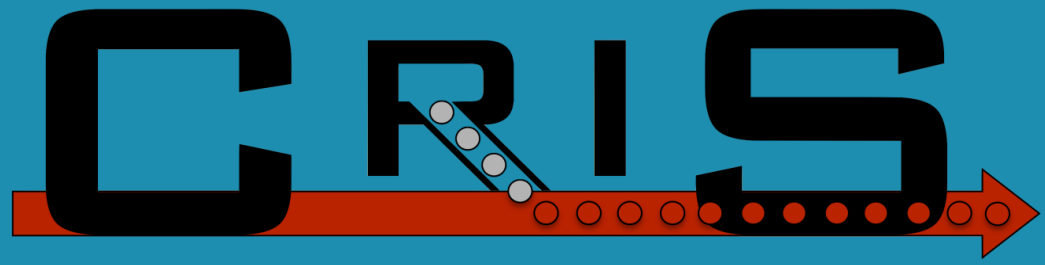
KU LEUVEN

Laser ionization spectroscopy of AcF

M. Athanasakis-Kaklamanakis, S.G. Wilkins, M. Au, R. Berger, A. Borschevsky, K. Chrysalidis, T.E. Cocolios, R.P. de Groote, Ch.E. Düllmann, K.T. Flanagan, R.F. Garcia Ruiz, S. Geldhof, R. Heinke, T.A. Isaev, J. Johnson, A. Kiuberis, Á. Koszorús, L. Lalanne, M. Mougeot, G. Neyens, L. Nies, J. Reilly, S. Rothe, L. Schweikhard, A.R. Vernon, X.F. Yang

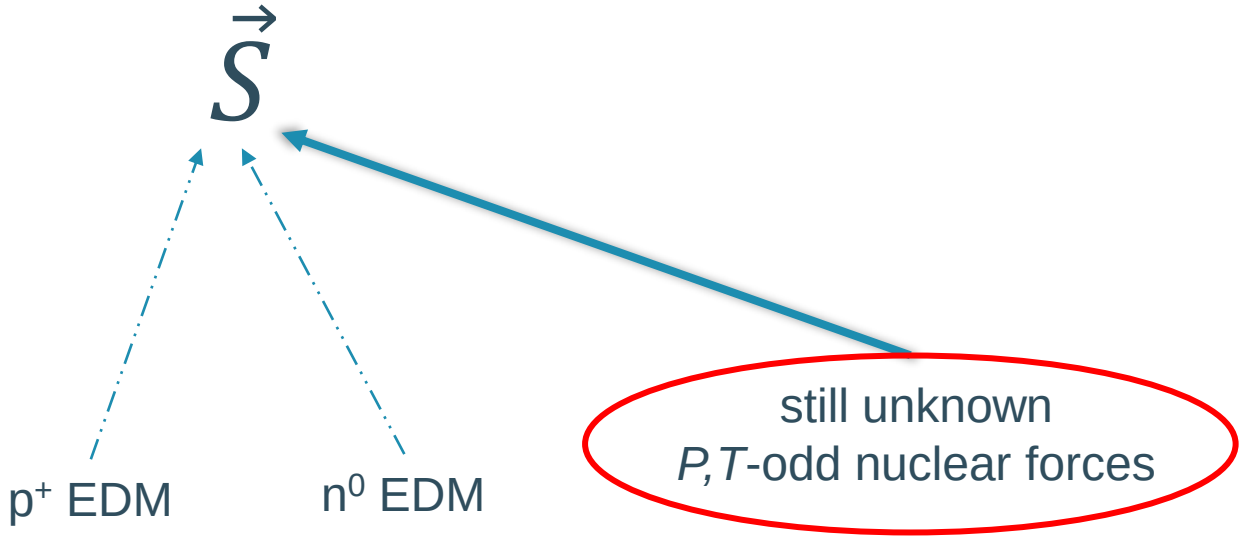


INTC-P-615

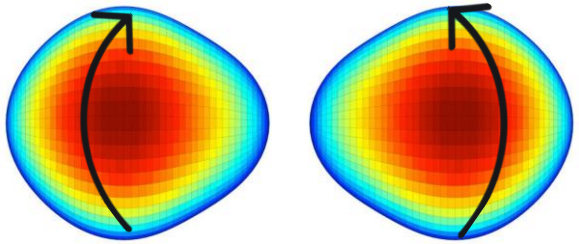
Request: 15 shifts w/o protons, 14 shifts w/ protons, scheduled across 2 runs

November 9, 2021 – **INTC 68, Open session**

New physics is hidden in the nuclear Schiff moment



Octupole deformation



Gaffney et al., Nature **497** (2013)

close-lying opposite-parity rotational doublet

$$|J^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(\,|\Omega\rangle \pm |-\Omega\rangle\,\right)$$

enhanced P,T-odd interaction mixing

$$\alpha = \frac{\langle J^{+}|\hat{W}|J^{-}\rangle}{E^{+}-E^{-}}$$

~keV

strongly enhanced $\vec{S}$

Flambaum & Dzuba, Phys. Rev. A **101** (2020)

$$\vec{S} \approx 1\times 10^{-4}\,\frac{J}{J+1}\,\beta_2\beta_3^2 Z A^{\frac{2}{3}}\,\frac{[keV]}{E^{+}-E^{-}}\;[e\eta fm^3]$$

b

^{225,227}Ac might have exceptionally large Schiff moments*

- Existing searches: ^{199}Hg, ^{129}Xe, ^{205}TlF, ^{225}Ra (deformed!)
- Large Z & A, and $\beta_3 \neq 0 \rightarrow$ strongly enhanced $\vec{S}$
- ^{227}Ac: largest S across nuclear chart (predicted!*)

$$S(^{227}Ac) = \mathbf{6}\, S(^{225}Ra) \quad *$$
$$S(^{225}Ac) = \mathbf{3}\, S(^{225}Ra)$$
$$S(^{237}Np) = \mathbf{4}\, S(^{225}Ra)$$
$$S(^{235}U) \leq \mathbf{3}\, S(^{225}Ra)$$
$$S(^{229}Pa) = \mathbf{40}\, S(^{225}Ra)$$
$$\vdots$$

opposite-parity doublet spacing not yet confirmed!

^{225,227}Ac are promising candidates for the 1st successful measurement of a Schiff moment

* Flambaum & Dzuba, Phys. Rev. A **101** (2020)

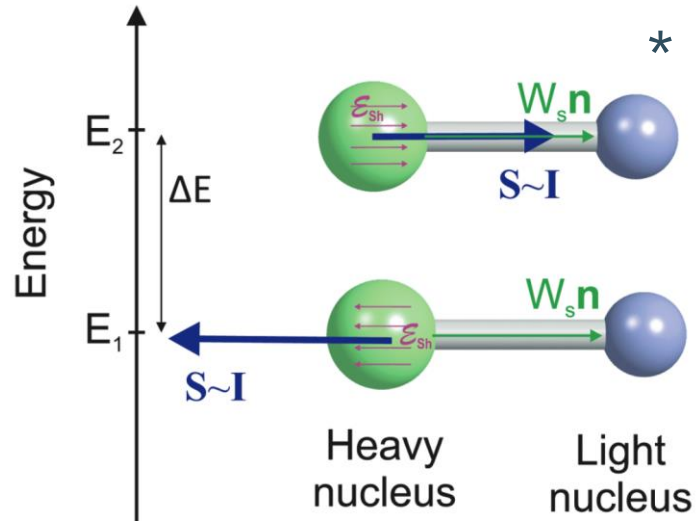
AcF is predicted to be highly sensitive to $S(^{227}Ac)$*

predicted!*

- AcF is exceptionally sensitive to $S(Ac)$

  → measurable with precision achieved in the 1990s!

- Quantum chemistry benchmark



CRIS can contribute to future Schiff moment searches by measuring the low-lying electronic and vibrational structure of AcF for the first time!

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

Fluoride extraction could expand availability of Ac at ISOLDE

- The range of accessible Ac isotopes is limited by the atomic release

Results from IS637
(K. Dockx, Private communication)

- Release rate @ ISOLDE: ~5 days

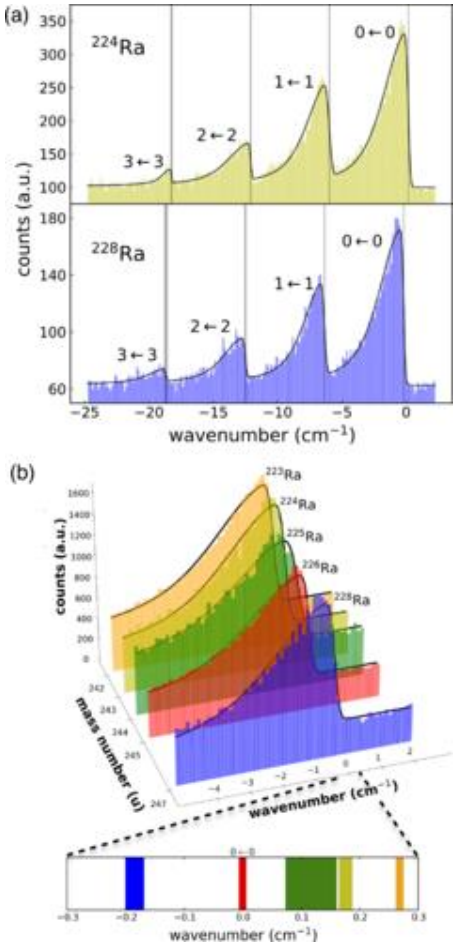
- Fluoride sideband extraction often enhances release of reactive/refractory species[a,b]

Studies on the release of AcF may reveal pathways for access to more Ac isotopes!

[a] Köster et al., EPJ Spec. Top. **150** (2007)
[b] Ballof et al., EPJ A **55** (2019)

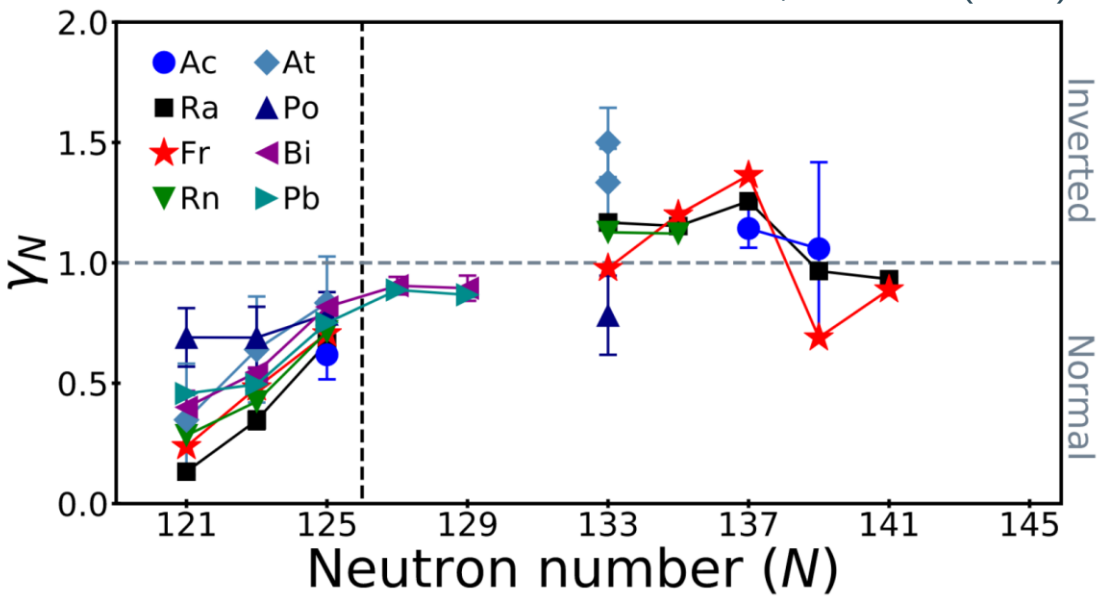
$\delta\langle r^2\rangle^{A',A}$ can be extracted accurately with molecular spectroscopy!

