JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

LARISSA

Shining light on neptunium

Laser spectroscopy for probing atomic structure

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02.09.2024

LISA
LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

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

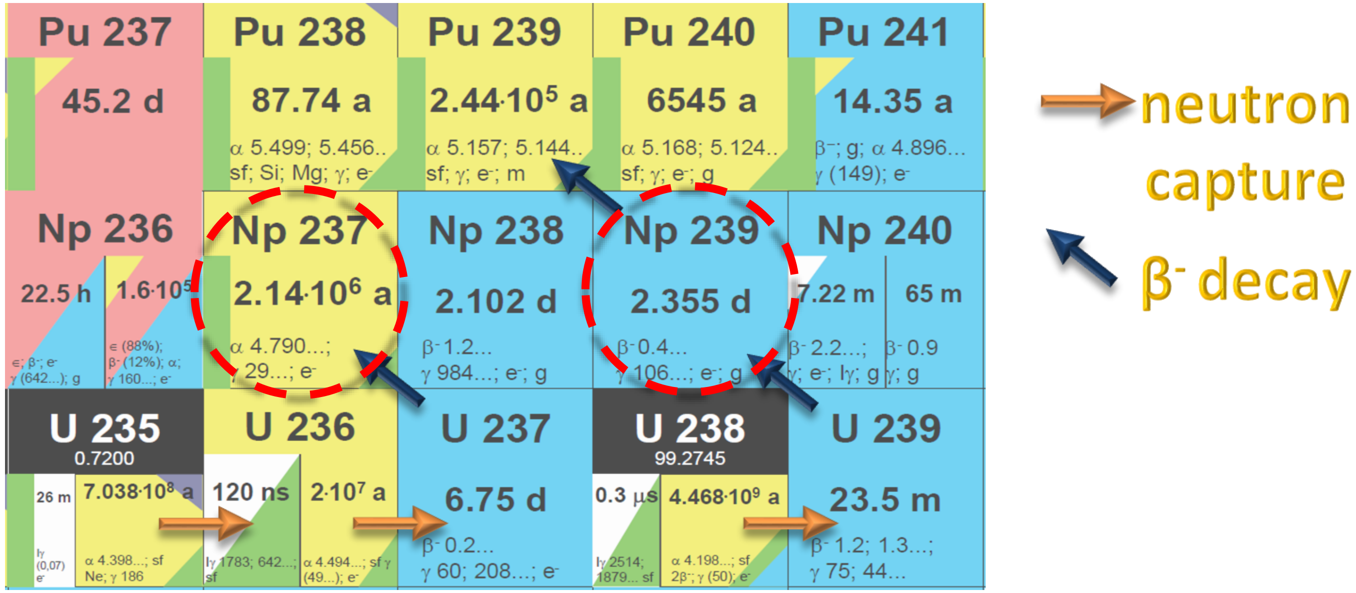
Neptunium

- Radioactive actinide
- Long half-life - ^{237}Np - $2.14 \cdot 10^6$ *y*
- High radiotoxicity

- Ionization potential 50 535(2) cm^{-1} [1]
  6.26554(25) eV
- 462 atomic levels known [2]
- ^{237}Np
  - Magnetic dipole moment +3.14(4) μ_N [3]
  - Electric quadrupole moment +3.886(4) *eb* [3]
- ^{239}Np
  - Nuclear moments unknown

[1] S. Kohler et al. Spectrochim. Acta B **52**, 717 – 726, (1997)
[2] V. Kazakov et al. Phys. Scr. **92**, 10, (2017)
[3] N.J. Stone, At. Data Nucl. Data Tables **90**, 1, 75-176, (2005)

Neptunium production and trace analysis



It is essentail to monitor **nuclear waste repositories** and their **long-term performance**

Trace analysis of environmental samples is of high relevance

- ^{239}Np as a tracer for precise quantification
- Identification of efficient ionization schemes:
  - High elemental selectivity
  - Isotope related effects like hyperfine structures (HFS) and isotope shift (IS)
    - large splitting and shifts observed in neptunium

Neptunium - on-line studies

- On-line studies of neptunium at ISOLDE
  - In-source laser resonance ionization spectroscopy of neptunium and plutonium (*Letter of Intent INTC-I-243*)
- Access to other isotopes
- Nuclear moments are only known for ^{237}Np
- Validation of theoretical estimates

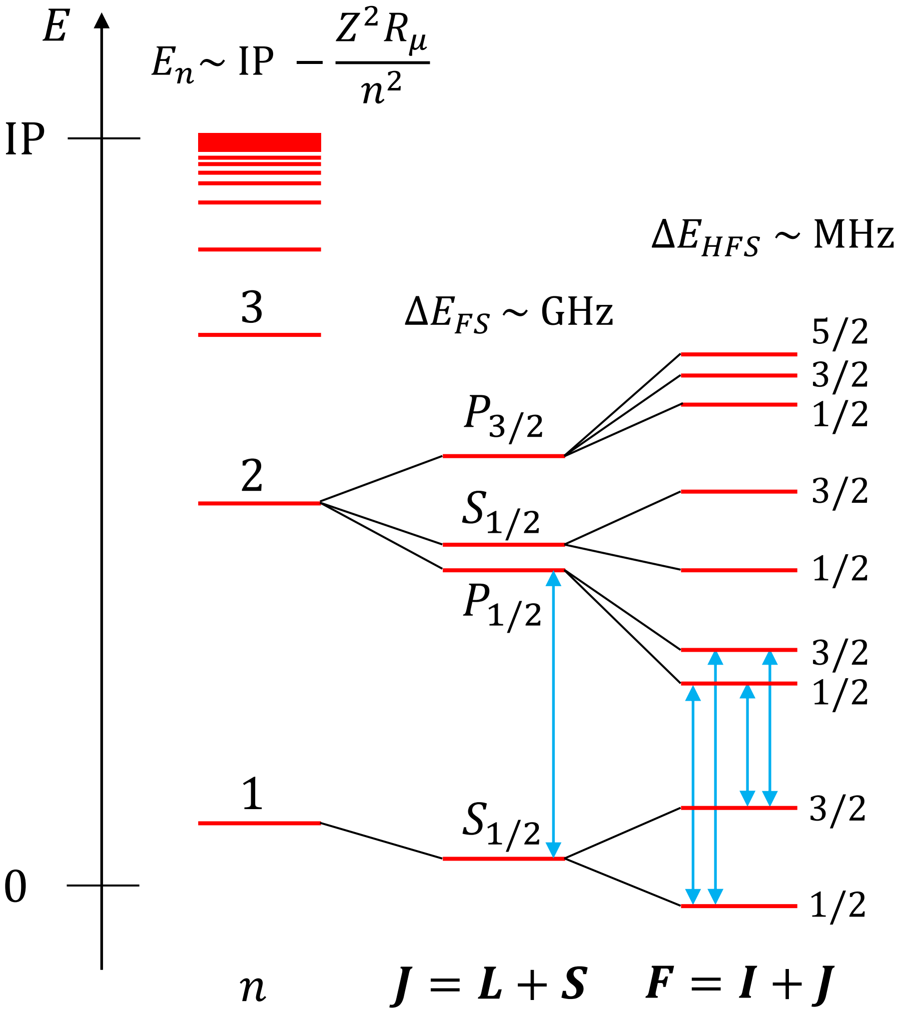
Need for efficient and selective ionization schemes

Technique and setup

Resonance ionization spectroscopy
The RISIKO mass separator
Laser ion source

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

Probing atomic structure with lasers



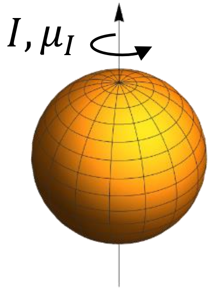
- Atomic level structure through optical transitions
- Ionization limit through Rydberg convergences
- Nuclear spins and electromagnetic moments through hyperfine interaction

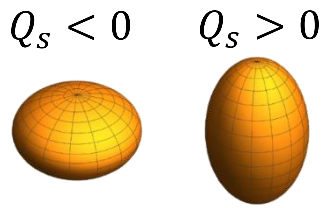
$$A = \frac{\mu_I \overline{H(0)}}{IJ} \qquad B = eQ_s \left\langle \frac{\partial^2 \phi}{\partial z^2} \right\rangle_{r=0}$$

magnetic field at nucleus

electric field gradient at nucleus

Atomic shell
Nucleus

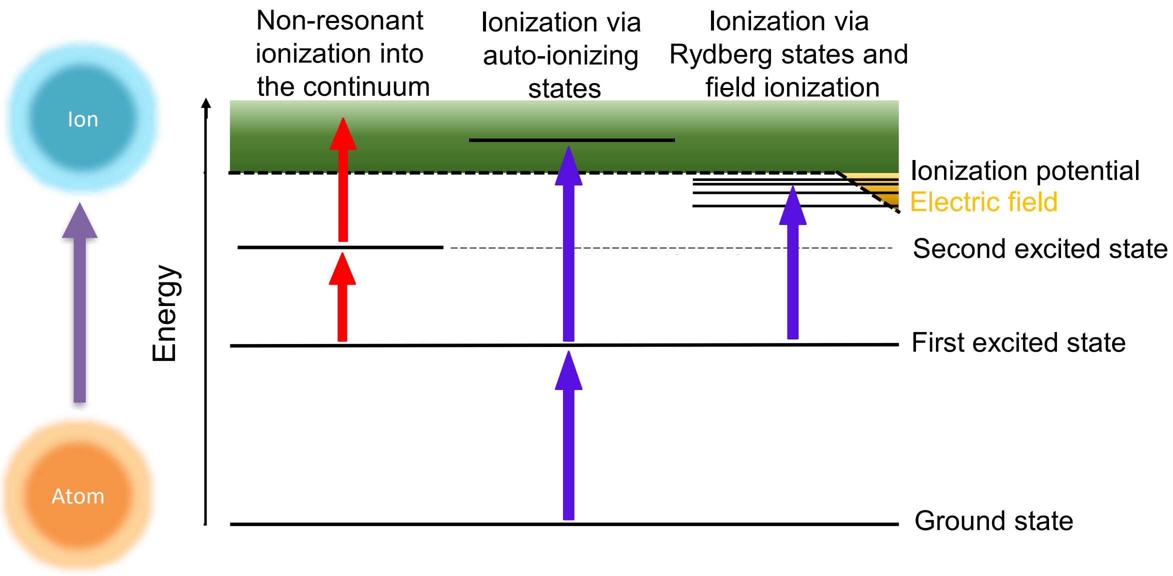




n – principal quantum number
Z – atomic number
S – total spin angular momentum.
I – nuclear spin
μ – magnetic dipole moment

IP – ionization potential
R – Rydberg constant
L – total orbital angular momentum
J – total angular momentum
Q – electric quadrupole moment

Resonance ionization mass spectrometry

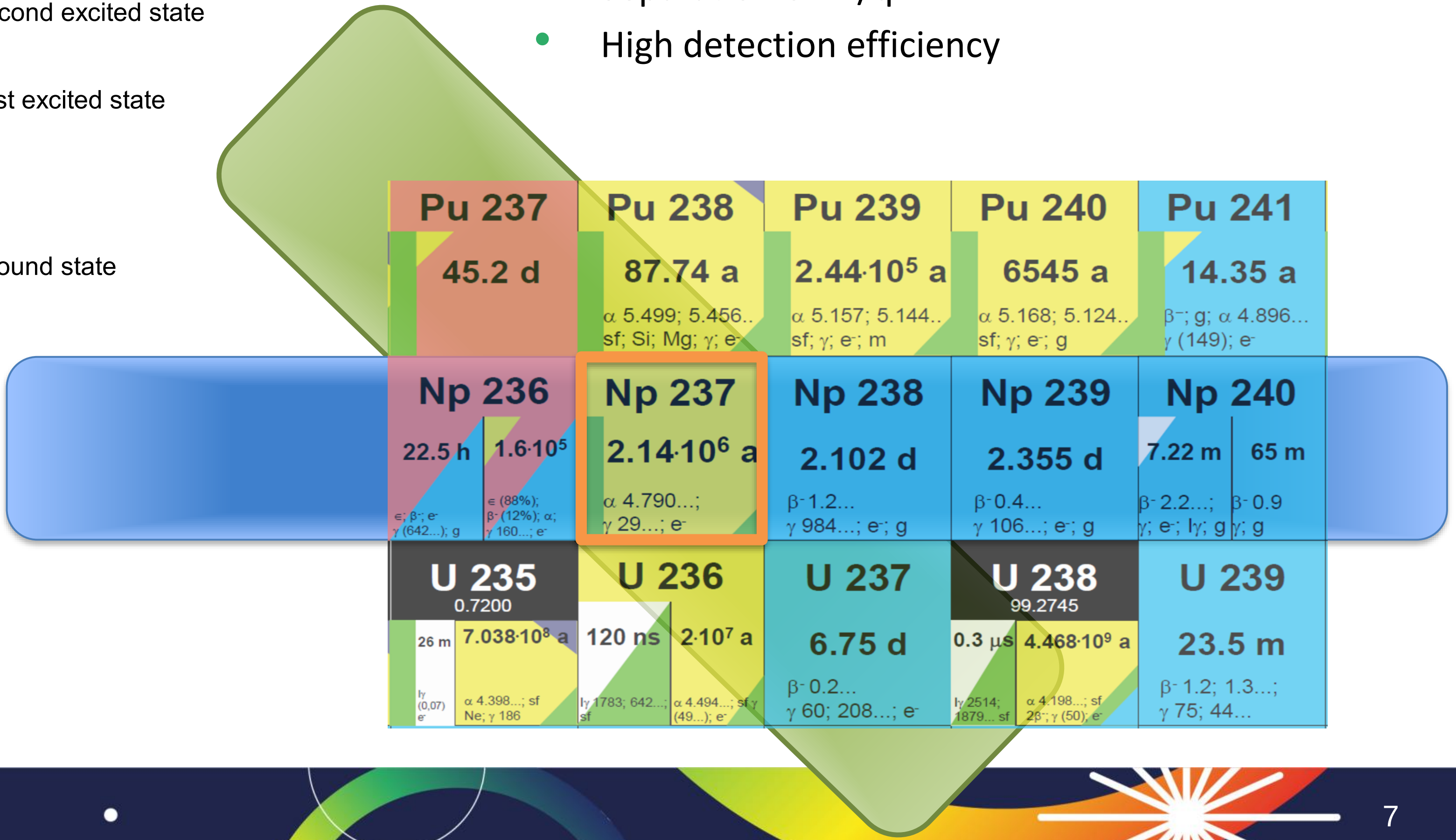


Laser ionzation and spectroscopy

- Highly efficient process
- High element selectivity

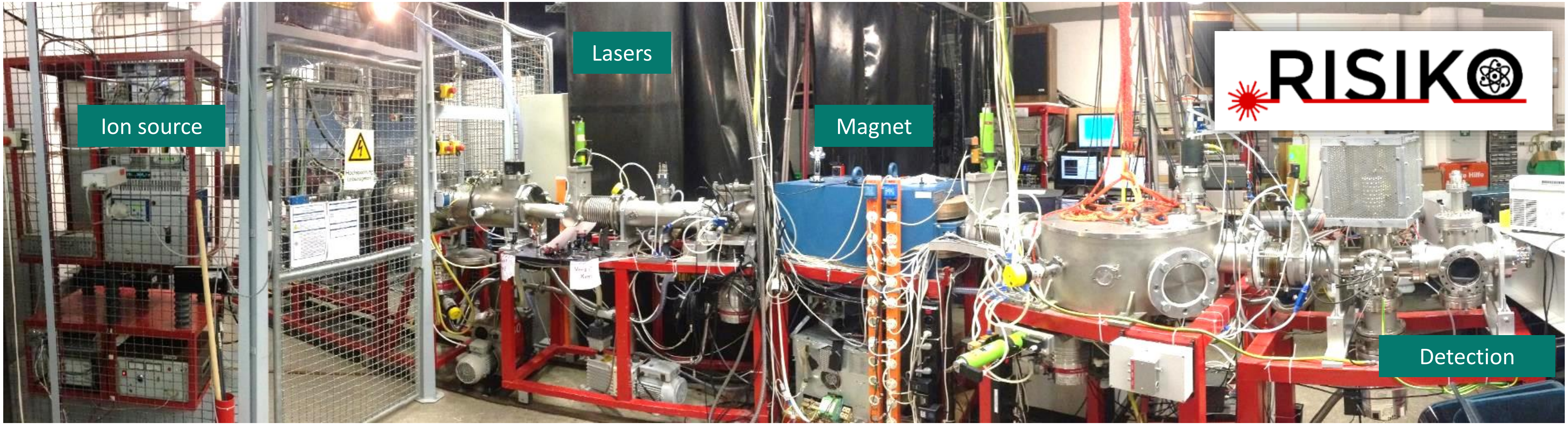
Mass spectrometry

- Separation of m/q
- High detection efficiency

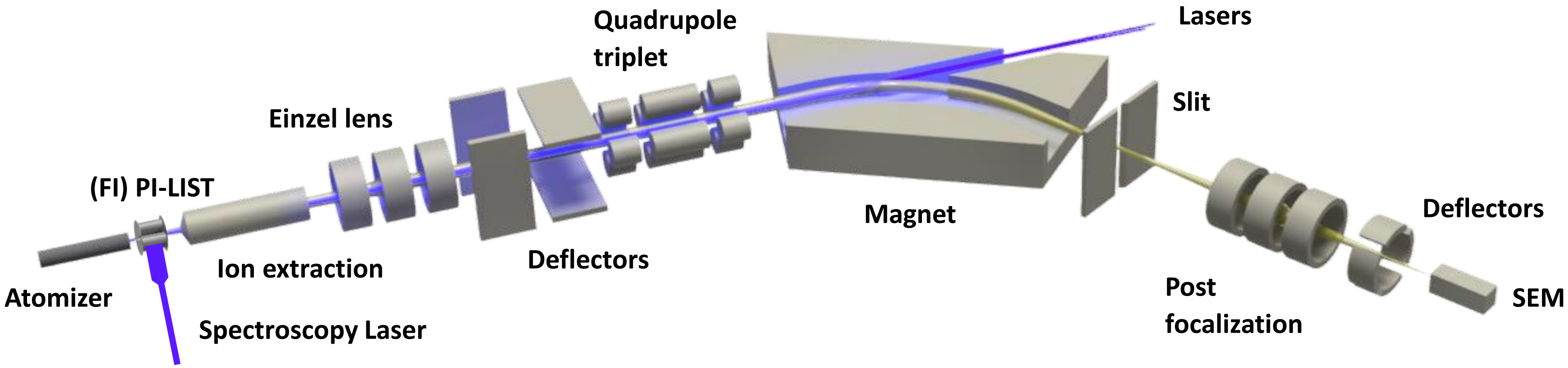


Pu 237 45.2 d	**Pu 238** 87.74 a α 5.499; 5.456.. sf; Si; Mg; γ; e^-	**Pu 239** $2.44 \cdot 10^5$ a α 5.157; 5.144.. sf; γ; e^-; m	**Pu 240** 6545 a α 5.168; 5.124.. sf; γ; e^-; g	**Pu 241** 14.35 a β^-; g; α 4.896... γ (149); e^-
Np 236 22.5 h ϵ; β^-; e^- γ (642...); g $1.6 \cdot 10^5$ ϵ (88%); β^- (12%); α; γ 160...; e^-	**Np 237** $2.14 \cdot 10^6$ a α 4.790...; γ 29...; e^-	**Np 238** 2.102 d β^- 1.2... γ 984...; e^-; g	**Np 239** 2.355 d β^- 0.4... γ 106...; e^-; g	**Np 240** 7.22 m β^- 2.2...; γ; e^-; Iγ; g 65 m β^- 0.9 γ; g
U 235 0.7200 26 m Iγ (0,07) e^- $7.038 \cdot 10^8$ a α 4.398...; sf Ne; γ 186	**U 236** 120 ns Iγ 1783; 642...; sf $2 \cdot 10^7$ a α 4.494...; sf γ (49...); e^-	**U 237** 6.75 d β^- 0.2... γ 60; 208...; e^-	**U 238** 99.2745 0.3 μs Iγ 2514; 1879... sf $4.468 \cdot 10^9$ a α 4.198...; sf 2β^-; γ (50); e^-	**U 239** 23.5 m β^- 1.2; 1.3...; γ 75; 44...

RISIKO mass separator



- Hot cavity laser ion source
- Pulsed multistep laser ionization
- 30 keV ion extraction
- Mass separation in dipole magnet
- Single ion detection



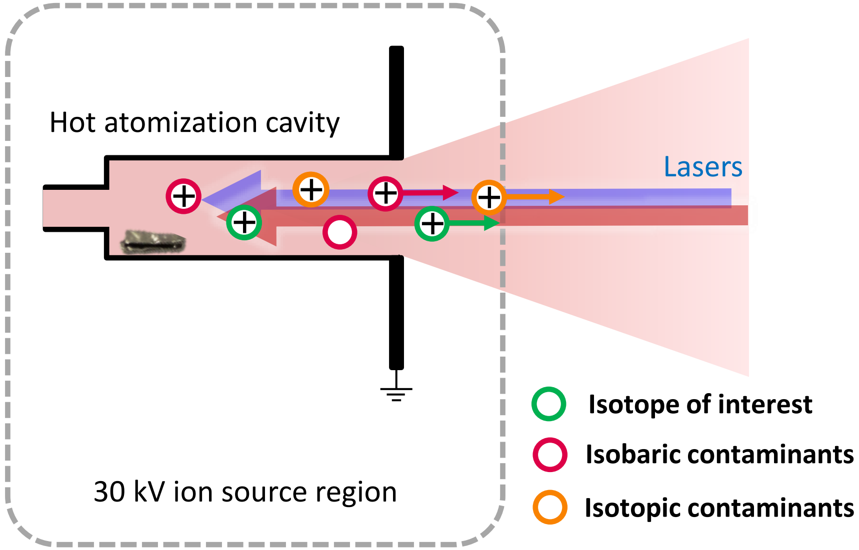
RISIKO laser ion source

- High operation temp. up to about 2000 °C
- Contamination caused by:
  - black body radiation
  - collisions
- Doppler broadening limiting spectral resolution

$$\Delta \upsilon = \upsilon_0 \sqrt{\frac{8k_B T \ln 2}{mc^2}} \sim \mathrm{GHz}$$

$\Delta \upsilon$ - linewidth
k_B - Boltzmann constant
m – atom mass

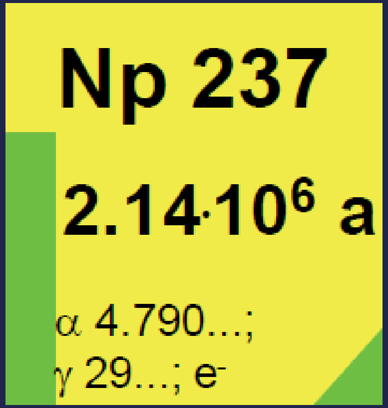
υ_0 - resonance freq. for a particle at rest
T - temperature
c – speed of light



Sample

Probing atomic structure

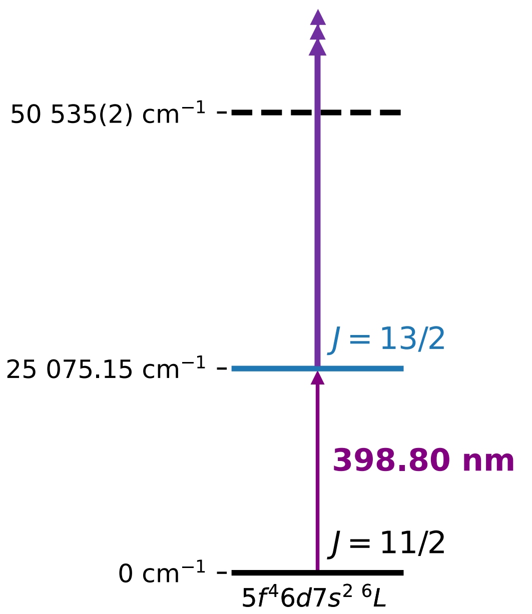
Scheme development
Line profiles
Ionization potential determination
Development and characterization of FI-LIST

