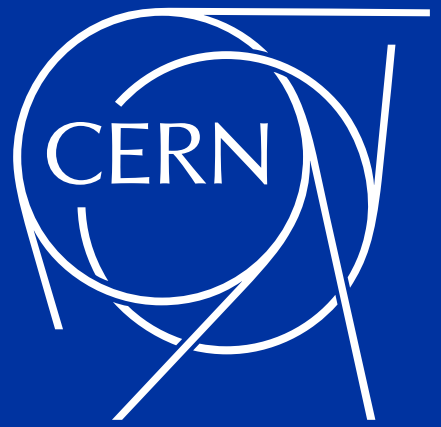


Developments for actinide molecular ion beams at ISOLDE

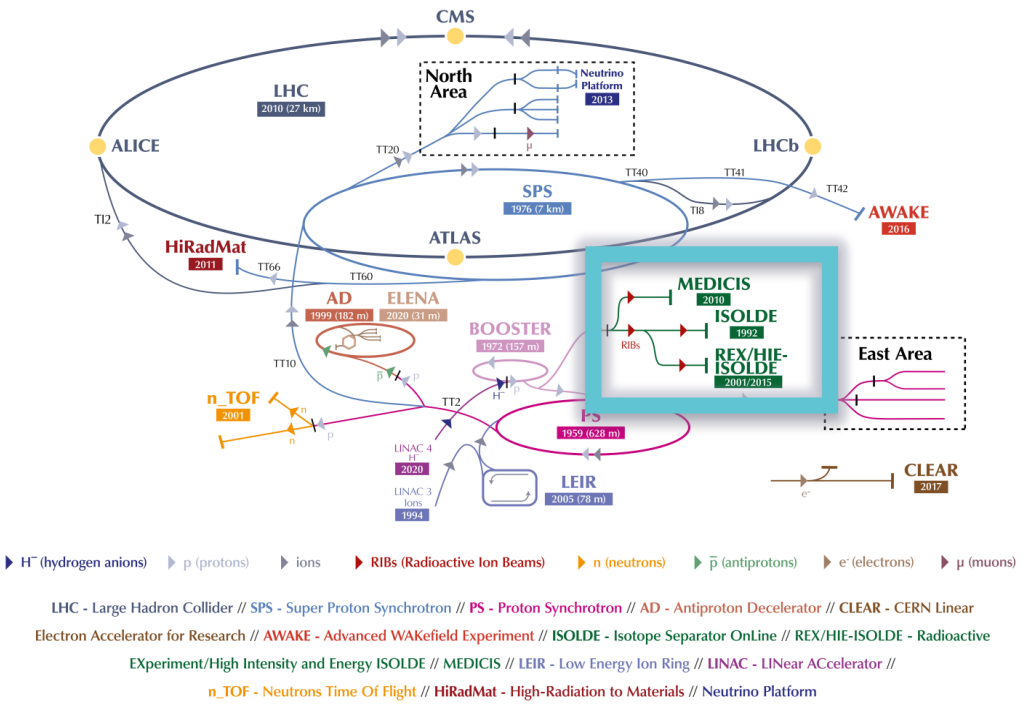
Mia Au

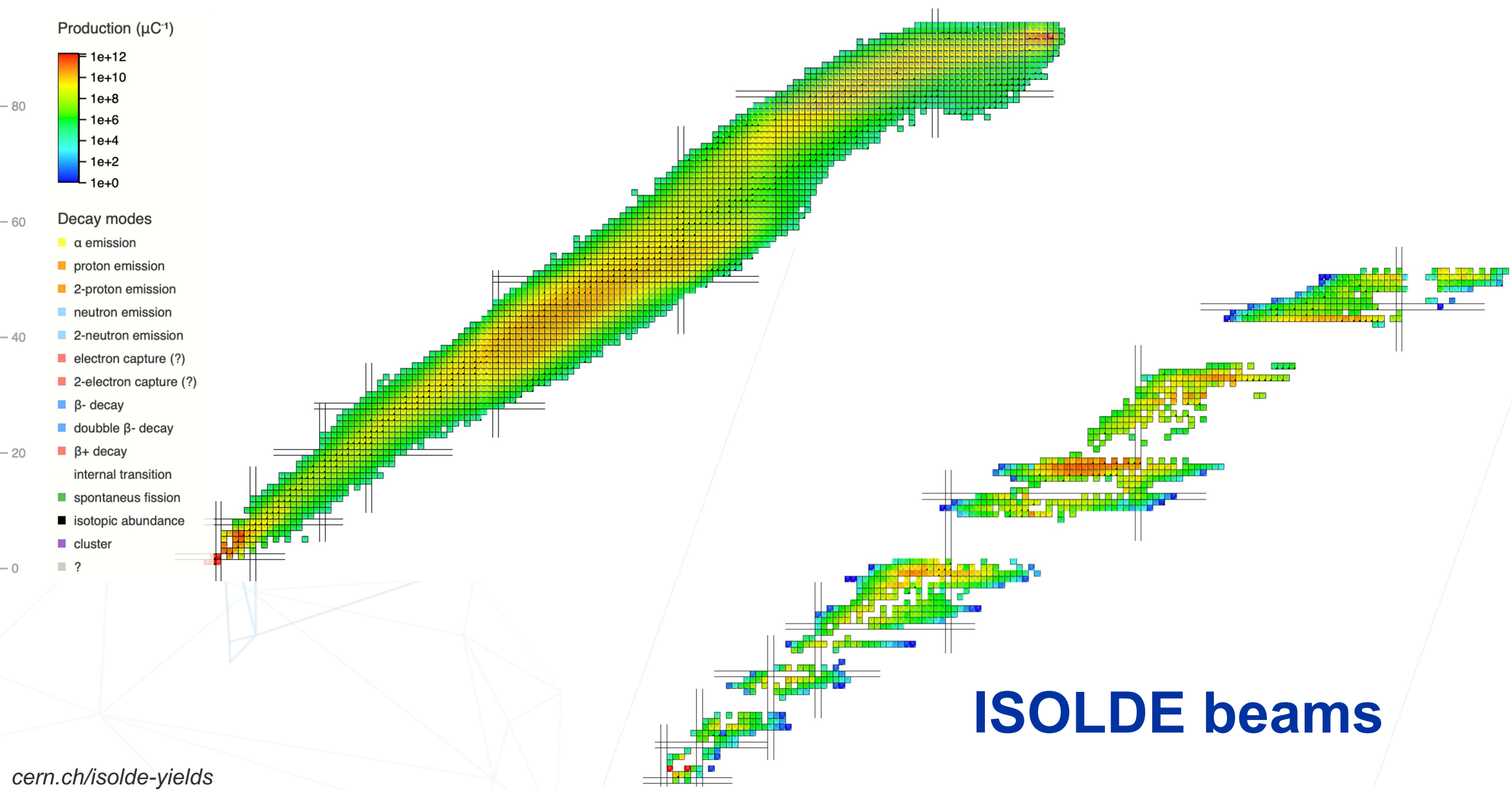
ISOLDE Workshop and Users Meeting 2022 Geneva, Switzerland

LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

Agenda

1. ISOLDE beams
2. Actinides at ISOLDE
3. Molecular beams at ISOLDE
4. Actinide molecules
5. Next steps



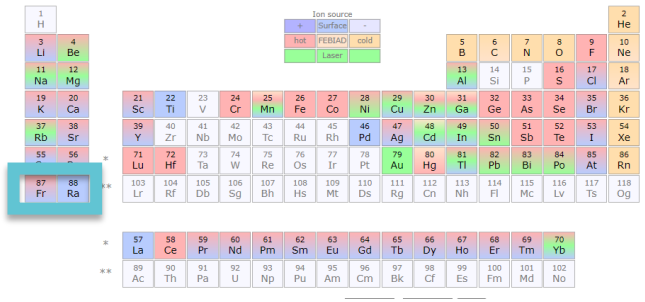


ISOLDE beams

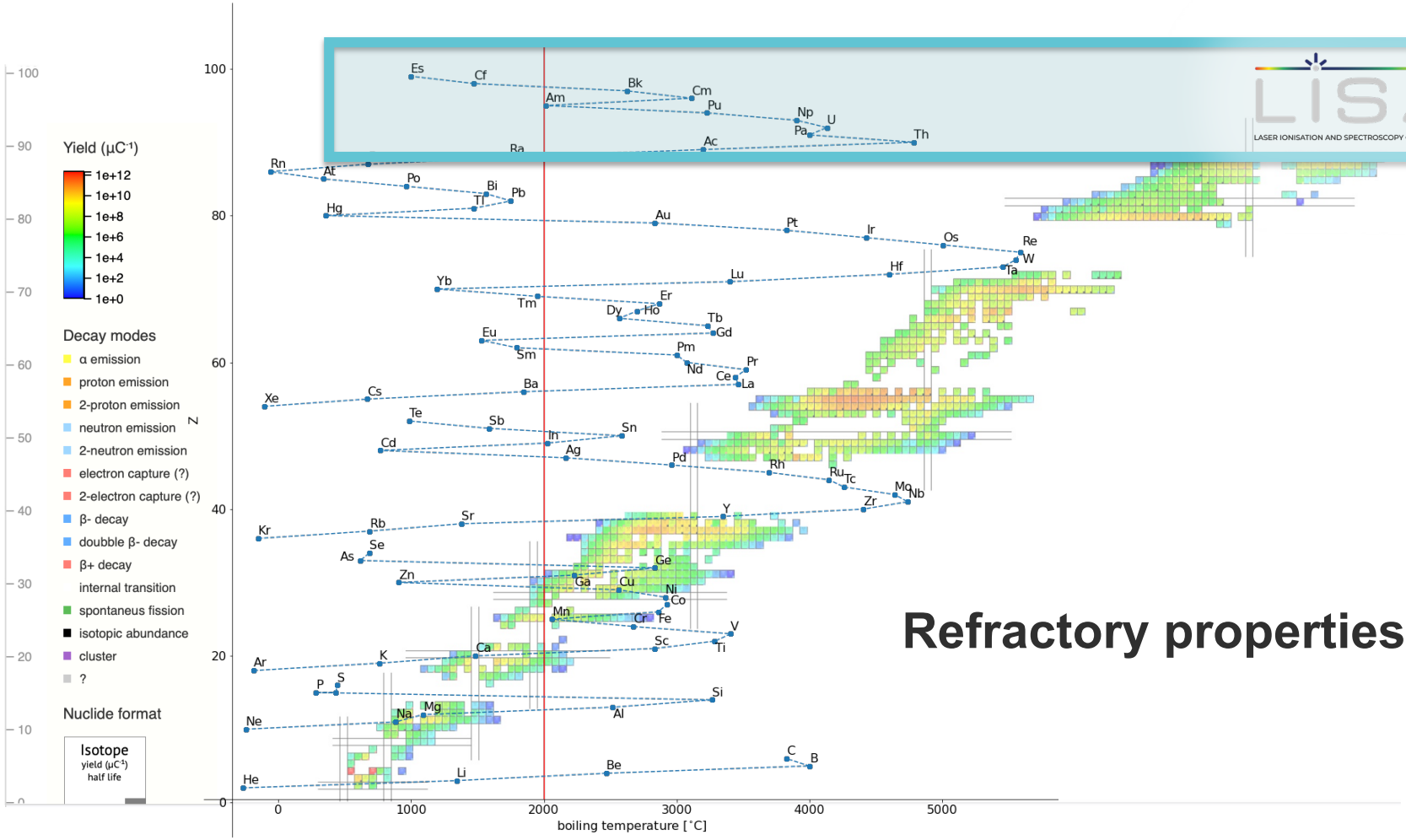
cern.ch/isolde-yields

Challenges

Contaminants



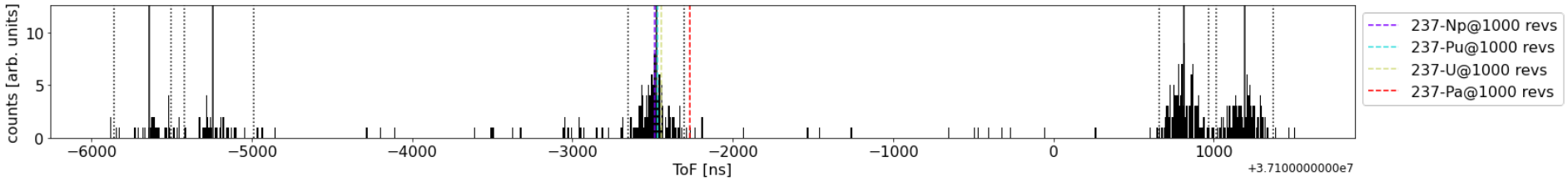
cern.ch/isolde-yields



Refractory properties

Mass resolving power

$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$

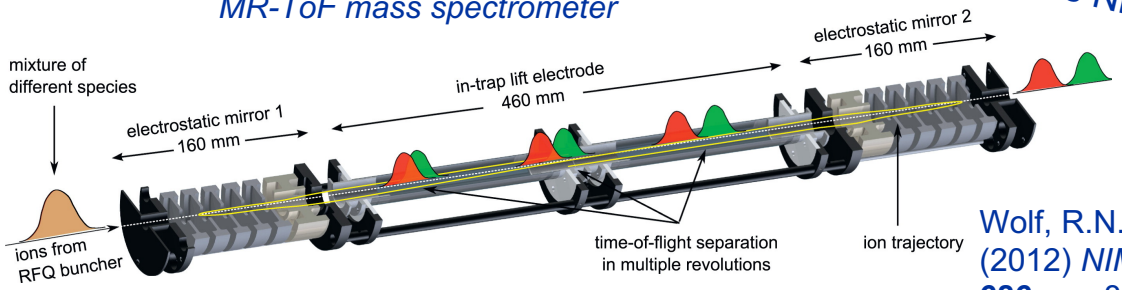


Actinide atomic beams

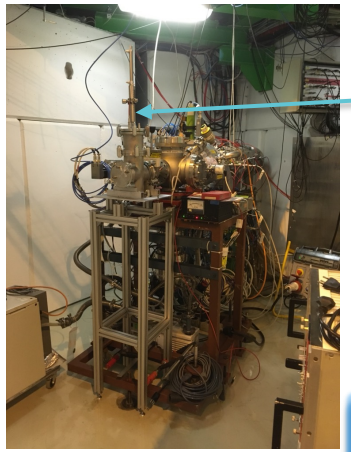
ISOLTRAP

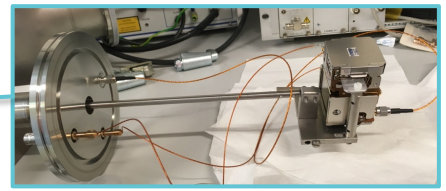
MR-ToF mass spectrometer

Talk by Lukas Nies



Wolf, R.N. *et al.* (2012) *NIM A* **686,** pp. 82-90.





