Shedding light on the heaviest elements

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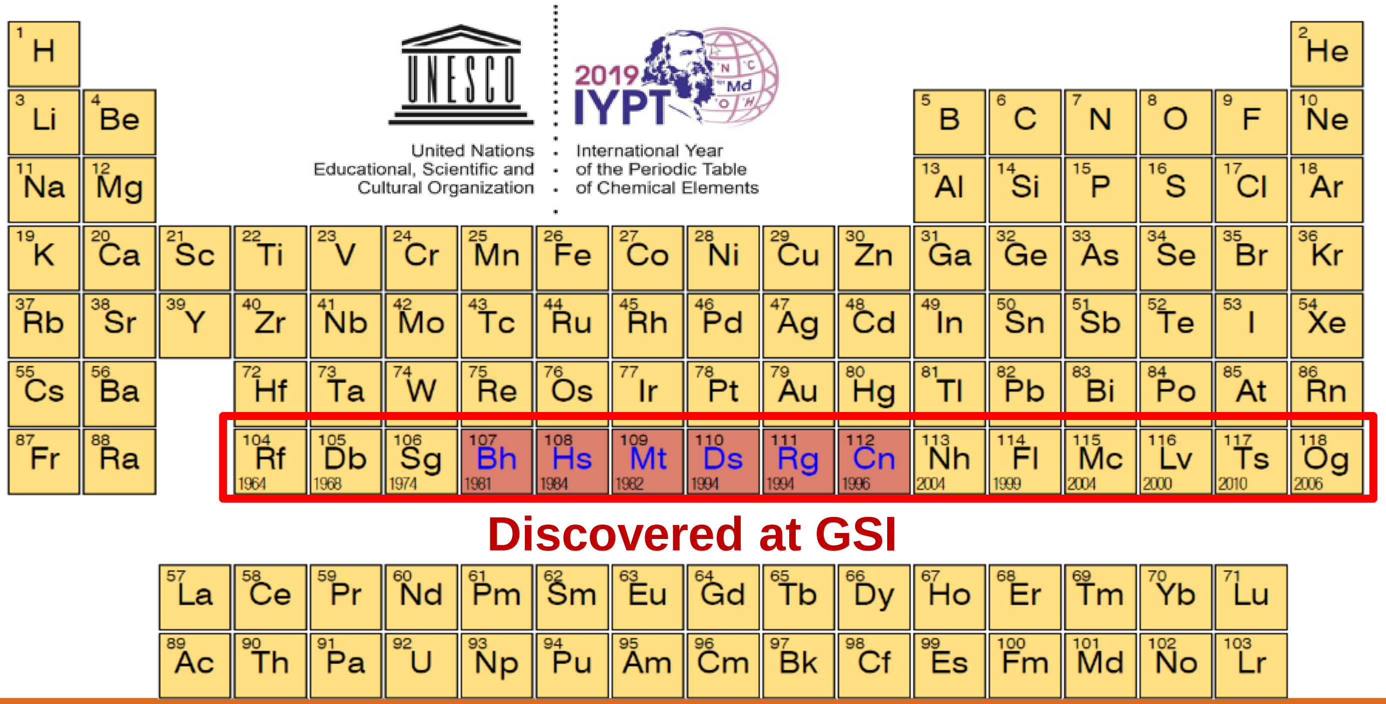
The Periodic Table of Elements

Elements at the limits of nuclear stability

- Why do SHE exist at all ?
- What is nuclear structure: what is their shape and size ?
- How are they best produced in the lab ?
- How do their atomic and chemical properties compare to known (lighter) elements ?