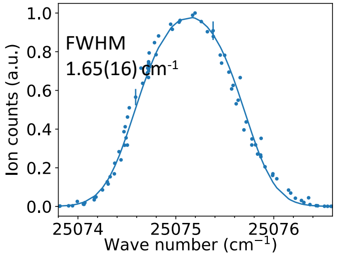


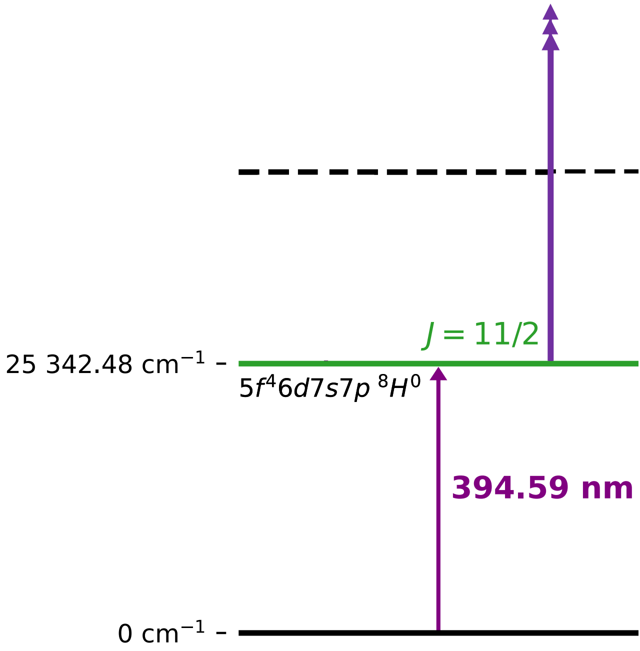
This Marie Sklodowska-Curie Action (MSCA) Innovative Training Networks (ITN) receives funding from the European Union's H2020 Framework Programme under grant agreement no. 861198

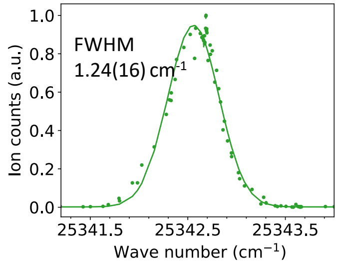
Ionization scheme development

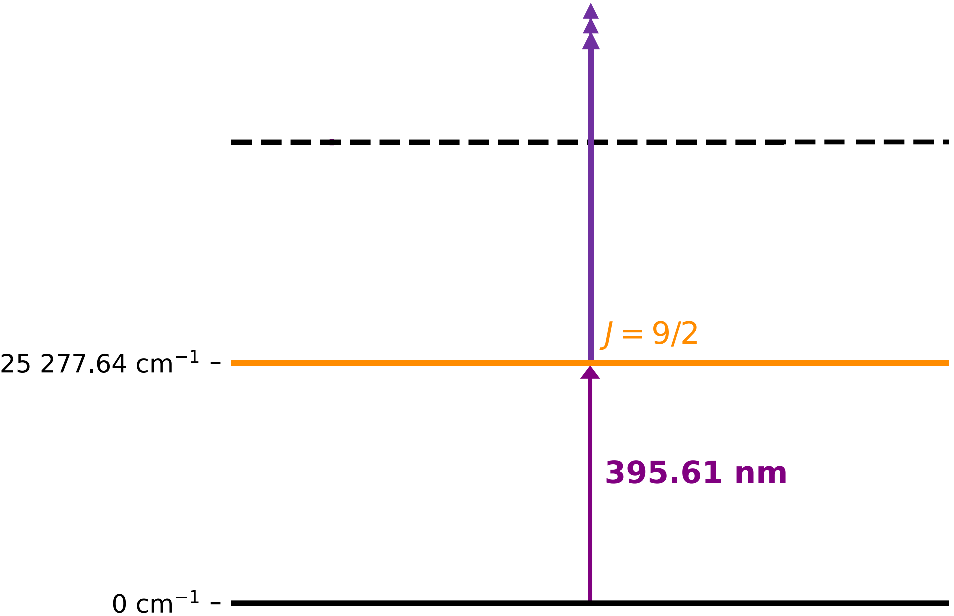
[1] M. Kaja et al., Eur. Phys. J. D **78**, 50 (2024)



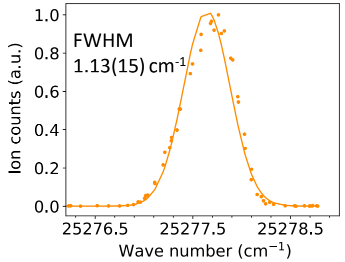








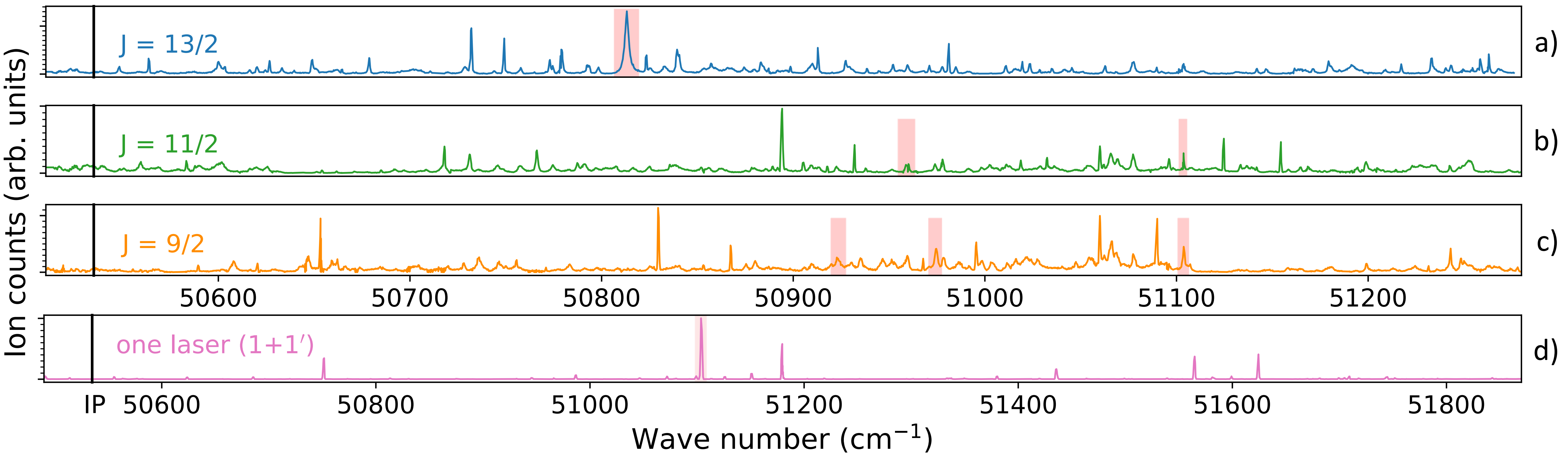
First excitation step (FES)
line profiles



All FESs:
S. Raeder et al.,
Spectrochim. Acta B
66, 242 – 247 (2011)

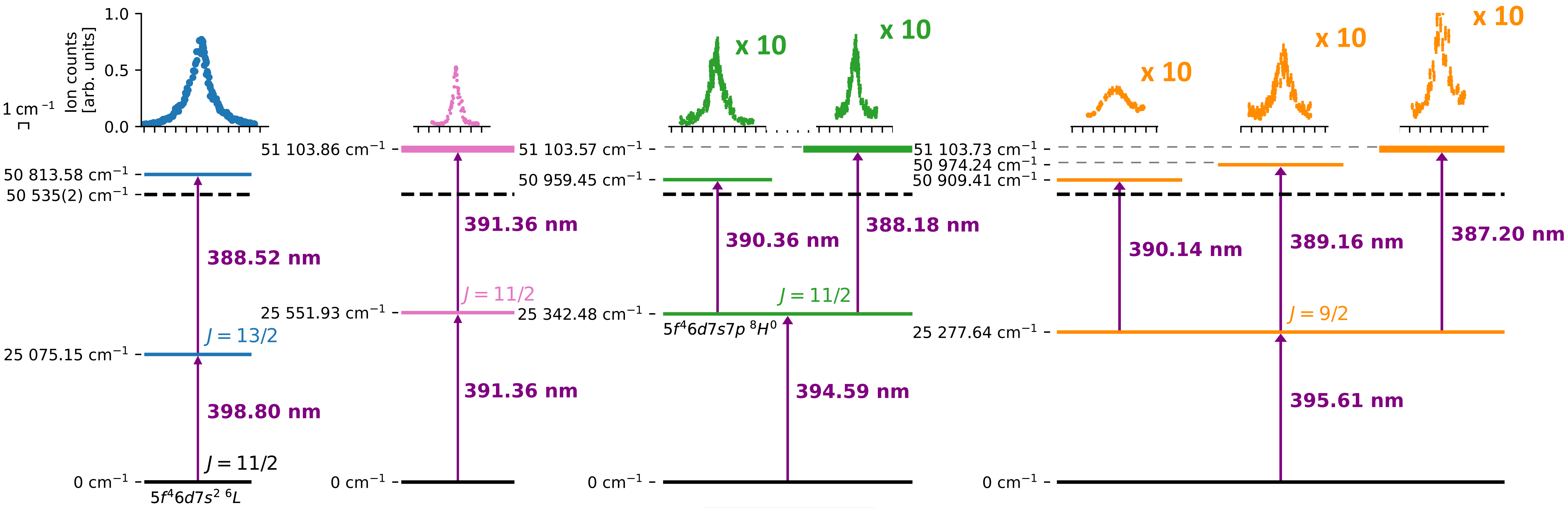
Ionization scheme development

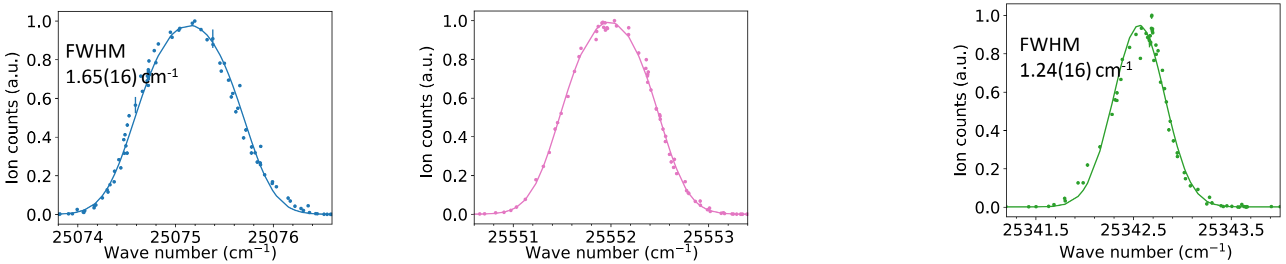
[1] M. Kaja et al., Eur. Phys. J. D, **78**, 50 (2024)



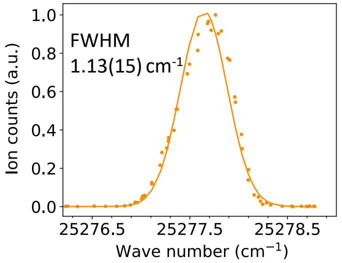
Ionization scheme development

[1] M. Kaja et al., Eur. Phys. J. D **78**, 50 (2024)





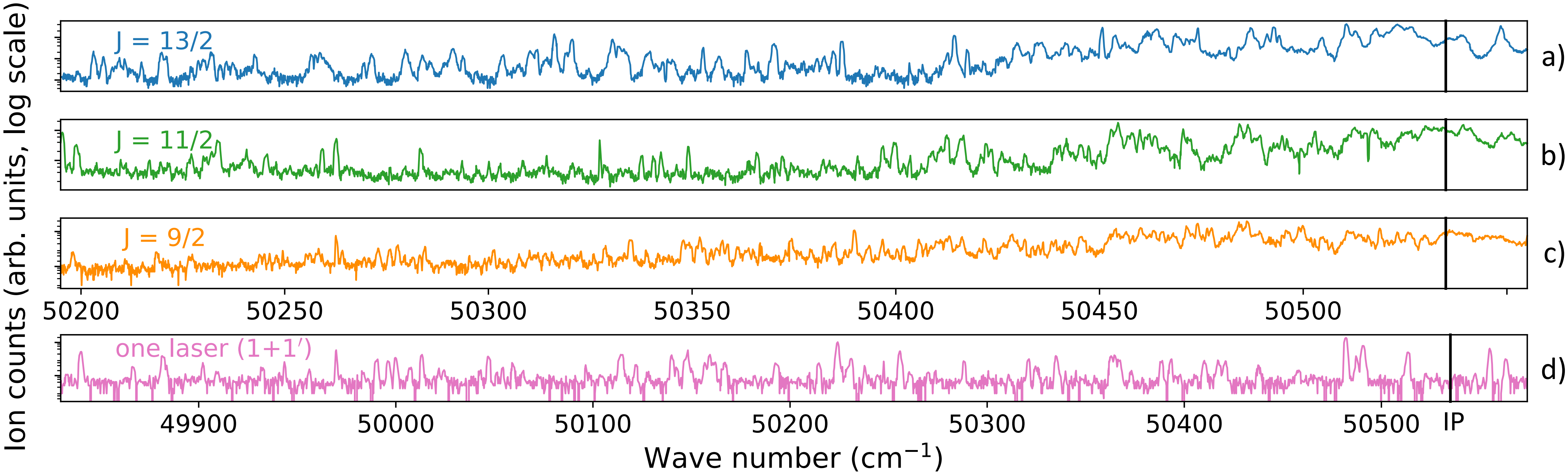
First excitation step (FES) line profiles



All FESs:
S. Raeder et al.,
Spectrochim. Acta B
66, 242 – 247 (2011)

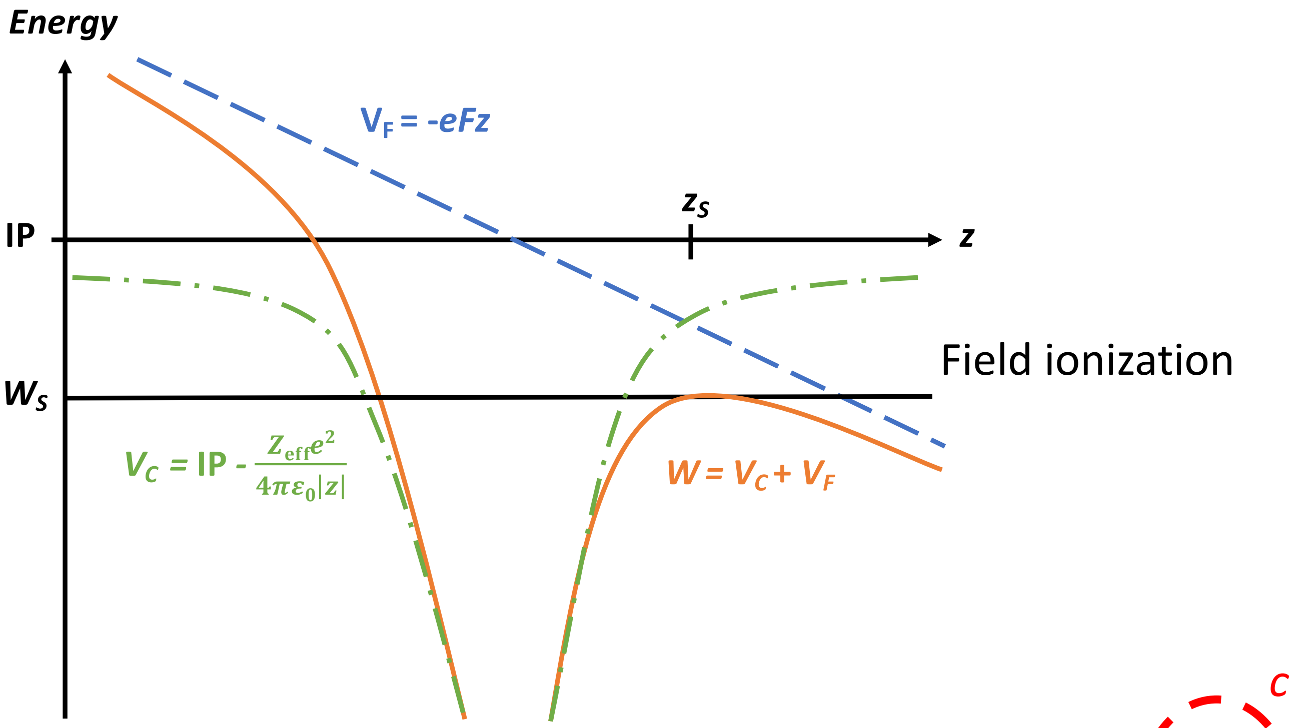
Spectra below the ionization potential

[1] M. Kaja et al., Eur. Phys. J. D, **78**, 50 (2024)



Assignment of levels or analysis of Rydberg Convergences fails for such a complex atomic systems

Field ionization - saddle point model



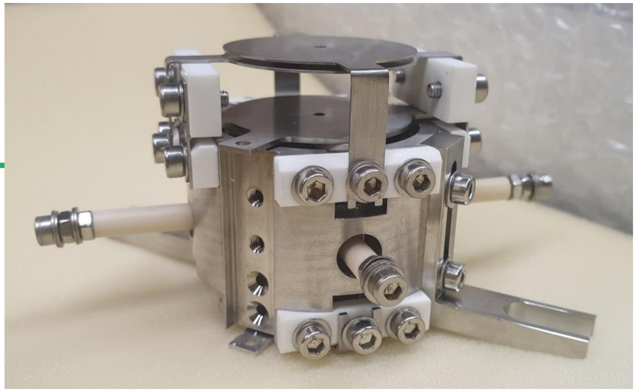
- Ionization threshold according to the saddle point model $W_S = IP - 2\boxed{\sqrt{\frac{Z_{\mathrm{eff}} e^3}{4\pi\varepsilon_0}}}\sqrt{F}$

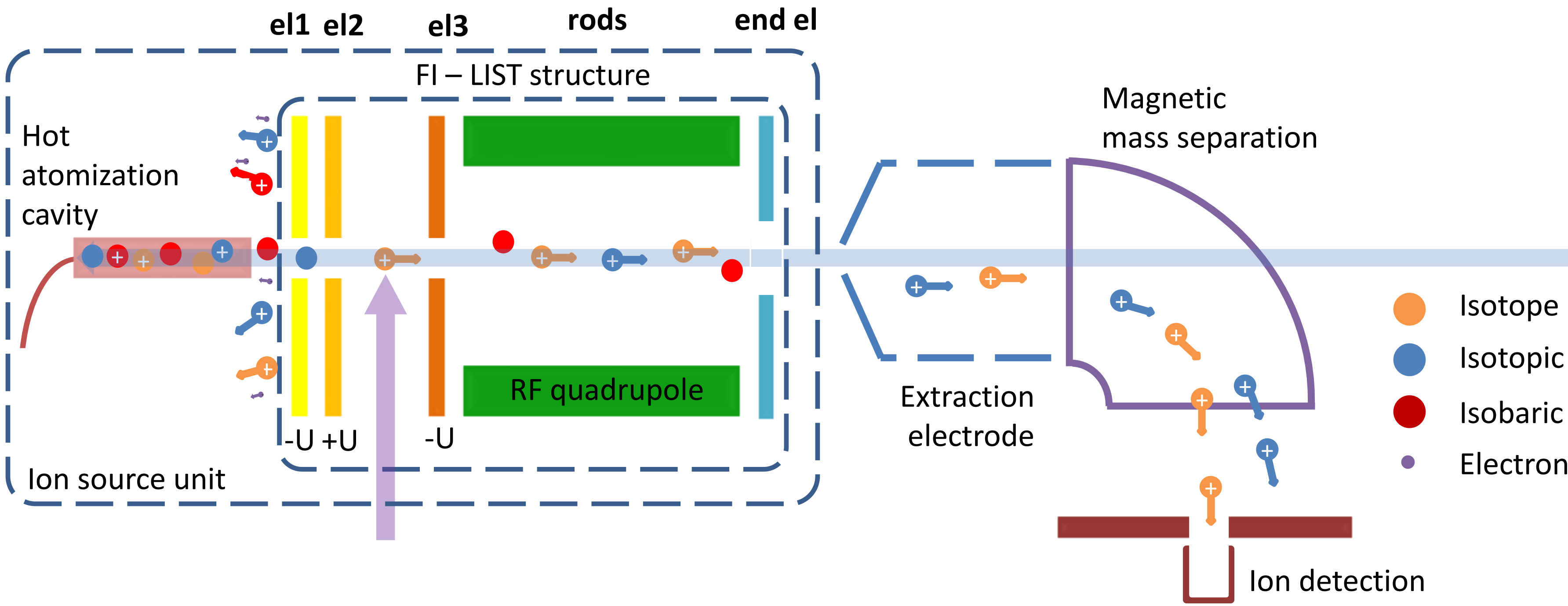
const

- Extrapolation to $F = 0\ \mathrm{V/cm}$ yields IP

Z_{eff} - effective charge
F - external field strength
ε_0- vacuum permittivity

FI-LIST – Field Ionization LIST





● Isotope of interest

● Isotopic contamination

● Isobaric contamination

● Electrons

- Well controllable electric field for ionization between el2 and el3
- Missing energy to ionize an atom is from the electric field $F = (el2 - el3)/1\ cm$

[1] M. Kaja et al., NIM B **547**, 165213 (2024)

Characterization of FI-LIST – ytterbium measurements

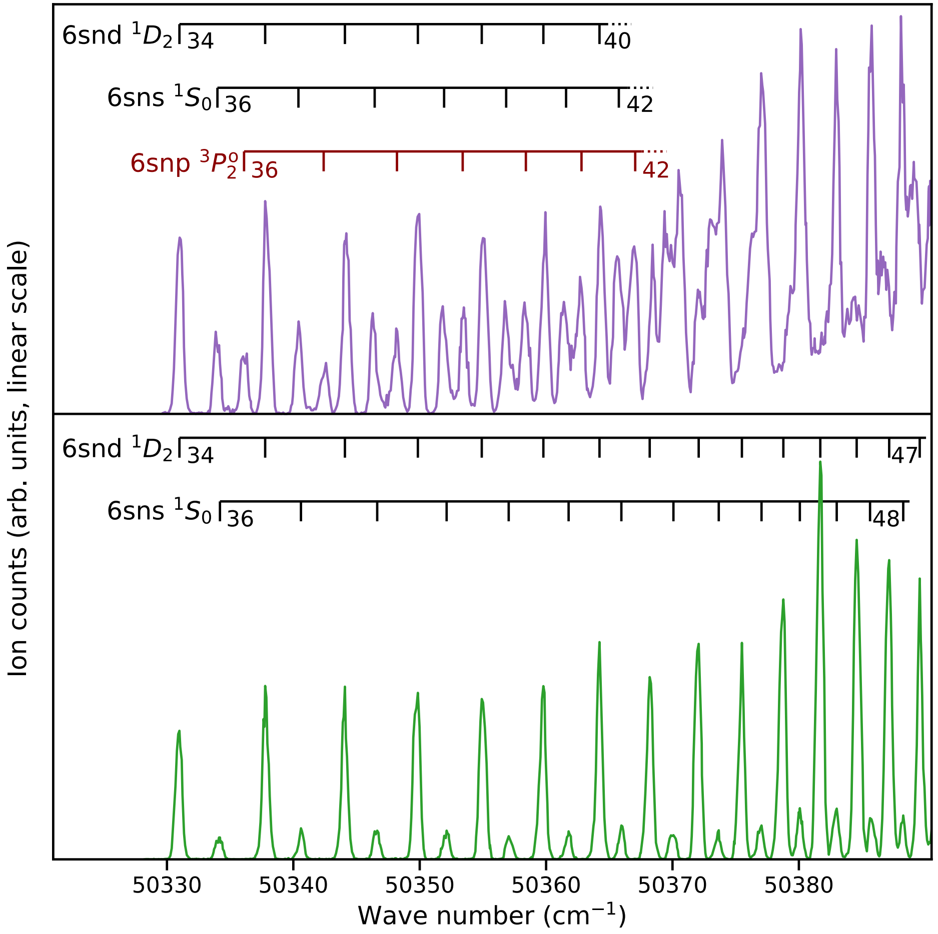
Why Yb?