Udrescu et al., PRL **127** (2021)



- Isotope shifts in $A^2\Pi_{1/2} \leftarrow X^2\Sigma^+$ in RaF
  $\rightarrow$ $\boldsymbol{\delta\langle r^2\rangle^{A',A}}$ **with 5-10% error!**
- Accurate $\delta\langle r^2\rangle^{A',A}$ from other molecules?
- AcF
  field shift more complex than in RaF
  mass shift still ignored

Verstraelen et al., PRC **100** (2019)



Ultimately: $\delta\langle r^2\rangle^{A',A}$ in reactive and refractory species!

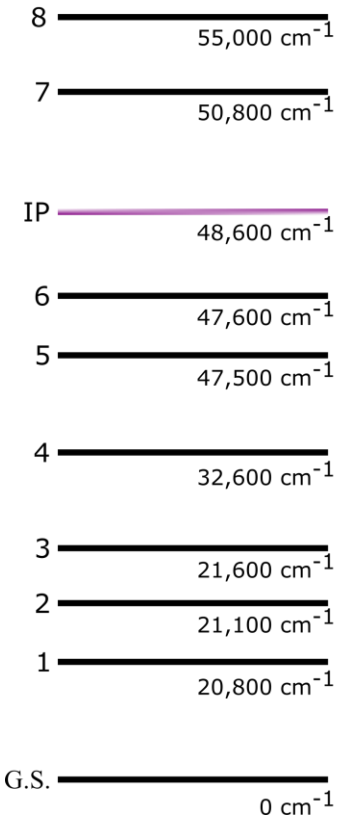
Dissociation energy of ^{225}AcF

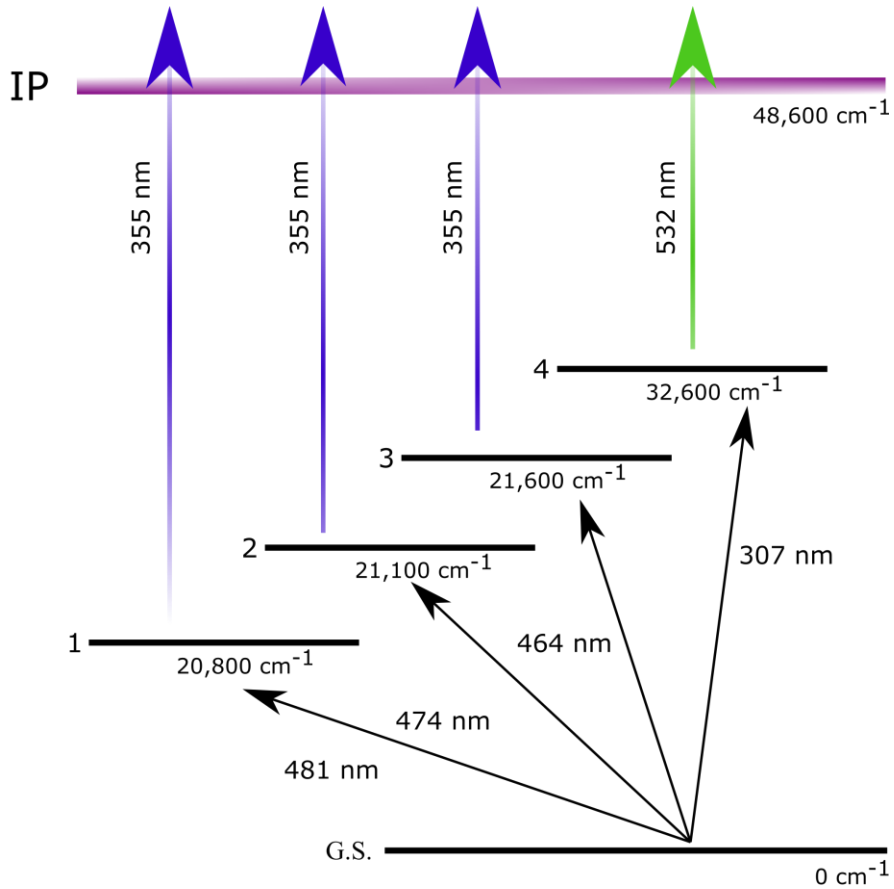
- ^{225}Ac for nuclear medicine
- Production at ISOL promising
- Release-limited
- Precise measurement of dissociation energy with laser spectroscopy

- AcF extraction + in-flight break-up →

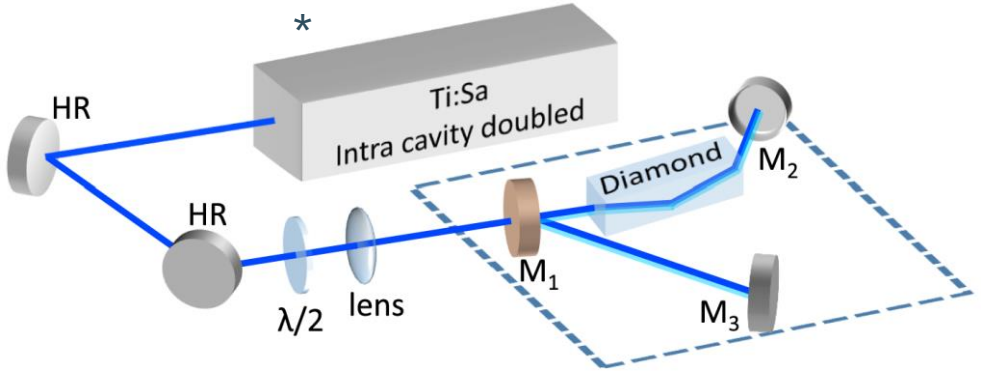
possible pathway for enhanced collection of ^{225}Ac?

The electronic levels of AcF have already been calculated

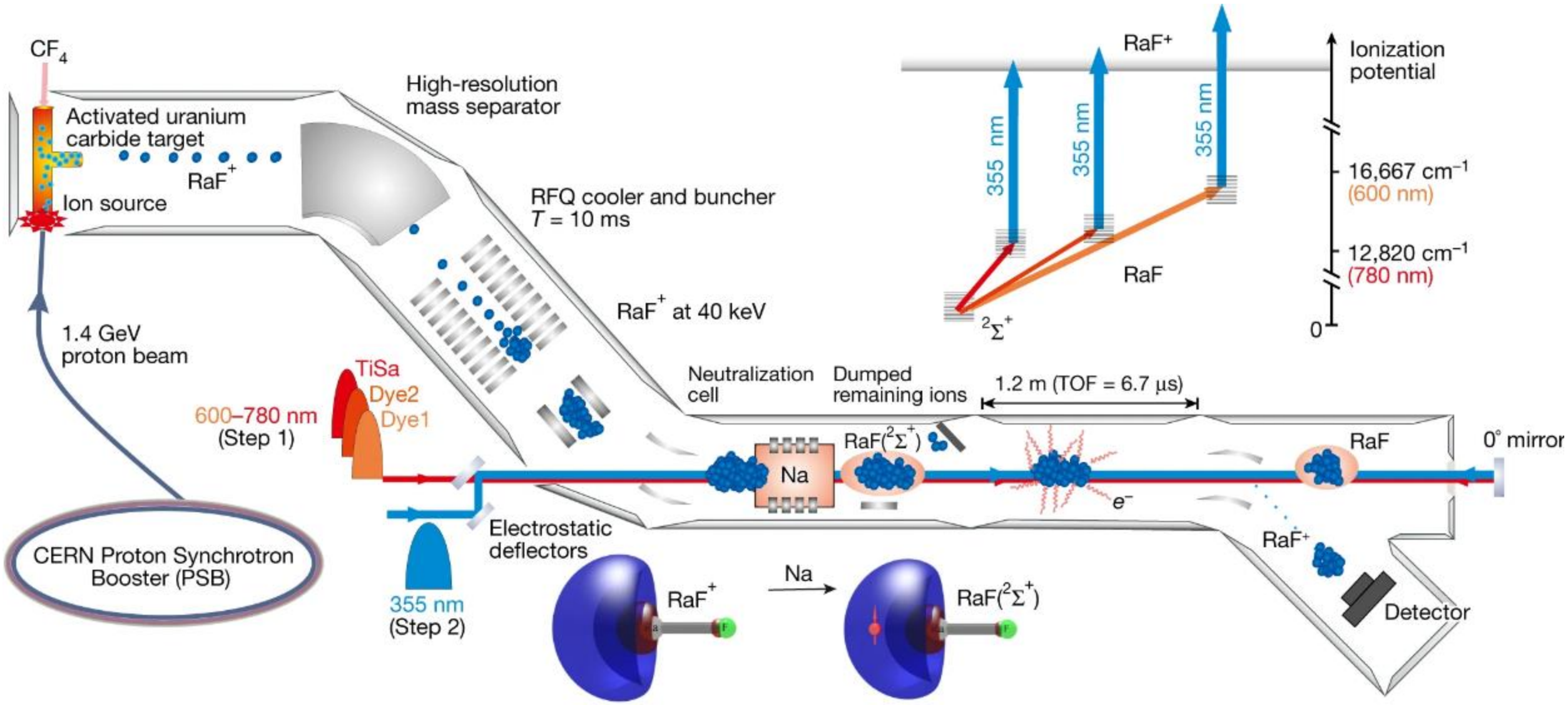




- Relativistic coupled cluster
- All electron correlations
- dyall.cv4z basis set
- **IP: 6.02(3) eV / 48,600 ± 250 cm^{-1}**



Chrysalidis et al., Opt. Lett. **44**(16) (2019)



Garcia Ruiz et al., Nature **581** (2020)

Beam time request

15 shifts without protons, 14 shifts with protons, in 2 runs

Motivation overview

- Enable future Schiff moment search in ^{227}AcF
- Benchmark quantum chemistry
- Explore fluoride sideband extraction of Ac
- Measure isotope shifts with molecular spectroscopy