TISD chamber

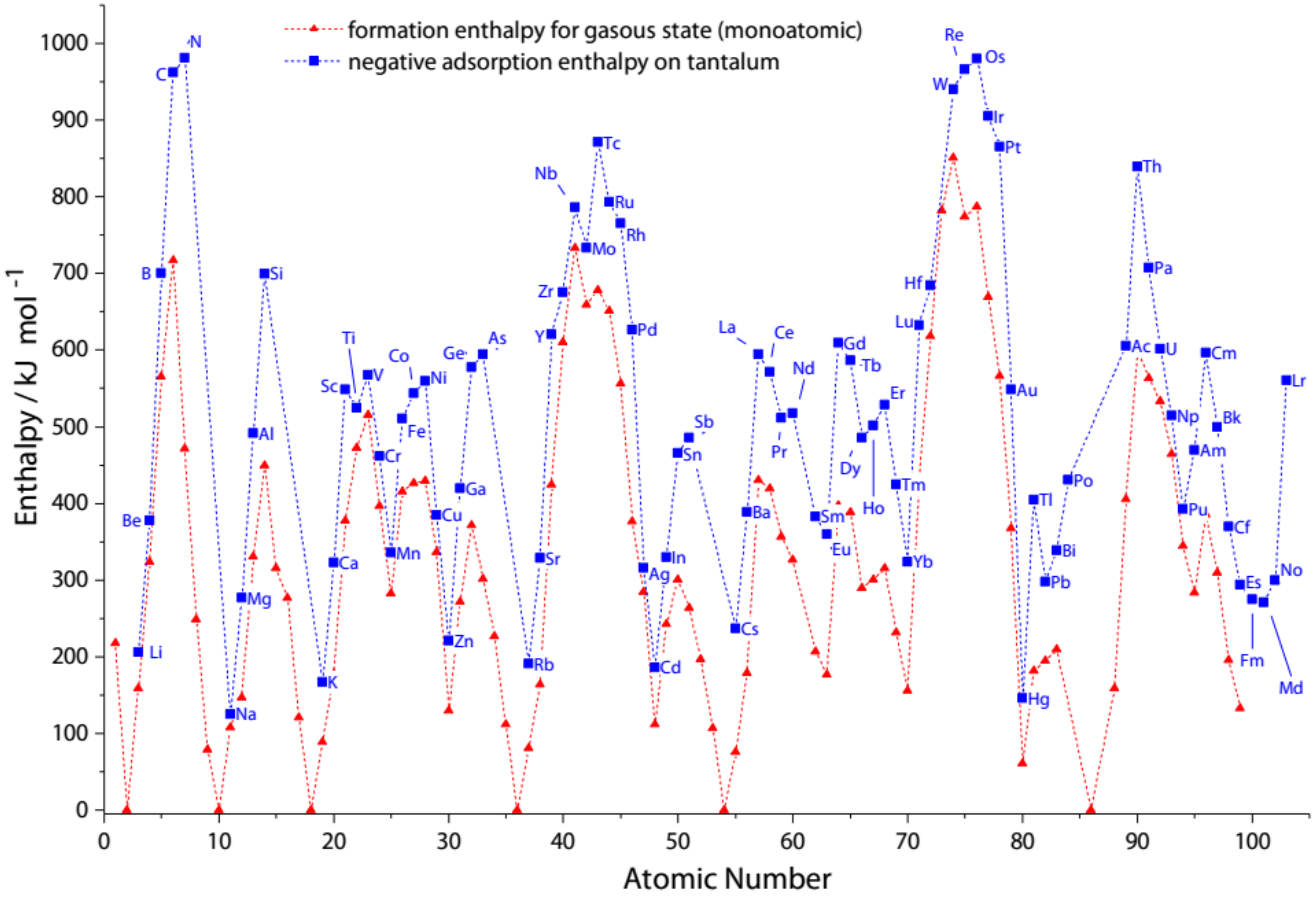
ISOLDE GLM

ISOLDE GPS

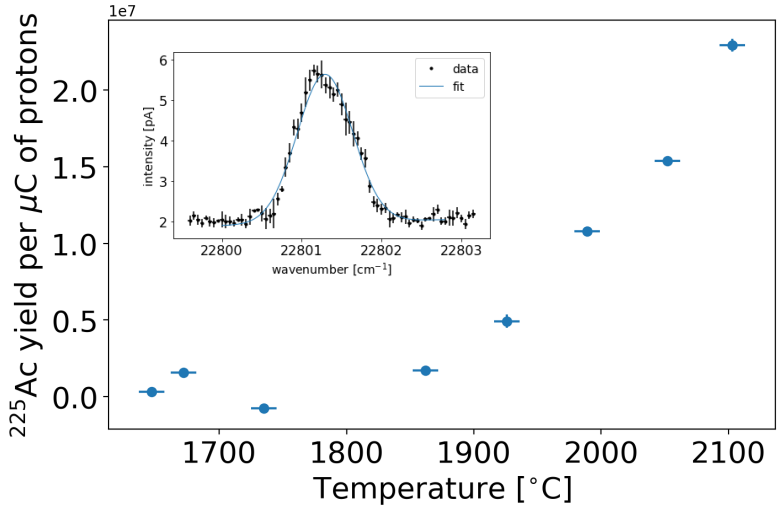
RILIS

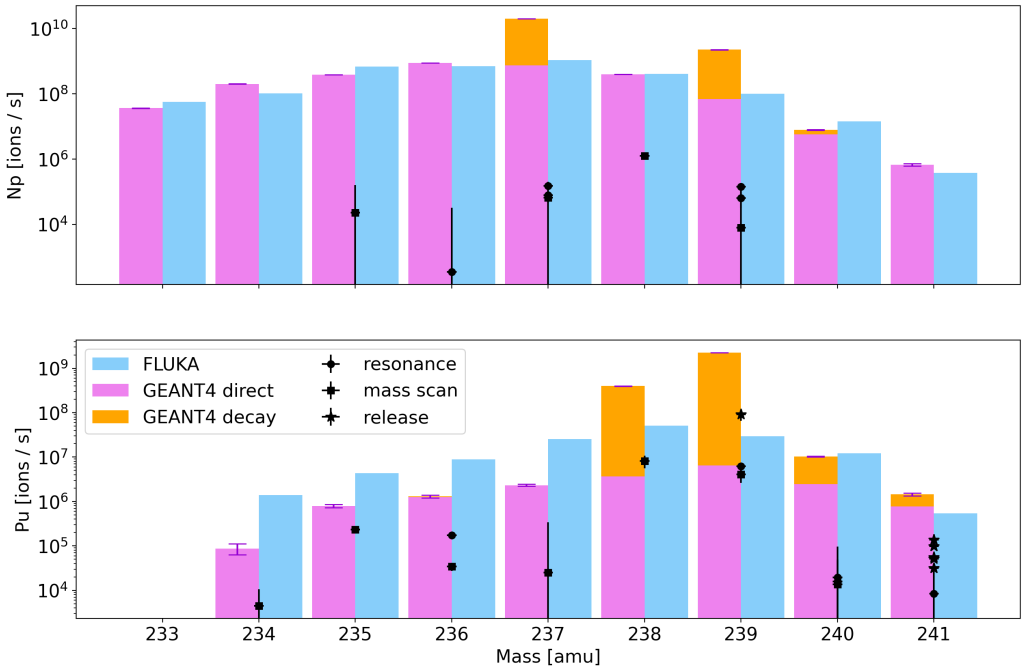
Ac, Pa, U, Np, Pu

Ac, Np, Pu

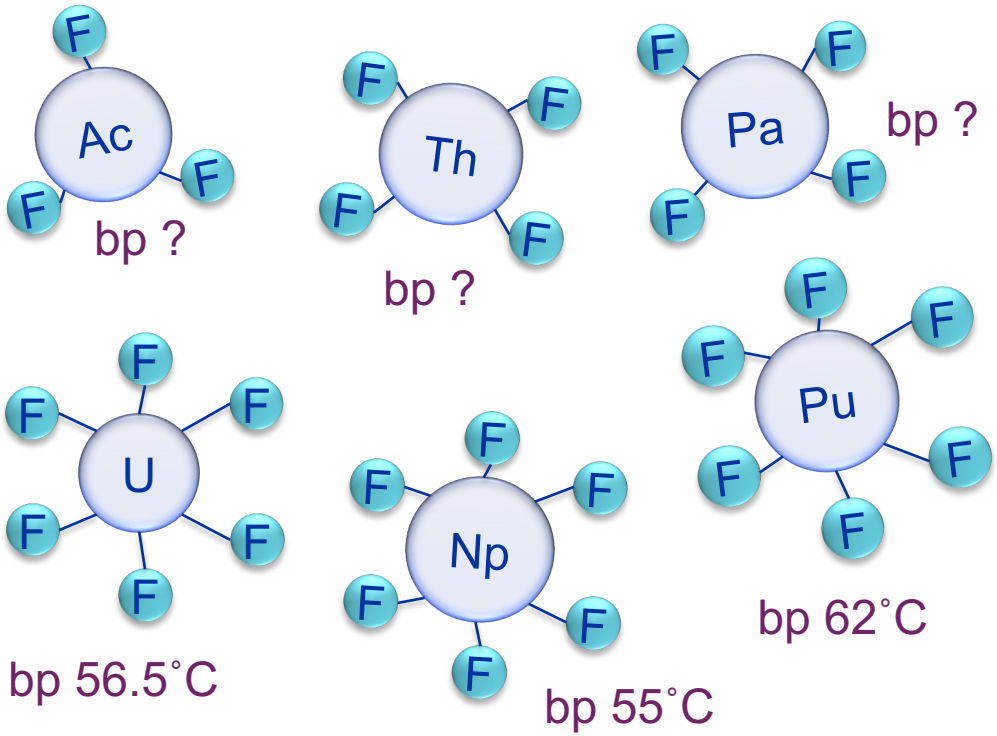


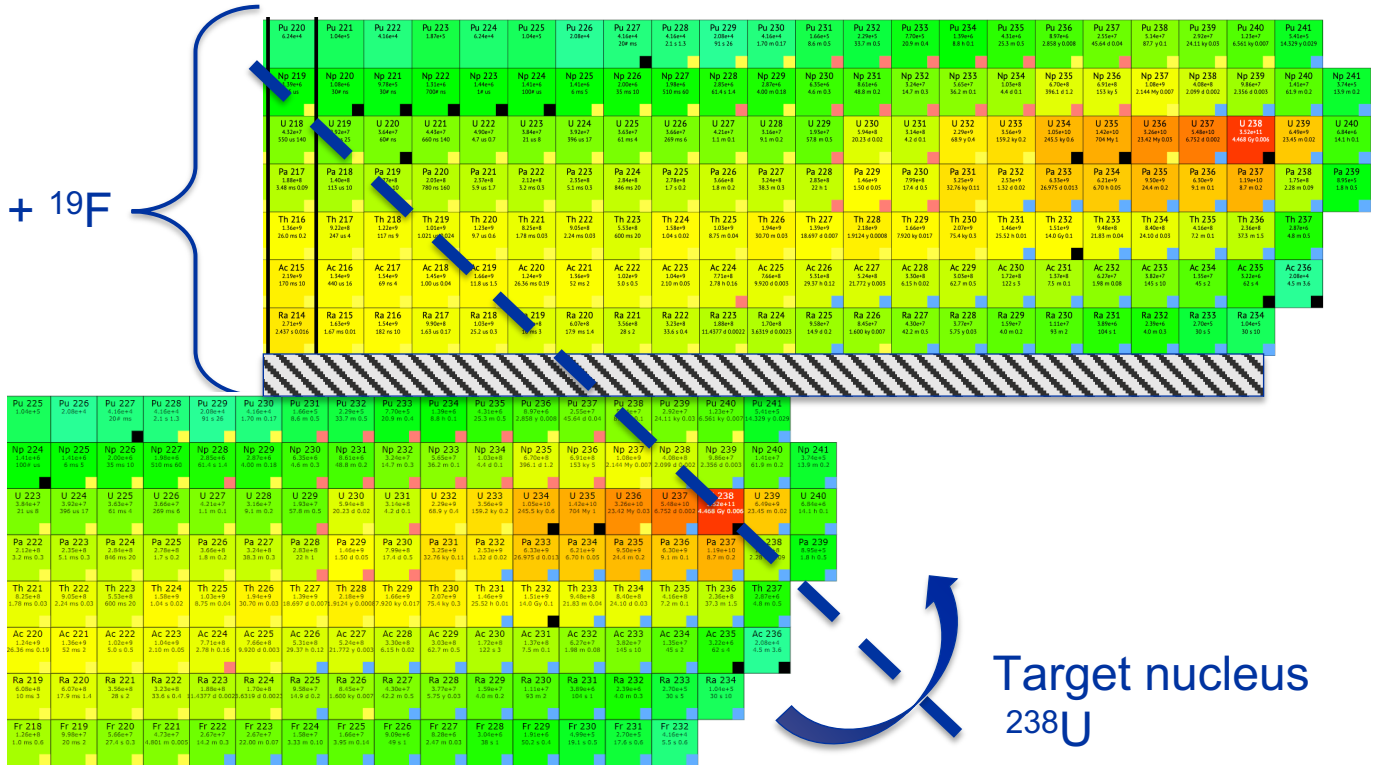
Ballof, J. (2021) Radioactive Molecular Beams at CERN-ISOLDE