Precisely known IP

IP = 50 443.07041(25) cm^{-1} [1]

Yb in electric field

levels shift, broaden and split
6*snp* series shows up [2]
due to Stark effect



20 V/cm

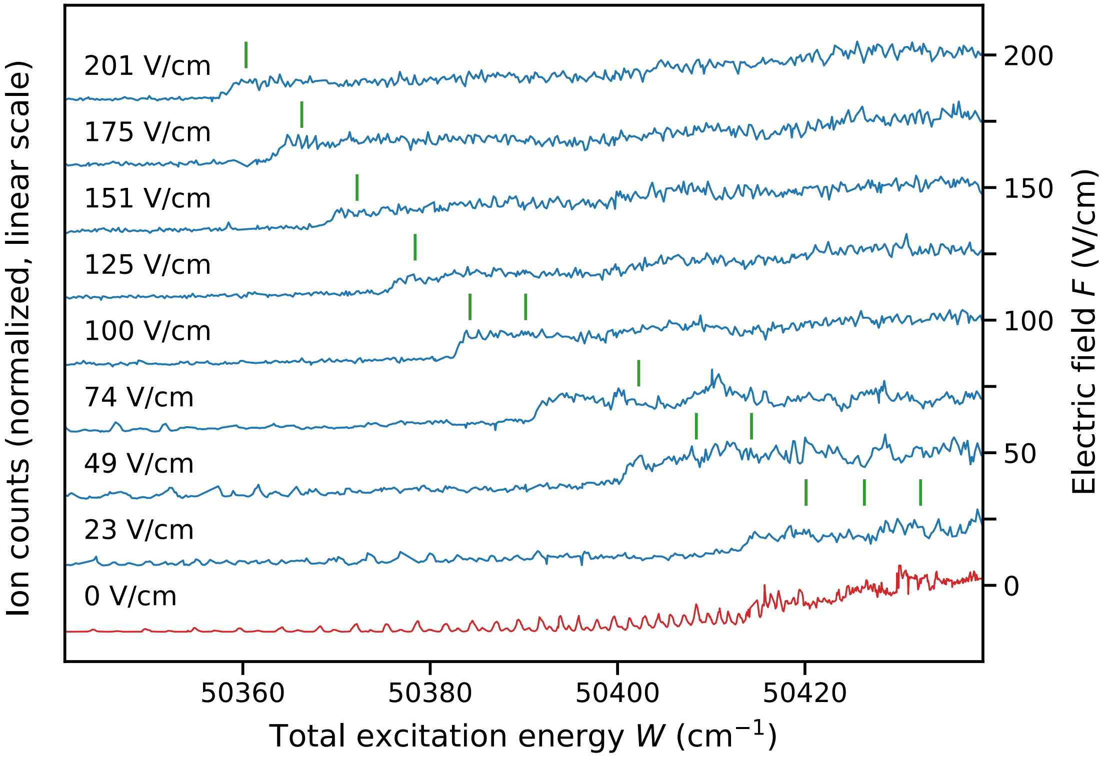
0 V/cm

[1] H. Lehec et al., Phys. Rev. A **98**, 062506, (2018)
[2] R. Li et al., Spectrochim. Acta B 174 (2020)
[3] M. Kaja et al., NIM B **547**, 165213 (2024)

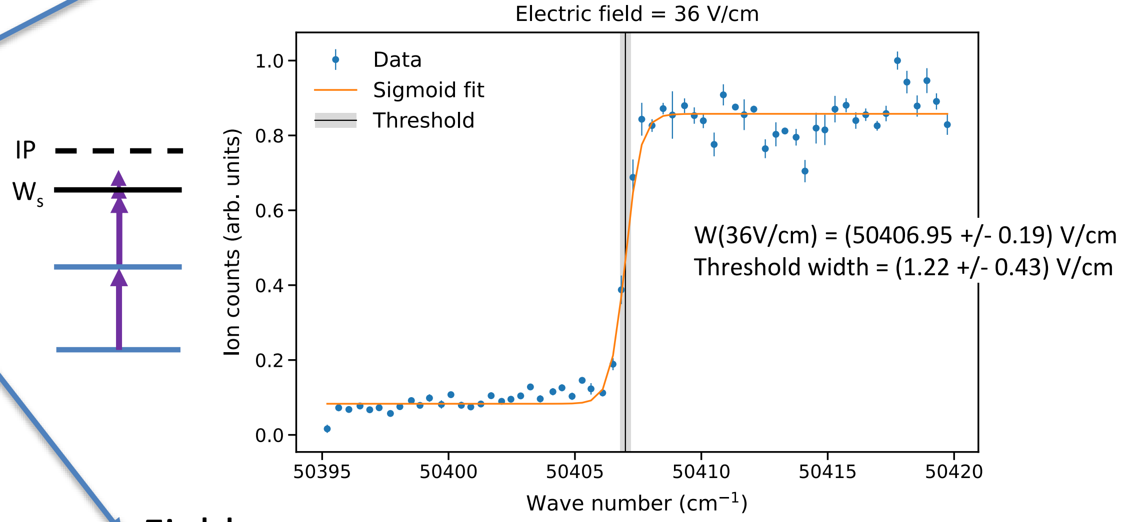
Ytterbium Ionization Potential

Determination of ionization thresholds

- 28 Wavelength scan for 14 different fixed e. fields
- 24 E. fields scans for 12 different fixed wavelengths



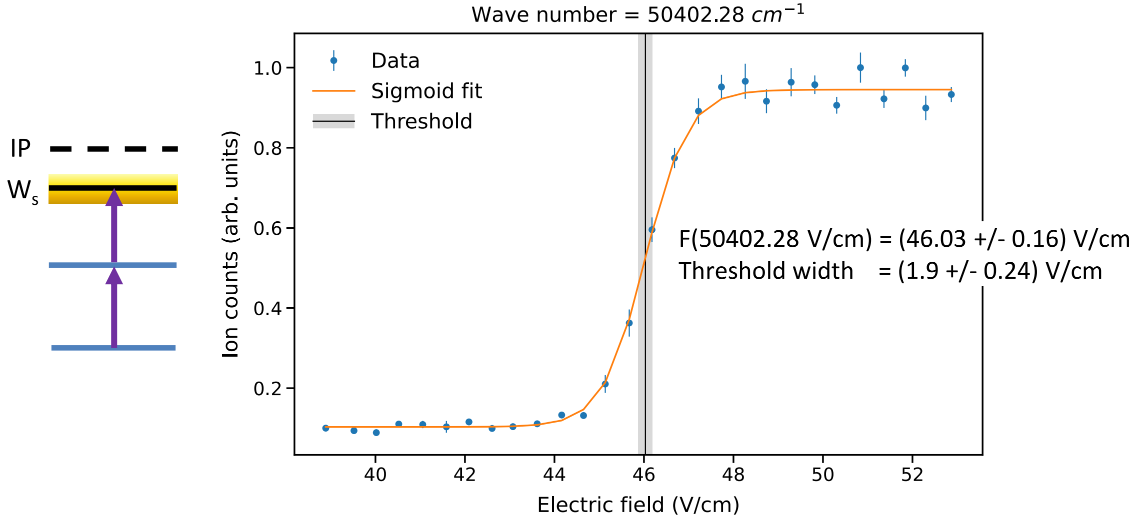
Wavelength scan



Electric field = 36 V/cm

W(36V/cm) = (50406.95 +/- 0.19) V/cm
Threshold width = (1.22 +/- 0.43) V/cm

Field scan



Wave number = 50402.28 cm^{-1}

F(50402.28 V/cm) = (46.03 +/- 0.16) V/cm
Threshold width = (1.9 +/- 0.24) V/cm

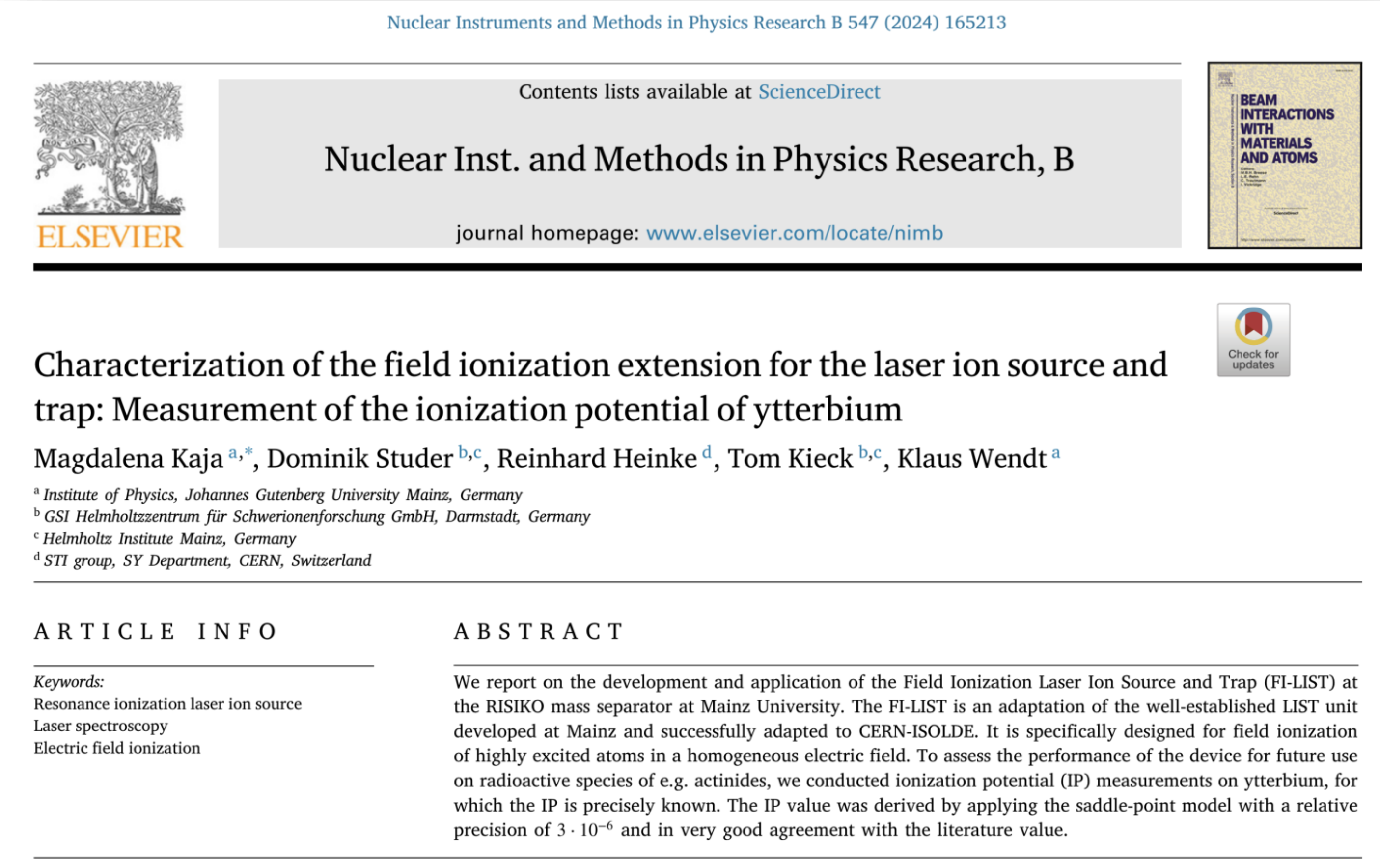
[1] M. Kaja et al., NIM B **547**, 165213 (2024)

Ytterbium Ionization Potential

$$W_s^F = 50\,443.21(13)\ cm^{-1} \ - 6.050(7)\ (Vcm)^{-\frac{1}{2}}\sqrt{F}$$

$$W_s^\lambda = 50\,443.05(15)\ cm^{-1} \ - 6.034(10)\ (Vcm)^{-\frac{1}{2}}\sqrt{F}$$

$$\mathbf{IP} = 50\,443.07041(25)\ cm^{-1}$$ [1]



Nuclear Instruments and Methods in Physics Research B 547 (2024) 165213

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ELSEVIER

BEAM INTERACTIONS WITH MATERIALS AND ATOMS

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Characterization of the field ionization extension for the laser ion source and trap: Measurement of the ionization potential of ytterbium

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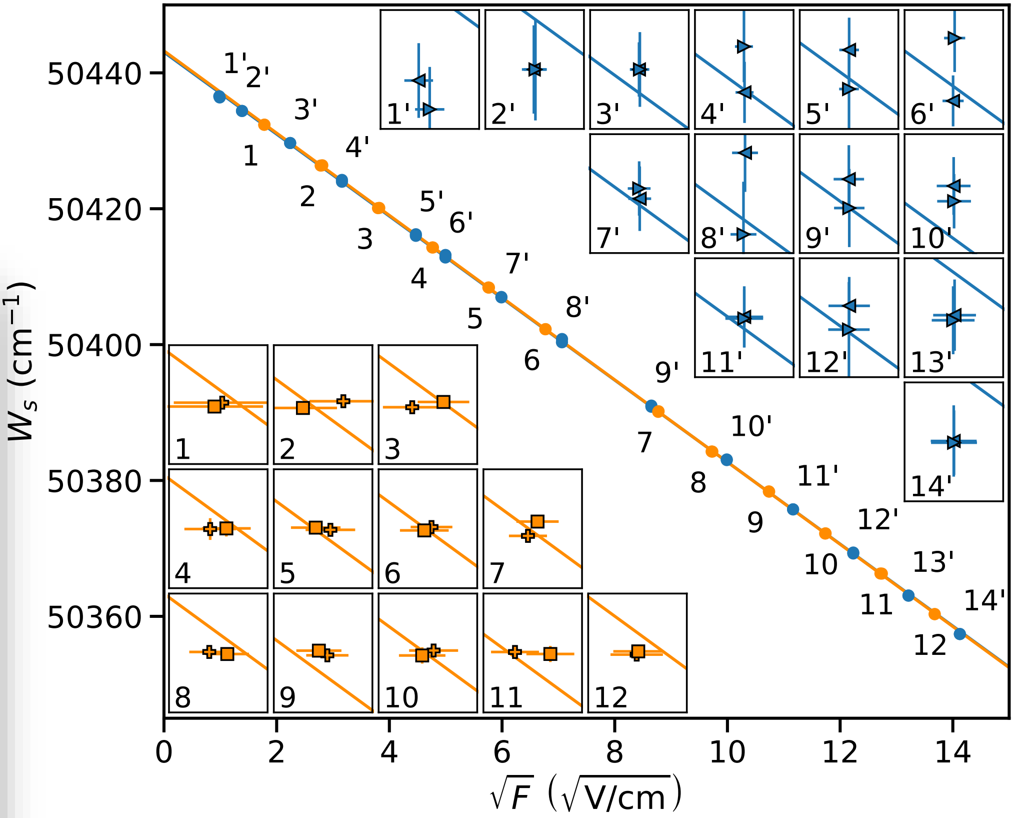
[b] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
[c] *Helmholtz Institute Mainz, Germany*
[d] *STI group, SY Department, CERN, Switzerland*

ARTICLE INFO

Keywords:
Resonance ionization laser ion source
Laser spectroscopy
Electric field ionization

ABSTRACT

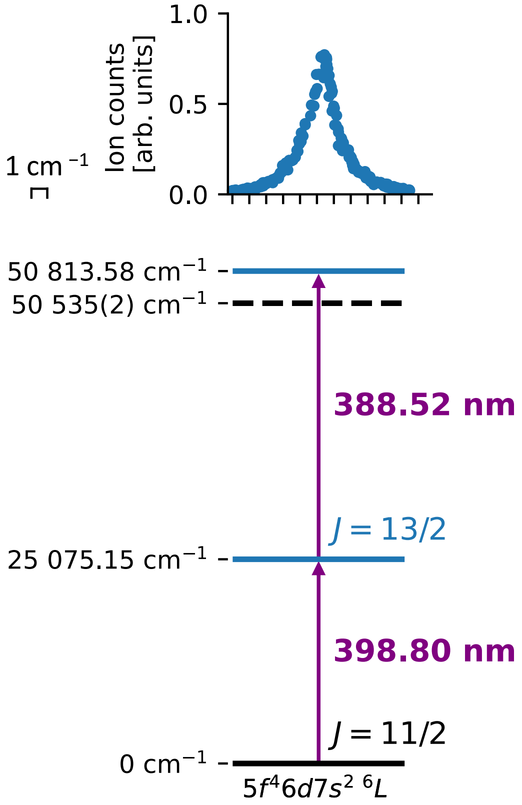
We report on the development and application of the Field Ionization Laser Ion Source and Trap (FI-LIST) at the RISIKO mass separator at Mainz University. The FI-LIST is an adaptation of the well-established LIST unit developed at Mainz and successfully adapted to CERN-ISOLDE. It is specifically designed for field ionization of highly excited atoms in a homogeneous electric field. To assess the performance of the device for future use on radioactive species of e.g. actinides, we conducted ionization potential (IP) measurements on ytterbium, for which the IP is precisely known. The IP value was derived by applying the saddle-point model with a relative precision of $3 \cdot 10^{-6}$ and in very good agreement with the literature value.

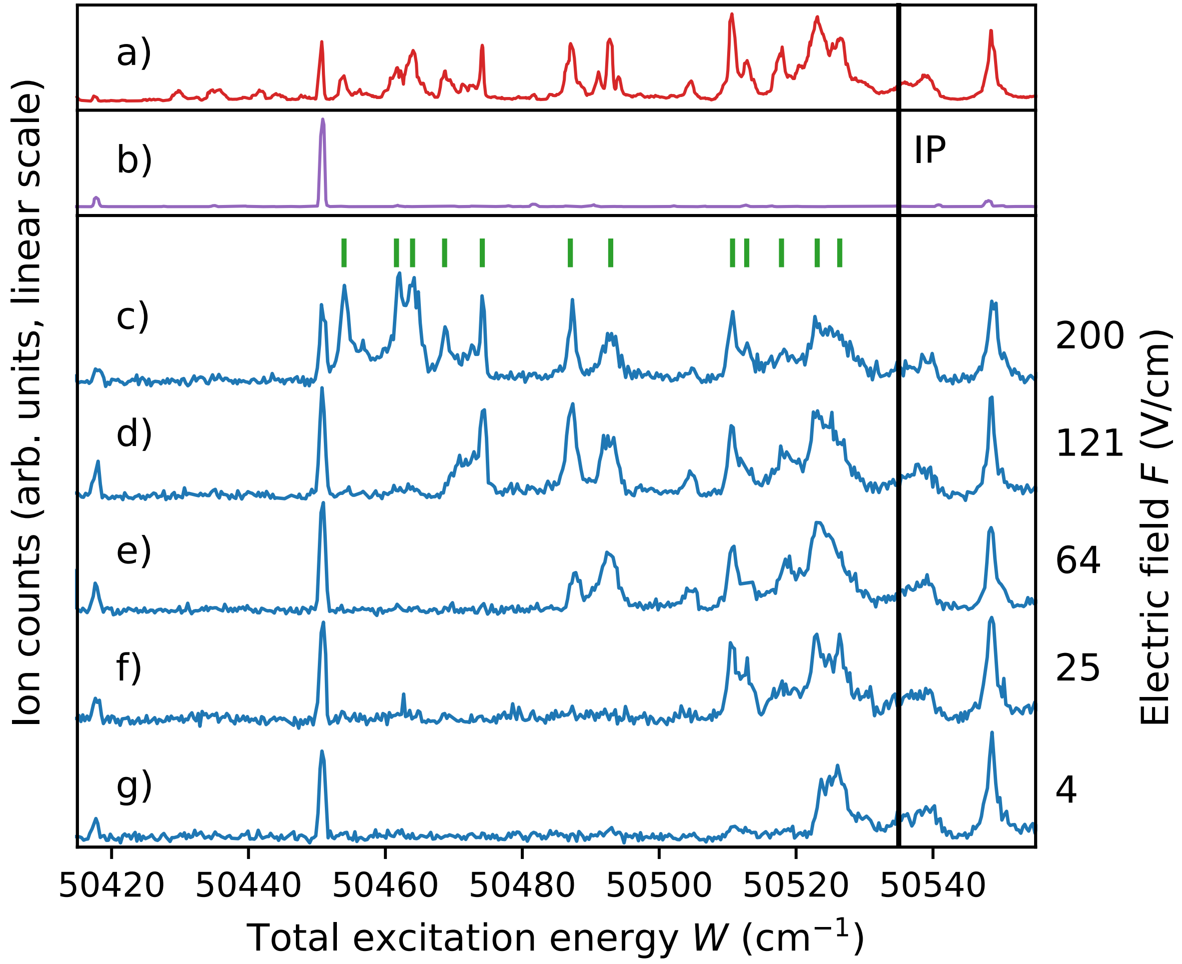


[1] H. Lehec et al., Phys. Rev. A **98**, 062506, (2018)
[2] M. Kaja et al., NIM B **547**, 165213 (2024)

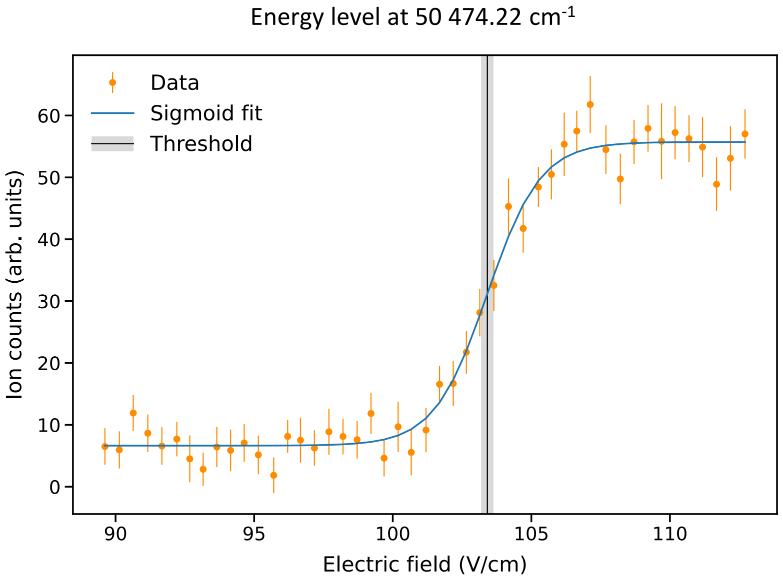
Ionization potential

[1] M. Kaja et al., Eur. Phys. J. D **78**, 50 (2024)