What we want to measure

- Low-lying vibronic structure
- Isotope shifts in $^{225\text{-}230}$AcF
- Ionization potential
- Dissociation energy

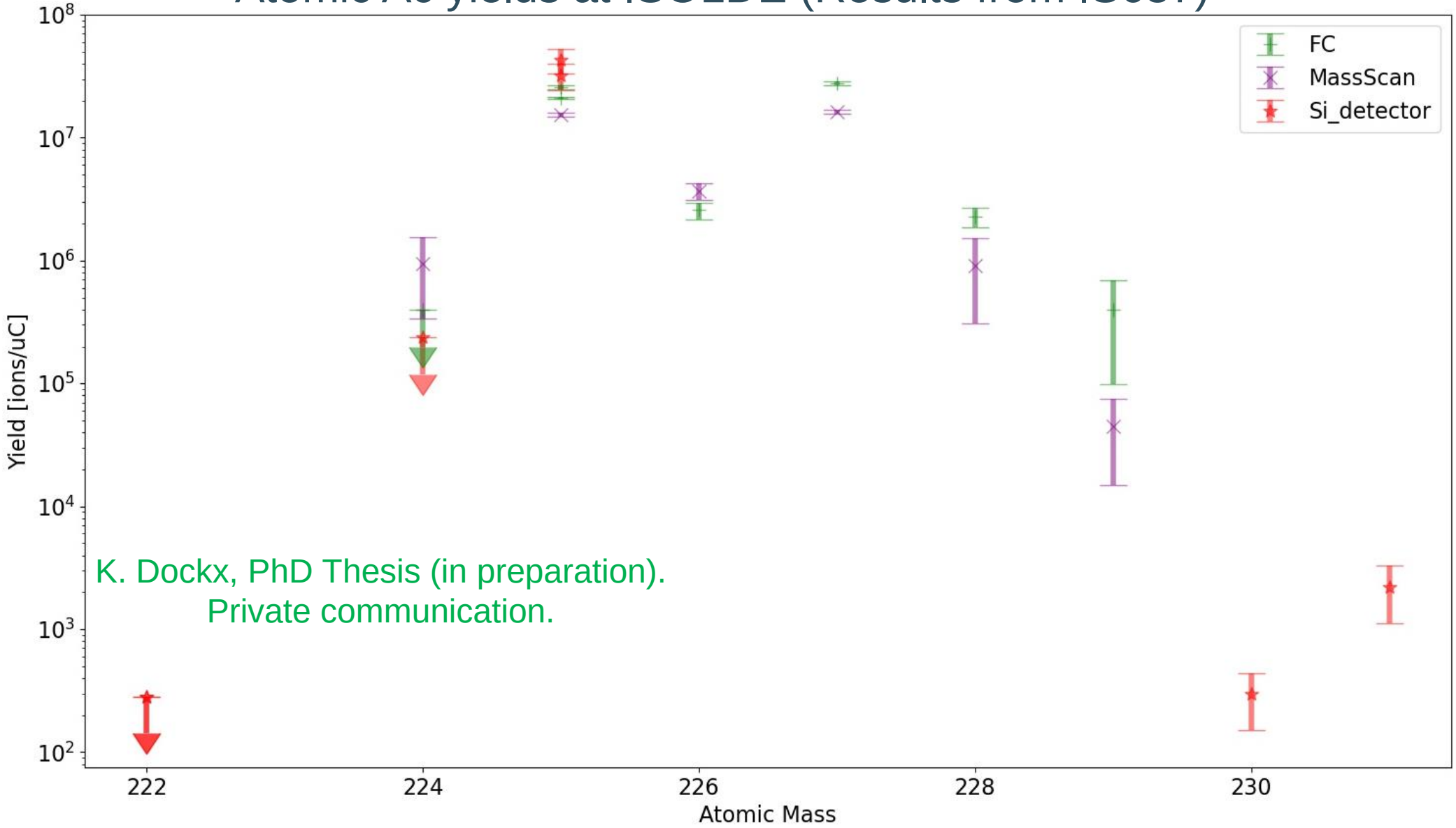
consistent with a scan rate of 1 cm^{-1}/minute

	Decay mode	$T_{1/2}$	Ac yield ions/μC	Shifts no protons	Shifts with protons
^{225}AcF	α	9.92 d	3×10^{7}	3	2
^{226}AcF	β^-	29.37 h	3×10^{6}		2
^{227}AcF	β^-	21.77 y	3×10^{7}	11	
^{228}AcF	β^-	6.15 h	2×10^{6}		2
^{229}AcF	β^-	62.7 min	3×10^{5}		2
^{230}AcF	β^-	122 s	3×10^{2}		4
MR-ToF MS				1	2
Total				15	14

Thank you!

Massachusetts Institute of Technology

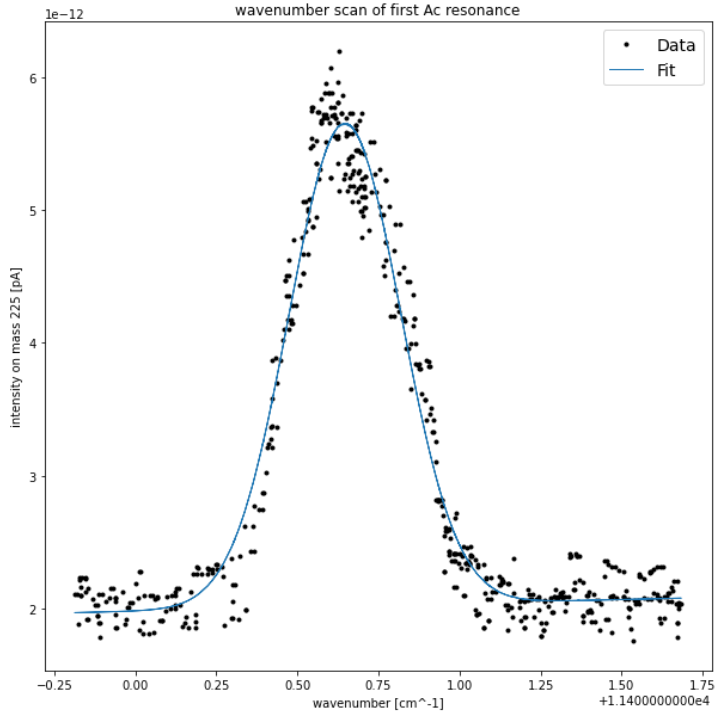
Atomic Ac yields at ISOLDE (Results from IS637)

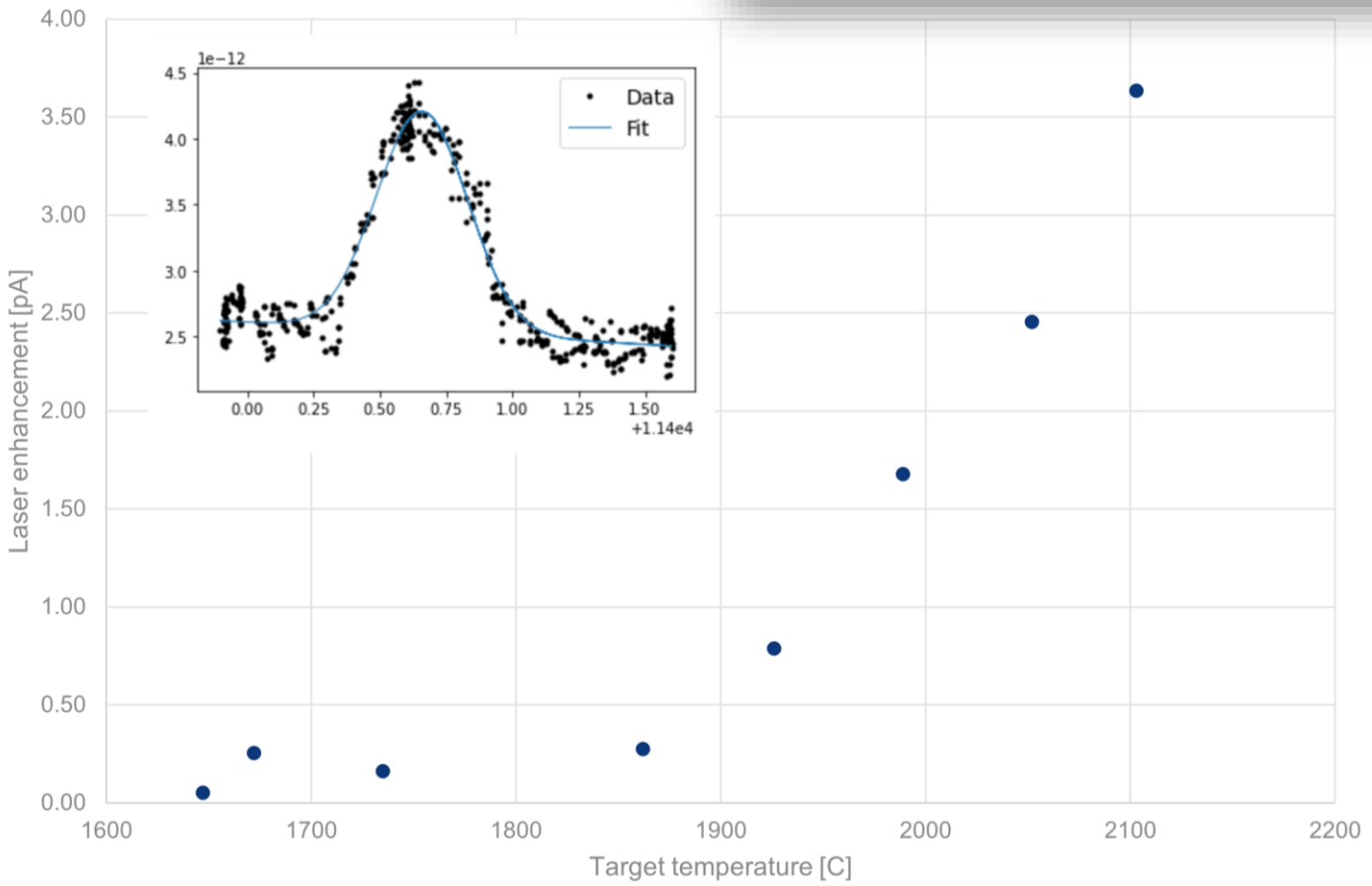


K. Dockx, PhD Thesis (in preparation).
Private communication.

TISD for LISA (June 2021)

- Target #638: UC_x Re surface source with RILIS
- @ 2100°C
- ^{225}Ac: laser enhancement on FC490
- **$2.2 \cdot 10^7$ ions / *μC***
- Close agreement with K. Dockx





EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Beam time request

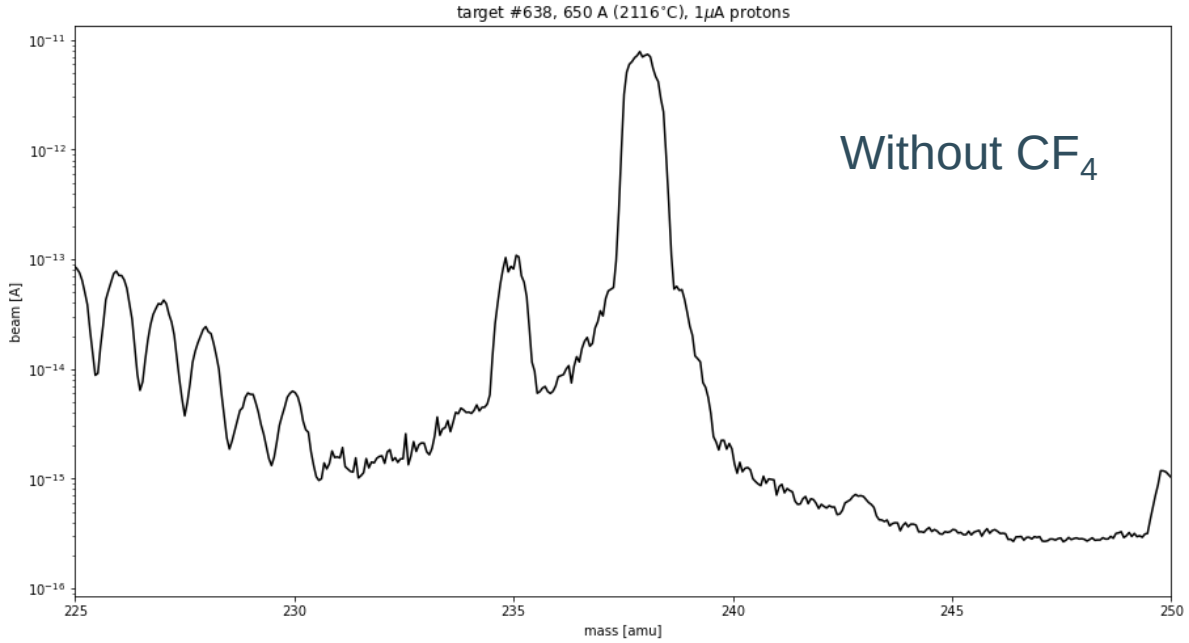
Pre-irradiated targets for LISA

November 8, 2021

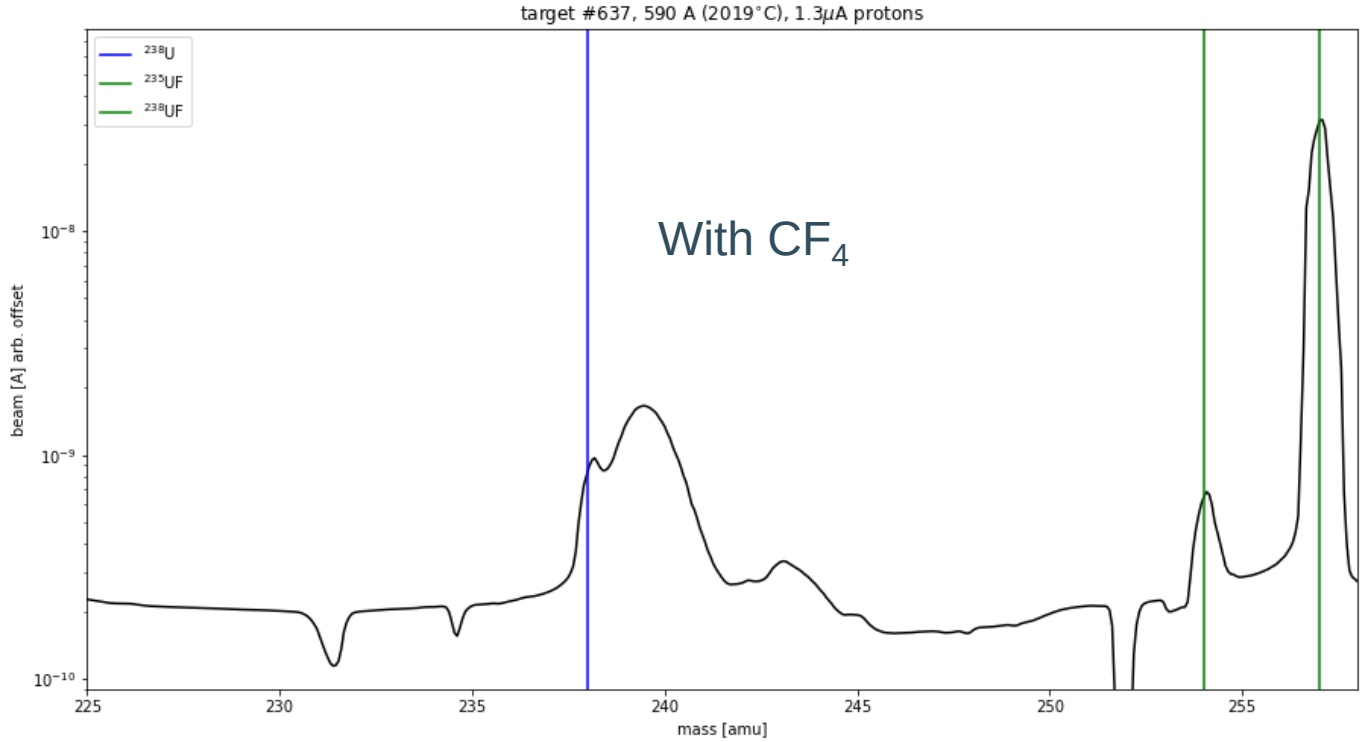
Mia Au[12], Bianca Reich[12], Sebastian Rothe[1], Valentine Fedosseev[1]

[1] *ISOLDE, CERN, Switzerland*
[2] *Johannes Gutenberg Universität Mainz, Germany*

Surface ionized background

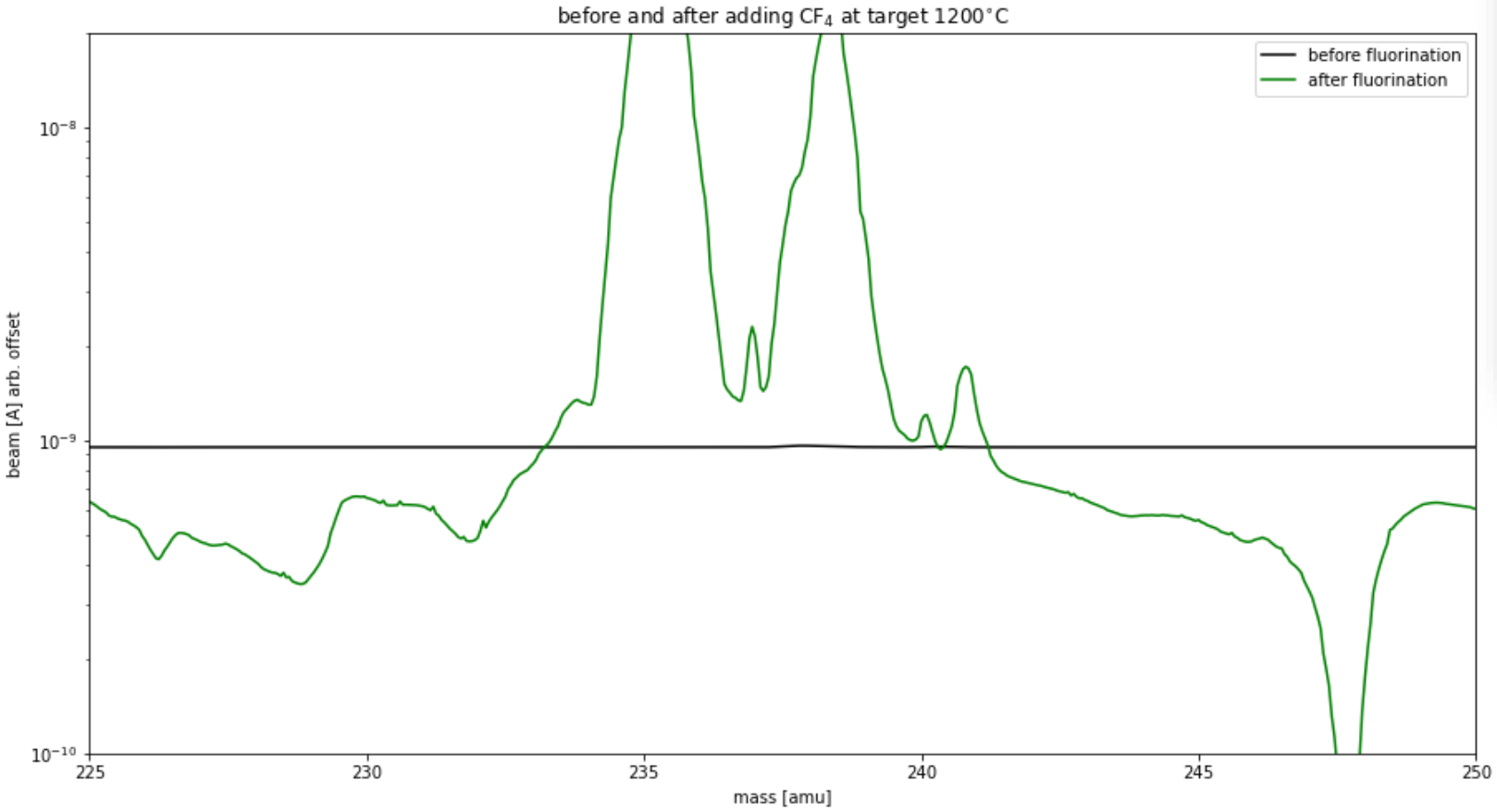


In-source dissociation of larger molecules



VD5 beam composition

- Background with VD5 w/ and w/o CF_4
- VD5 failure prevented further investigation
- TISD beam request for I-216, I-224, I-227