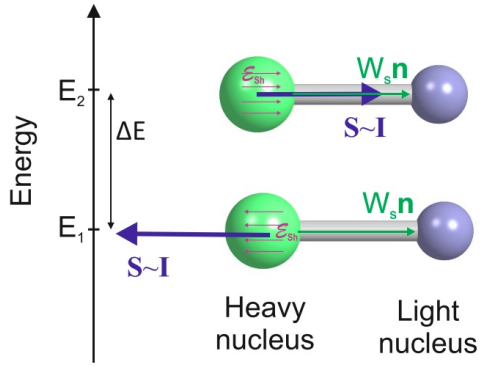
Au, M et al., (2022) In preparation





Molecular beams

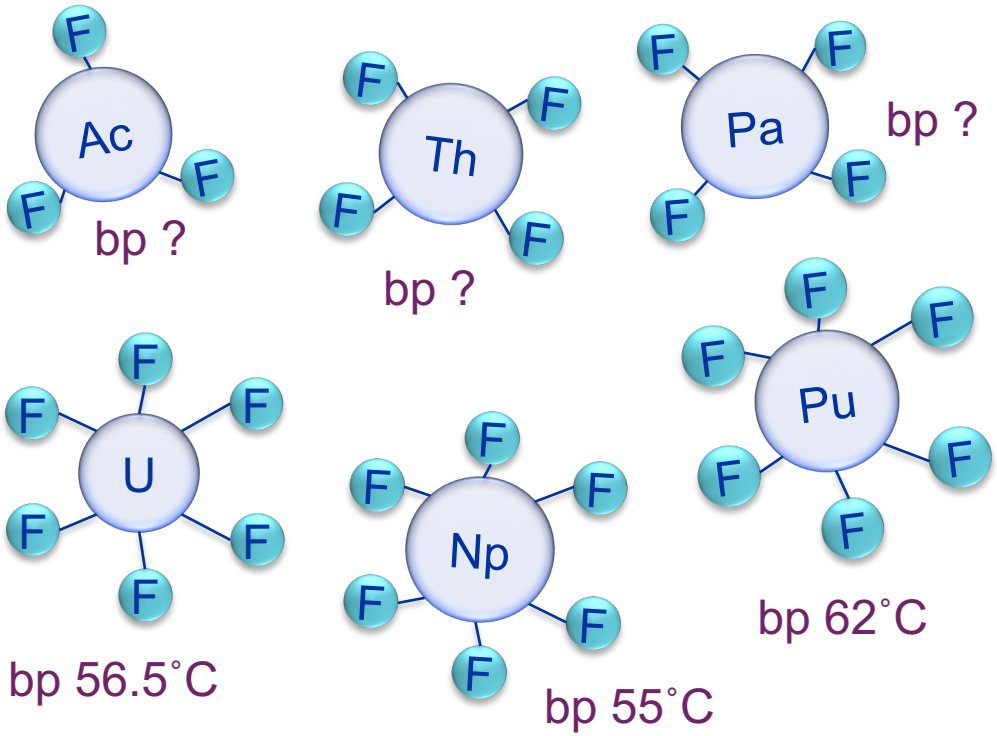
1. Volatilization
2. Sideband extraction
3. Research opportunities

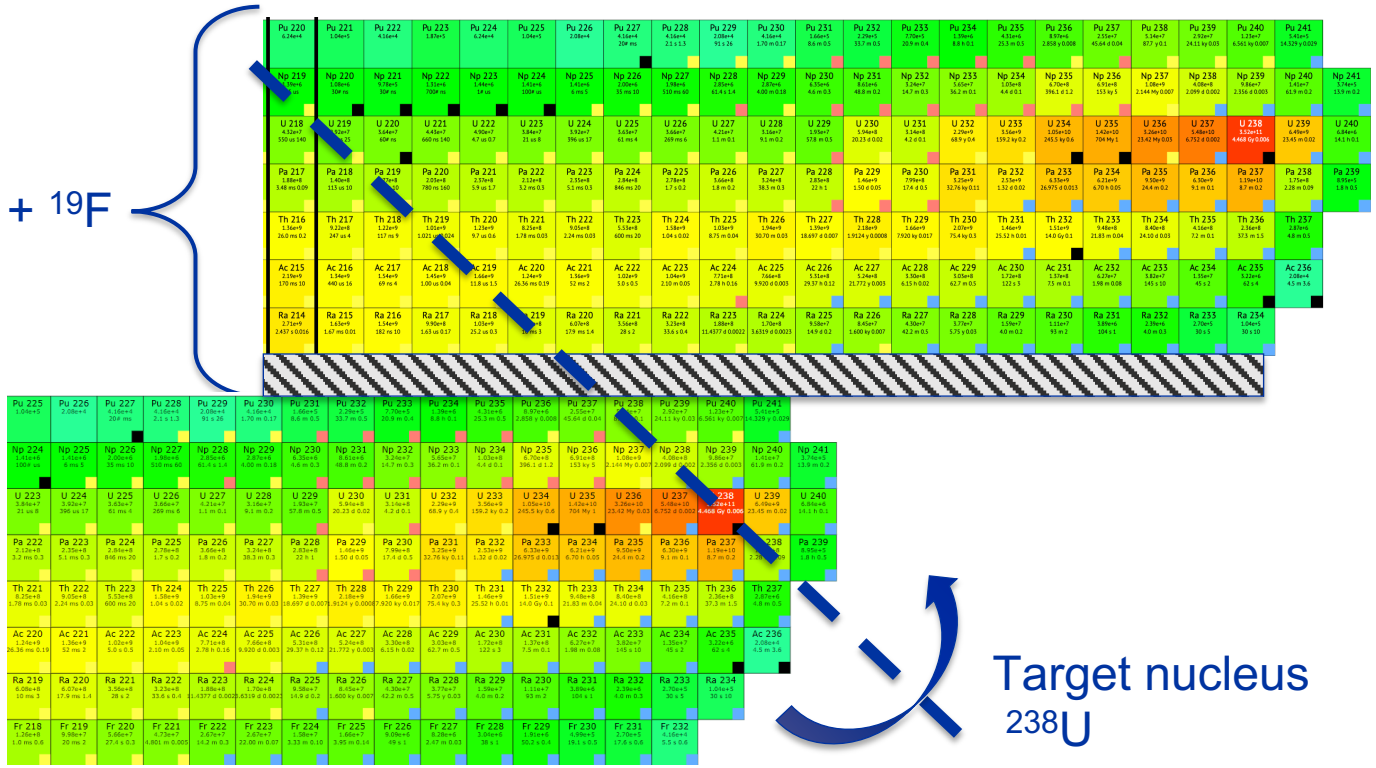


New results from the laser spectroscopy of RaF at CRIS towards searches for new physics
Michail Athanasakis-Kaklamanakis

Effect of temperature distribution on the spectra of RaF	*Carlos Mario Fajardo Zambrano et al.*
503/1-001 - Council Chamber, CERN	17:48 - 17:50
Molecular Ions as Powerful Low-Energy Probes for Fundamental Physics	*Carsten Zuelch*
503/1-001 - Council Chamber, CERN	18:02 - 18:04

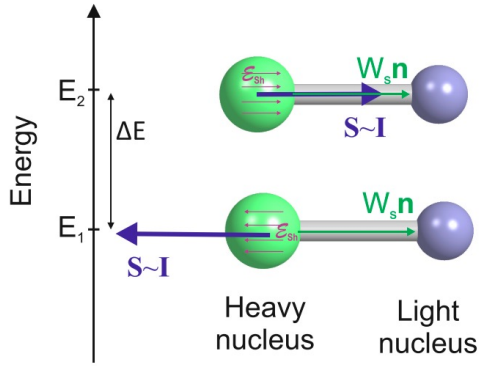
Garcia Ruiz et al. (2020) Nature 581. 396
Safronova, Budker, DeMille et al. (2018) Rev. Mod. Phys. *90. 2,*
Skripnikov et al. (2020) Phys. Chem. Chem. Phys. *22. 33, 18374*





Molecular beams

1. Formation
2. Detection
3. Identification



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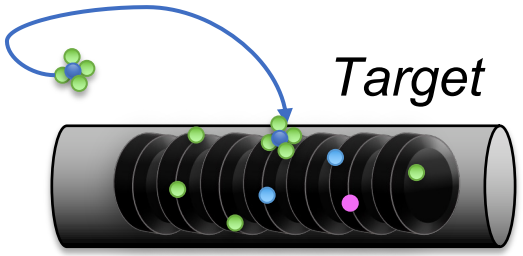
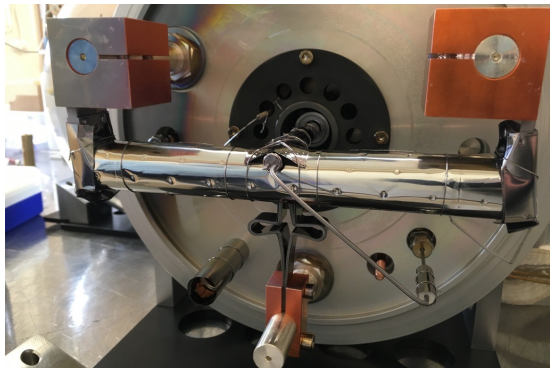
Skripnikov et al. (2020) Phys. Chem. Chem. Phys. *22. 33, 18374*