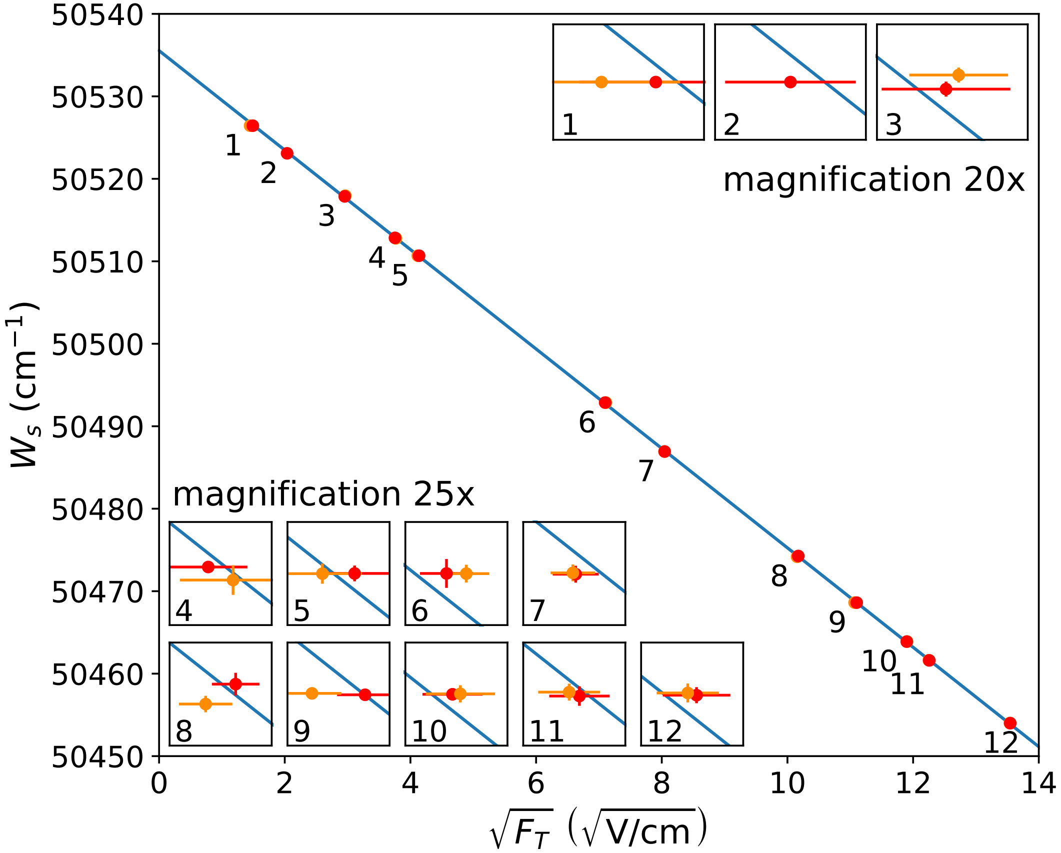
Ionization potential



$$W_s^F = 50\,535.54(15)\ cm^{-1} - 6.029(9)\ (Vcm)^{-\frac{1}{2}}\sqrt{F}$$

$$\mathrm{IP} = 50\,535(2)cm^{-1}\ [1]$$

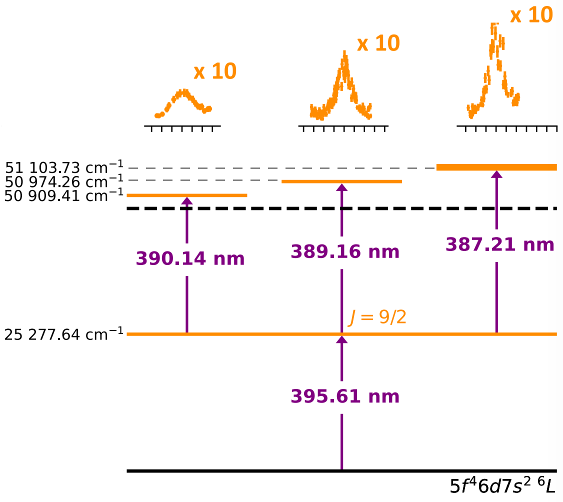
More than 10 times higher precision



[1]S. Köhler et al., Spectrochim. Acta B **52** (6) (1997)
[2] M. Kaja et al., Eur. Phys. J. D **78**, 50 (2024)

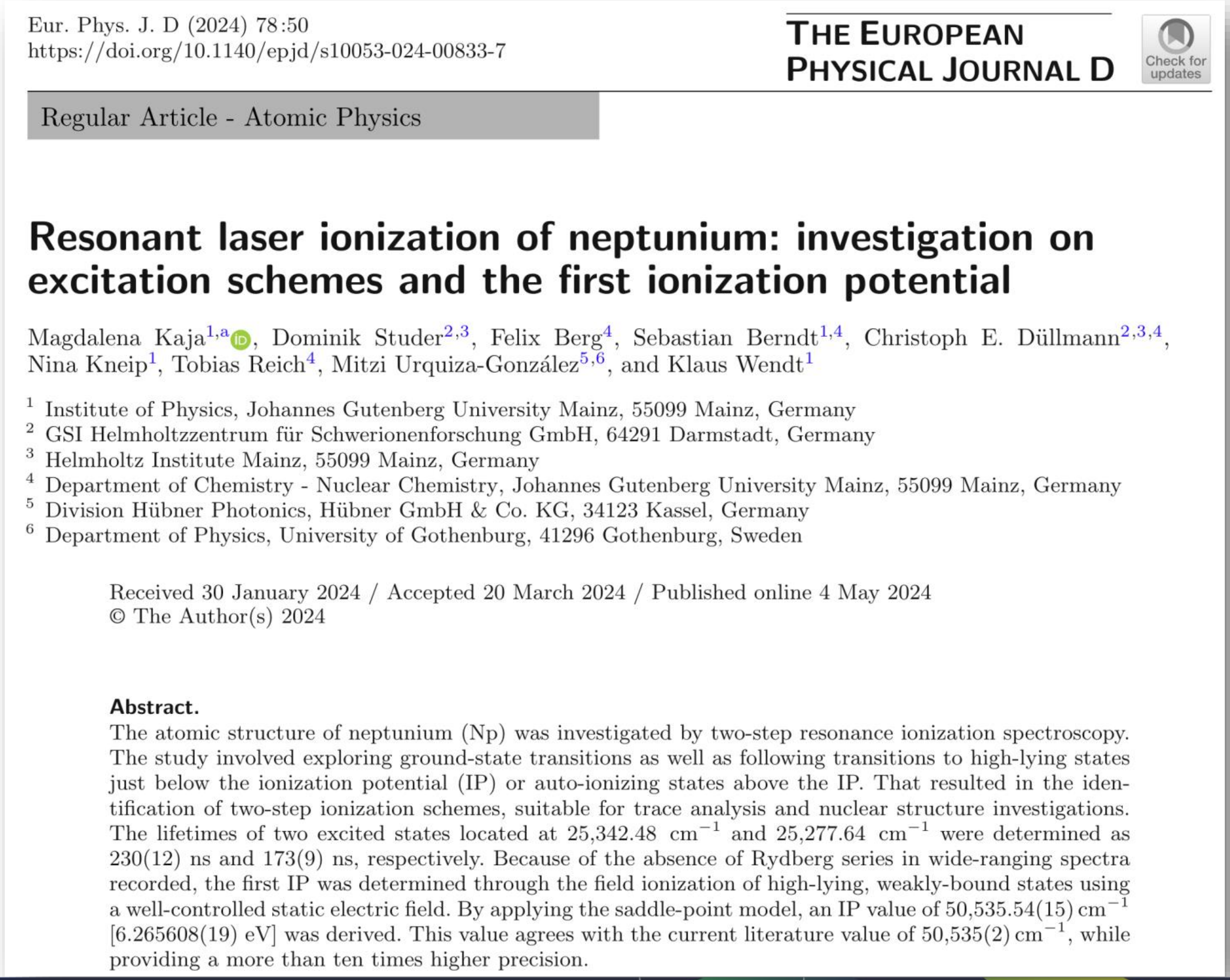
Ionization potential

Scheme investigation



Ionization potential

$$IP = 50\,535.54(15)\ cm^{-1}$$



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https://doi.org/10.1140/epjd/s10053-024-00833-7

THE EUROPEAN
PHYSICAL JOURNAL D

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Regular Article - Atomic Physics

Resonant laser ionization of neptunium: investigation on excitation schemes and the first ionization potential

Magdalena Kaja[1,a], Dominik Studer[2,3], Felix Berg[4], Sebastian Berndt[1,4], Christoph E. Düllmann[2,3,4], Nina Kneip[1], Tobias Reich[4], Mitzi Urquiza-González[5,6], and Klaus Wendt[1]

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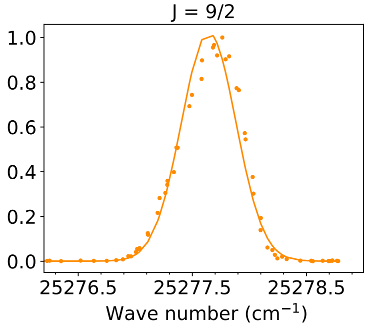
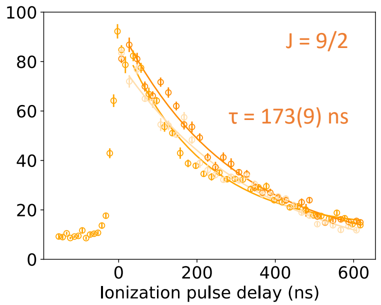
Abstract. The atomic structure of neptunium (Np) was investigated by two-step resonance ionization spectroscopy. The study involved exploring ground-state transitions as well as following transitions to high-lying states just below the ionization potential (IP) or auto-ionizing states above the IP. That resulted in the identification of two-step ionization schemes, suitable for trace analysis and nuclear structure investigations. The lifetimes of two excited states located at 25,342.48 cm^{-1} and 25,277.64 cm^{-1} were determined as 230(12) ns and 173(9) ns, respectively. Because of the absence of Rydberg series in wide-ranging spectra recorded, the first IP was determined through the field ionization of high-lying, weakly-bound states using a well-controlled static electric field. By applying the saddle-point model, an IP value of 50,535.54(15) cm^{-1} [6.265608(19) eV] was derived. This value agrees with the current literature value of 50,535(2) cm^{-1}, while providing a more than ten times higher precision.

Line profiles

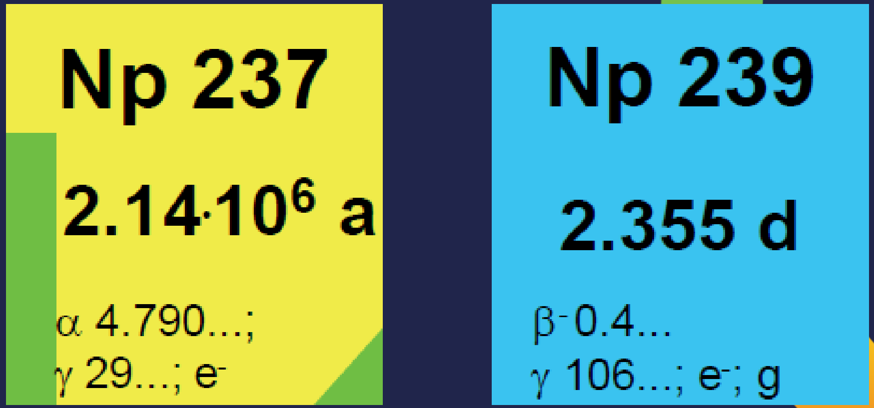


Lifetimes measurements



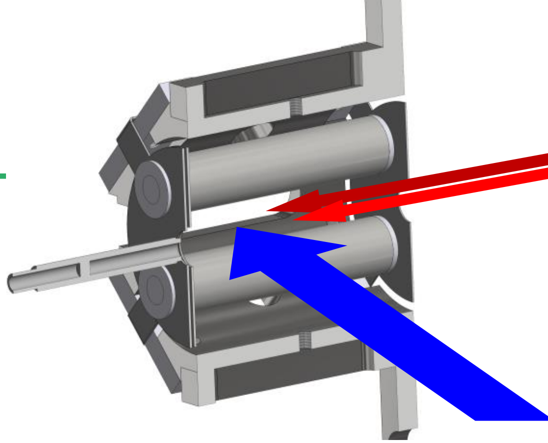
High-resolution spectroscopy

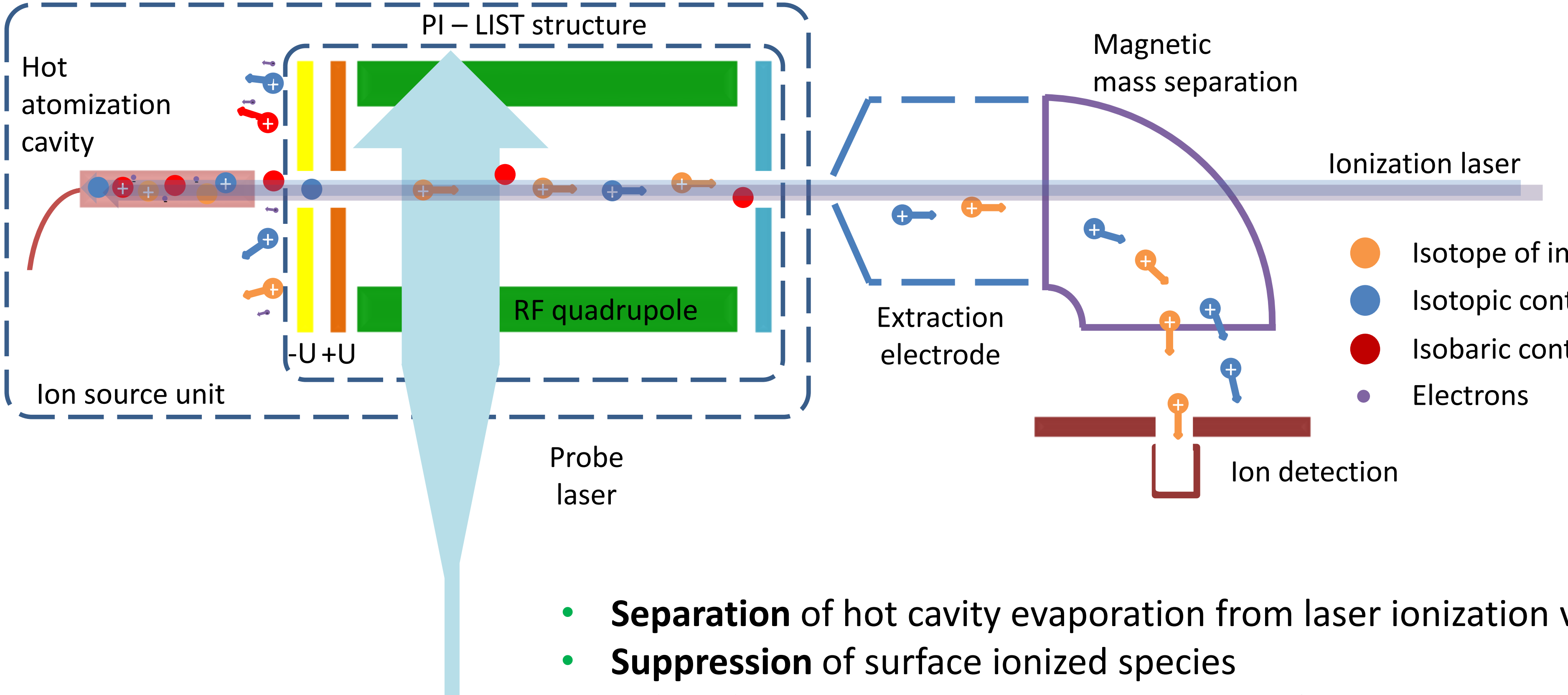
Hyperfine structure measurements
Extraction of nuclear moments



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

PI-LIST - Perpendicularly Illuminated LIST





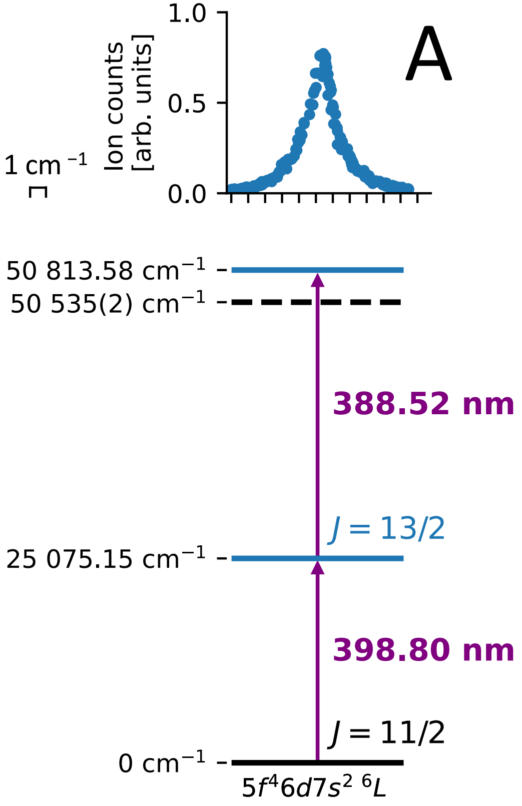
- 🟠 Isotope of interest
- 🔵 Isotopic contamination
- 🔴 Isobaric contamination
- • Electrons

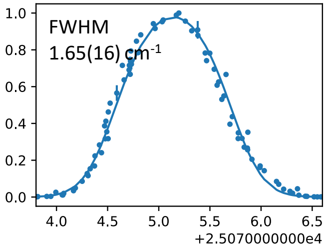
- **Separation** of hot cavity evaporation from laser ionization volume
- **Suppression** of surface ionized species
- **Pulsed laser ionzation** inside RF quadrupole structure
- **Reduced Doppler width** in laser transversal interaction

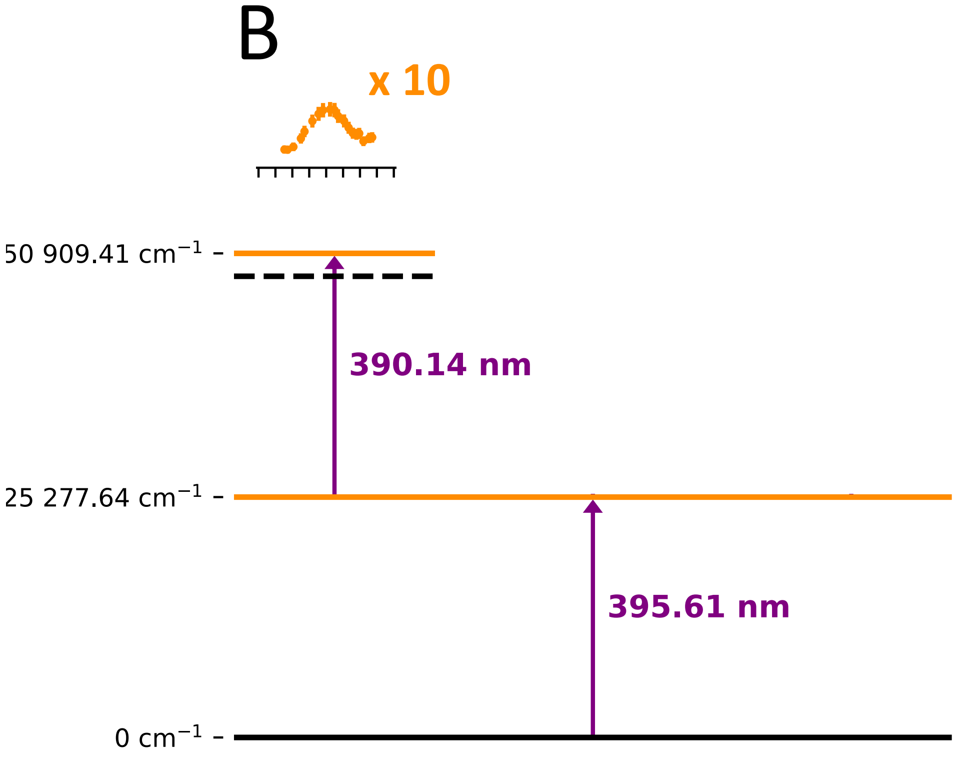
[1] R. Heinke et al., Hyperfine Interact **238**, 6 (2017)
[2] R. Heinke, … , M. Kaja et. al., NIM B, **541**, 8-12, (2023)

Ionization scheme development

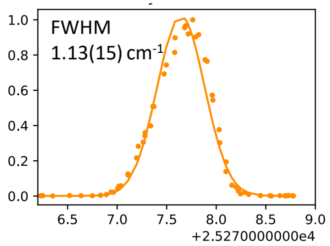
[1] M. Kaja et al., Eur. Phys. J. D **78**, 50 (2024)







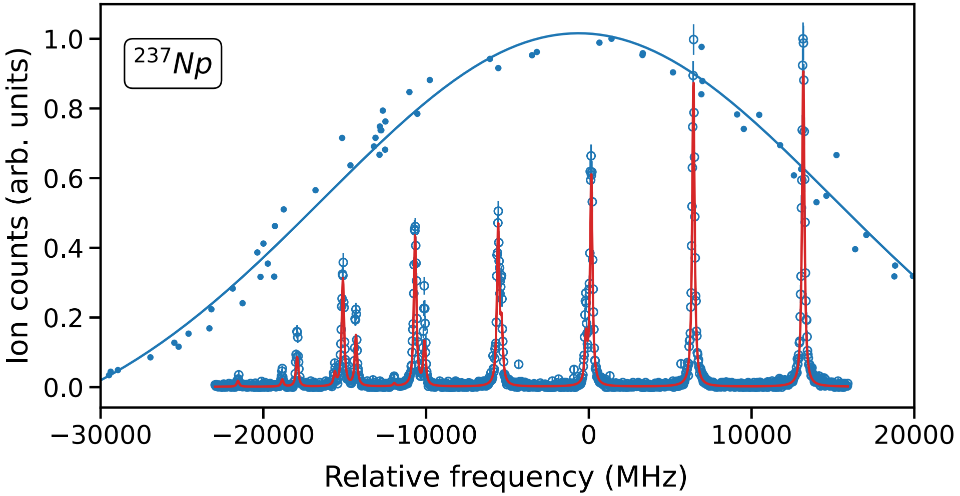
FES line profiles

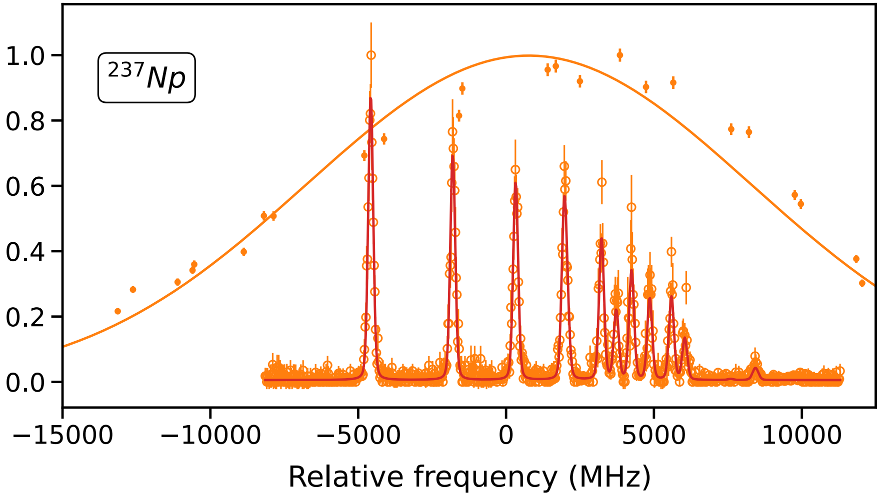


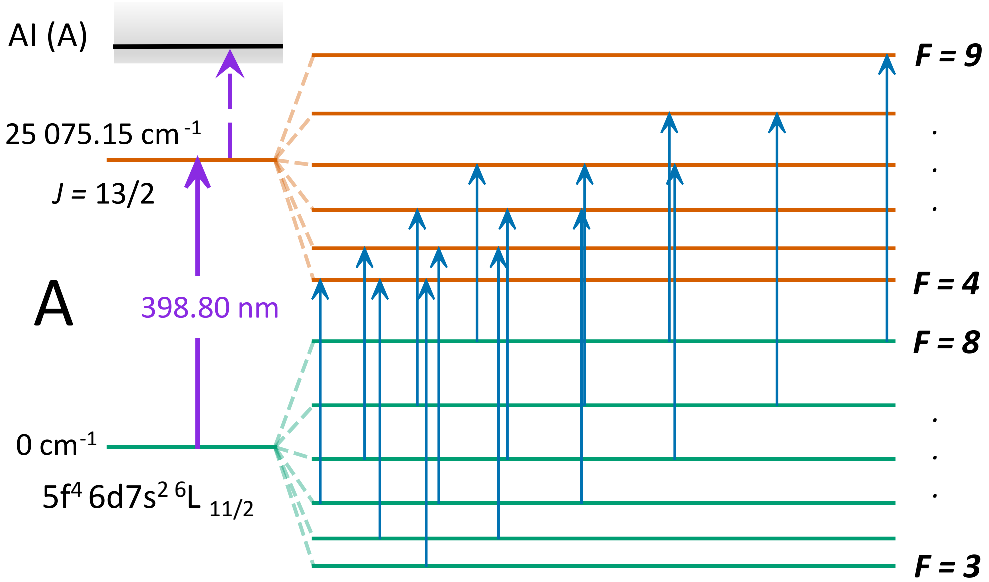
All FESs:
S. Raeder et al.,
Spectrochim. Acta B,
66, 242 – 247 (2011)