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Beam time request

TISD for LISA

November 8, 2021

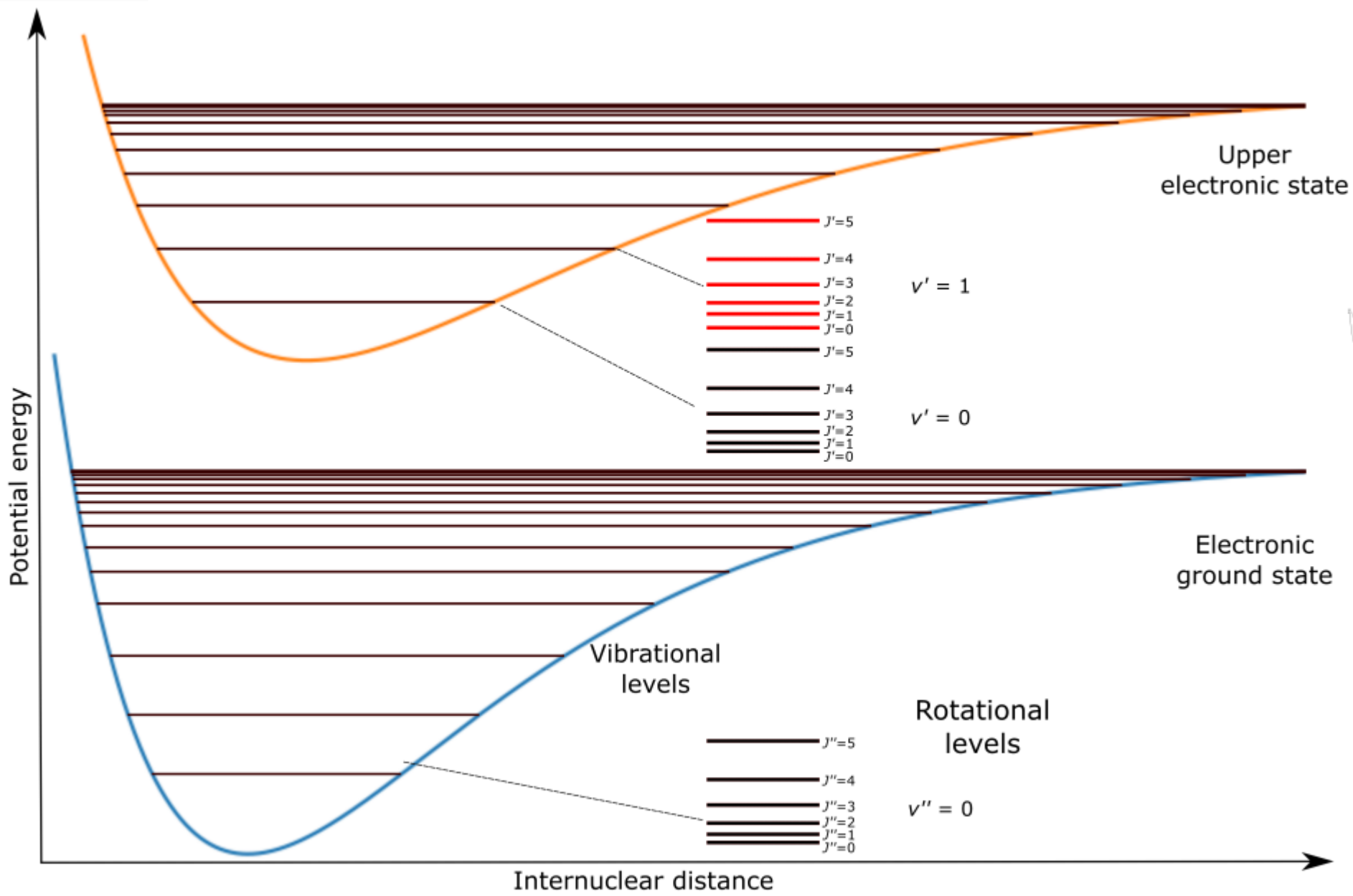
Mia Au[1,2], Michail Athanasakis-Kaklamanakis[3,4], Jochen Ballof[1,2], Reinhard Heinke[1], Bruce Marsh[1], Maxime Mougeot[3], Lukas Nies[3,5], Bianca Reich[1,2], Sebastian Rothe[1], Simon Stegemann[1]

[1] *SY-STI, CERN, Switzerland*
[2] *Johannes Gutenberg-Universität Mainz, Germany*
[3] *EP-SME, CERN, Switzerland*
[4] *KU Leuven, Belgium*
[5] *Universität Greifswald, Germany*
[6] *MIT, USA*

Spokesperson: Mia Au mia.au@cern.ch
Contact person: Lukas Nies lukas.nies@cern.ch
Maxime Mougeot maxime.mougeot@cern.ch

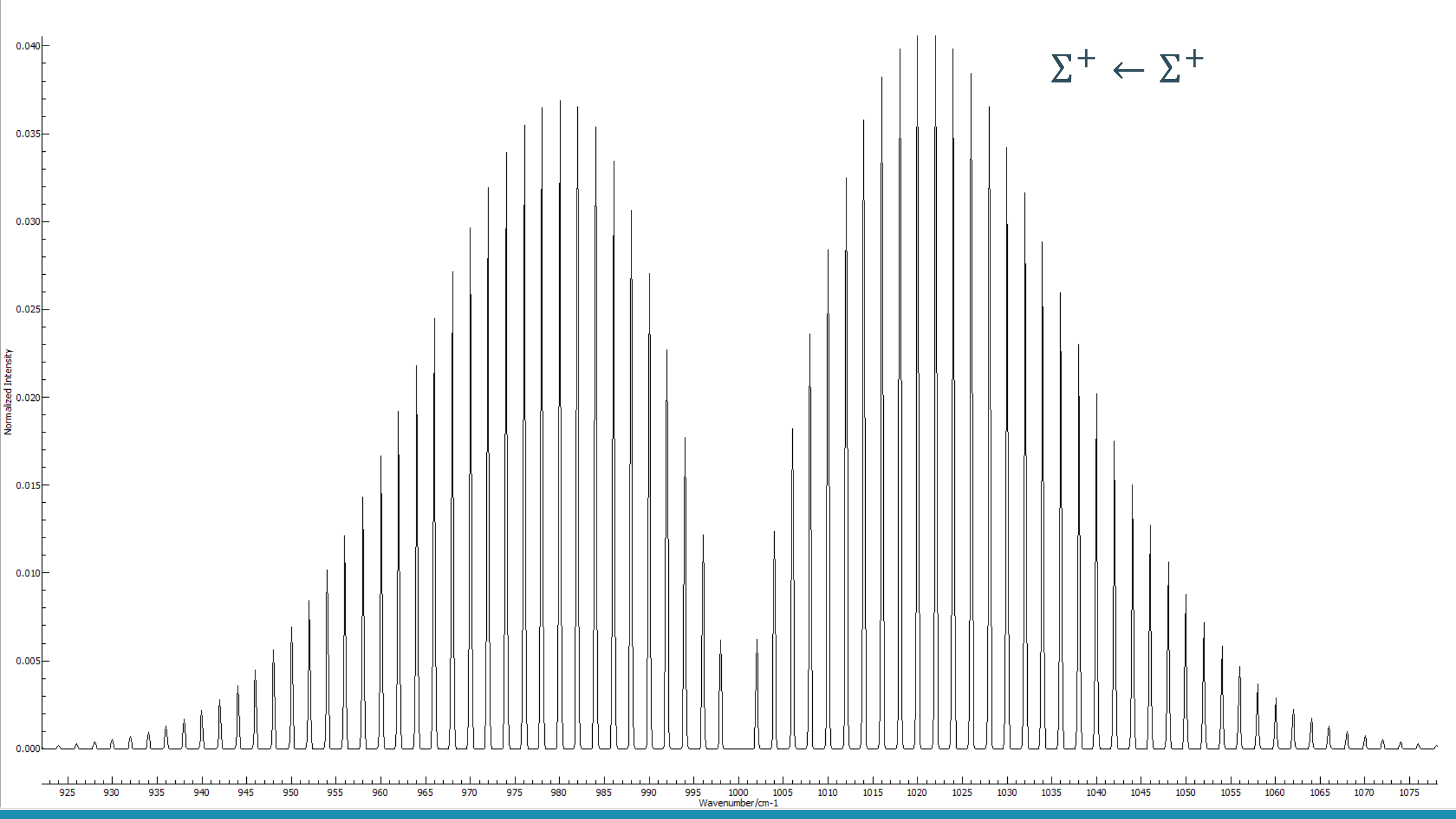
Abstract: This target and ion source development proposes to use a UC_x target and the ISOLTRAP high-precision online mass spectrometer to check yields and optimize release conditions for actinide beams and molecules.

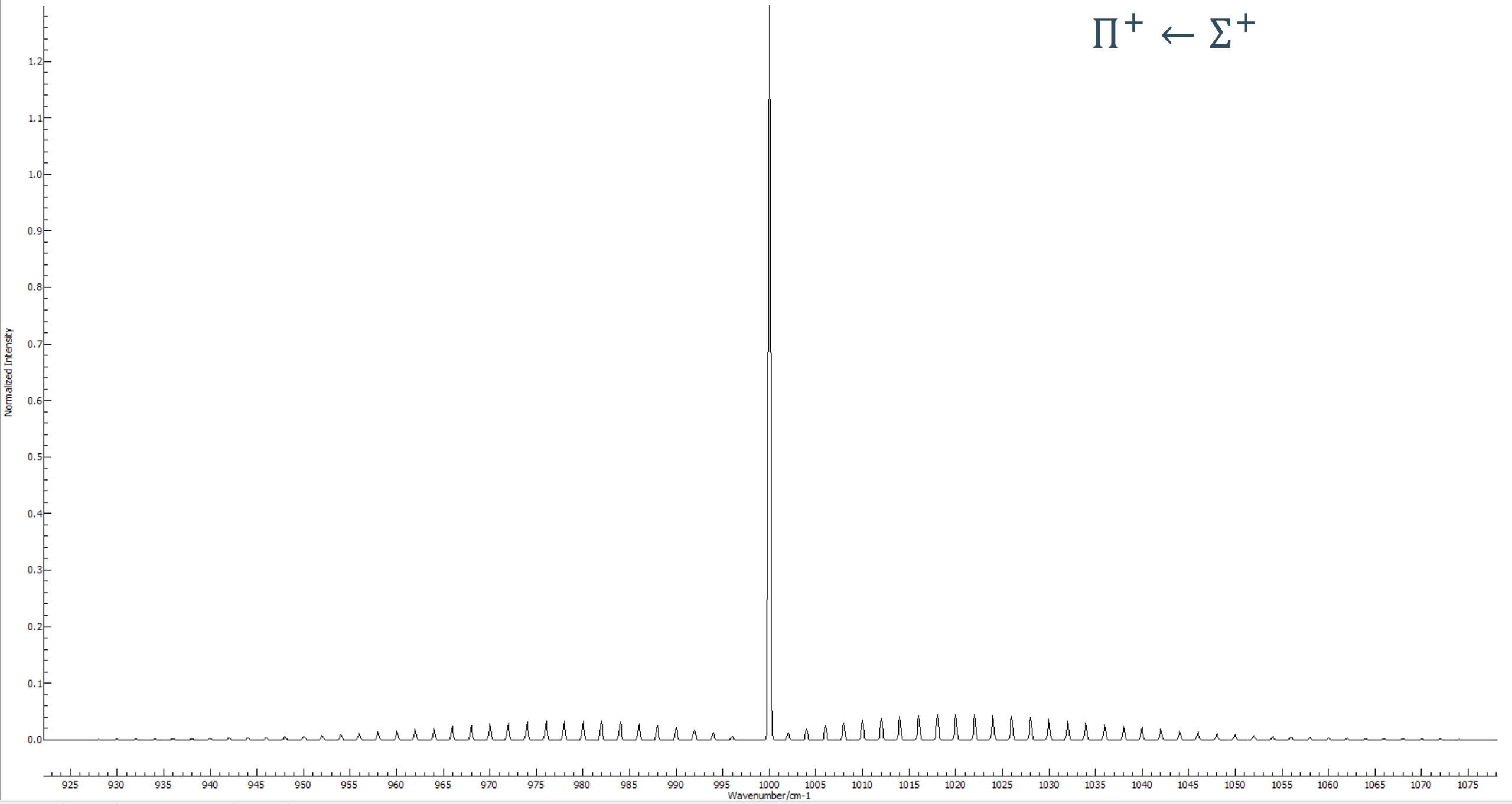
This project has received funding from the European's Union Horizon 2020 Research and Innovation Programme under grant agreement number 861198 project 'LISA' (Laser Ionization and Spectroscopy of Actinides) Marie Sklodowska-Curie Innovative Training Network (ITN).



