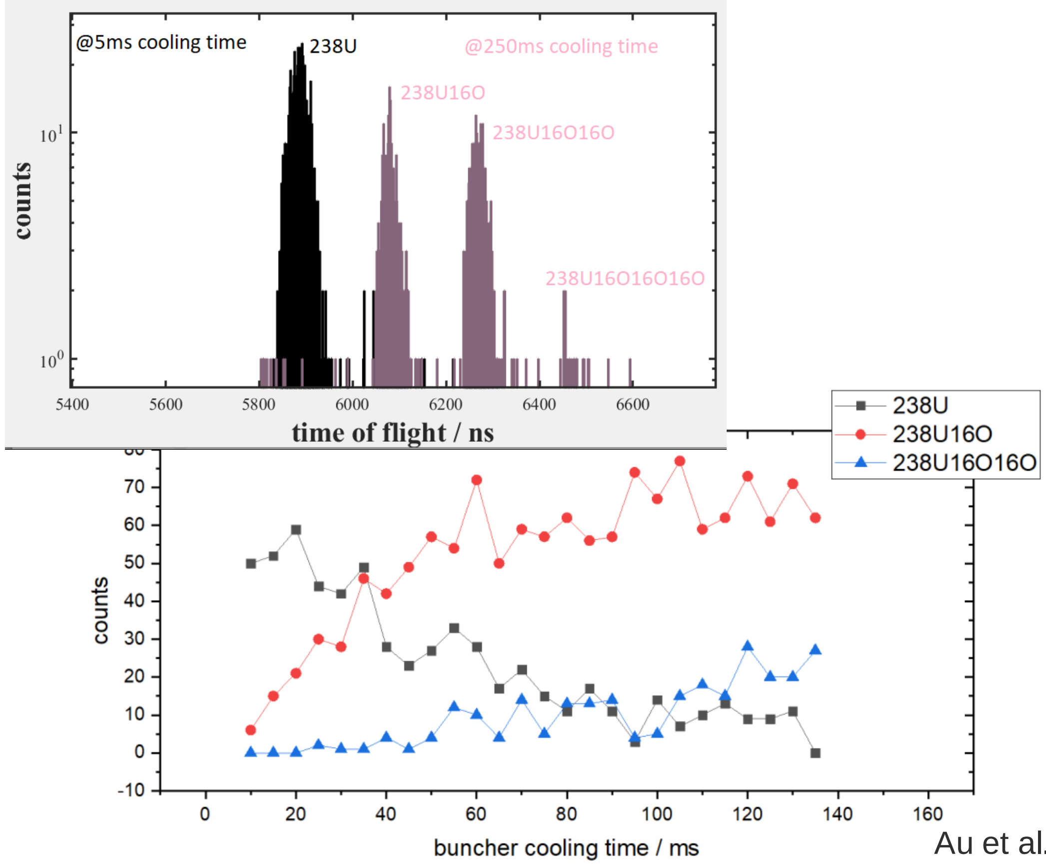
Au et al. (2023) *NIM B.* **541** (375-379)

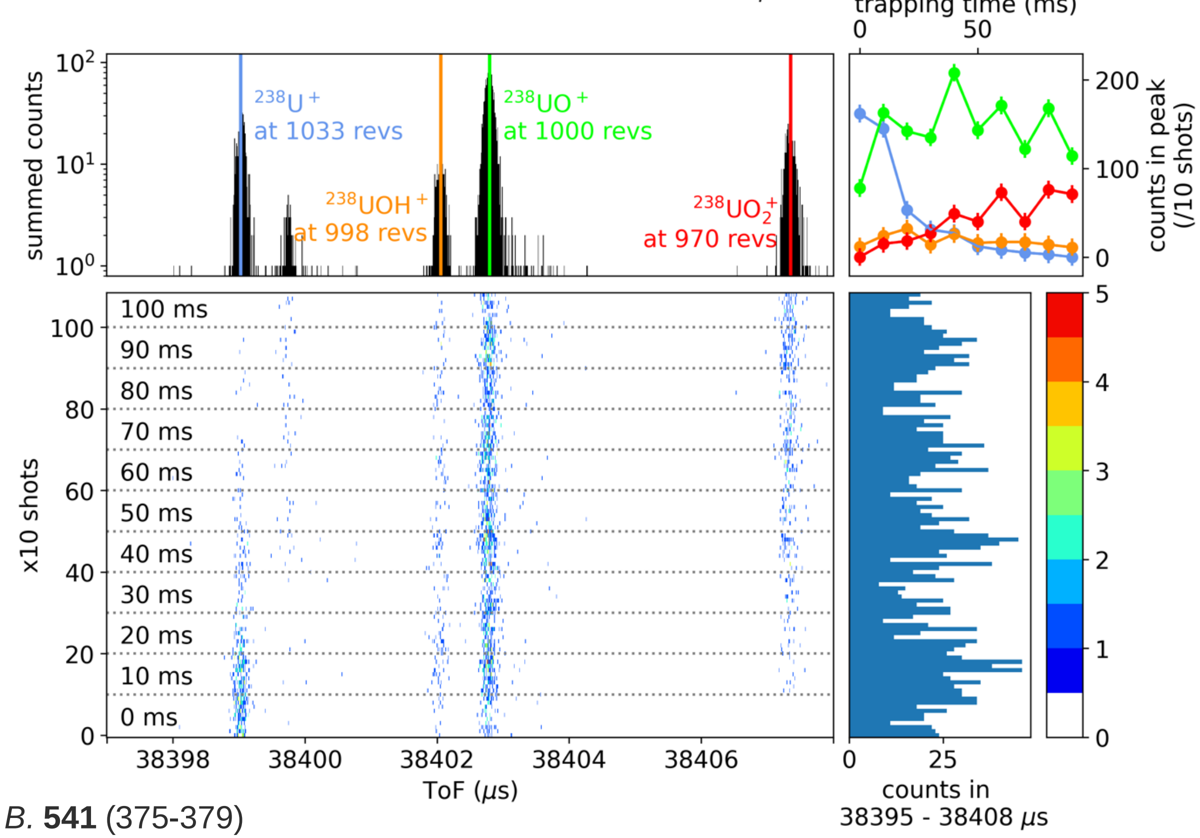
In-trap: identification

UO_x, TaO_x

- Residual gas and primary mass-separated beam
- ID by ToF and revs vs ToF







Au et al. (2023) *NIM B.* **541** (375-379)