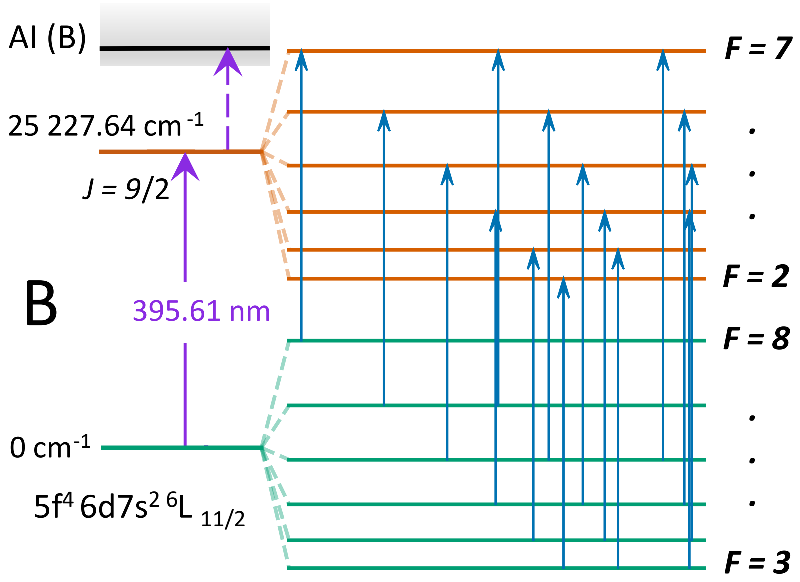
Hyperfine spectroscopy in ^{237}Np (I = 5/2)

[1] M. Kaja et al., Eur. Phys. J. A **60**, 140 (2024)

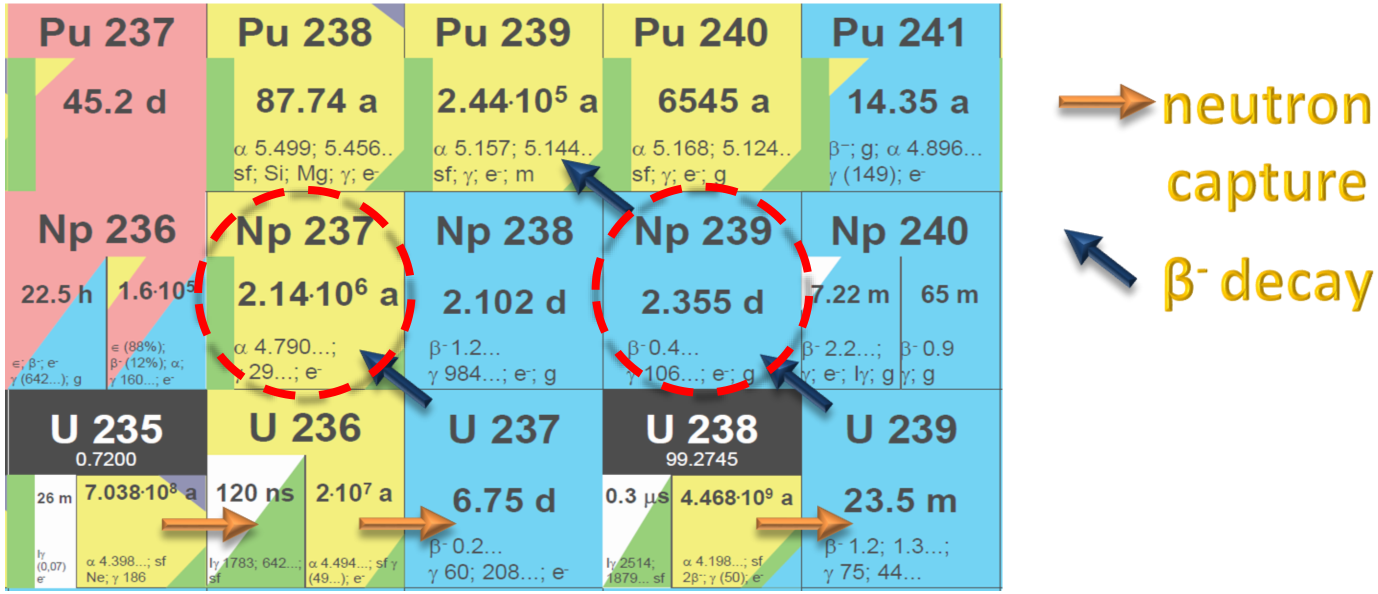








Neptunium production and trace analysis



Sample:

- 10^{13} atoms of ^{237}Np
- 10^{11} atoms of ^{239}Np

^{239}Np production:

- irradiation of ^{238}U at
- reactor TRIGA Mark II Mainz

^{237}Np – stock solution

Trace analysis of environmental samples is of high relevance

- ^{239}Np as a tracer for precise quantification
- Identification of efficient ionization schemes:
  - High elemental selectivity
  - Isotope related effects like hyperfine structures (HFS) and isotope shift (IS)
    - large splitting and shifts observed in neptunium

Hyperfine spectroscopy in ^{237}Np and ^{239}Np

[1] M. Kaja et al., Eur. Phys. J. A **60**, 140 (2024)

Np 239

2.355 d

β^- 0.4...
γ 106...; e^-; g

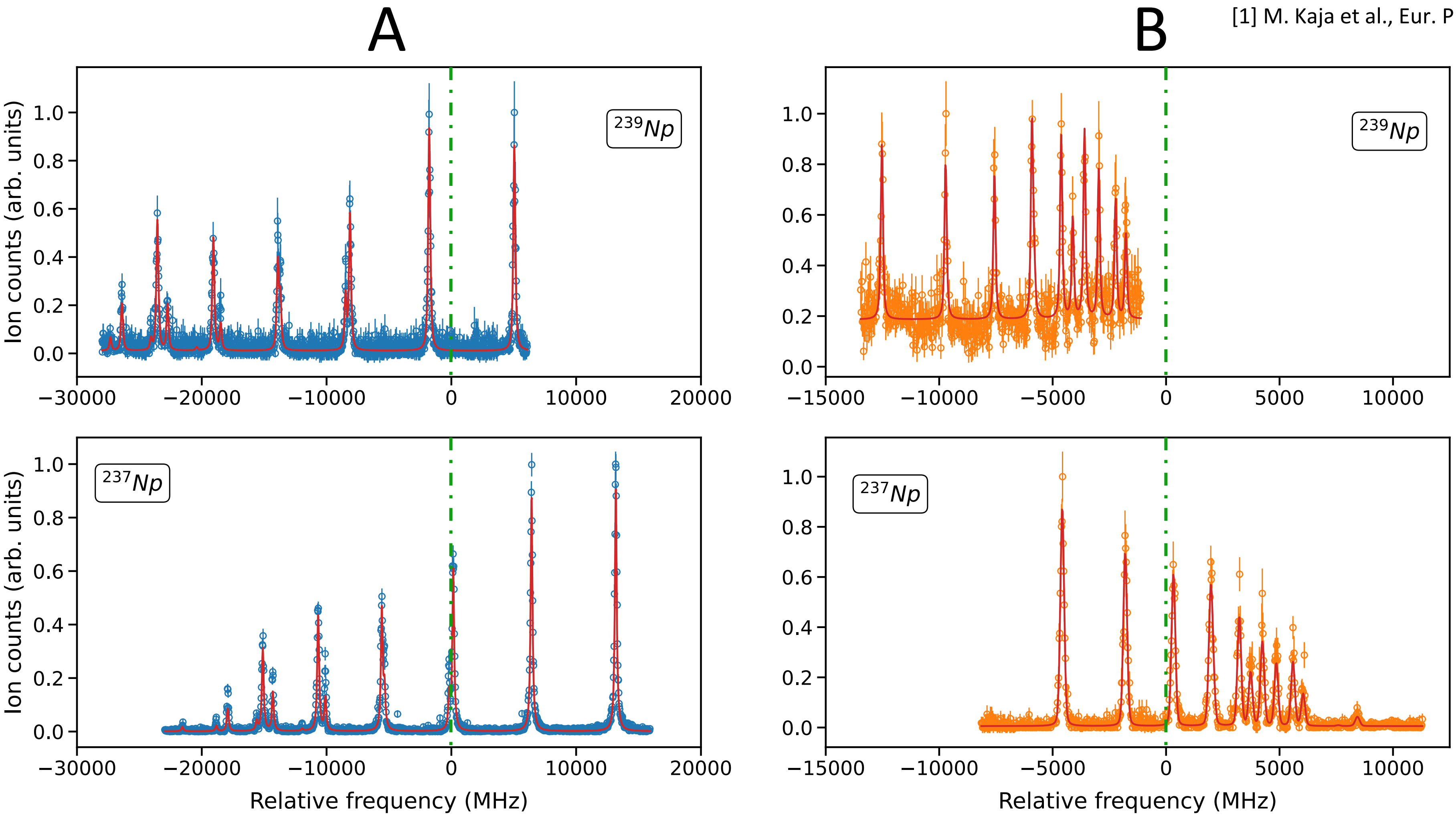
I = 5/2

Np 237

$2.14 \cdot 10^6$ a

α 4.790...;
γ 29...; e^-

I = 5/2



$$\delta\nu_i^{A,A'} = \nu_i^{A'} - \nu_i^{A}$$

$$\boxed{\delta\nu_{399\,\mathrm{nm}}^{237,239} = -8\,168(17)\ \mathrm{MHz}}$$

$$\boxed{\delta\nu_{396\,\mathrm{nm}}^{237,239} = -7\ 892(13)\ \mathrm{MHz}}$$

Hyperfine parameters and nuclear moments

			^{237}Np		
State	E (cm^{-1})	J	$\mathcal{A}_{exp}$	$\mathcal{B}_{exp}$	$\mathcal{A}_{lit}^{[2]}$
GS	0	11/2	776.08(20)	928(10)	778
FES$_A$	25 075.15	13/2	1470.09(18)	323(8)	1470
FES$_B$	25 277.64	9/2	570.08(22)	-302(9)	-

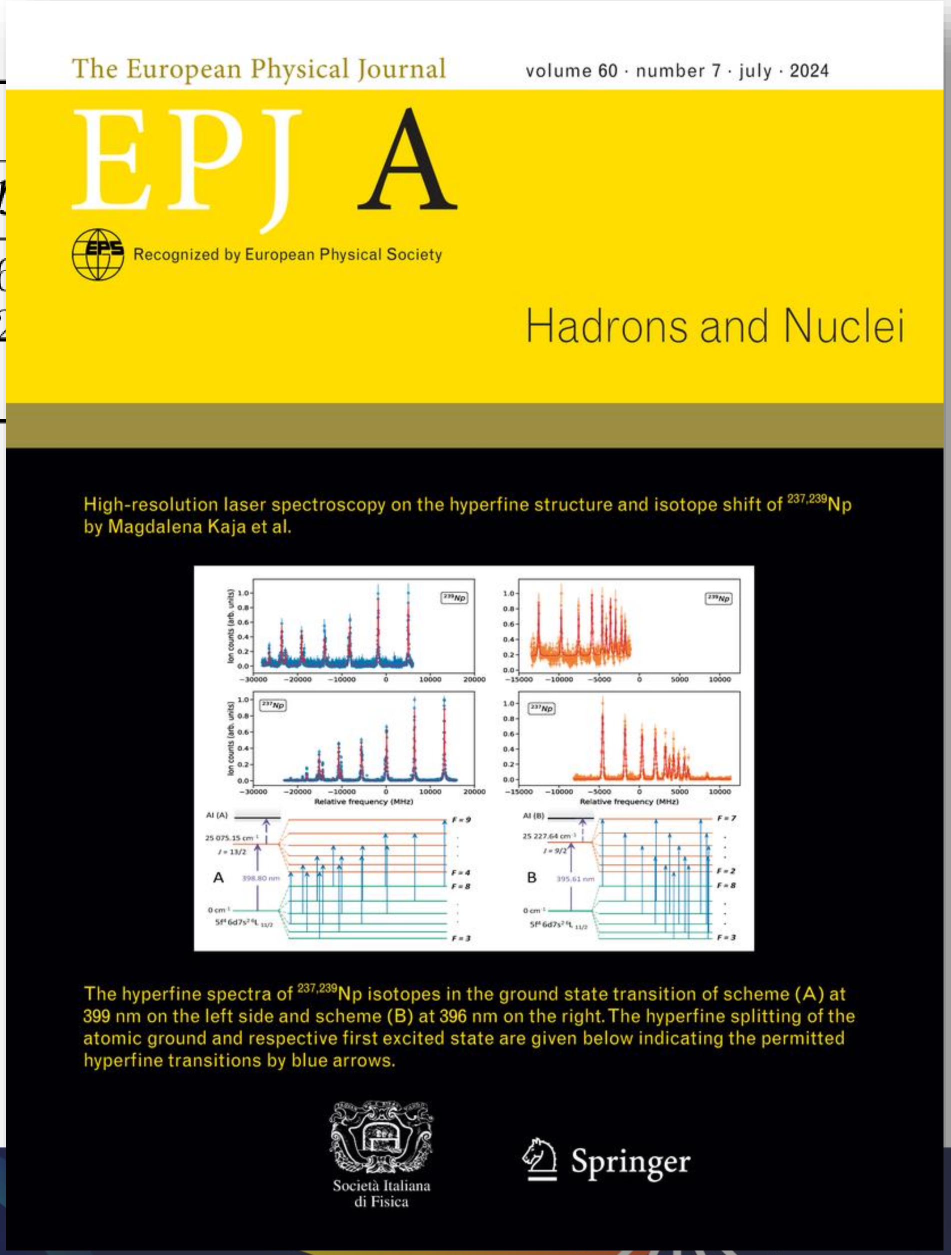
Determination of nuclear moments

$$\frac{A}{A_{\text{ref}}} = \frac{I_{\text{ref}}}{I}\,\frac{\mu_I}{\mu_{I,\text{ref}}} \qquad \frac{B}{B_{\text{ref}}} = \frac{Q_s}{Q_{s,\text{ref}}}$$

measured literature

Isotope	I	μ_I [μ_N]	Q_s [eb]
^{237}Np	5/2	+3.14(4) [3]	+3.886(6) [4]
^{239}Np	5/2	+3.18(4)	+4.05(2)

reference



The European Physical Journal

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EPJ A

Recognized by European Physical Society

Hadrons and Nuclei

High-resolution laser spectroscopy on the hyperfine structure and isotope shift of ^{237,239}Np by Magdalena Kaja et al.

The hyperfine spectra of ^{237,239}Np isotopes in the ground state transition of scheme (A) at 399 nm on the left side and scheme (B) at 396 nm on the right. The hyperfine splitting of the atomic ground and respective first excited state are given below indicating the permitted hyperfine transitions by blue arrows.

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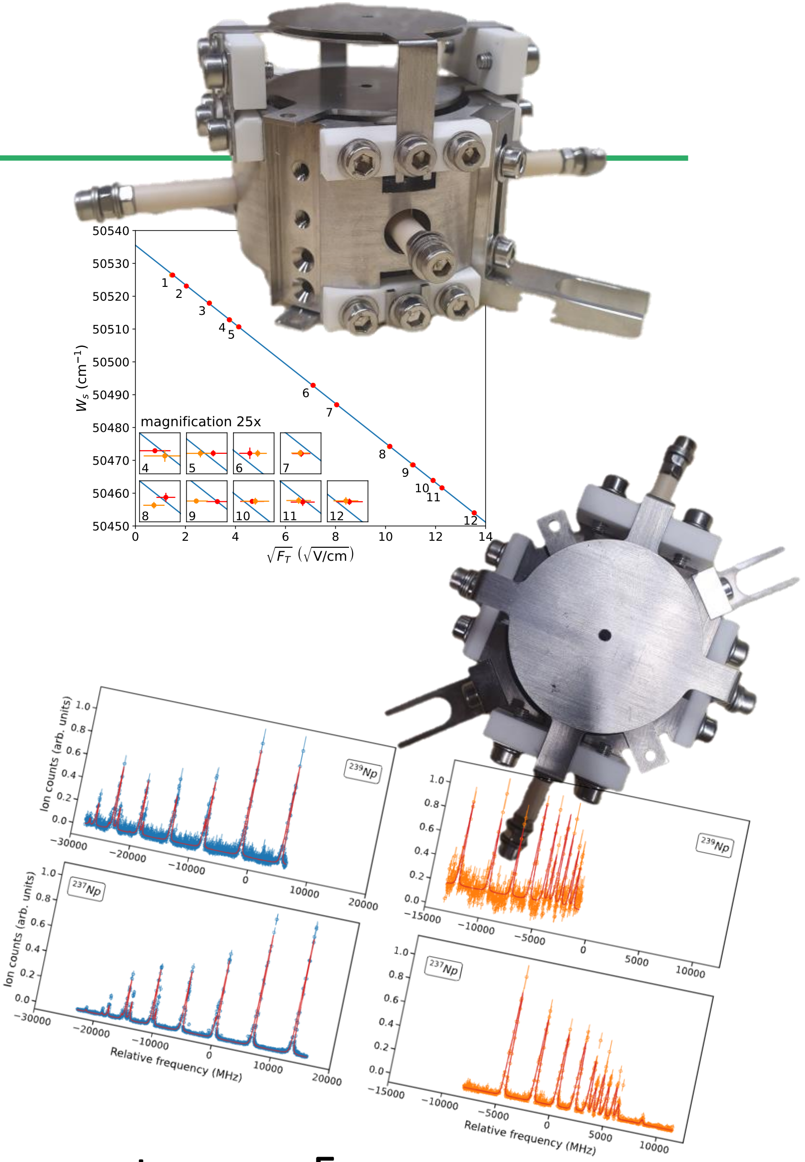
Conclusion

- Atomic structure investigations of neptunium
  - Ionization schemes, atomic energy levels, lifetimes
  - Precise IP determination of 50 535.54(15) cm^{-1}
  - *M. Kaja et al., Eur. Phys. J. D **78**, 50 (2024)*
- The FI-LIST – a new useful type of the PI-LIST
  - Dedicated tool for IP studies on rare elements with complex structure
  - Suitable off-line as well as on-line applications
  - Capable of measurements at very low electric fields of ~ 1 V/cm
  - *M. Kaja et al., NIM B **547**, 165213 (2024)*
- High resolution spectroscopy in ^{237}Np and ^{239}Np
  - Isotope shifts
  - Nuclear moments for ^{239}Np
  - *M. Kaja et al., Eur. Phys. J. A **60**, 140 (2024)*



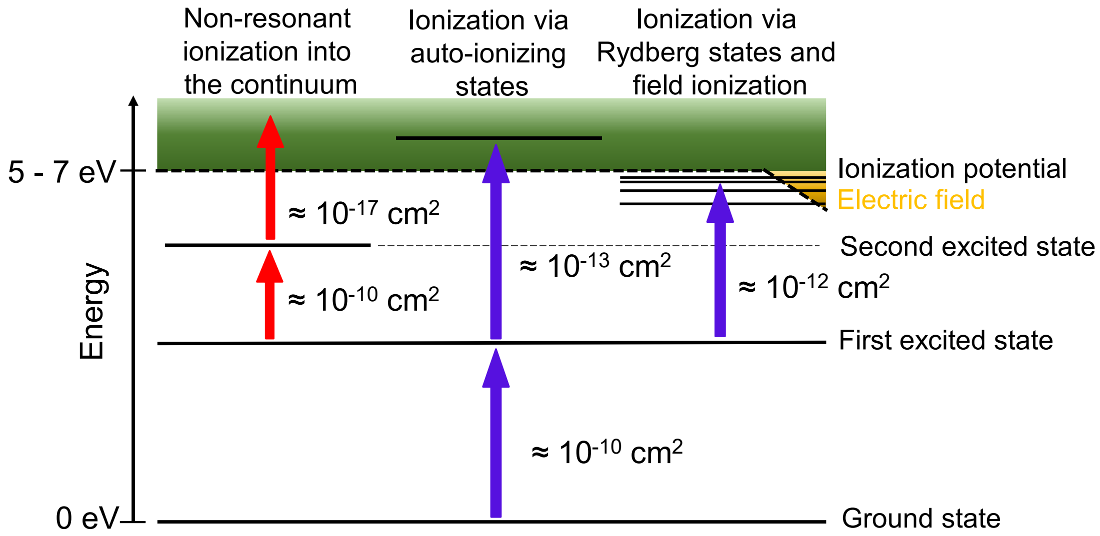
Outlook

- Off- and on-line IP determination of other elements with complex spectra, e.g. Fm
- Extension of the high-resolution spectroscopy to other isotopes of neptunium

LARISSA

Thank you!

Technique: Resonance ionization mass spectrometry

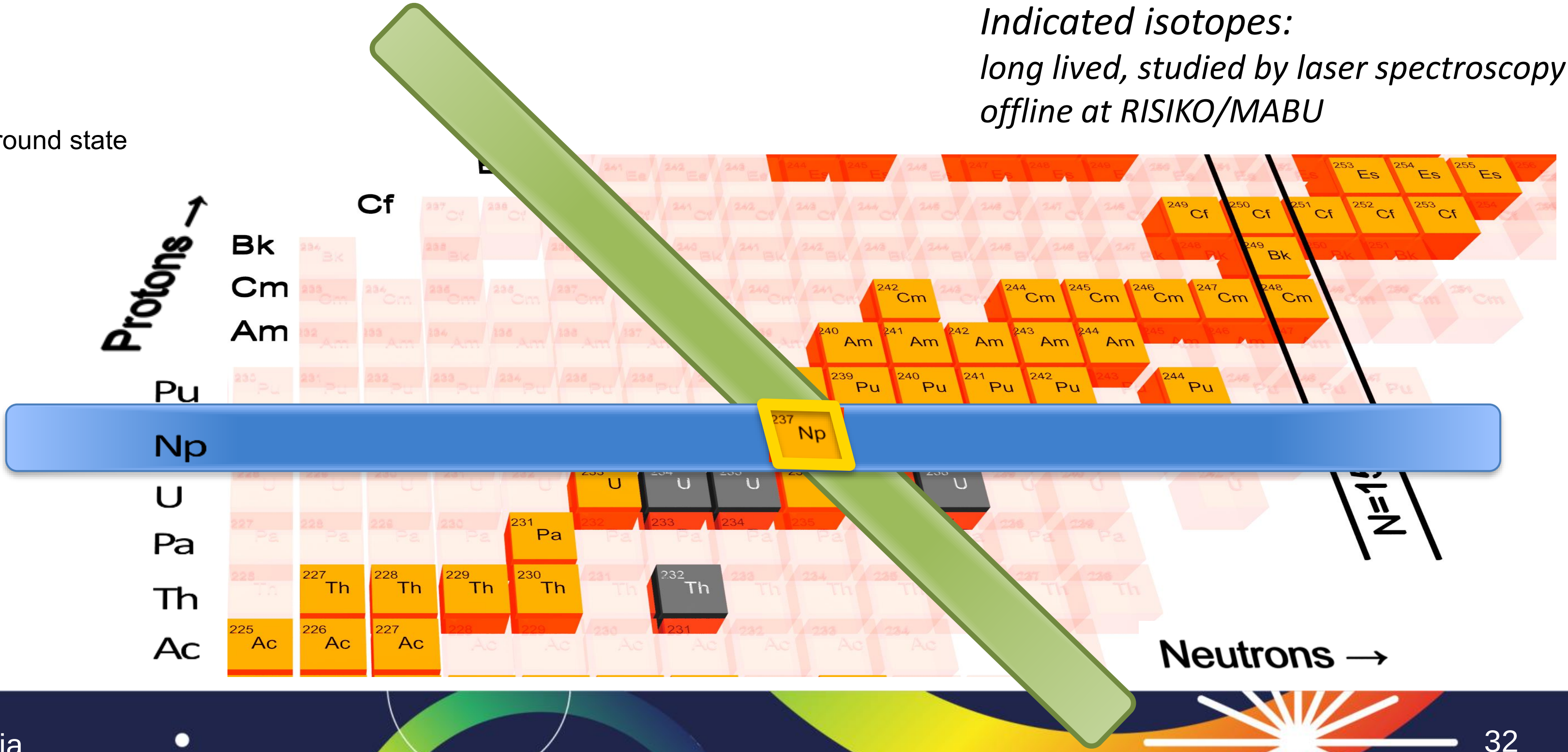


Mass spectrometry

- Separation of m/q
- High detection efficiency

Laser ionzation and spectroscopy

- Highly efficient process
- High element selectivity

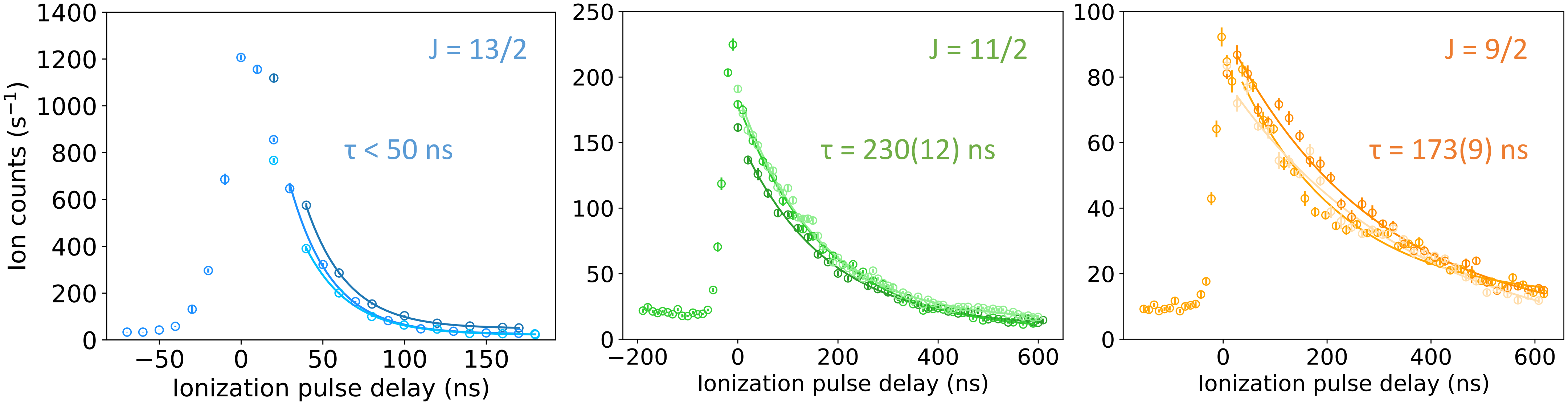


Indicated isotopes:
long lived, studied by laser spectroscopy offline at RISIKO/MABU