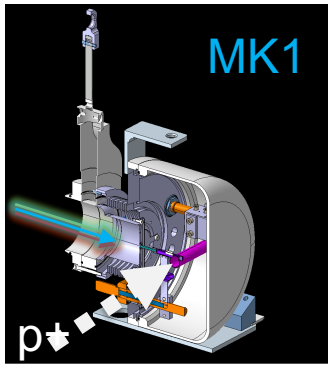
Formation: Making the molecules

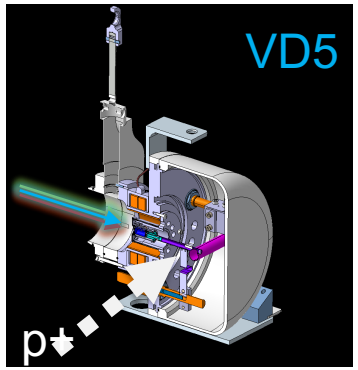
In-target

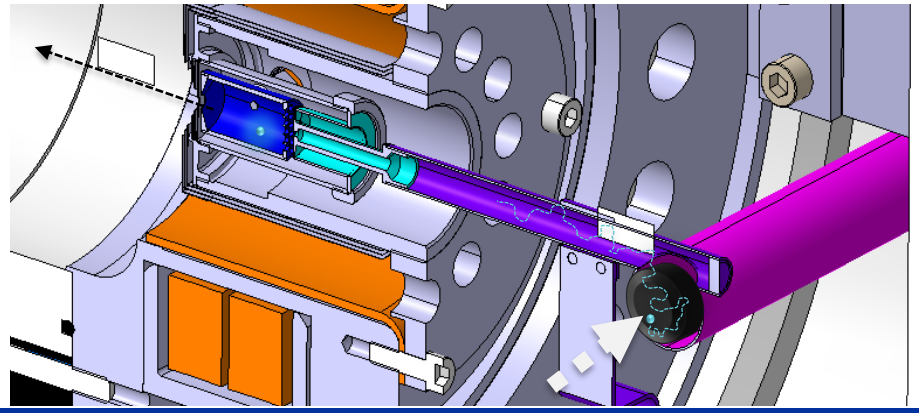
Reactive gas:
CF_4, NF_3, SF_6





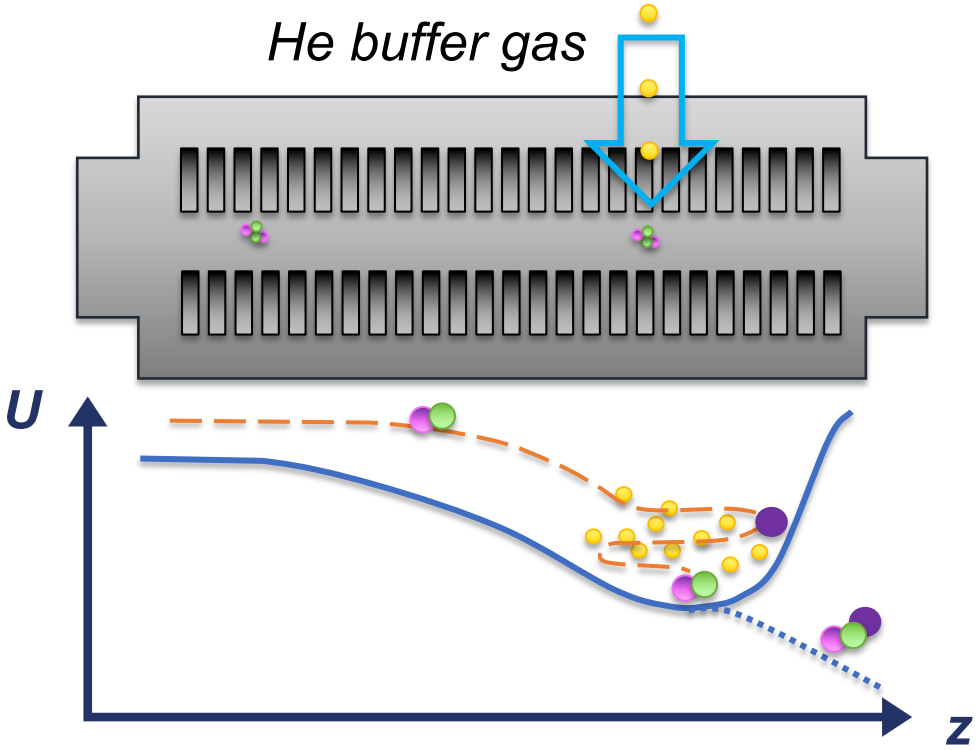






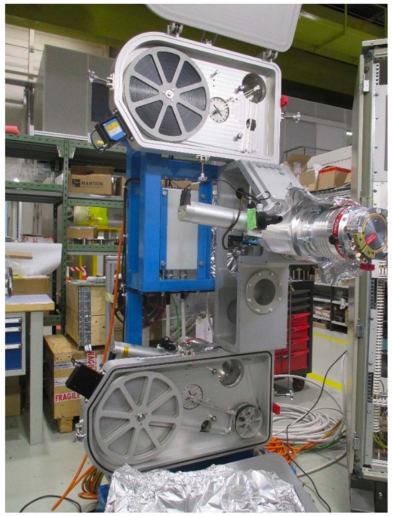
In-trap

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

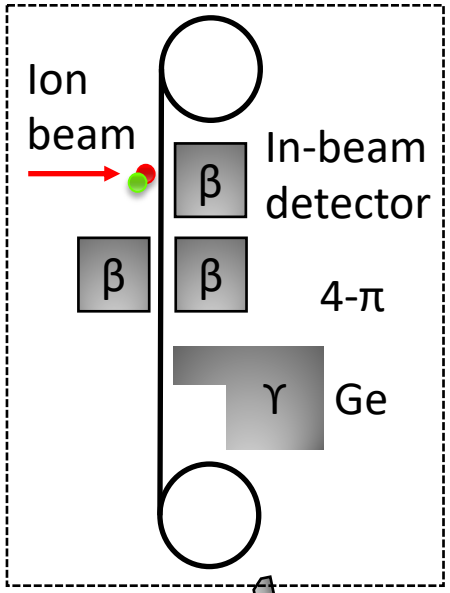


Detection and identification

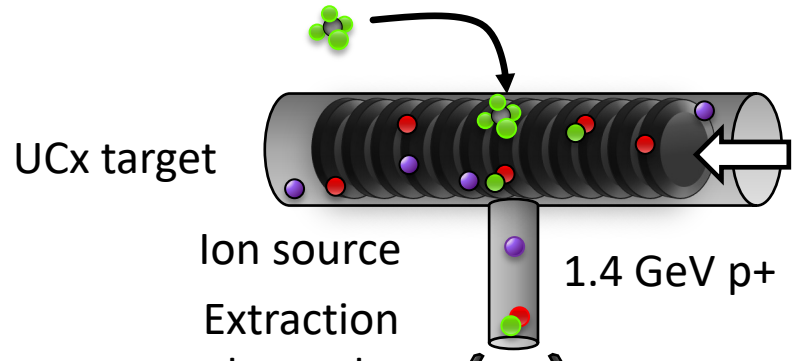
- Contaminant ions
- Contaminant neutrals
- Isotope of interest
- Neutral molecule of interest
- Molecular ion of interest
- Reactive gas
- Buffer gas



Catherall, R. et al. (2017)
J. Phys. G. **44**, 9

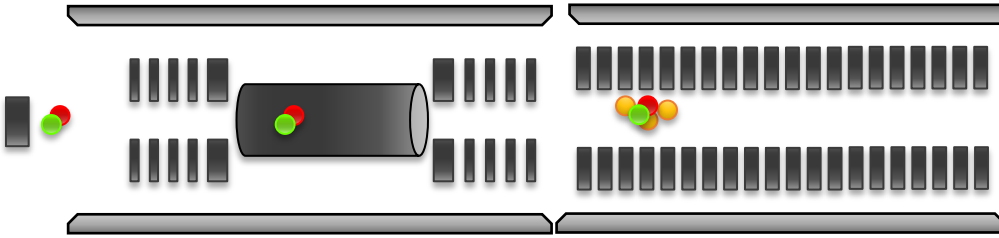


ISOLDE FTS



ISOLDE HRS

Mass separator

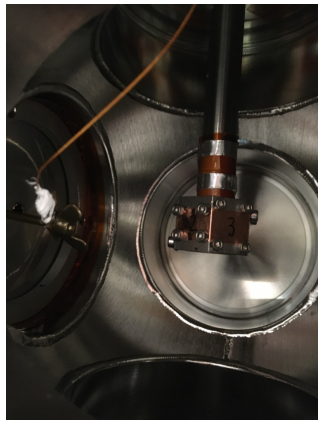


ISOLTRAP MR-ToF MS

ISOLTRAP RFQ-cb

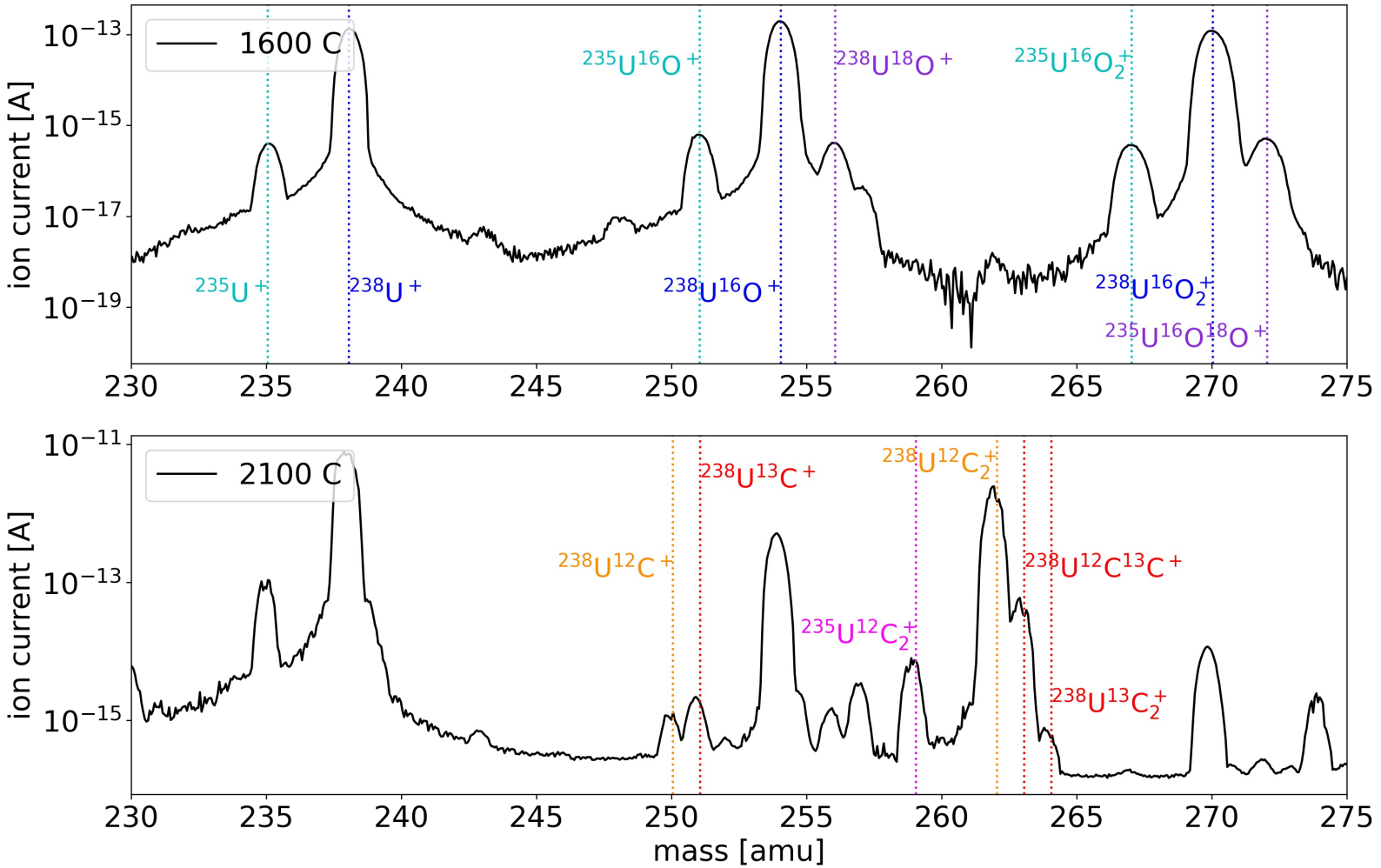
ISOLDE LA1

collections chamber



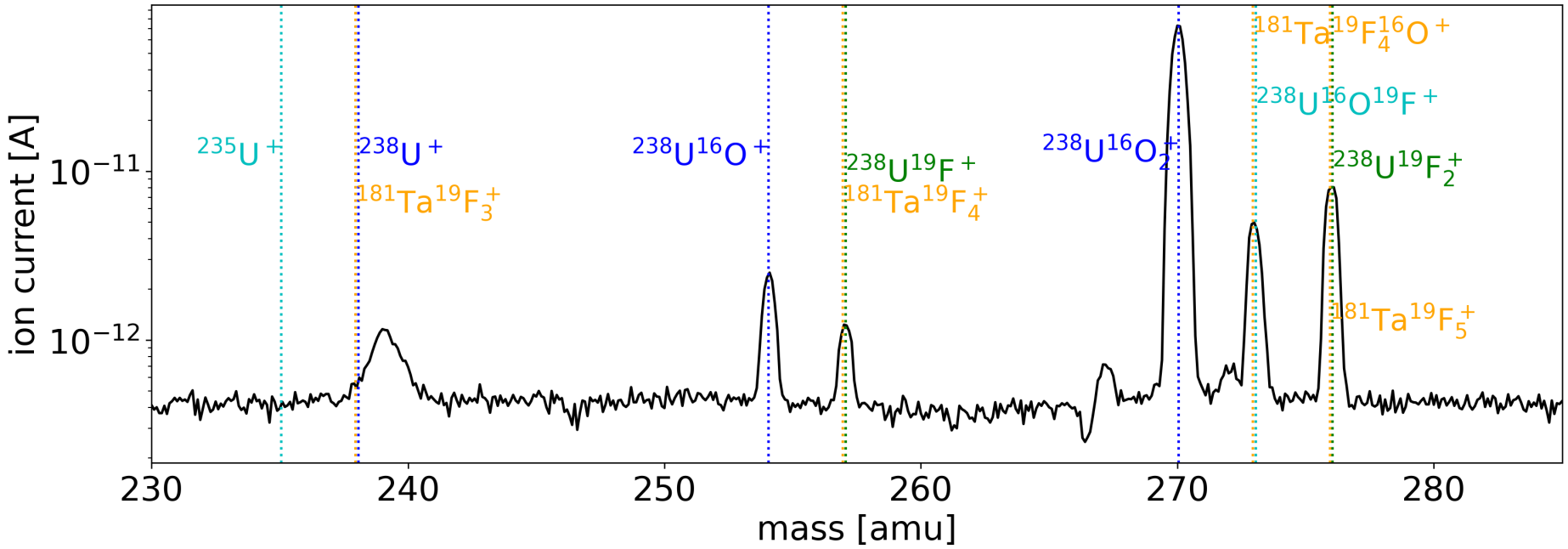
Surface ionized target molecules

Species	Rate [ions/s]
$^{235}U^{+}$	7E5
$^{238}U^{+}$	3.7E7
$^{238}U^{12}C^{+}$	7.5E3
$^{235}U^{16}O^{+}$	1.3E4
$^{238}U^{16}O^{+}$	4.2E6
$^{238}U^{18}O^{+}$	9E3
$^{235}U^{12}C_2^{+}$	6.5E4
$^{238}U^{12}C_2^{+}$	1.1E7
$^{238}U^{12}C^{13}C^{+}$	4.8E5
$^{238}U^{13}C_2^{+}$	1.65E3
$^{235}U^{16}O_2^{+}$	2E3
$^{238}U^{16}O_2^{+}$	7E5
$^{235}U^{16}O^{18}O^{+}$	2.5E3



Fluorination

Species	Rate [ions/s]
$^{238}U^{+}$	?
$^{235}U^{16}O^{+}$	1.3E4
$^{238}U^{16}O^{+}$	4.2E6
$^{238}U^{19}F^{+}$	?
$^{181}Ta^{19}F_5^{+}$	?
$^{238}U^{16}O_2^{+}$	7E5
$^{181}Ta^{19}F_4{}^{16}O^{+}$	?
$^{238}U^{19}F^{16}O^{+}$	?
$^{238}U^{19}F_2^{+}$	?
$^{181}Ta^{19}F_5^{+}$	?



Metastable molecular ions

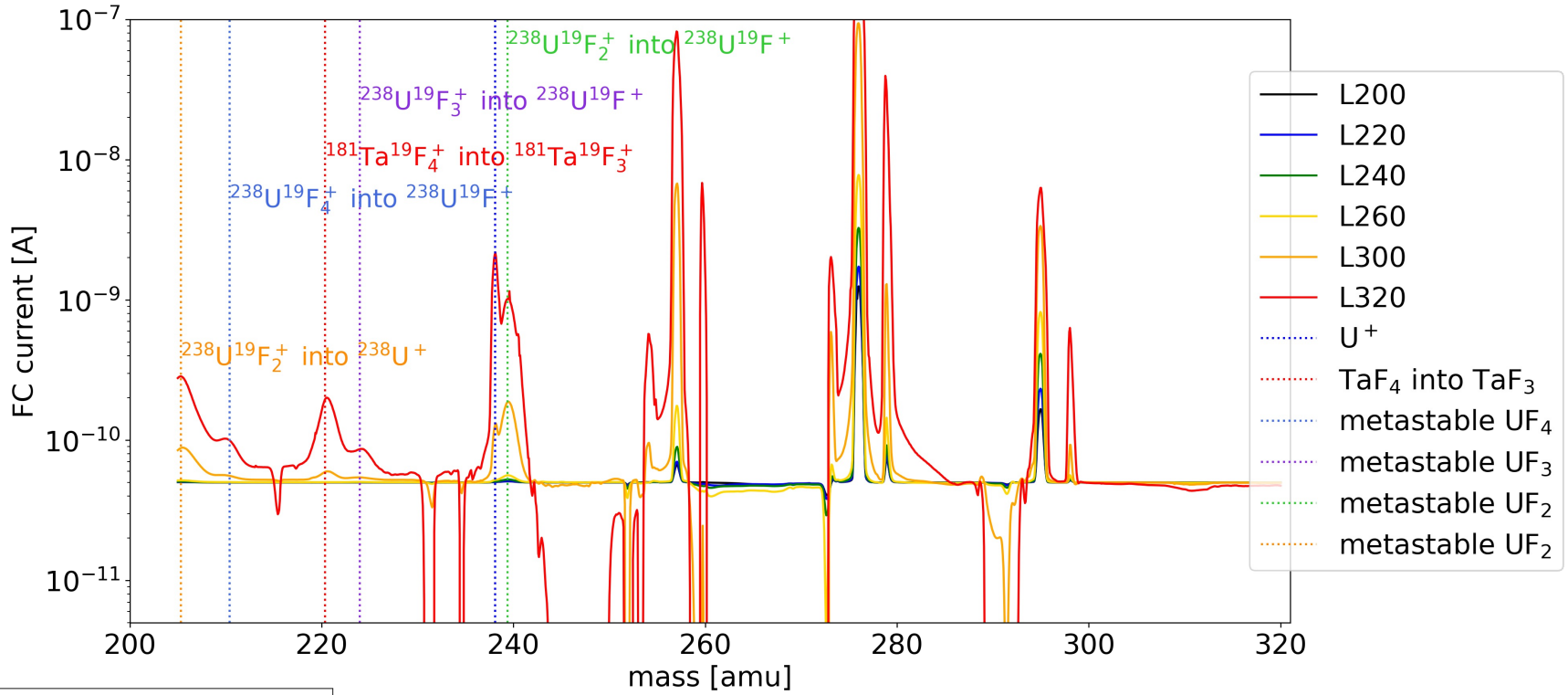
Dissociation **after** acceleration, **before** mass separation.