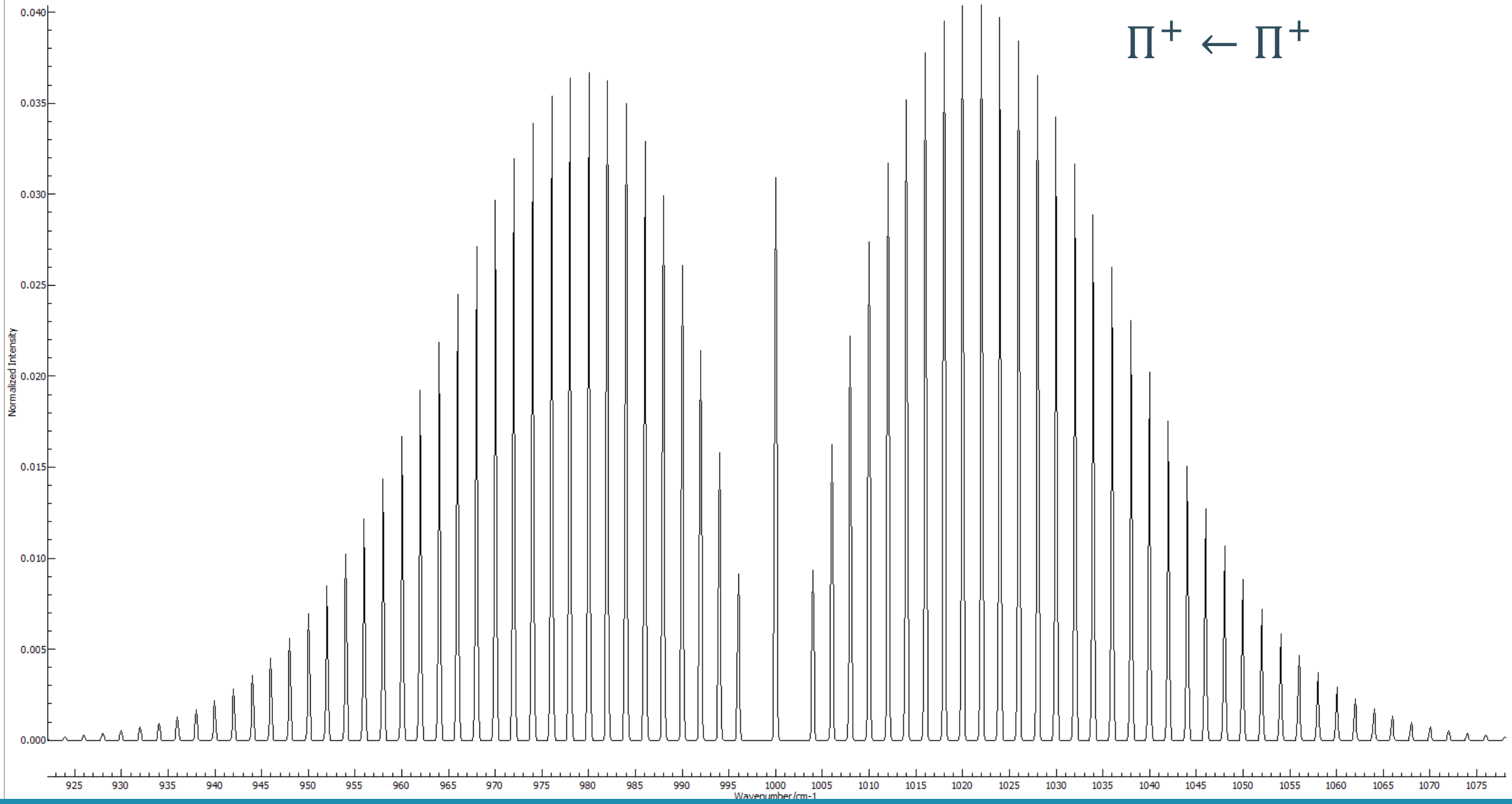
In rovibronic transitions (high-resolution):

- *P*-branch: $J' = J'' - 1$
- *Q*-branch: $J' = J''$
- *R*-branch: $J' = J'' + 1$

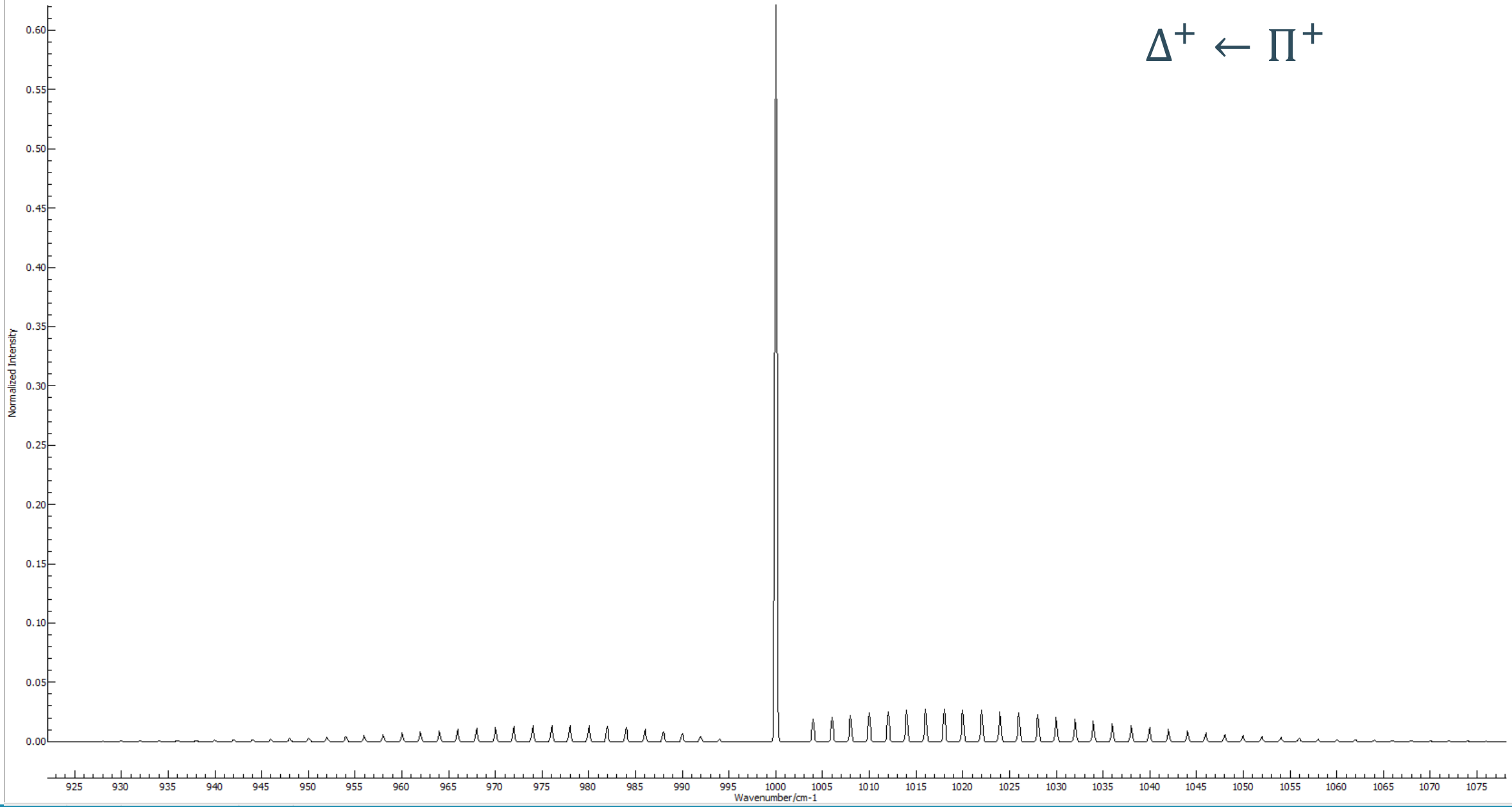

$\Sigma^+ \leftarrow \Sigma^+$
Normalized Intensity
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
925 930 935 940 945 950 955 960 965 970 975 980 985 990 995 1000 1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055 1060 1065 1070 1075
Wavenumber/cm-1


$\Pi^+ \leftarrow \Sigma^+$
Normalized Intensity
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
925
930
935
940
945
950
955
960
965
970
975
980
985
990
995
1000
1005
1010
1015
1020
1025
1030
1035
1040
1045
1050
1055
1060
1065
1070
1075
Wavenumber/cm-1