Lifetime investigations of first excited states

[1] M. Kaja et al., Eur. Phys. J. D **78**, 50 (2024)

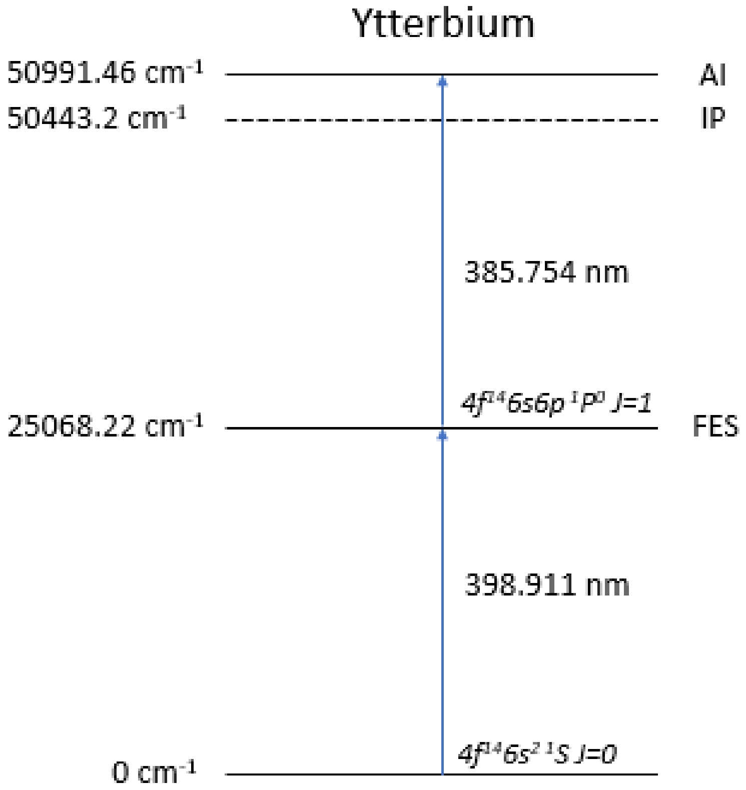
The excited-state population decay as a function of the ionization-pulse delay.



Population development in the "dark“ time between pulses corresponds to an exponential distribution.

This method is applicable to lifetimes much longer than the laser-pulse duration (≈50ns) and much shorter than the collision lifetime of the excited atoms within the laser beam in the atomizer tube(≈3µs)

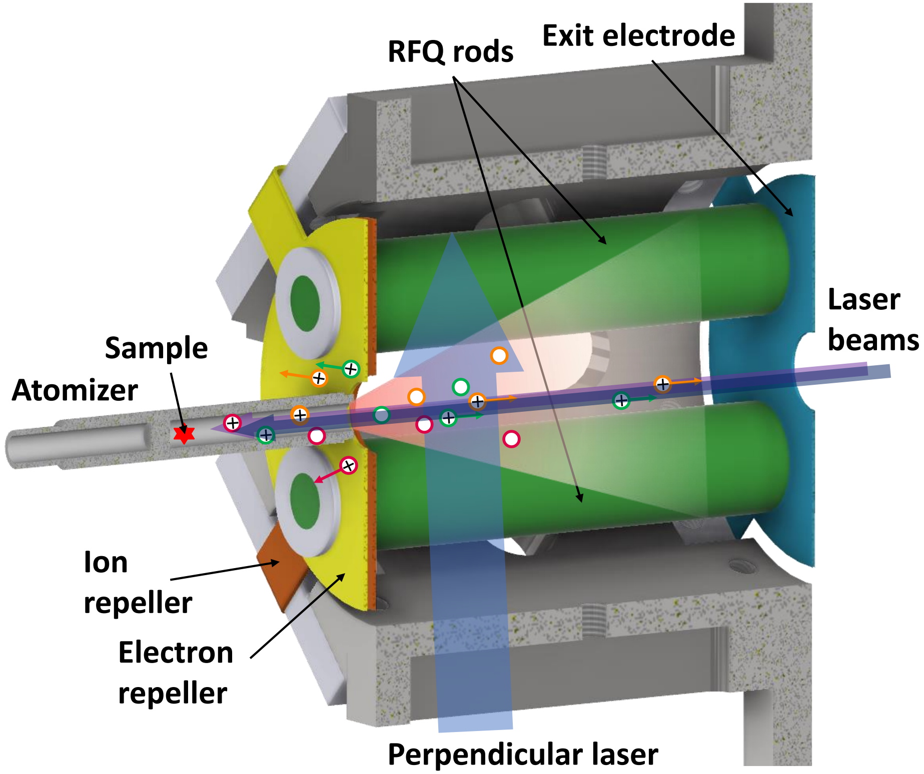
Ytterbium


Ytterbium
50991.46 cm⁻¹
AI
50443.2 cm⁻¹
IP
385.754 nm
4f¹⁴6s6p ¹P⁰ J=1
25068.22 cm⁻¹
FES
398.911 nm
4f¹⁴6s² ¹S J=0
0 cm⁻¹

Laser Ion Source and Trap (LIST)

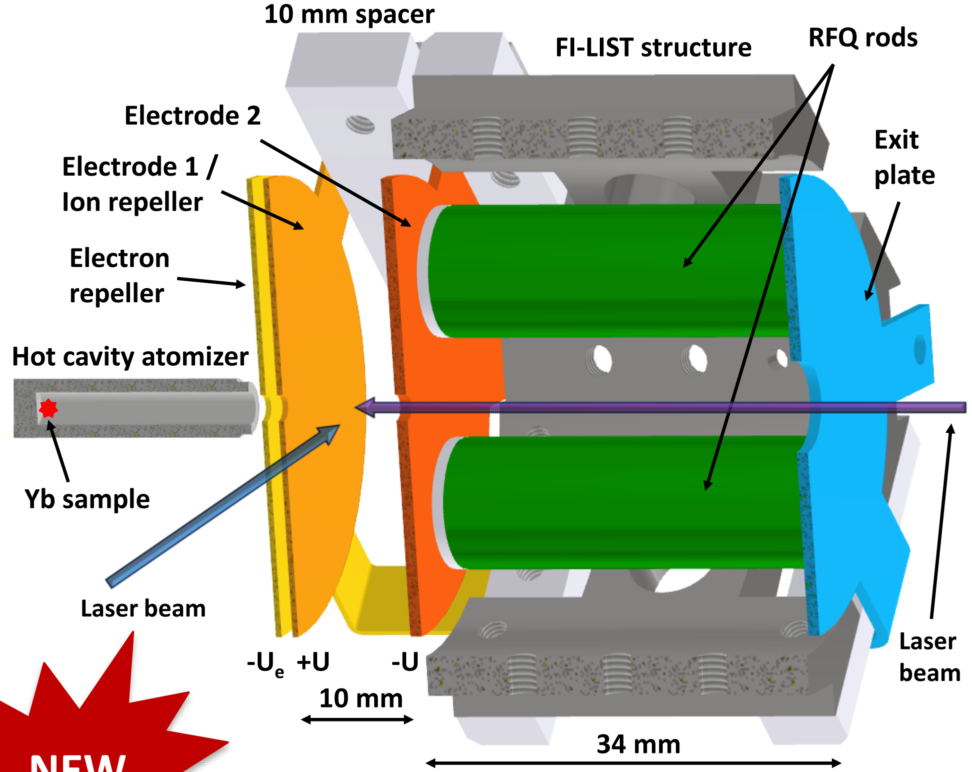
Perpendicularly Illuminated LIST

PI-LIST



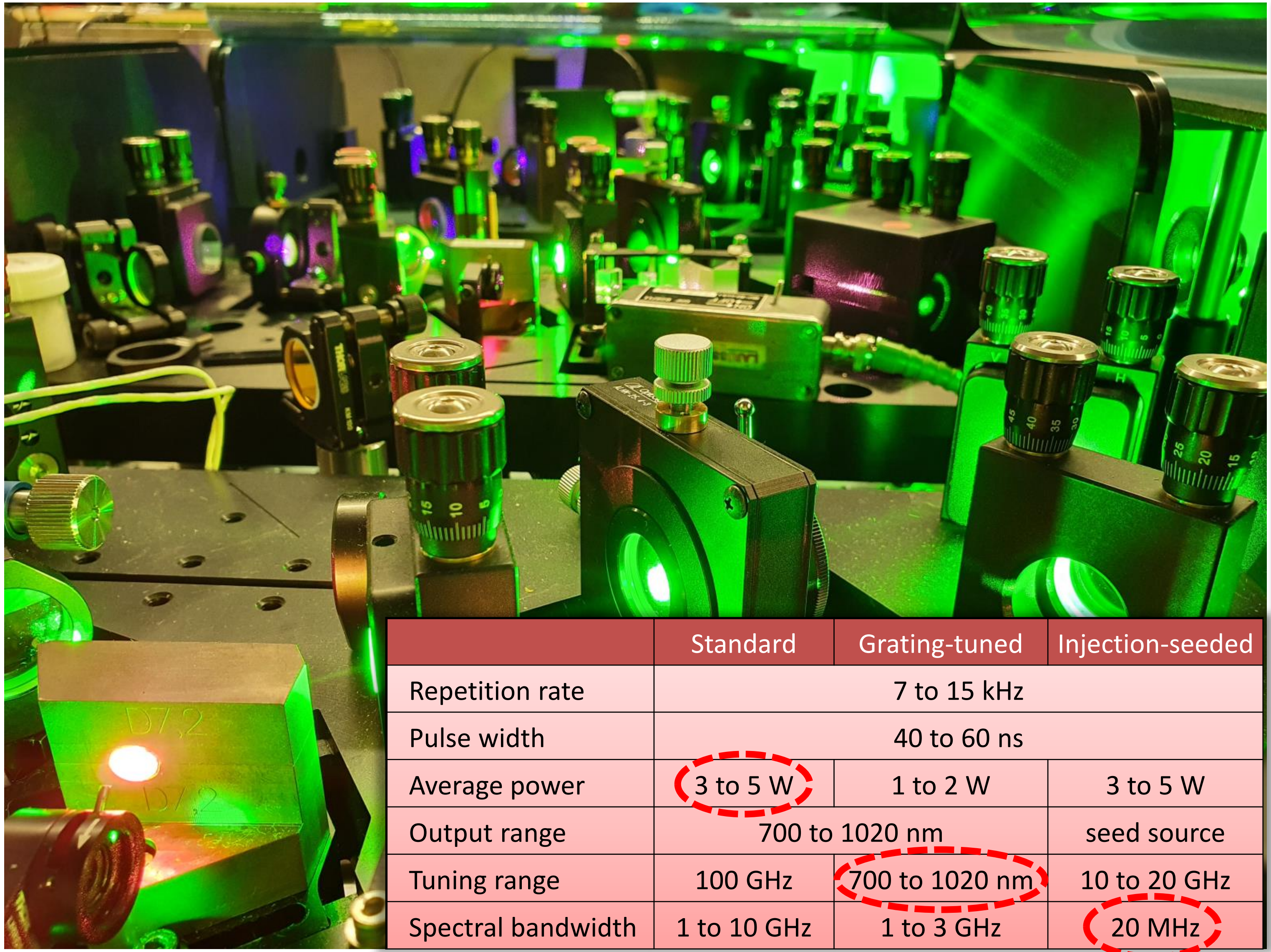
Field Ionization LIST

FI-LIST

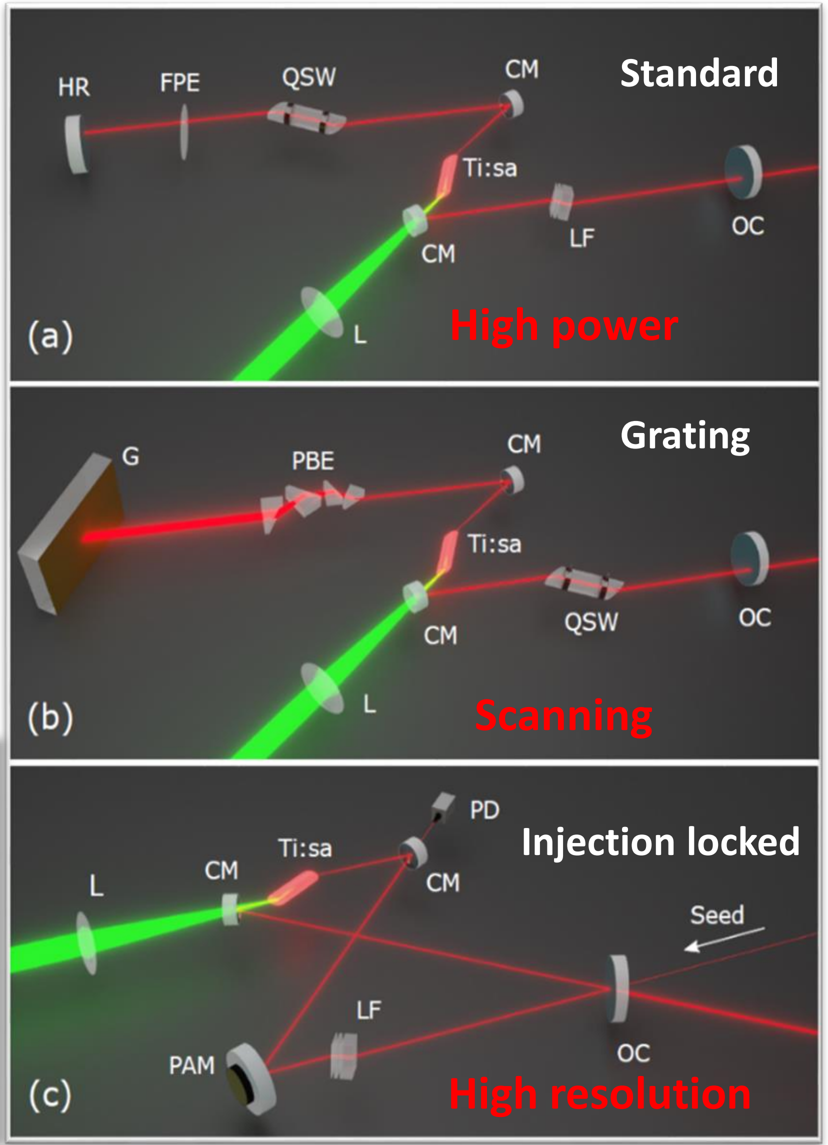


NEW

Ti:Sapphire lasers system



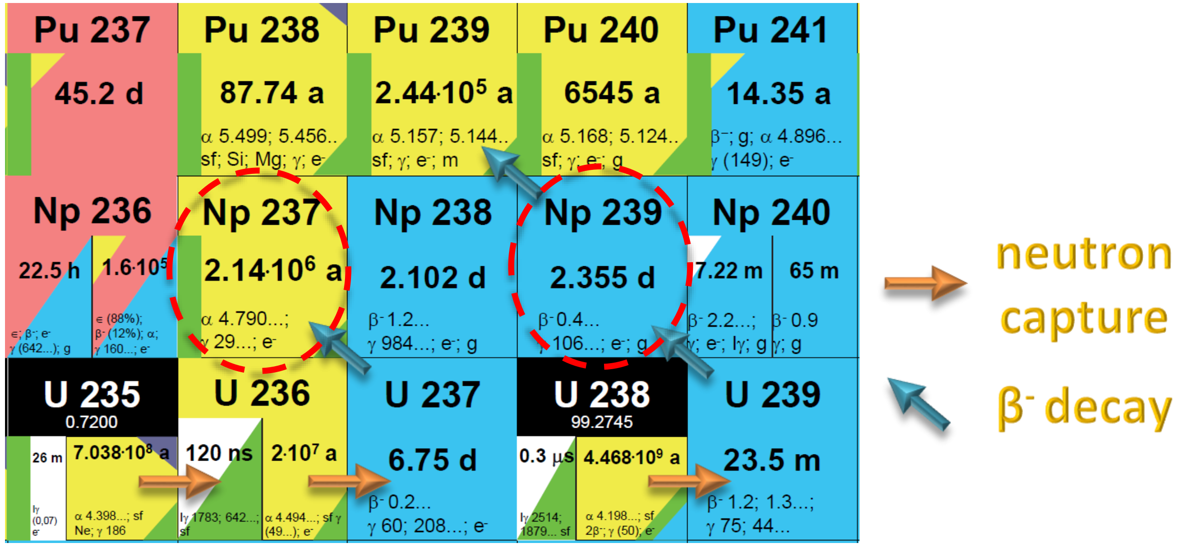
	Standard	Grating-tuned	Injection-seeded
Repetition rate	7 to 15 kHz		
Pulse width	40 to 60 ns		
Average power	3 to 5 W	1 to 2 W	3 to 5 W
Output range	700 to 1020 nm		seed source
Tuning range	100 GHz	700 to 1020 nm	10 to 20 GHz
Spectral bandwidth	1 to 10 GHz	1 to 3 GHz	20 MHz



Neptunium

- Radioactive actinide
- Long half-life - $^{237}Np - 2.14 \cdot 10^{6}$ y
- High radiotoxicity

Neptunium production



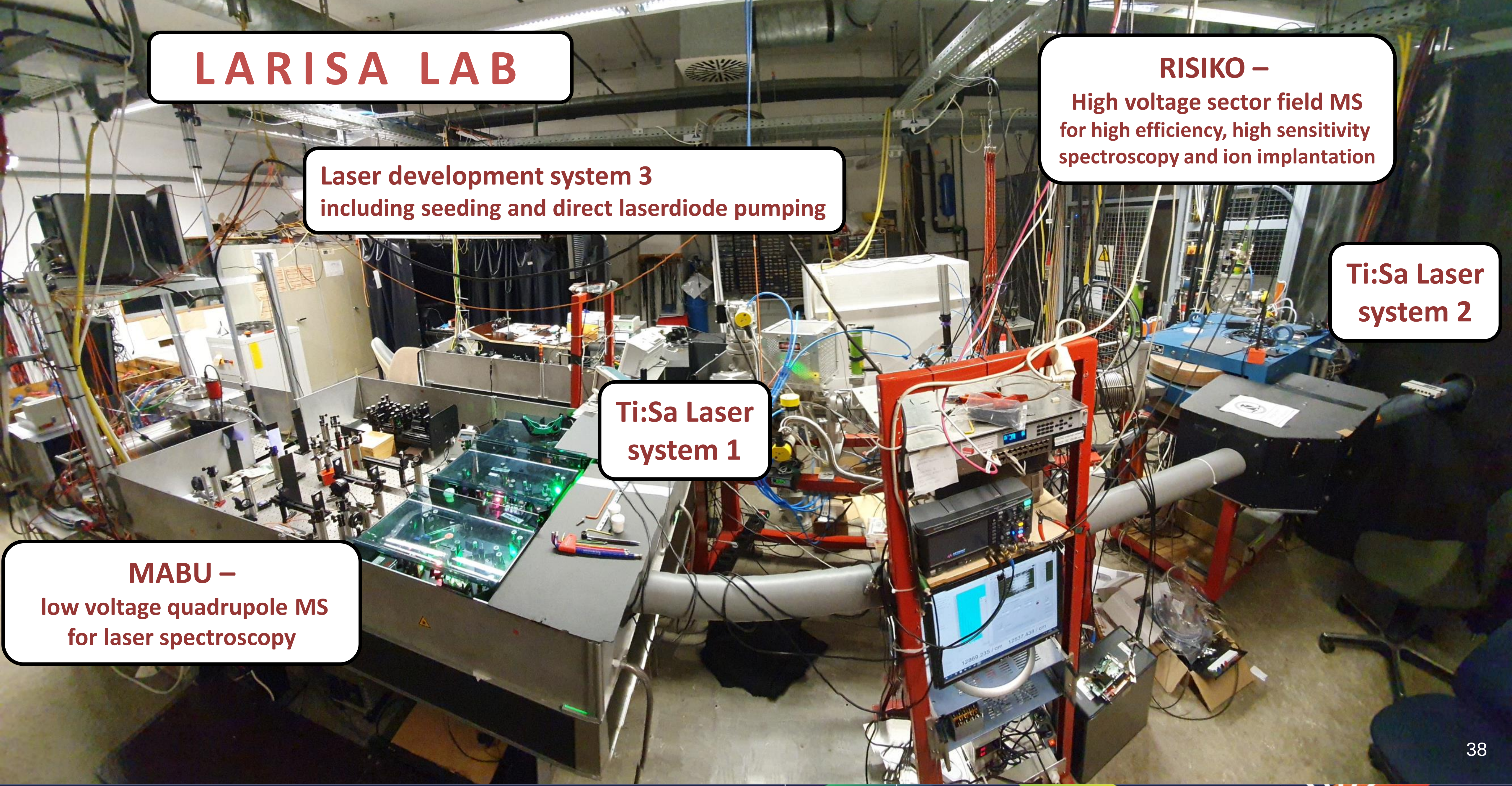
The development of efficient and selective laser ionization schemes plays an important role for Np spectroscopy and trace analysis.

It is important to take into account
the isotope-related effects in ionization schemes
coming from hyperfine structure (HFS) and isotope shift (IS).