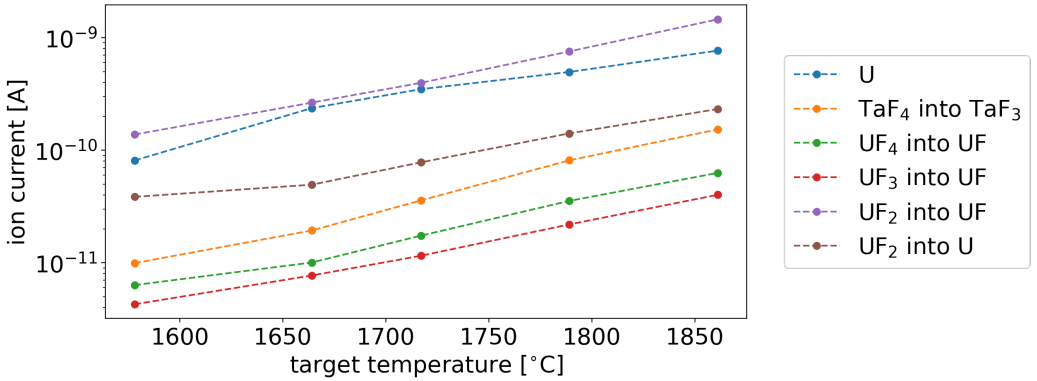
apparent mass: $m^* = \frac{m_f^2}{m_p}$

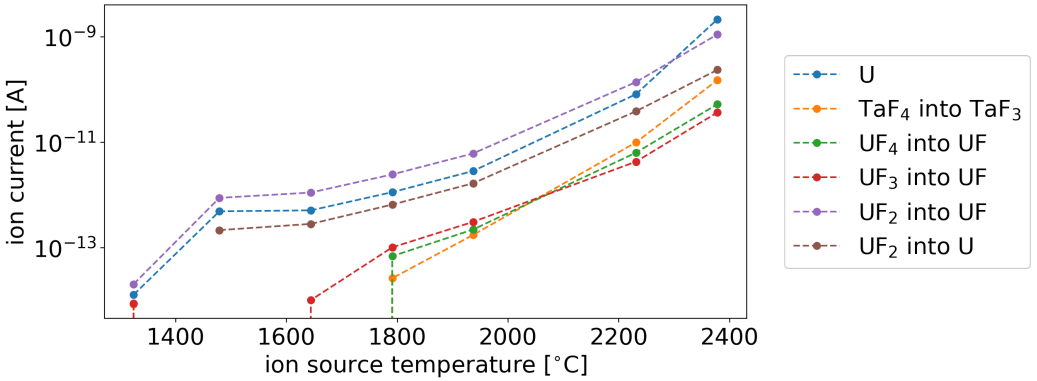
- m_f: mass of fragment ion
- m_p: mass of precursor ion

Ex: UF_2^+ into $UF^+ + F$

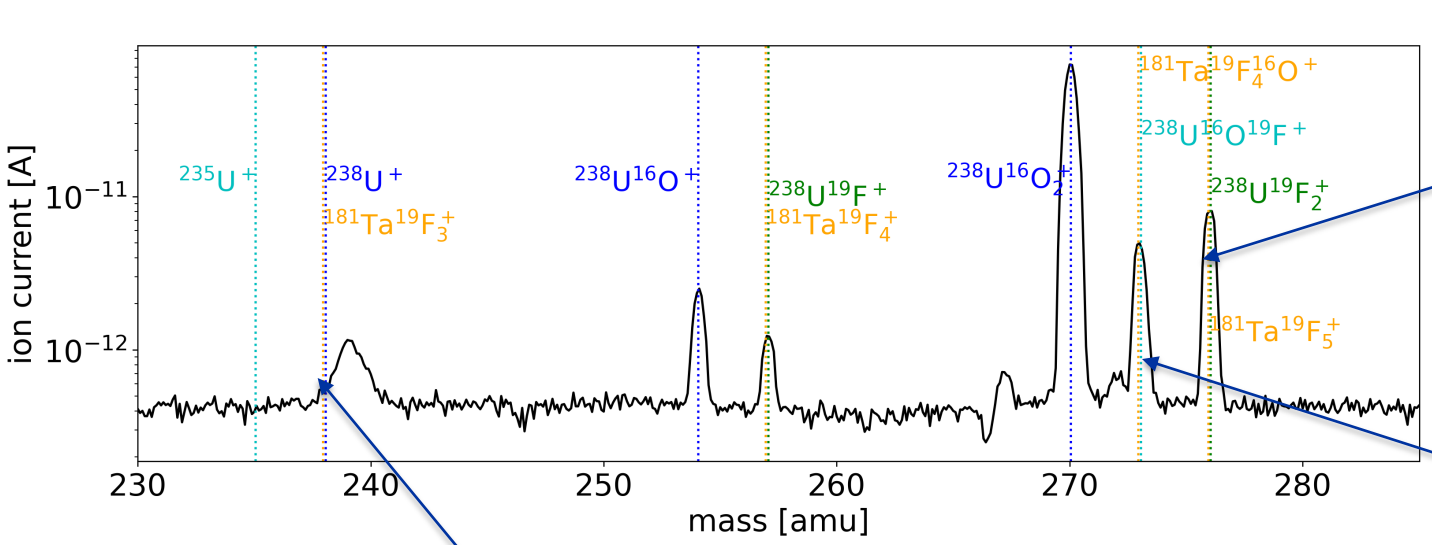
$$m^* = \frac{(238+19)^2}{238+2(19)} = 239.31$$