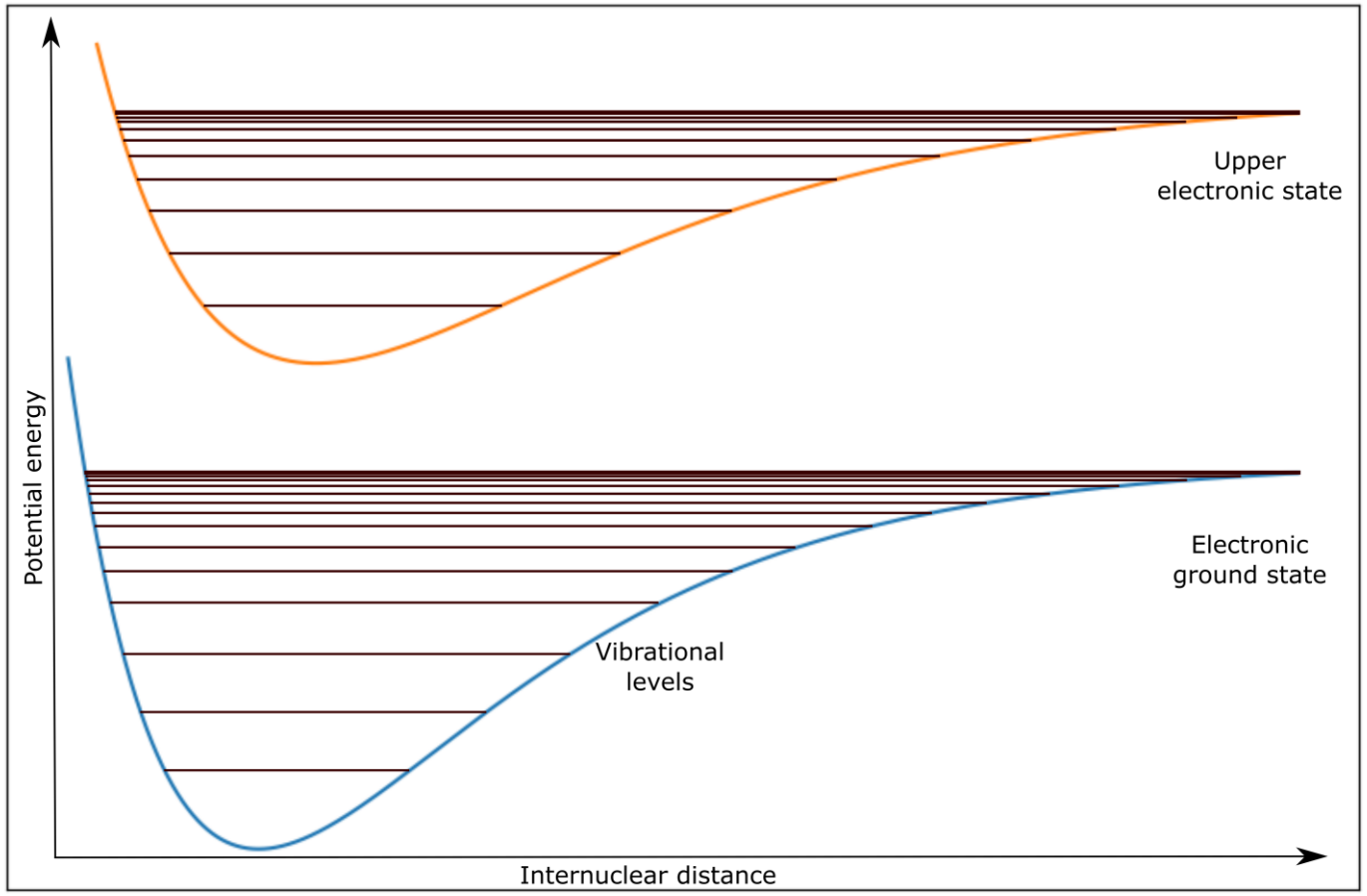
$\Pi^+ \leftarrow \Pi^+$



$\Delta^+ \leftarrow \Pi^+$

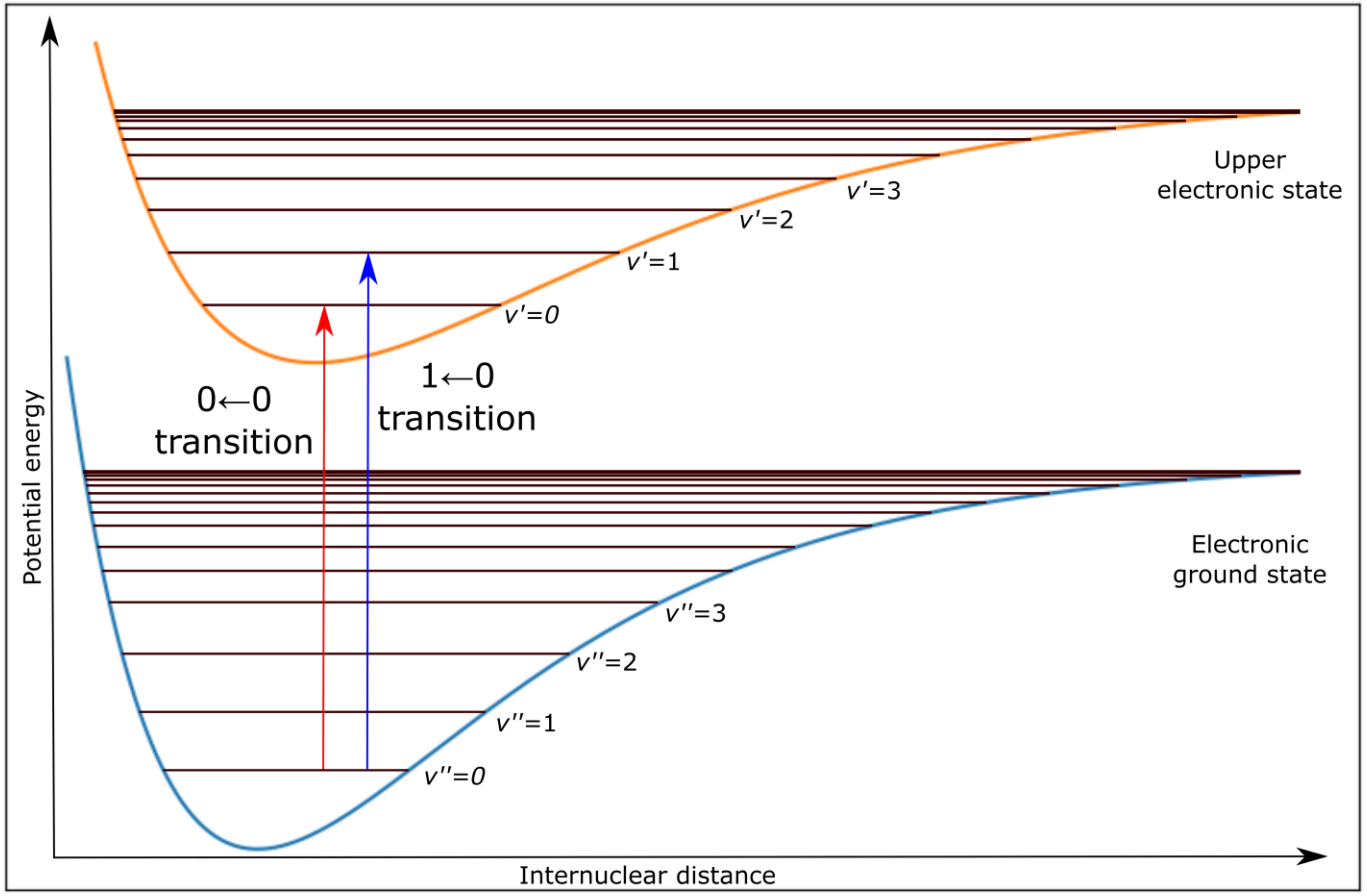


Dissociation energy of ^{225}AcF



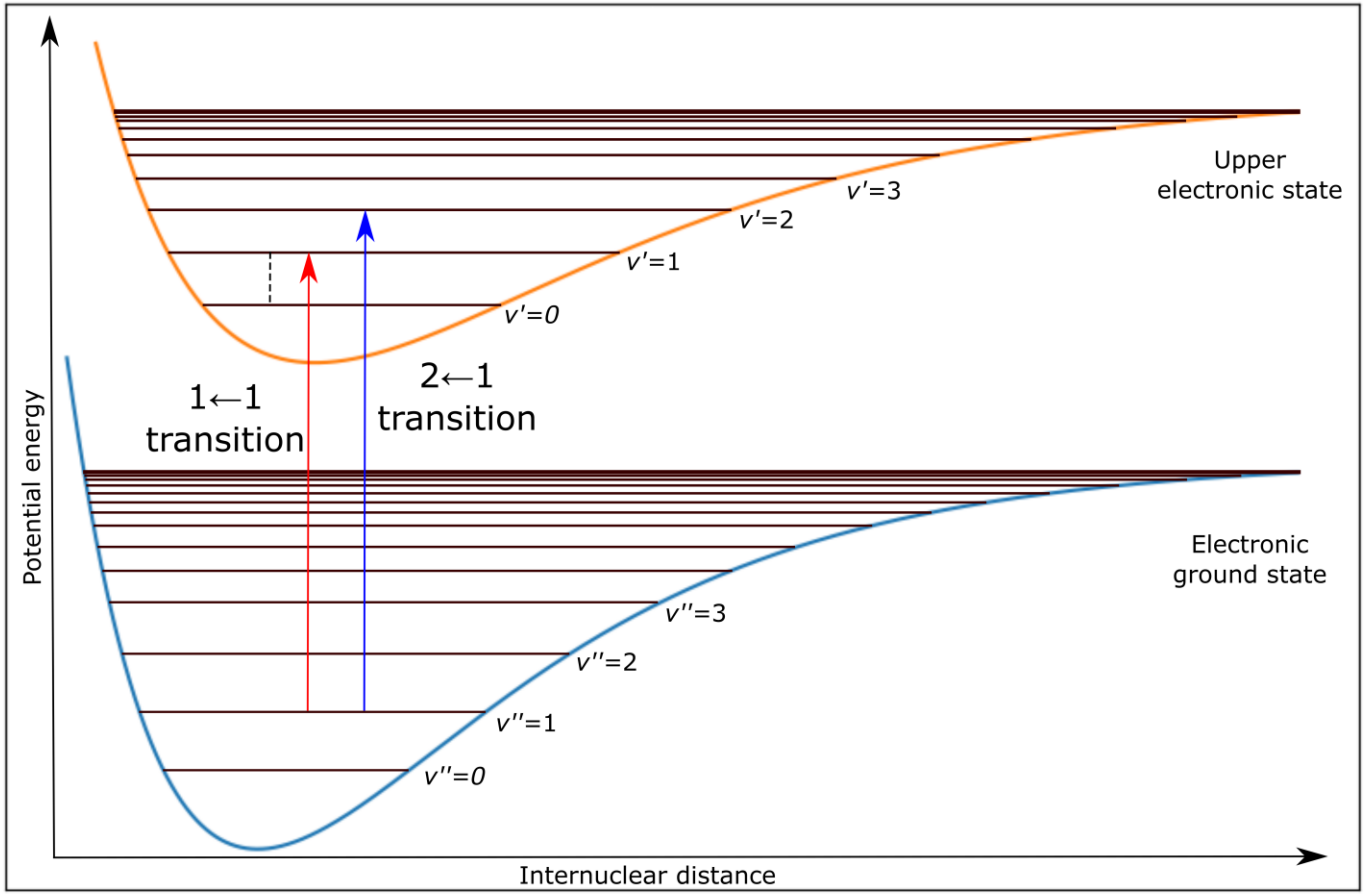
- An accurate measurement of the dissociation energy of ^{225}AcF can be explored towards a pathway for the enhanced extraction and isolation of the medical isotope ^{225}Ac