- ^{239}Np
  - Moments unknown

[1] Kohler, S; et al. Spectrochim. Acta B,52, 717 – 726, (1997)
[2] Kazakov, V; et al. Phys. Scr., 92, 10, (2017)
[3] Stone, N.J. At. Data Nucl. Data Tables, 90, 1, 75-176, (2005)

LARISA LAB



Laser development system 3
including seeding and direct laserdiode pumping

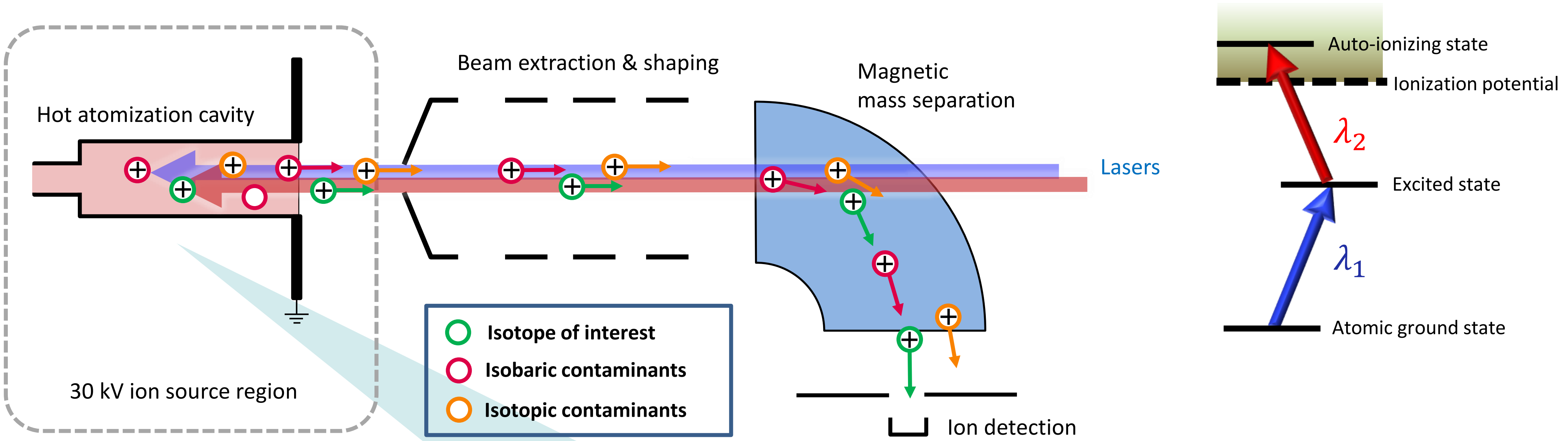
RISIKO –
High voltage sector field MS
for high efficiency, high sensitivity
spectroscopy and ion implantation

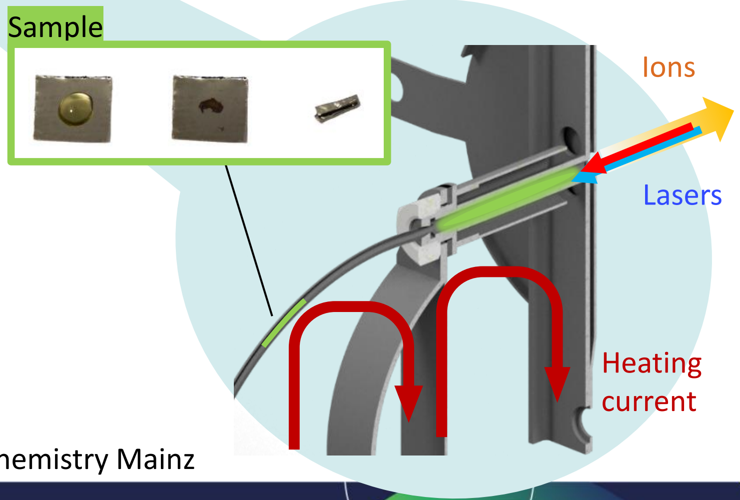
Ti:Sa Laser system 2

Ti:Sa Laser system 1

MABU –
low voltage quadrupole MS
for laser spectroscopy

RISIKO mass separator

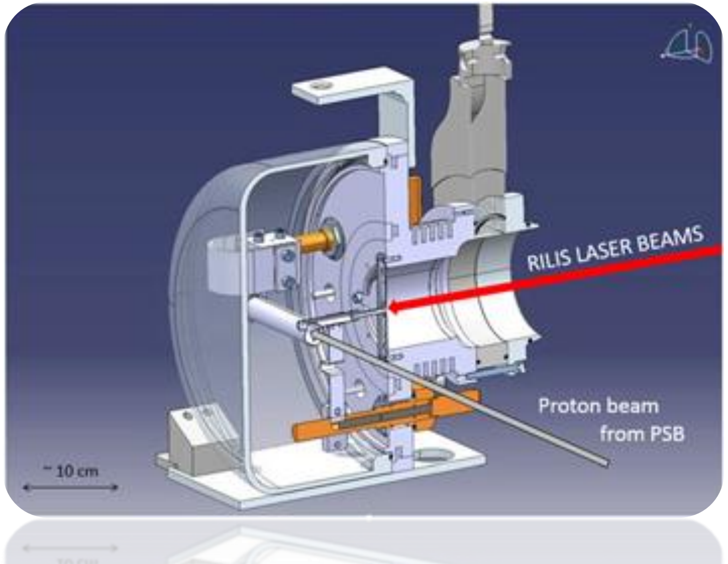




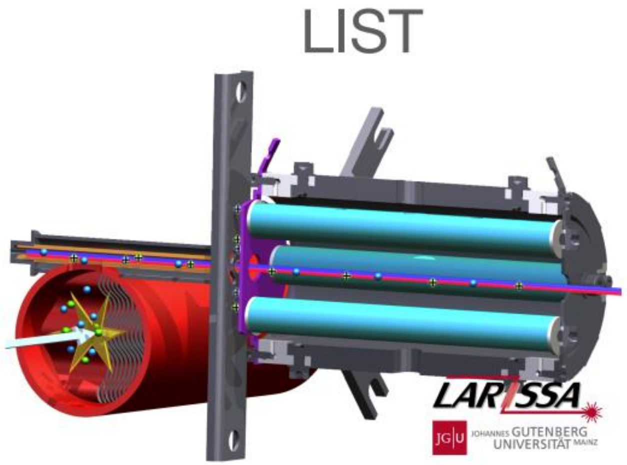
- Chemical sample preparation*
- Sample evaporation in hot cavity
- Multi-step photoionization by pulsed lasers
- Mass separation in dipole magnet $\frac{m}{\Delta m} \approx 800$
- Single ion detection

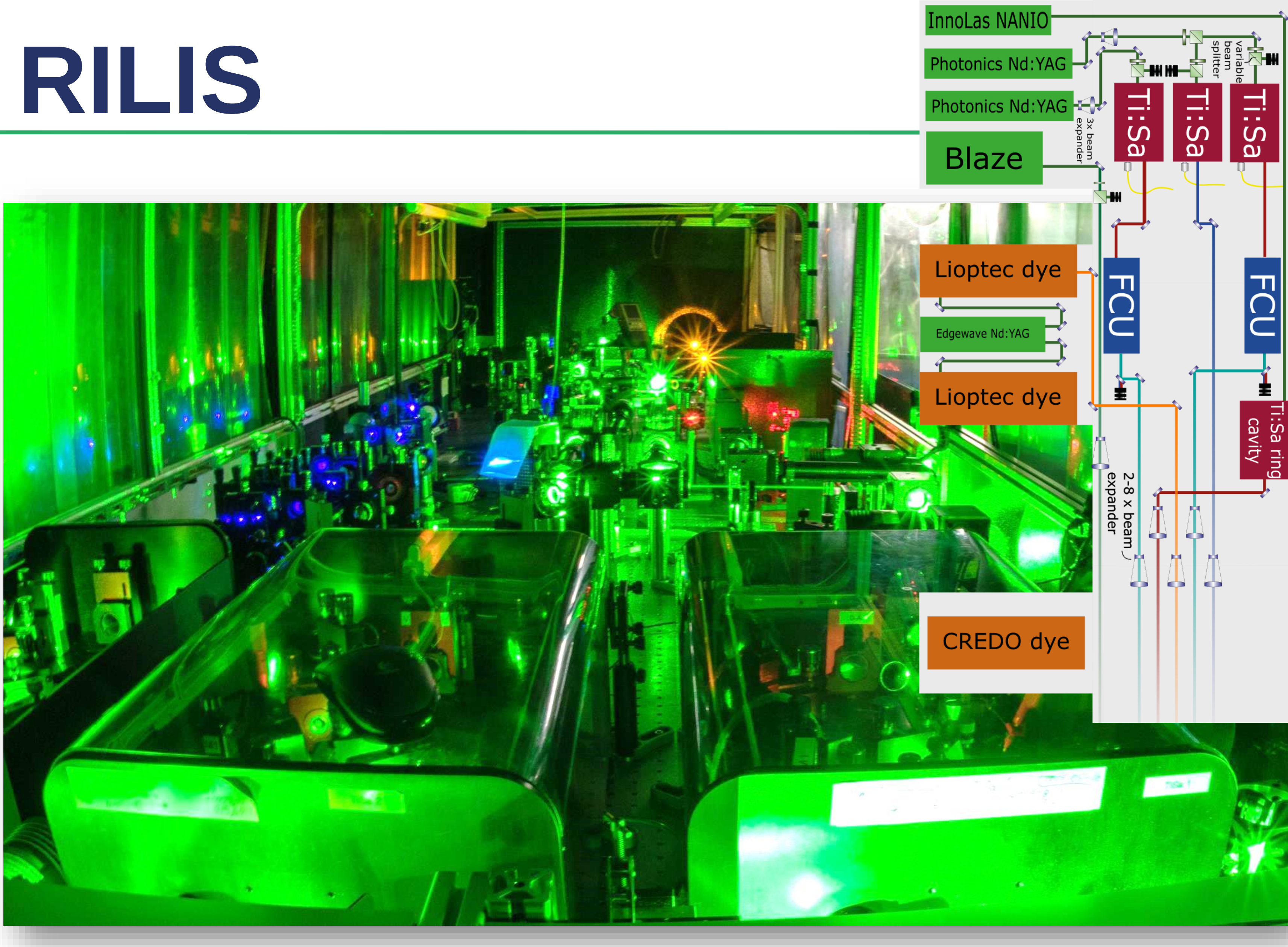
*in collaboration with Dpt. of Nuclear Chemistry Mainz

ISOLDE RILIS



Valentin Fedosseev et al 2017 J. Phys. G: Nucl. Part. Phys. 44 084006

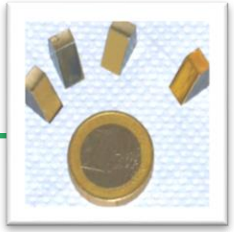


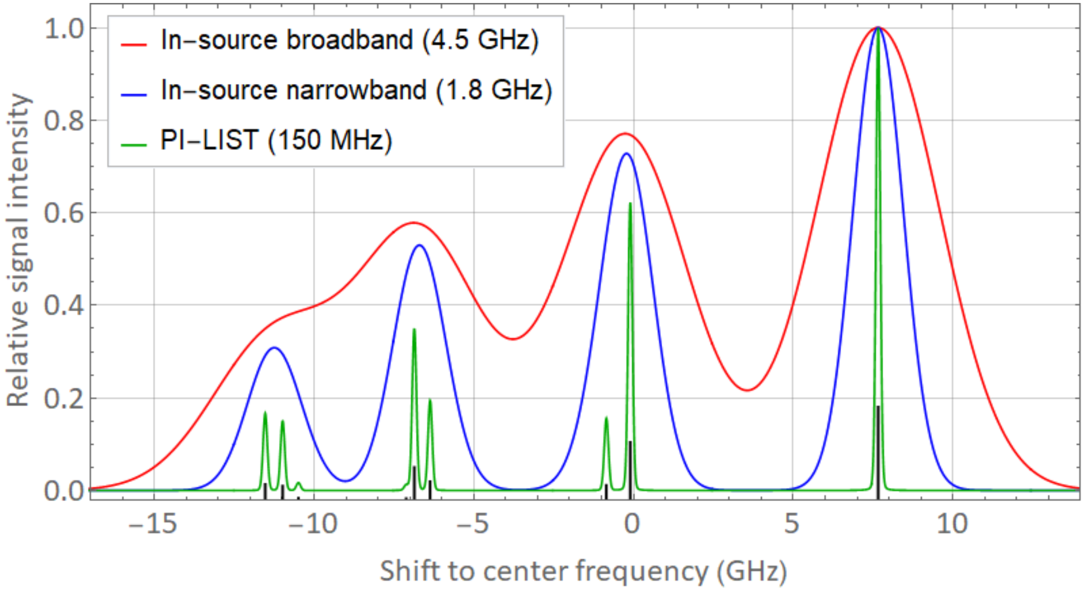


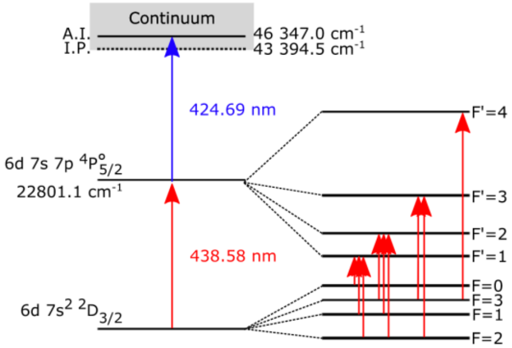
Courtesy of Reinhard Heinke and Asar AH Jaradat

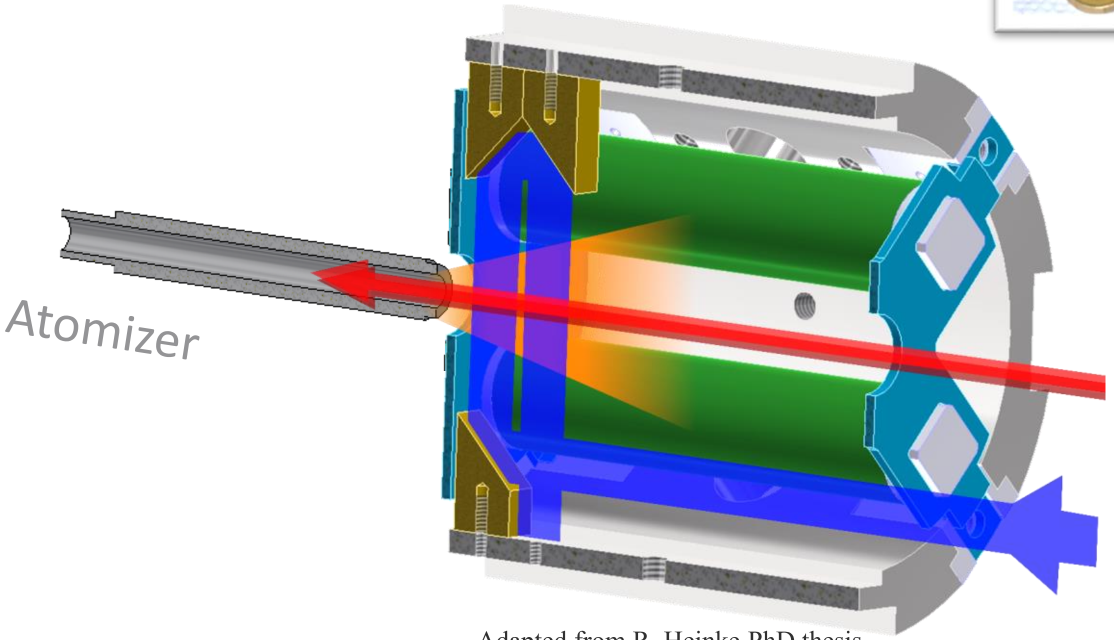
“Sub-Doppler” Hot Cavity In-source Spectroscopy

Robust metallic mirrors









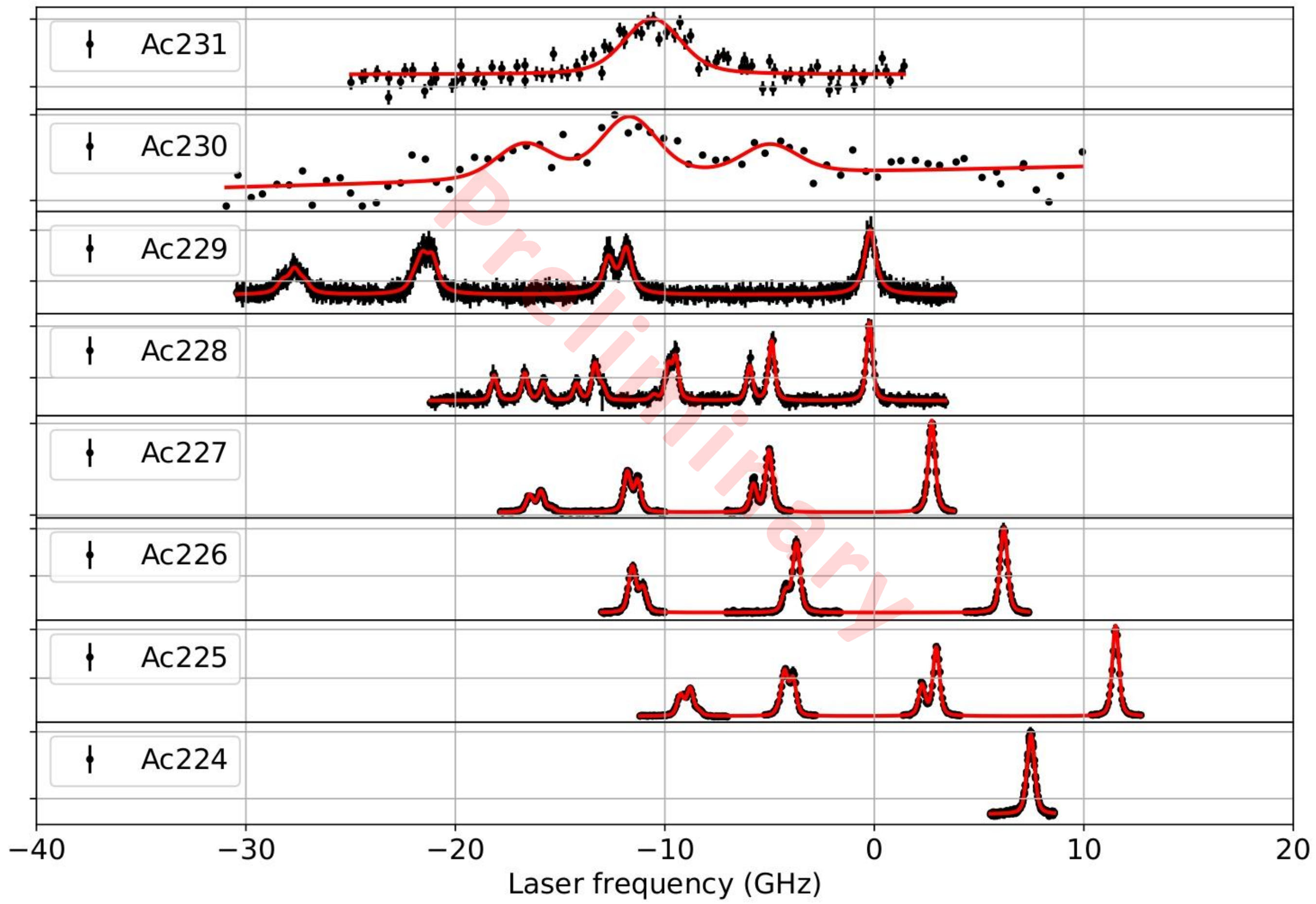
Adapted from R. Heinke PhD thesis

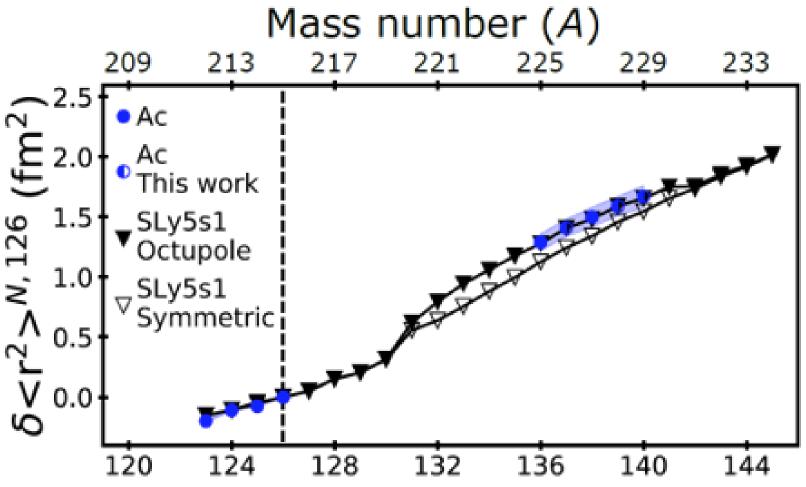
- Crossed atom beam / laser geometry in LIST structure
- Selection of **reduced Doppler ensemble** in laser intersection volume
- Suitable **narrow-band laser**

E. Verstraelen et al, PHYSICAL REVIEW C 100, 044321 (2019)

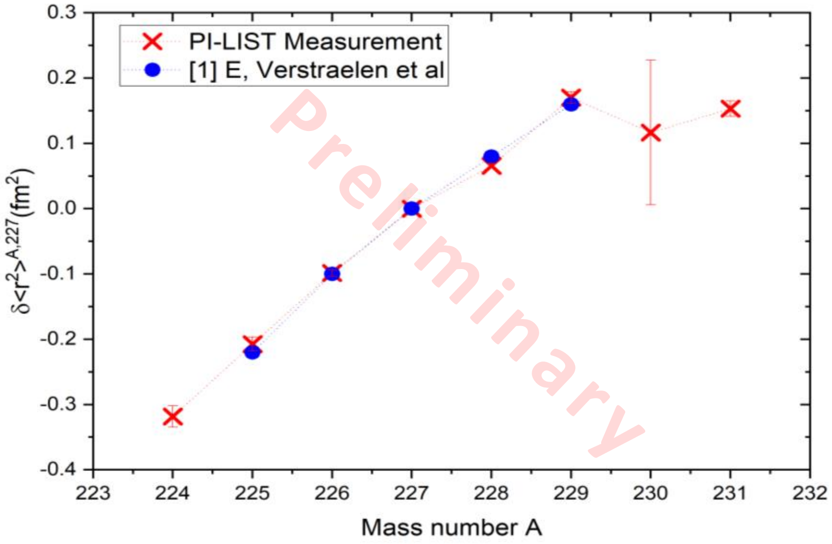
Courtesy of Reinhard Heinke and Asar AH Jaradat

Actinium high resolution sprectroscopy





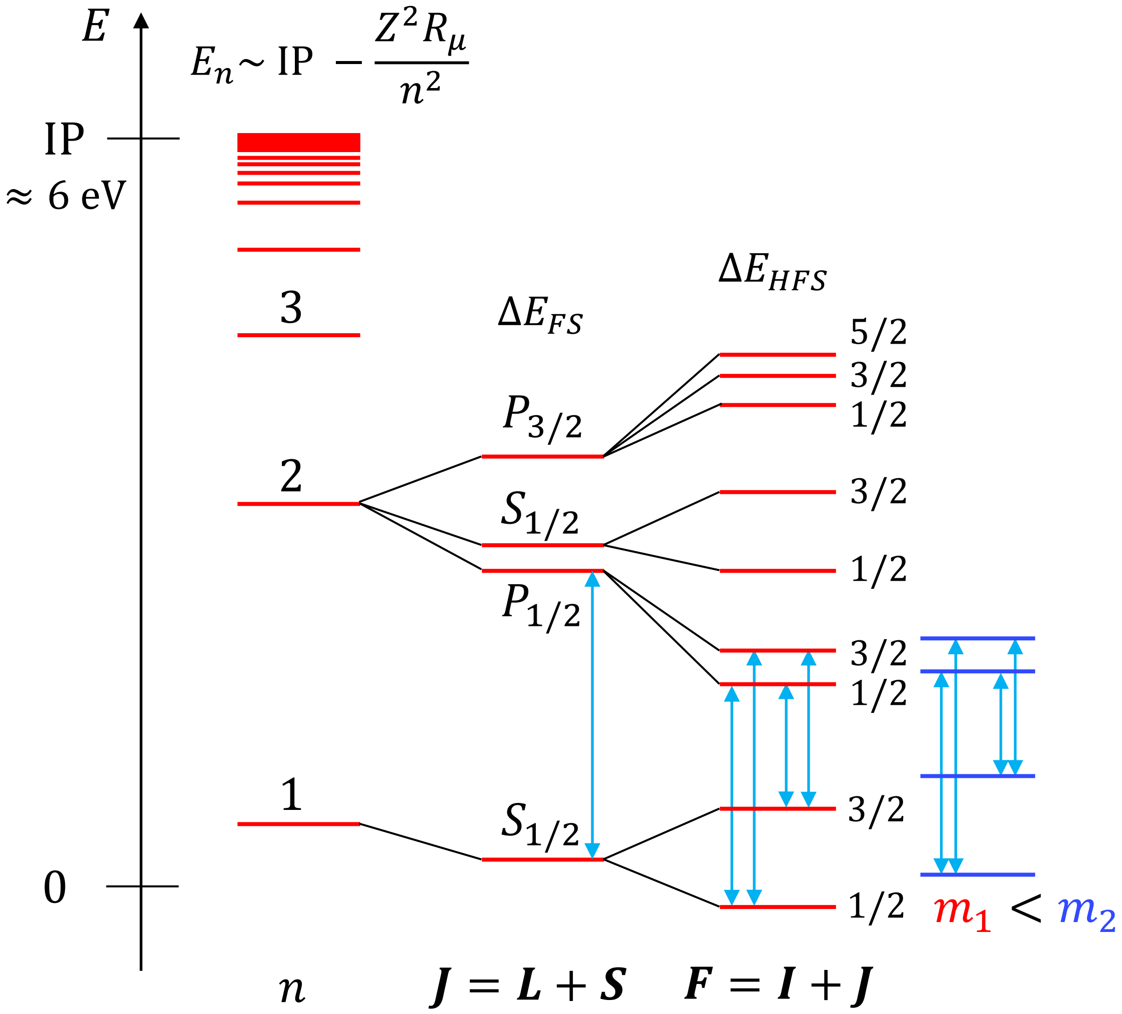
E. Verstraelen et al, PHYSICAL REVIEW C 100, 044321 (2019)



analysis by Michael Heines

Courtesy of Reinhard Heinke and Asar AH Jaradat

Probing atomic structure with lasers



- Atomic level structure through optical transitions
- Ionization limit through Rydberg convergences
- Nuclear spins and electromagnetic moments through hyperfine interaction