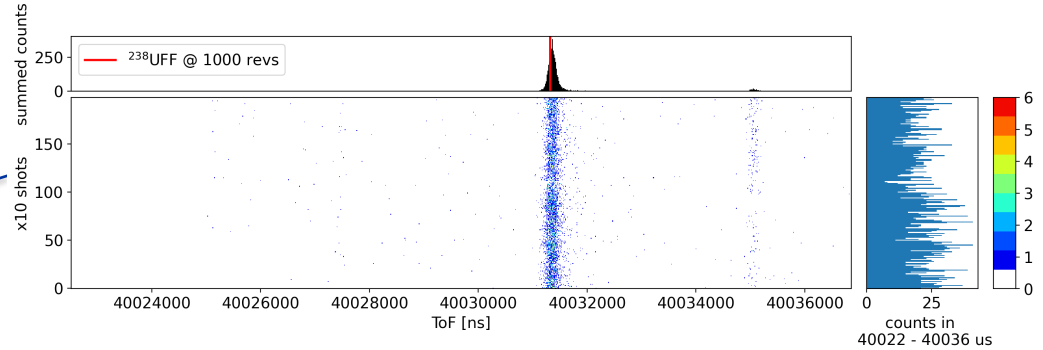


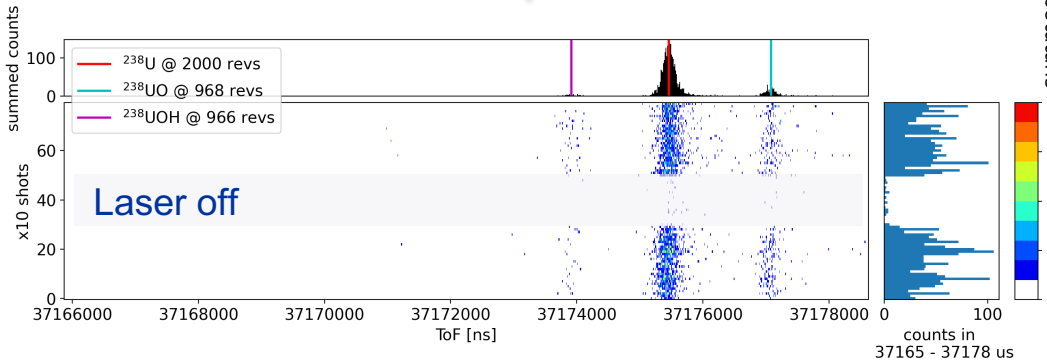


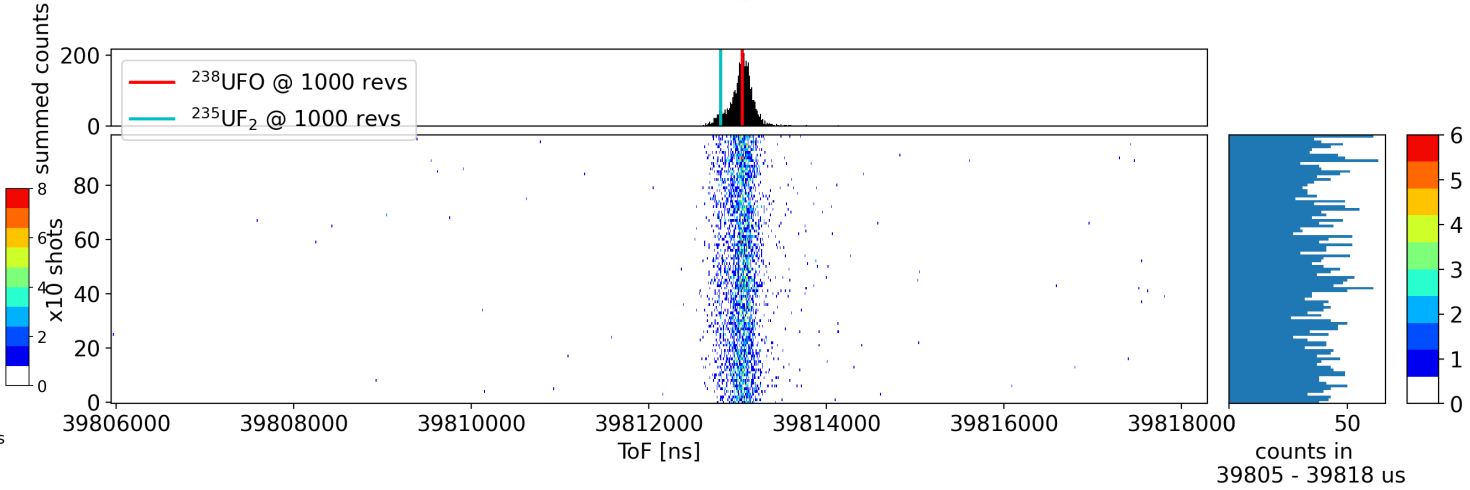


Decomposing mass spectra



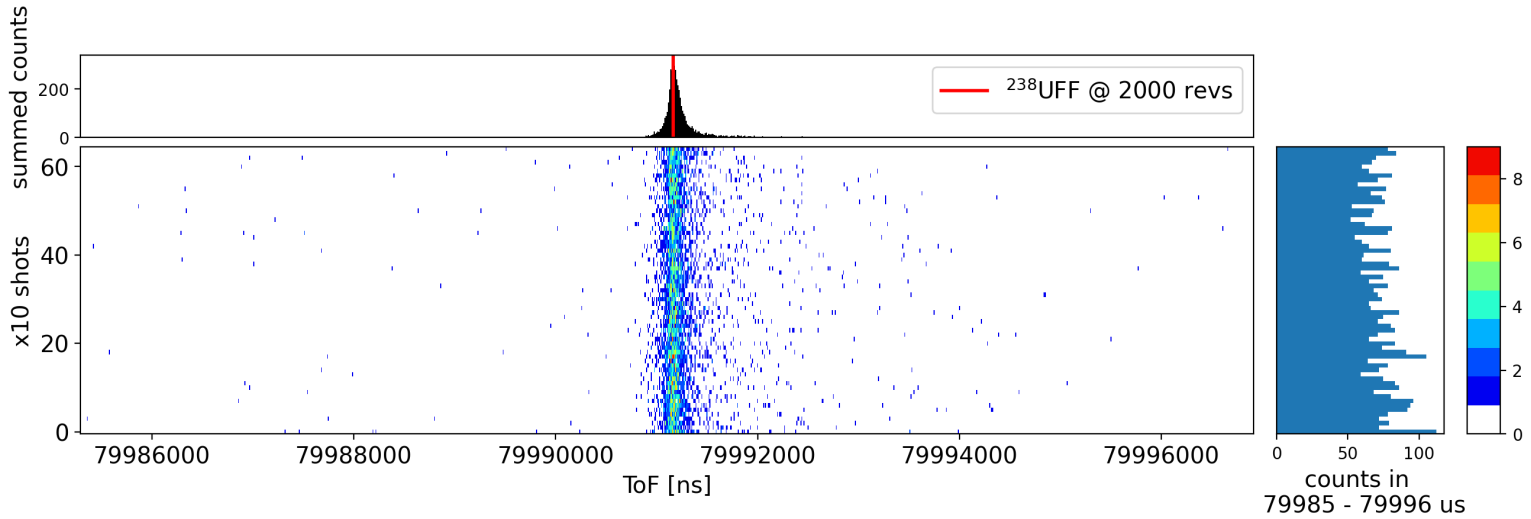


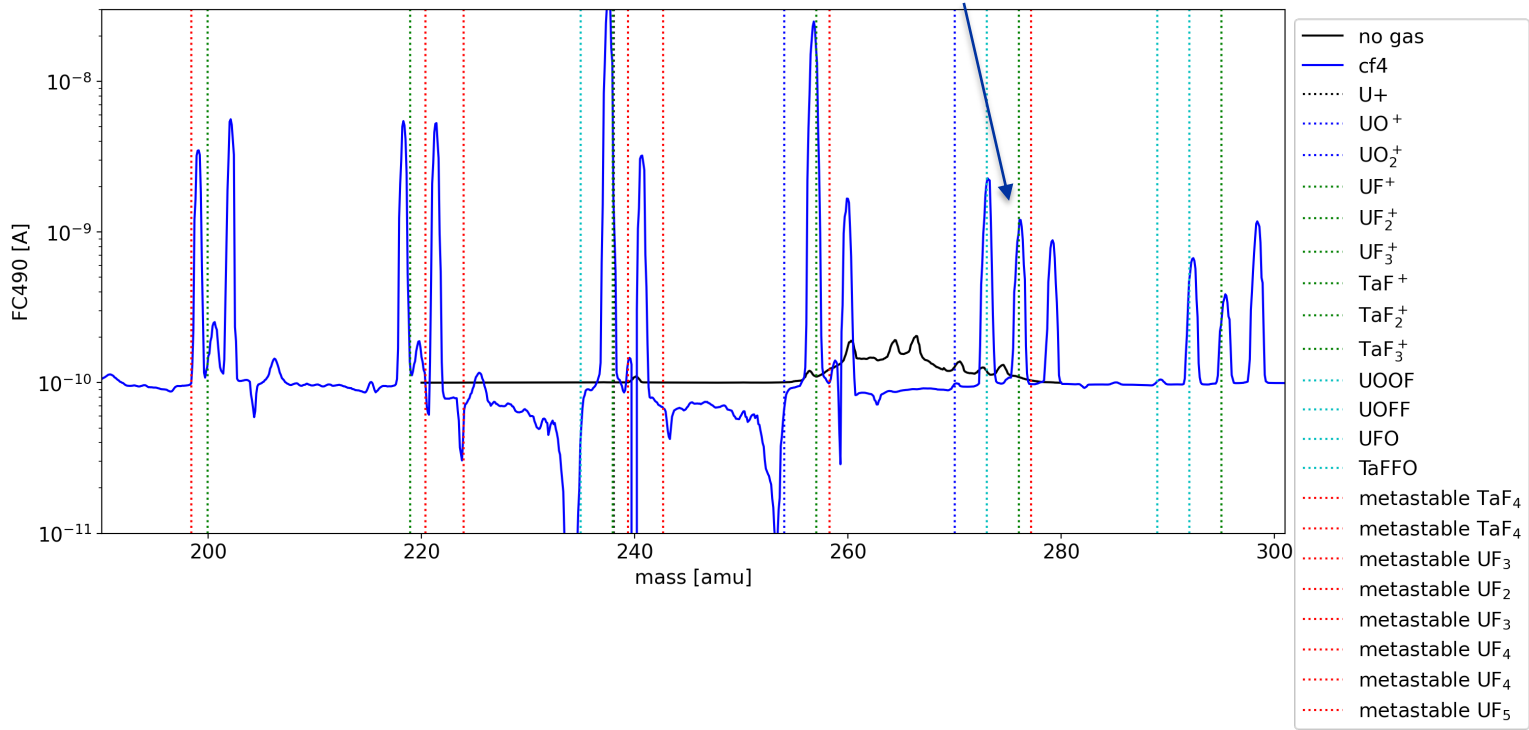




Plasma ionization

- High efficiency
- Low selectivity
- Dissociation

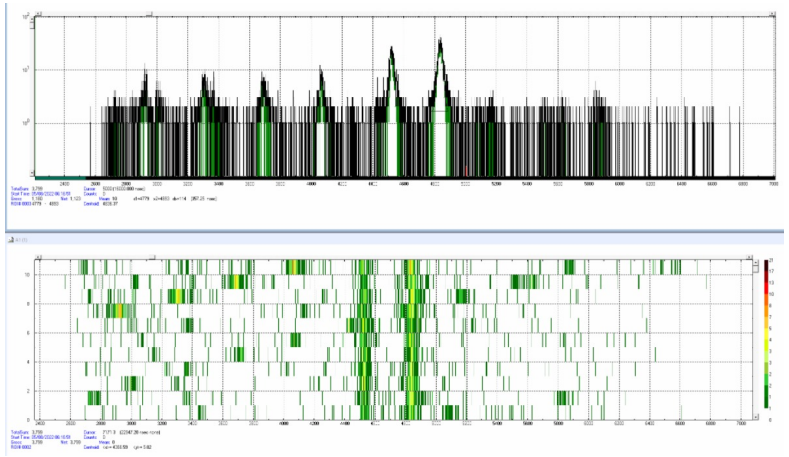


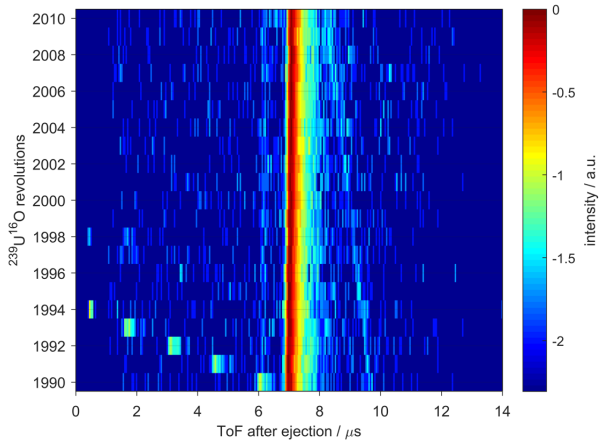


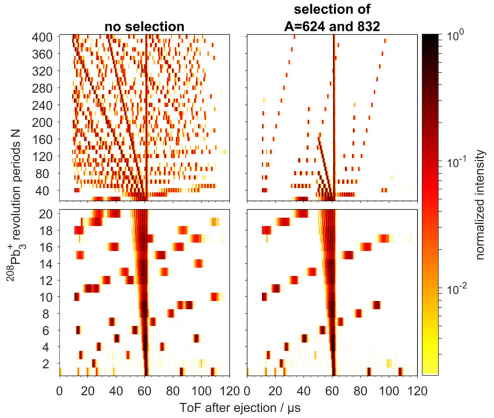
In-trap formation

UO_x, TaO_x

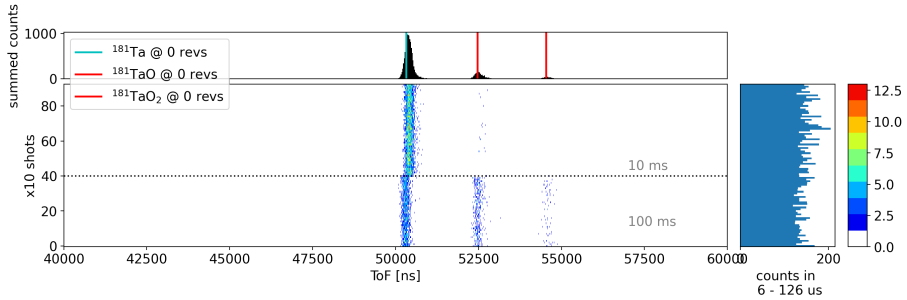
- ID by ToF and revs vs ToF
- Sideband populations

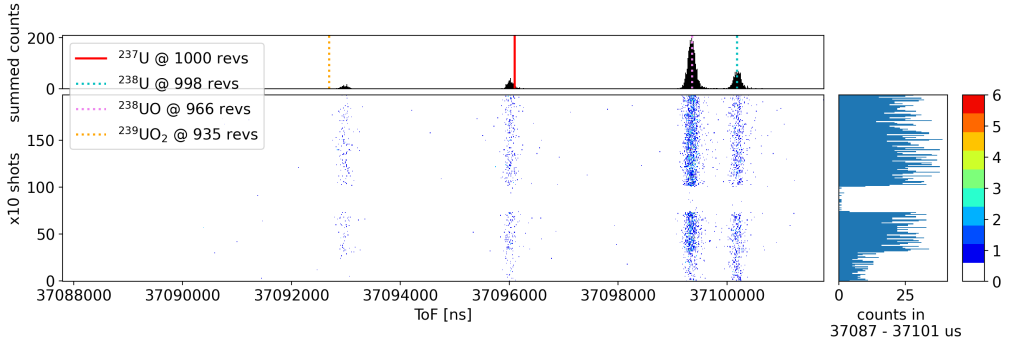


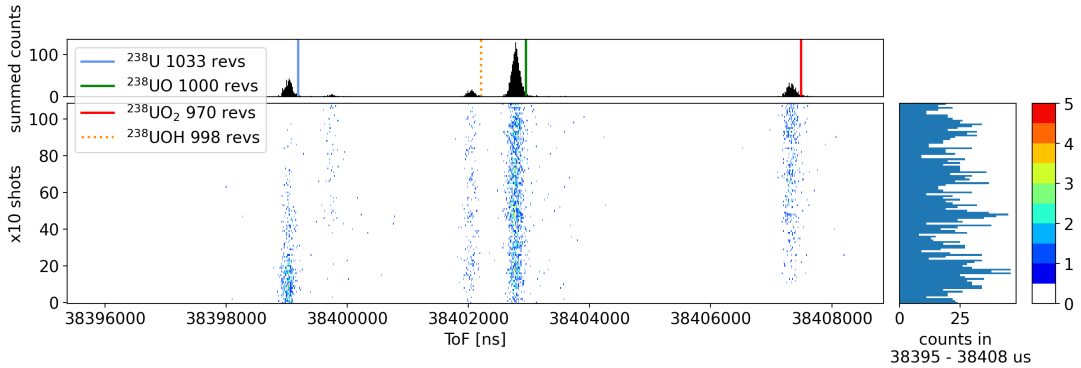


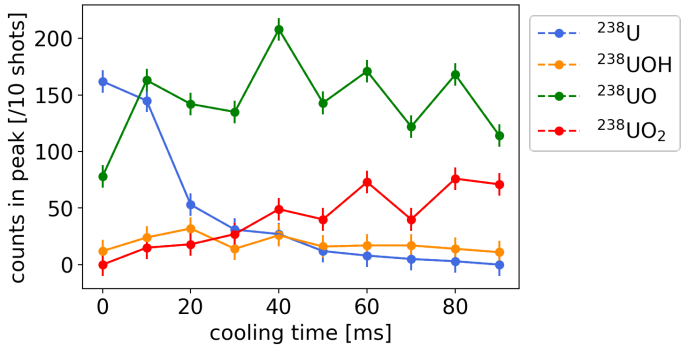


Fischer, Schweikhard (2020) Rev. Sci. Inst. **91**, 023201, *DOI 10.1063/1.5131582*









In-target formation

AcF_x

- Ac
  - Enhanced extraction
- AcF
  - Laser spectroscopy
- AcF_x
  - Coordination chemistry
- ^{225}Ac
  - Radiopharmaceutical “theranostic”
  - Optimized production

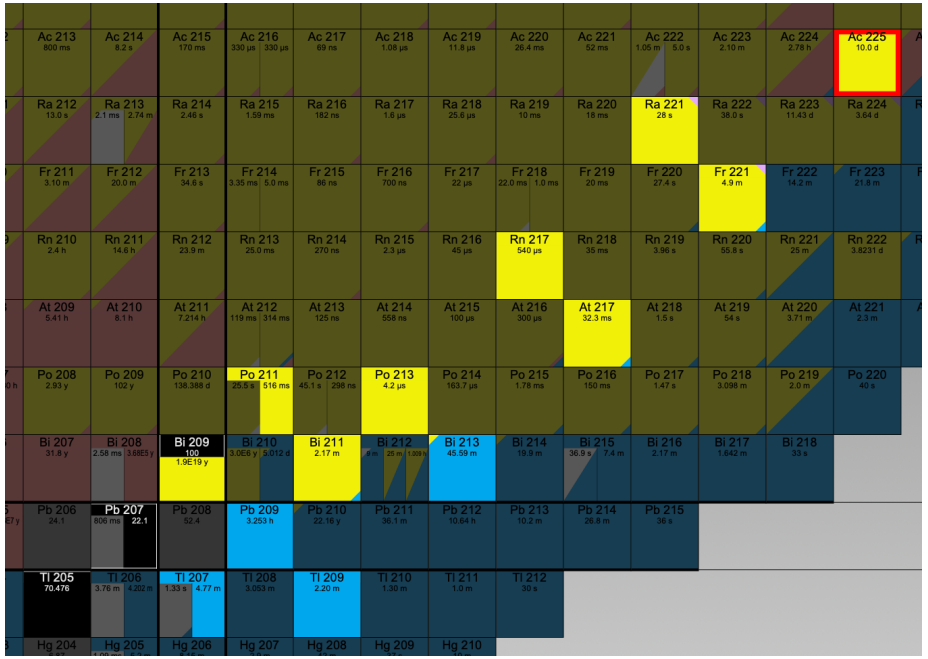
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