Dissociation energy of ^{225}AcF



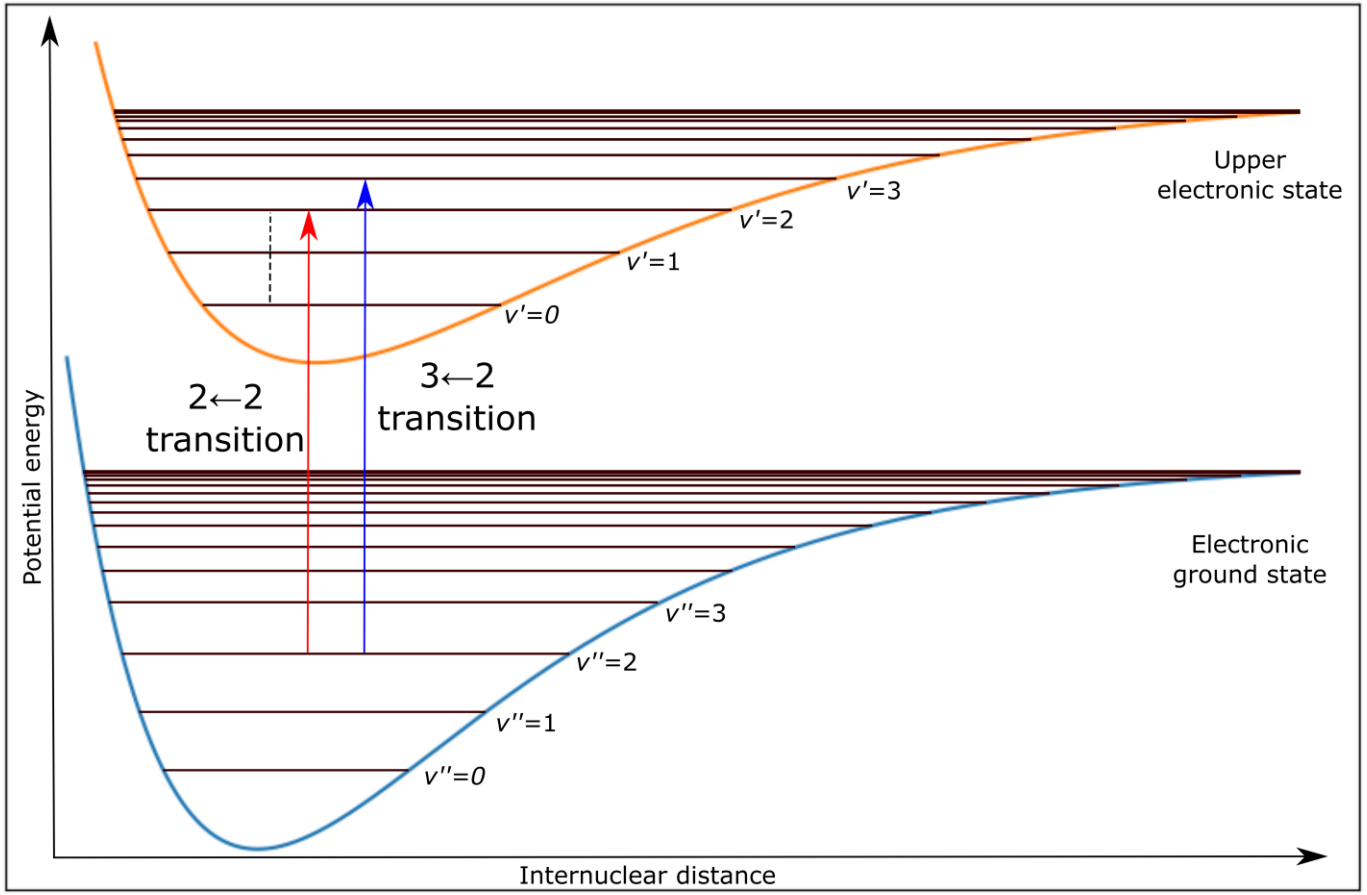
- Measure diagonal ($\nu' = \nu''$) and non-diagonal ($\nu' = \nu'' + 1$) transitions

Dissociation energy of ^{225}AcF



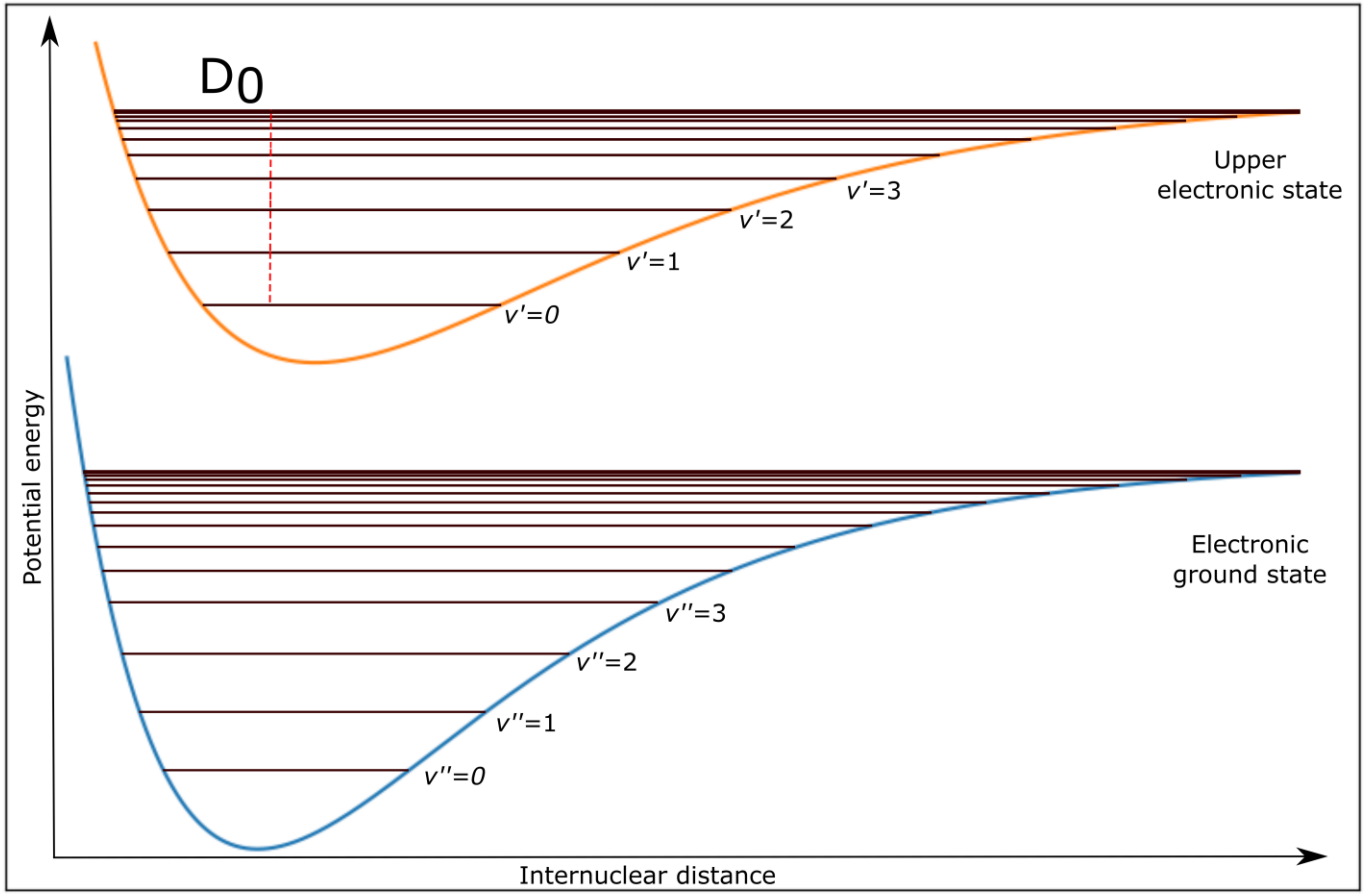
- Find their difference to indirectly extract the $\nu' + 1 \leftarrow \nu'$ transition in the upper state

Dissociation energy of ^{225}AcF

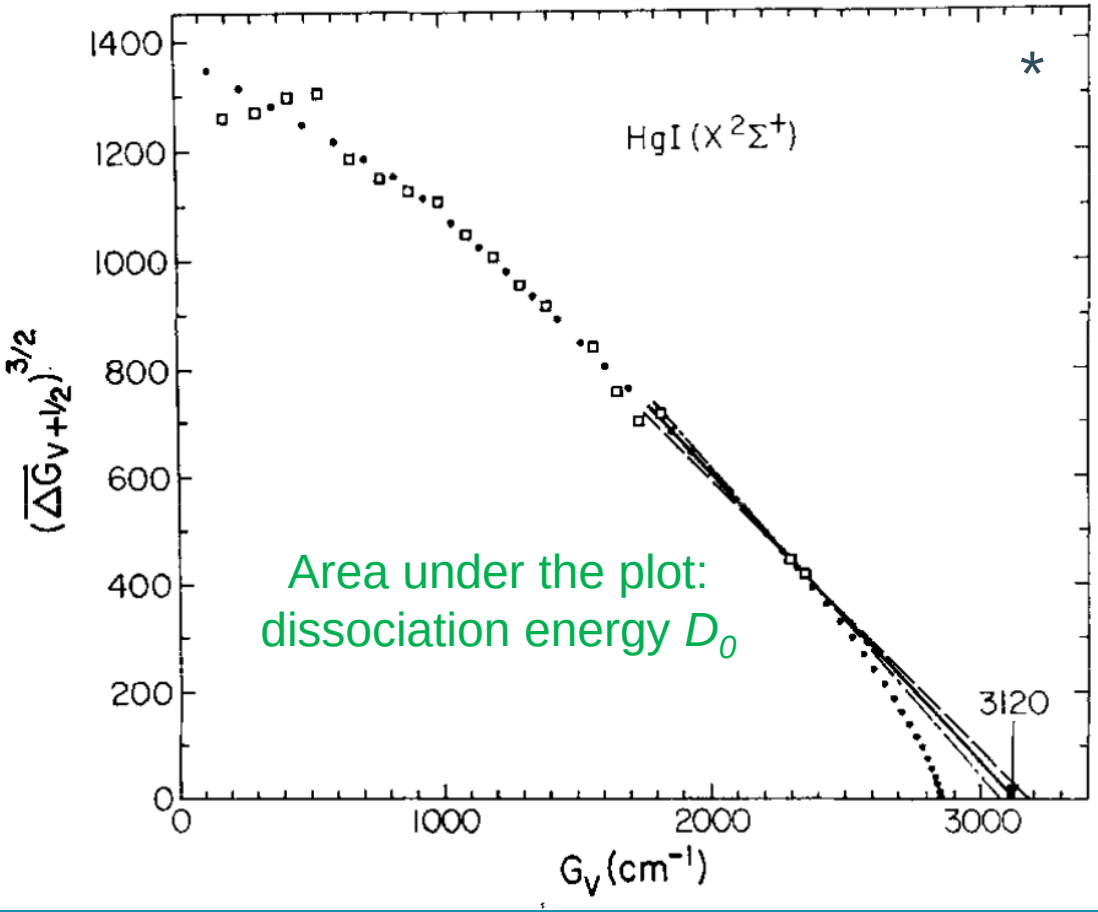


- Continue with higher-v'' diagonal and non-diagonal terms
- Stop when the peak intensity falls below the background level

Dissociation energy of ^{225}AcF



- Create LeRoy-Bernstein-modified Birge-Sponer plot with the measured points to extract D_0.



* Wilcomb & Bernstein, J. Mol. Spectrosc. **62**, 442-448 (1976)