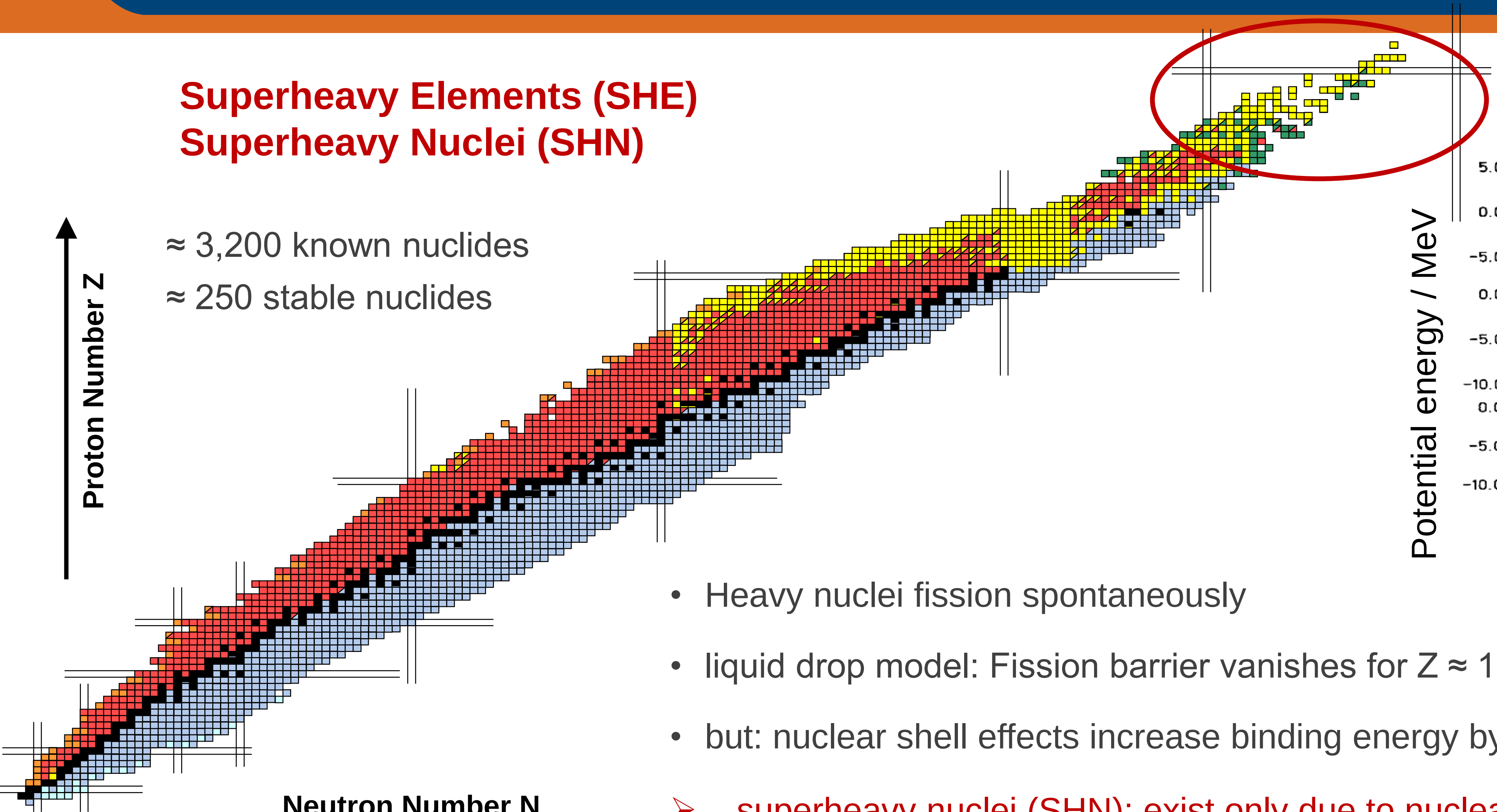
Superheavy Elements

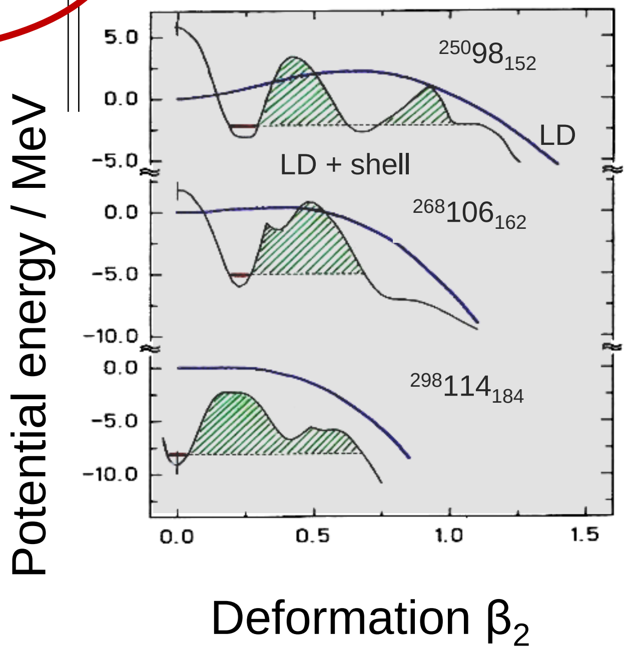
= transactinides

Chart of Nuclides

Superheavy Elements (SHE)
Superheavy Nuclei (SHN)