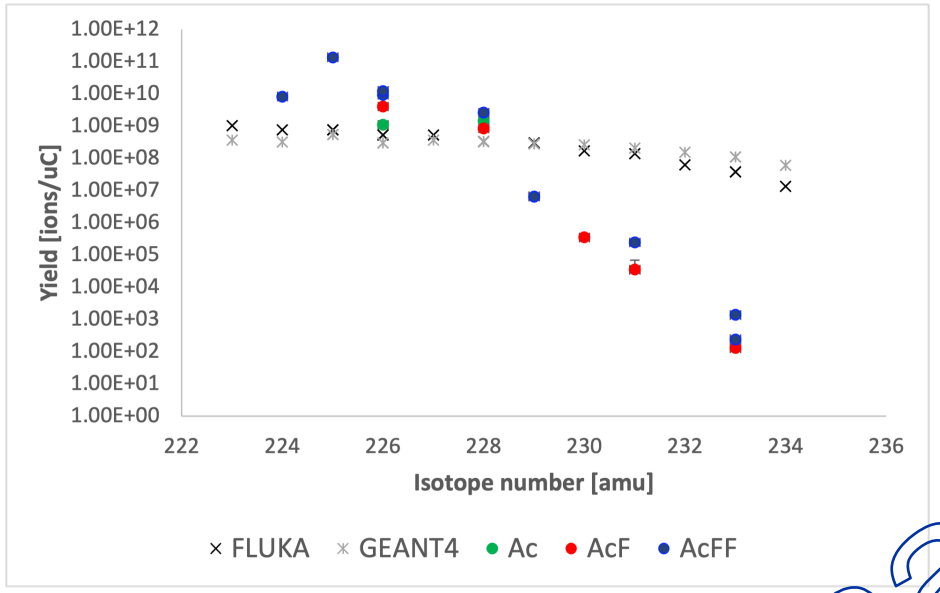
Laser ionization spectroscopy of AcF

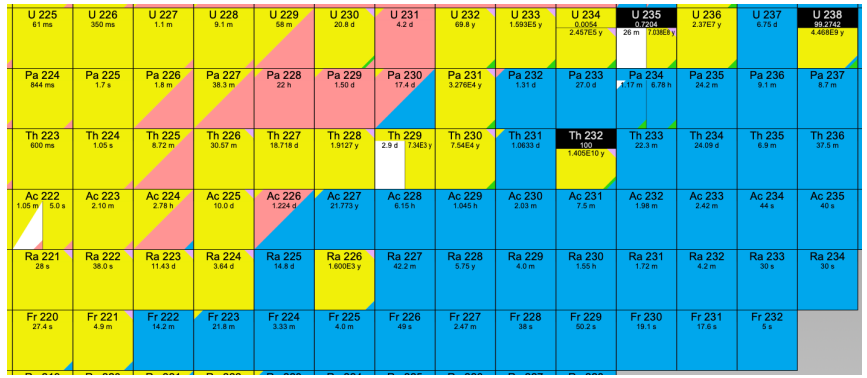
September 28, 2021

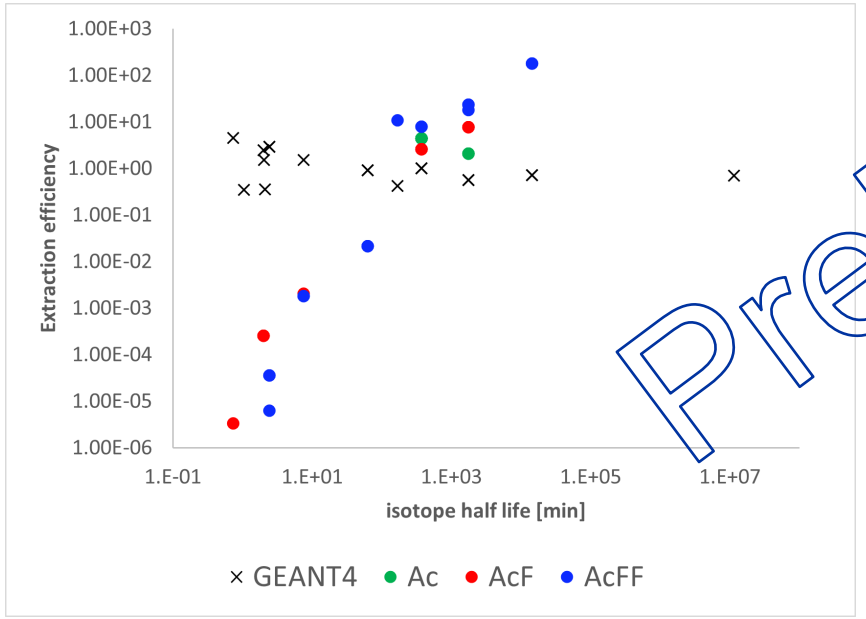
M. Athanasakis-Kaklamanakis[1,2], S.G. Wilkins[3], M. Au[4,5], R. Berger[6], A. Borschevsky[7], K. Chrysalidis[8], T.E. Cocolios[2], R.P. de Groote[2], Ch.E. Düllmann[5,9,10], K.T. Flanagan[11,12], R.F. Garcia Ruiz[3], S. Geldhof[2], R. Heinke[8], T.A. Isaev[13], J. Johnson[2], A. Kiuberis[7], Á. Koszorús[1], L. Lalanne[2], M. Mougeot[1], G. Neyens[2], L. Nies[1,14], J. Reilly[11], S. Rothe[4], L. Schweikhard[14], A.R. Vernon[3], X.F. Yang[15]

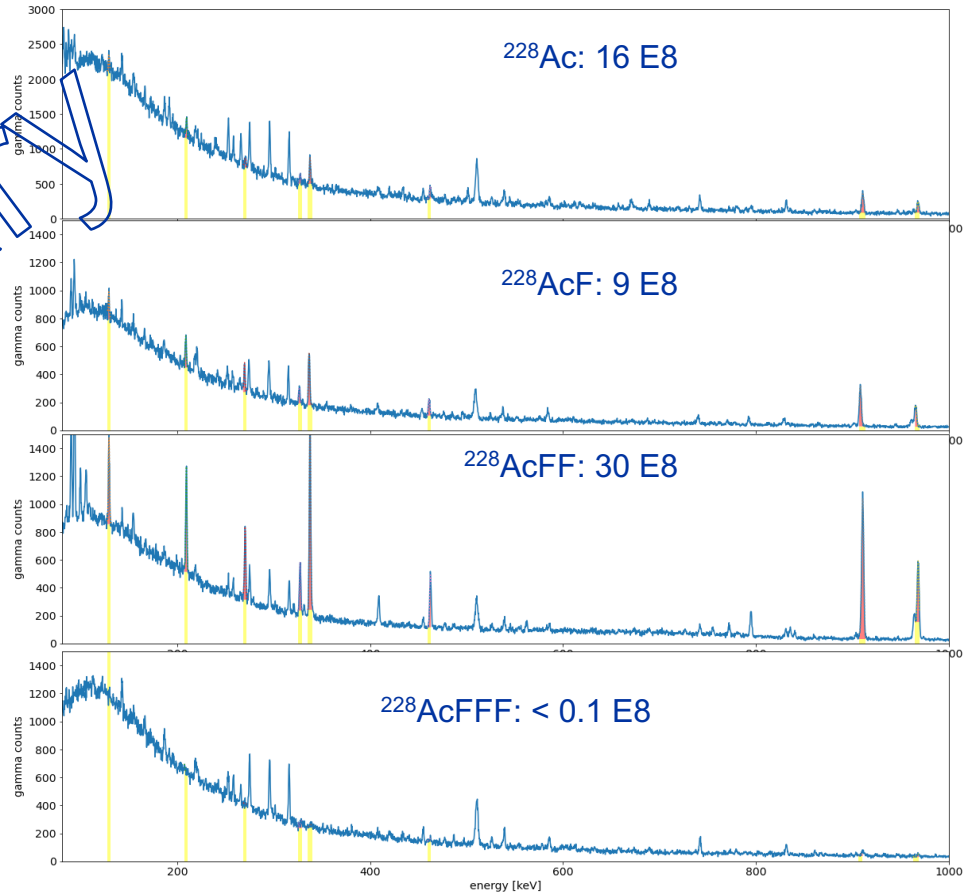


AcF_x

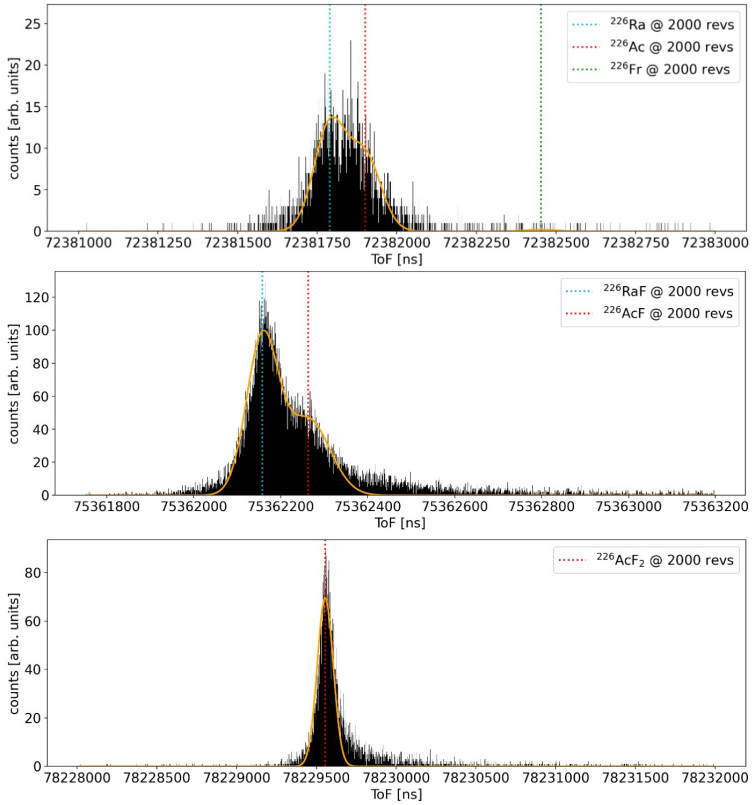




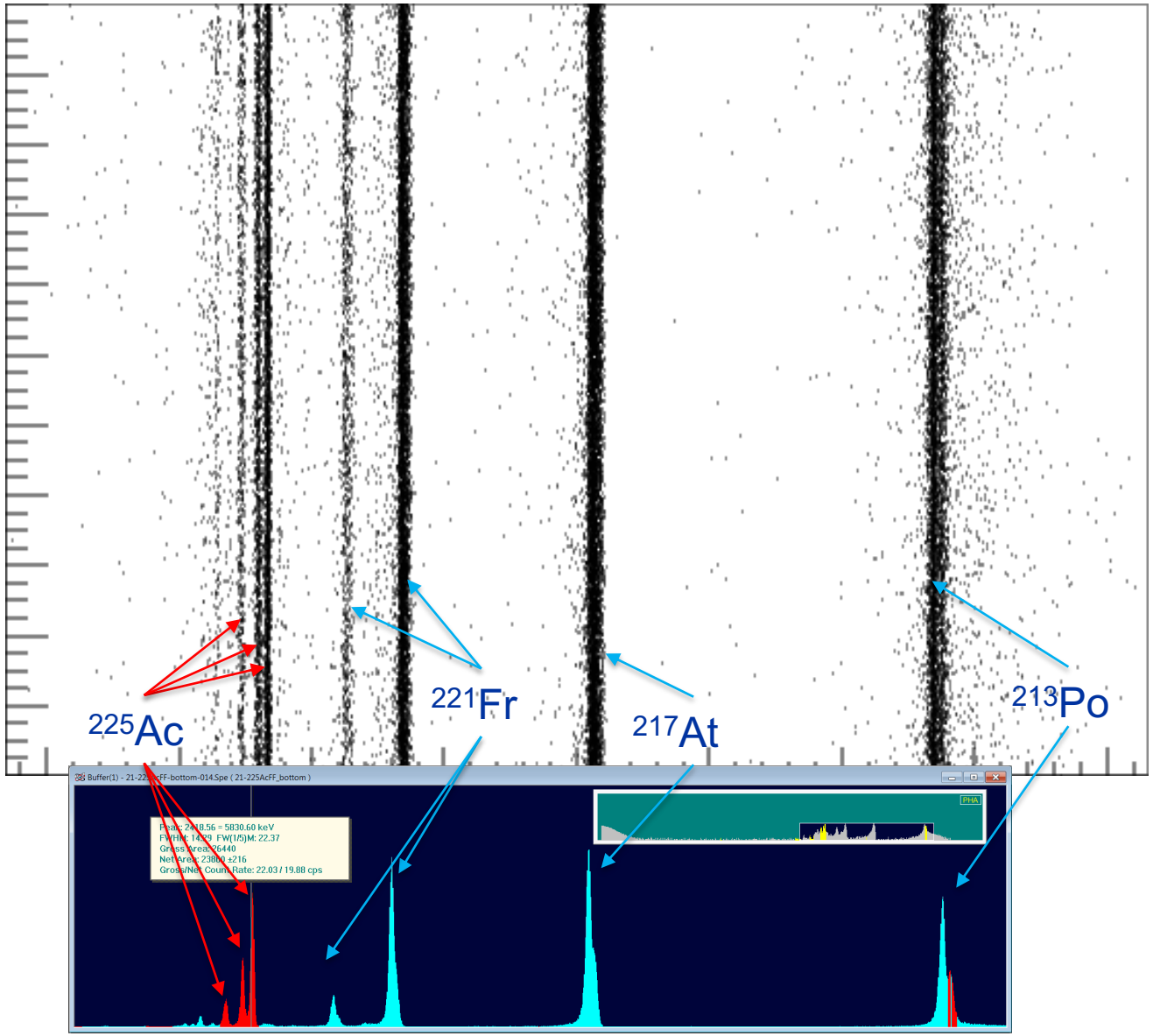




AcF_x



	Yield [ions / uC p^+]	Efficiency [%]
sample: ^{229}AcFF	1.6 (1) E5	0.05 (2)
sample: ^{225}AcFF	1.93 (0.05) E7	2.5 (0.04)



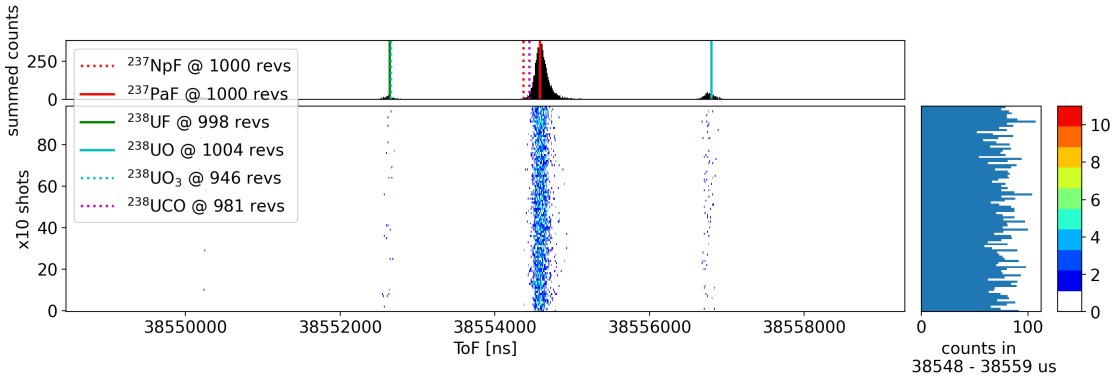
Outlook: Other actinides?