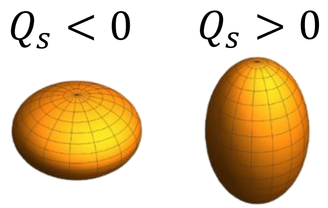
$$A = \frac{\mu_I \overline{H(0)}}{IJ}$$

magnetic field at nucleus

$$B = eQ_s \left\langle \frac{\partial^2 \phi}{\partial z^2} \right\rangle_{r=0}$$

electric field gradient at nucleus

Atomic shell
Nucleus



n – principal quantum number
L – total orbital angular momentum
J – total angular momentum
Q – electric quadrupole moment
S – total spin angular momentum
I – nuclear spin
μ – magnetic dipole moment

Neptunium production

93 Np

- Radioactive actinide
- Long half-li
- High radiot

neutron capture

β⁻ decay

LASER IONISATION AND SPECTROSCOPY OF ACTINIDES

@LISA_ITN

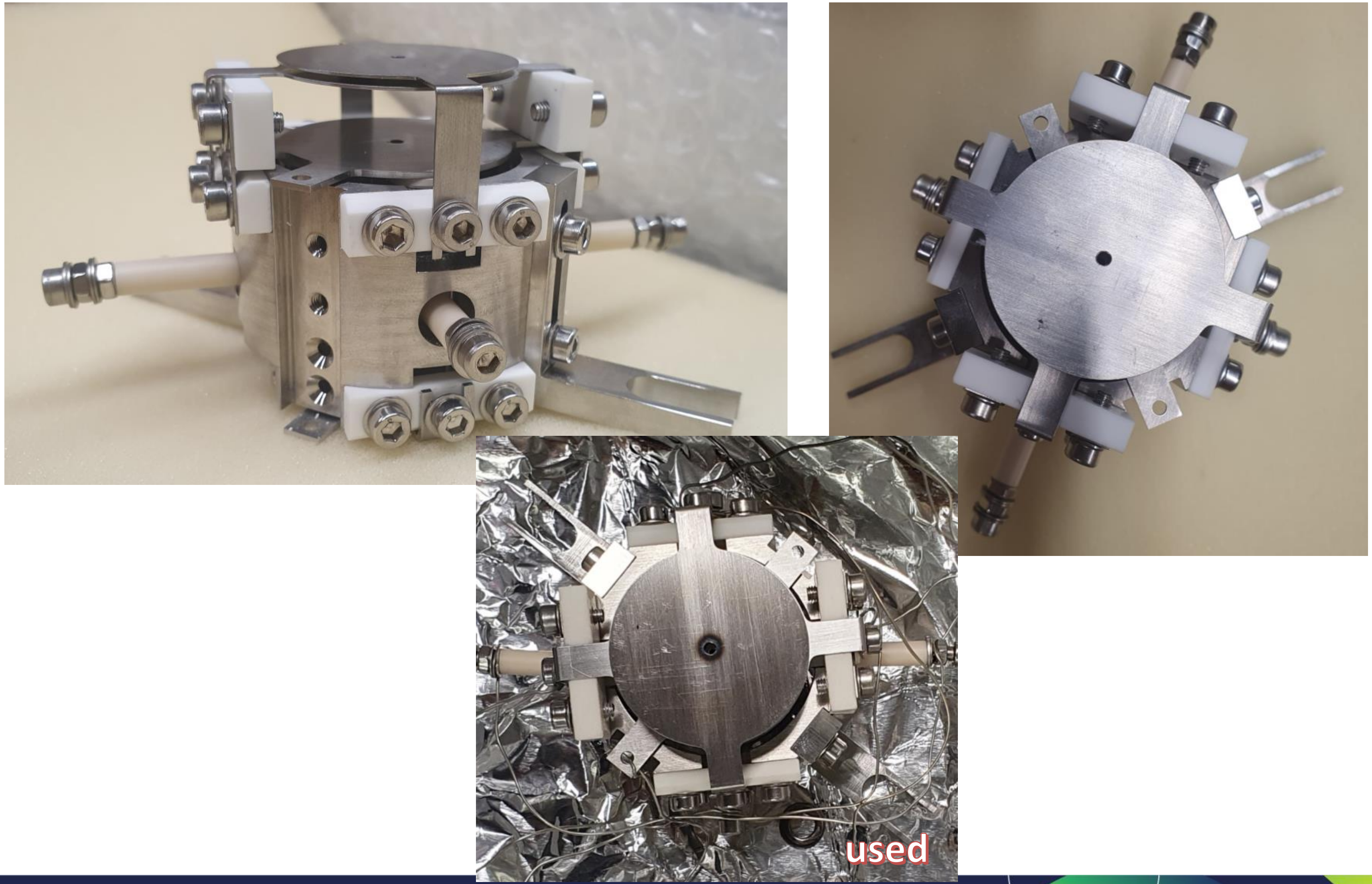
https://lisa-itn.web.cern.ch/

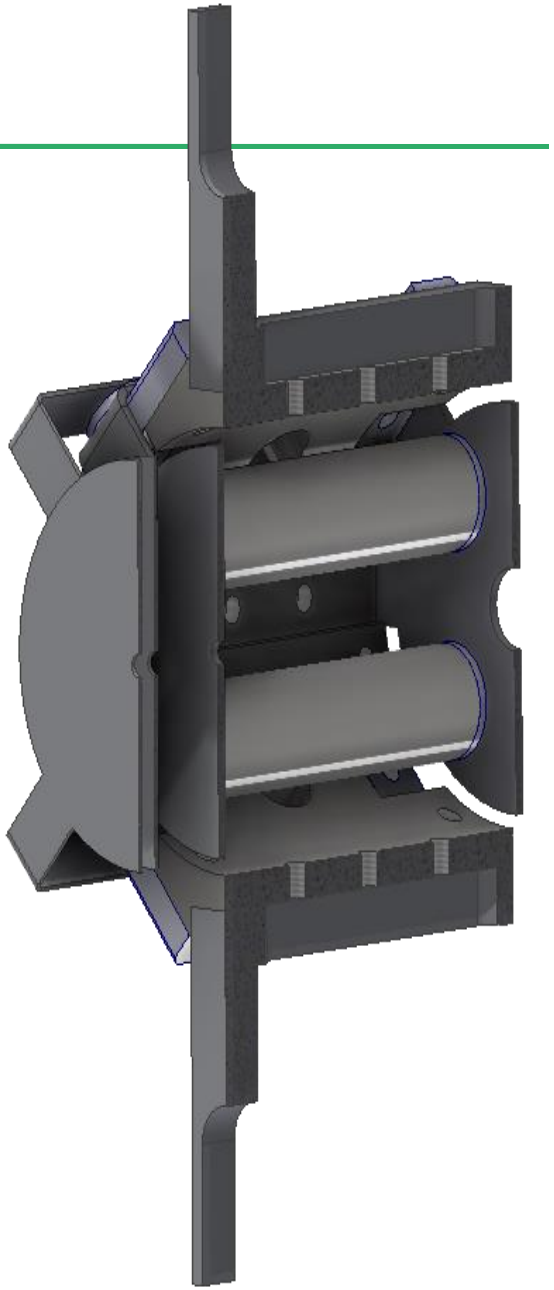
ion schemes
e analysis.

count
tion schemes
coming from hyperfine structure (HFS) and isotope shift (IS).

[1] Kohler, S; et al. Spectrochim. Acta B,52, 717 – 726, (1997)
[2] Kazakov, V; et al. Phys. Scr., 92, 10, (2017)
[3] Stone, N.J. At. Data Nucl. Data Tables, 90, 1, 75-176, (2005)

FI-LIST Field Ionization LIST





HFS result and nuclear moments in Np

[1] Fred, M; et al, J. Opt. Soc. Am., 67, 1 (1977)

Np 237

$2.14 \cdot 10^6$ a

α 4.790...;
γ 29...; e^-

	Fit		Literature [1]		
FES [cm^{-1}]	A [MHz]	B [MHz]	A [MHz]	B [MHz]	J
0	776.10(18)	929(5)	778(10)	645(100)	11/2
25 075.1	1470.02(10)	327(5)	1470(10)	264(100)	13/2
25 277.64	570.08(14)	-307(4)	X	X	9/2

μ_I [μ_N]	Q_s [barn]
+3.14(4) [2]	+3.886(4) [2]

[2] Stone, N.J. At. Data Nucl. Data Tables, 90, 1, 75-176, (2005)

Np 239

2.355 d

β^- 0.4...
γ 106...; e^-; g

	Fit		
FES [cm^{-1}]	A [MHz]	B [MHz]	J
0	785.26(39)	949(10)	11/2
25 075.15	1487.06(25)	336(9)	13/2
25 277.63	576.74(40)	-319(11)	9/2

Determination of nuclear moments

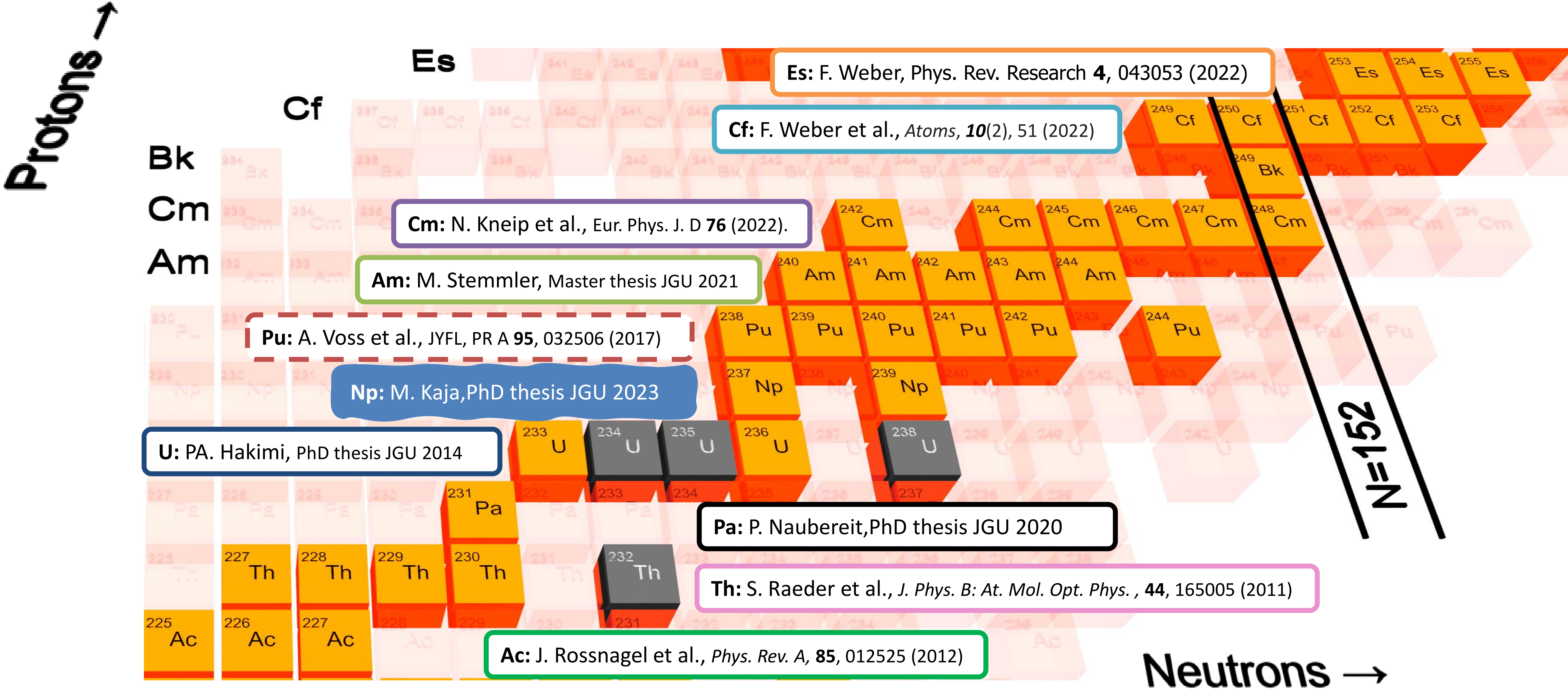
$$\frac{A}{A_{\mathrm{ref}}} = \frac{I_{\mathrm{ref}}}{I}\frac{\mu_I}{\mu_{I,\mathrm{ref}}} \qquad \frac{B}{B_{\mathrm{ref}}} = \frac{Q_s}{Q_{s,\mathrm{ref}}}$$

measured literature

μ_I [μ_N]	Q_s [barn]
+3.18(3)	+3.98(8)

Presented results are preliminary, to be published by M. Kaja et al.

Larissa activities on laser spectroscopy in the actinides



Es: F. Weber, Phys. Rev. Research **4**, 043053 (2022)

Cf: F. Weber et al., *Atoms*, ***10***(2), 51 (2022)

Cm: N. Kneip et al., Eur. Phys. J. D **76** (2022).

Am: M. Stemmler, Master thesis JGU 2021

Pu: A. Voss et al., JYFL, PR A **95**, 032506 (2017)

Np: M. Kaja,PhD thesis JGU 2023

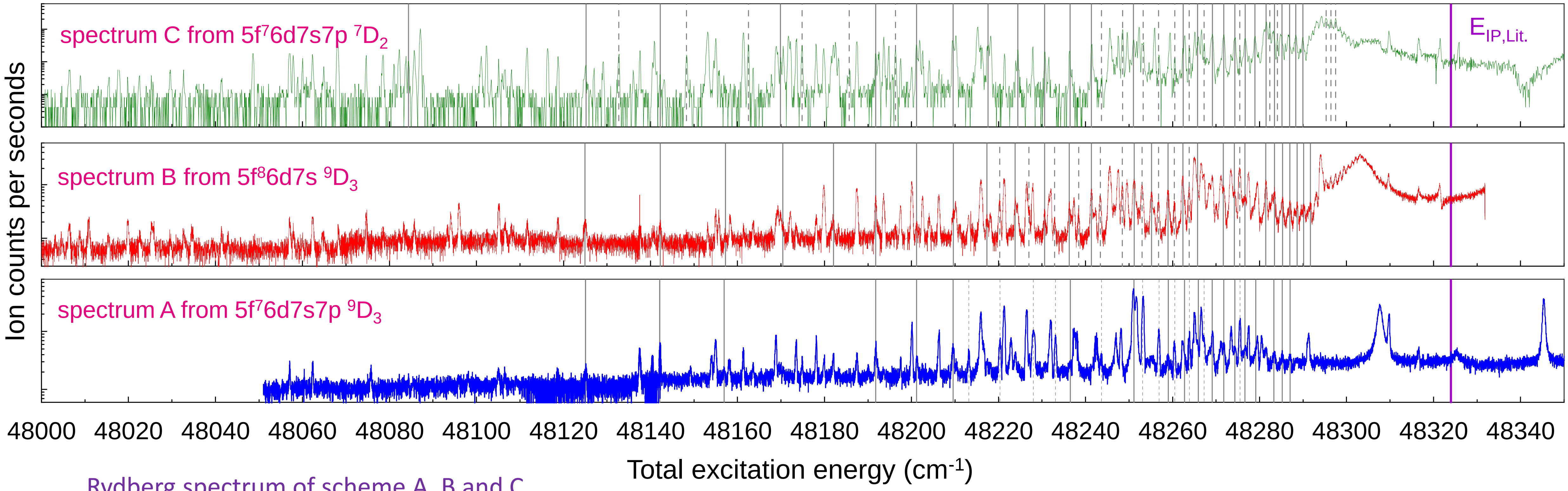
U: PA. Hakimi, PhD thesis JGU 2014

Pa: P. Naubereit,PhD thesis JGU 2020

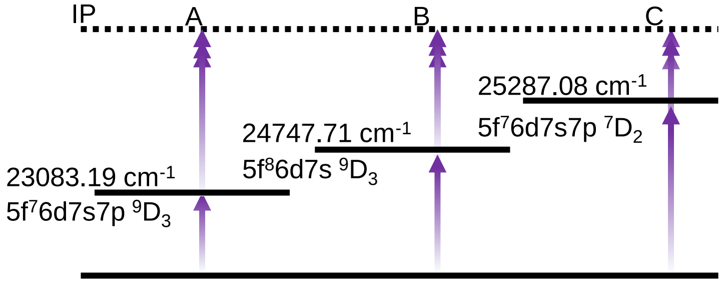
Th: S. Raeder et al., *J. Phys. B: At. Mol. Opt. Phys. ,* **44**, 165005 (2011)

Ac: J. Rossnagel et al., *Phys. Rev. A*, **85**, 012525 (2012)

Ionization potential determination of curium



Rydberg spectrum of scheme A, B and C

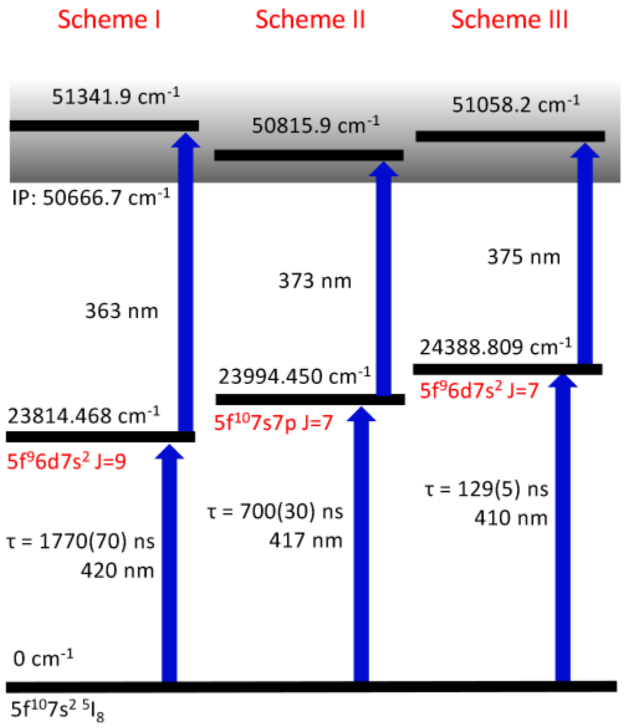


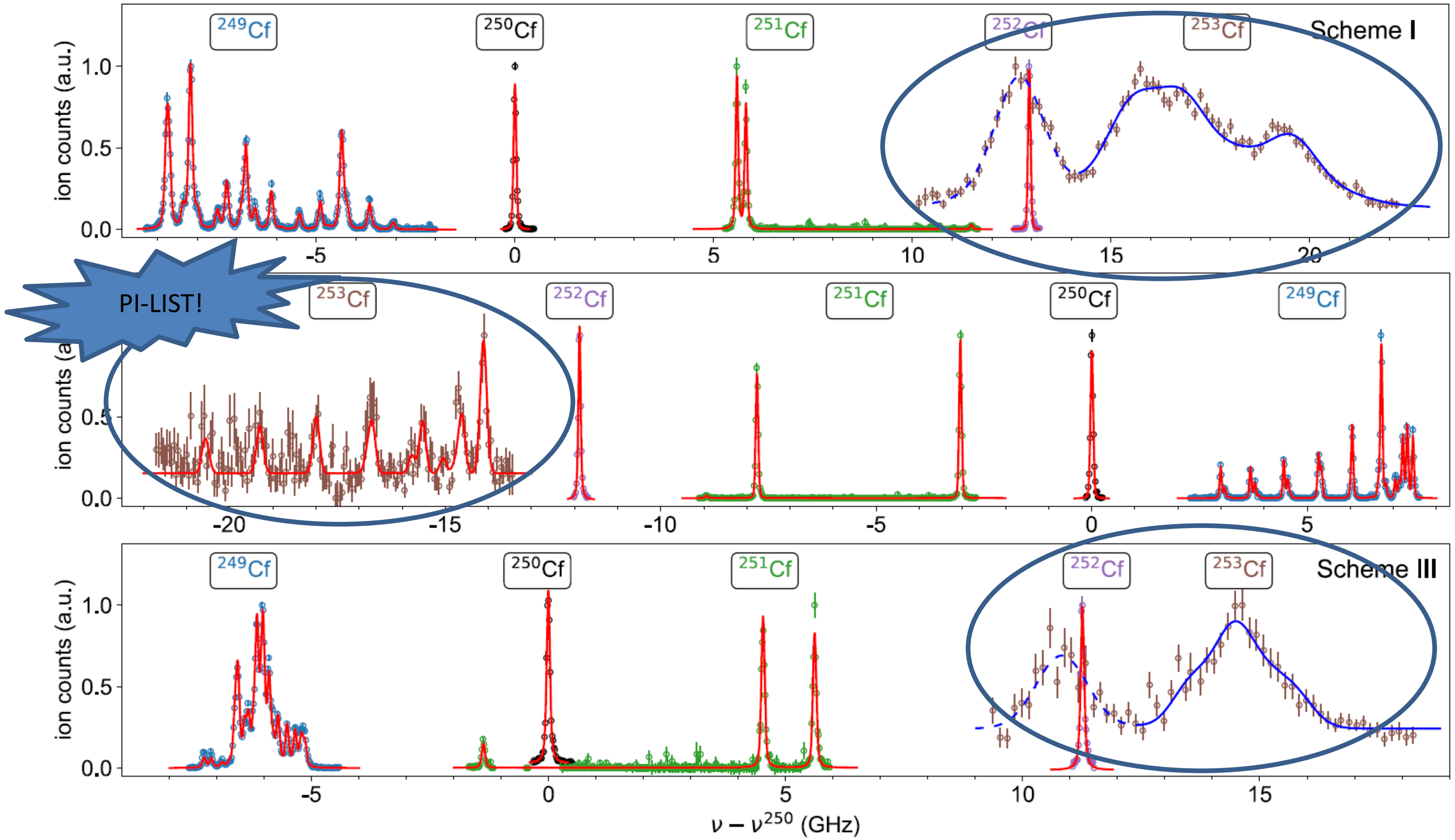
Investigation of the Rydberg spectrum A, B and C

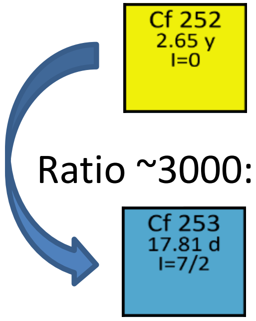
- Spectral scan range 400 cm^{-1}
- IP = 48330.68(12) cm^{-1}

N. Kneip,.., M.K., et al., Eur. Phys. J. D **76** (2022)

High resolution spectroscopy of californium







Cf 252
2.65 y
I=0

1e11 atoms (40 pg)
α-spectrometry

Ratio ~3000:1

Cf 253
17.81 d
I=7/2

<5e7 atoms (20 fg)
mass spectrometry

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