Actinide fluorides

- NpF_x
- PuF_x

Next up

- Improving statistics



	Yield [ions / micro C p^+]	Efficiency [%]
sample 12: ^{238}NpFF	1.6 (0.2) E3	0.039 (5)
sample 13: ^{234}Np	< 3.5	--
sample 24: ^{234}NpF	1.4 E2	0.00013
sample 14: ^{234}NpFF	3.8 (1) E2	0.037 (10)
sample 23: ^{234}NpFFF	< 1.2 E2	< 0.0001

Conclusion

1. Surface, plasma beam compositions for actinide mass region
2. In-trap formation (UO_x , TaO_x)
3. In-target formation : AcF_x production, ID and measurement
4. Molecular spectroscopy of AcF: ongoing!
5. Outlook: AnF_x

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IS706 experimental team

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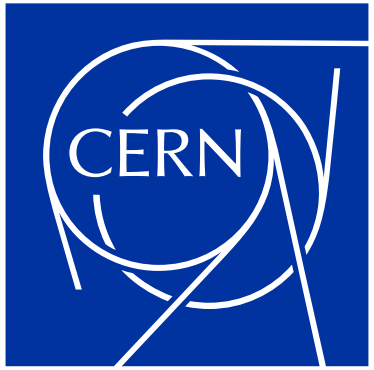

Thank you!

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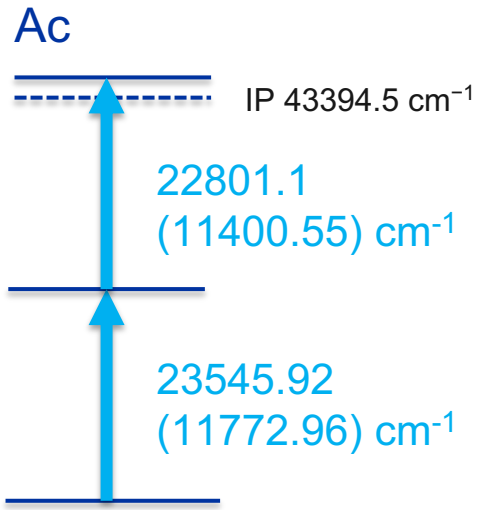
Laser ionization schemes used



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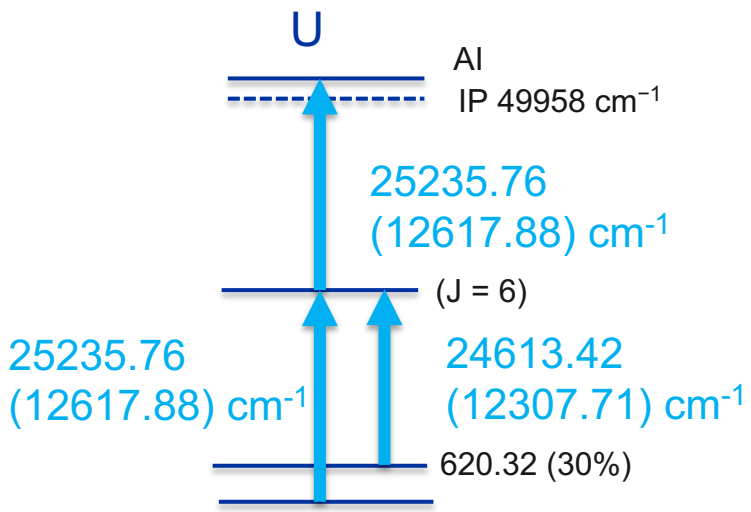

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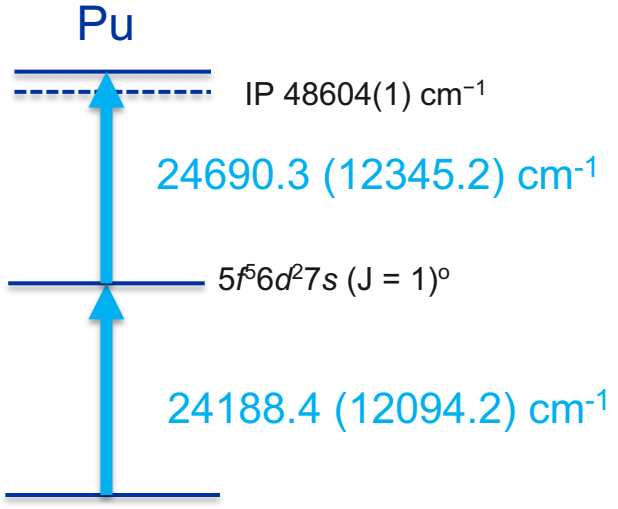

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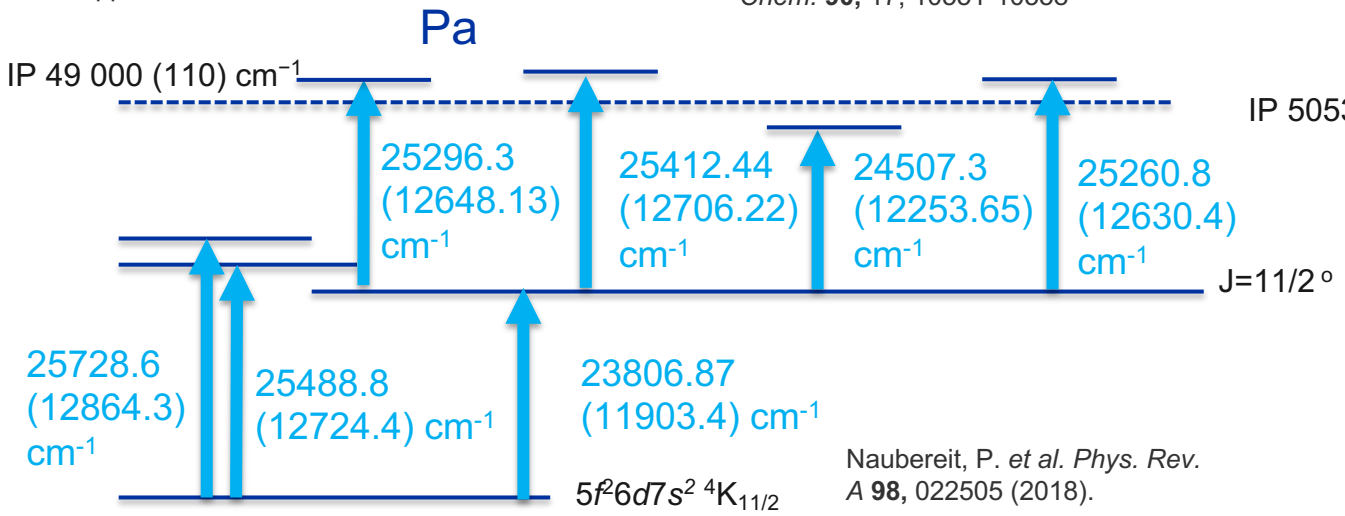

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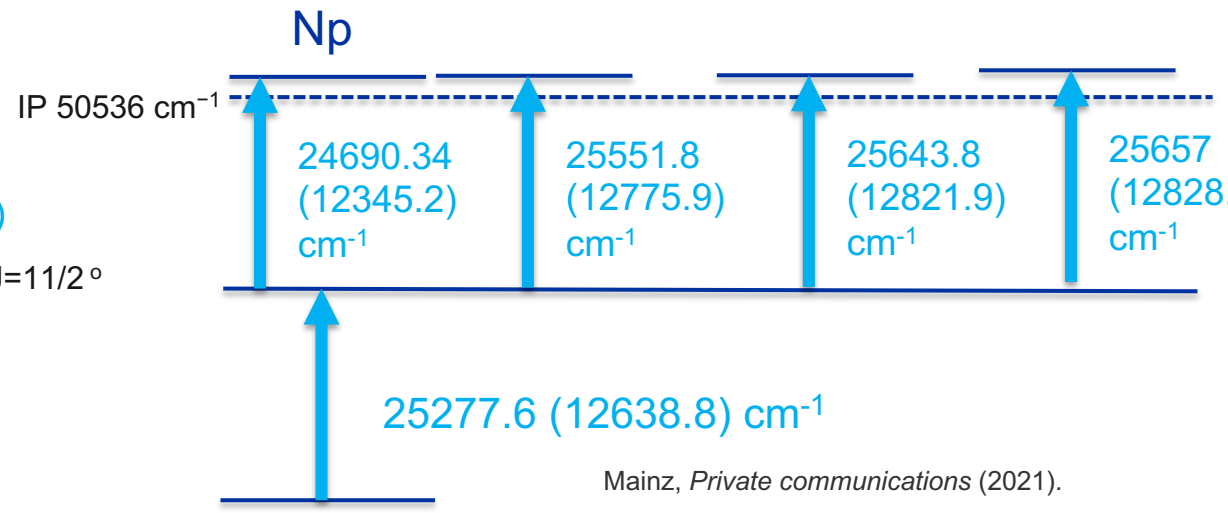

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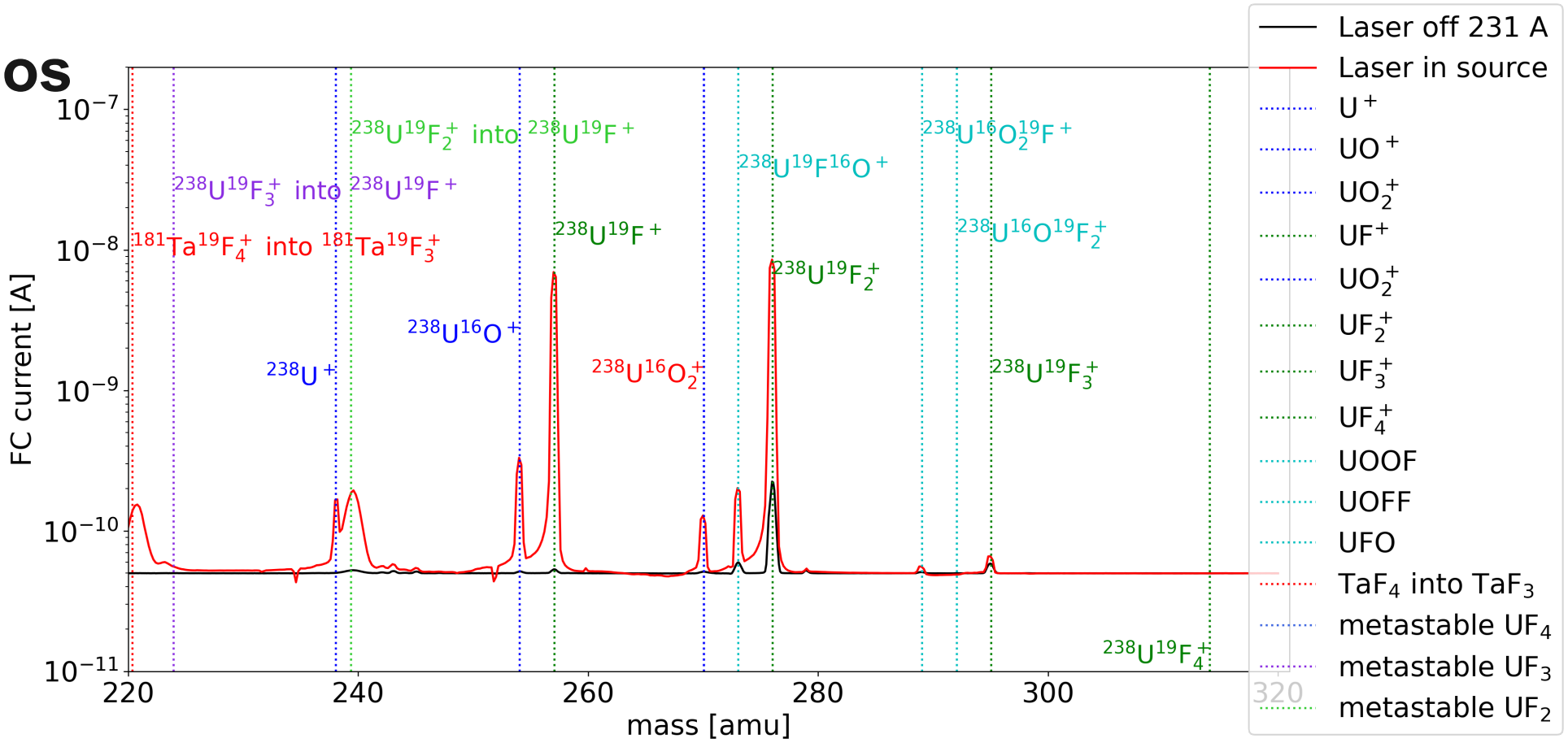
Surface ionization vs laser enhancement

Outgassing over time

Sideband ratios



AcF_x

Ac^+, AcF^+, $AcFF^+$, $AcFO^+$