≈ 3,200 known nuclides
≈ 250 stable nuclides





- Heavy nuclei fission spontaneously
- liquid drop model: Fission barrier vanishes for Z ≈ 104
- but: nuclear shell effects increase binding energy by several MeV

➢ superheavy nuclei (SHN): exist only due to nuclear shell effects

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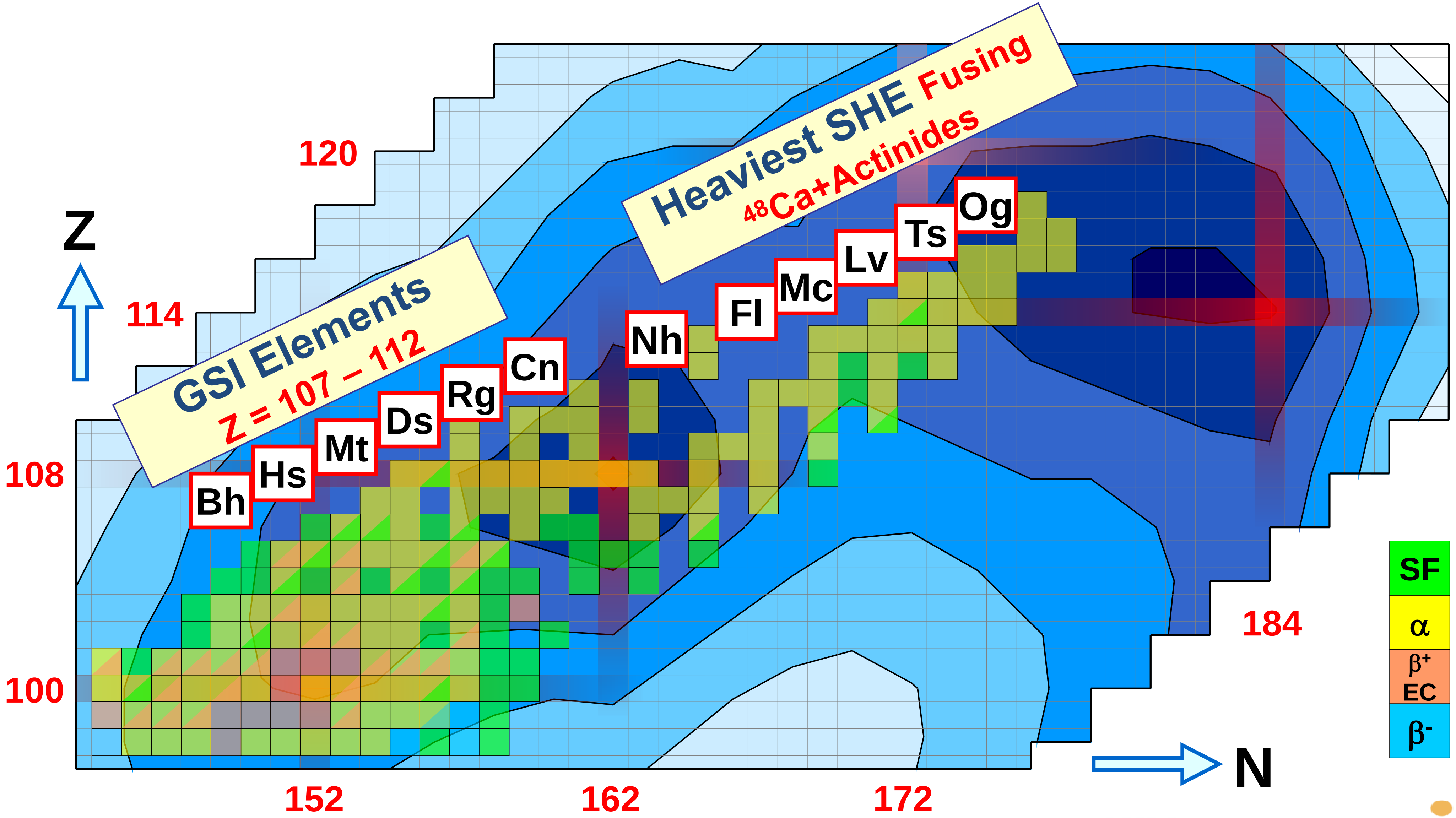
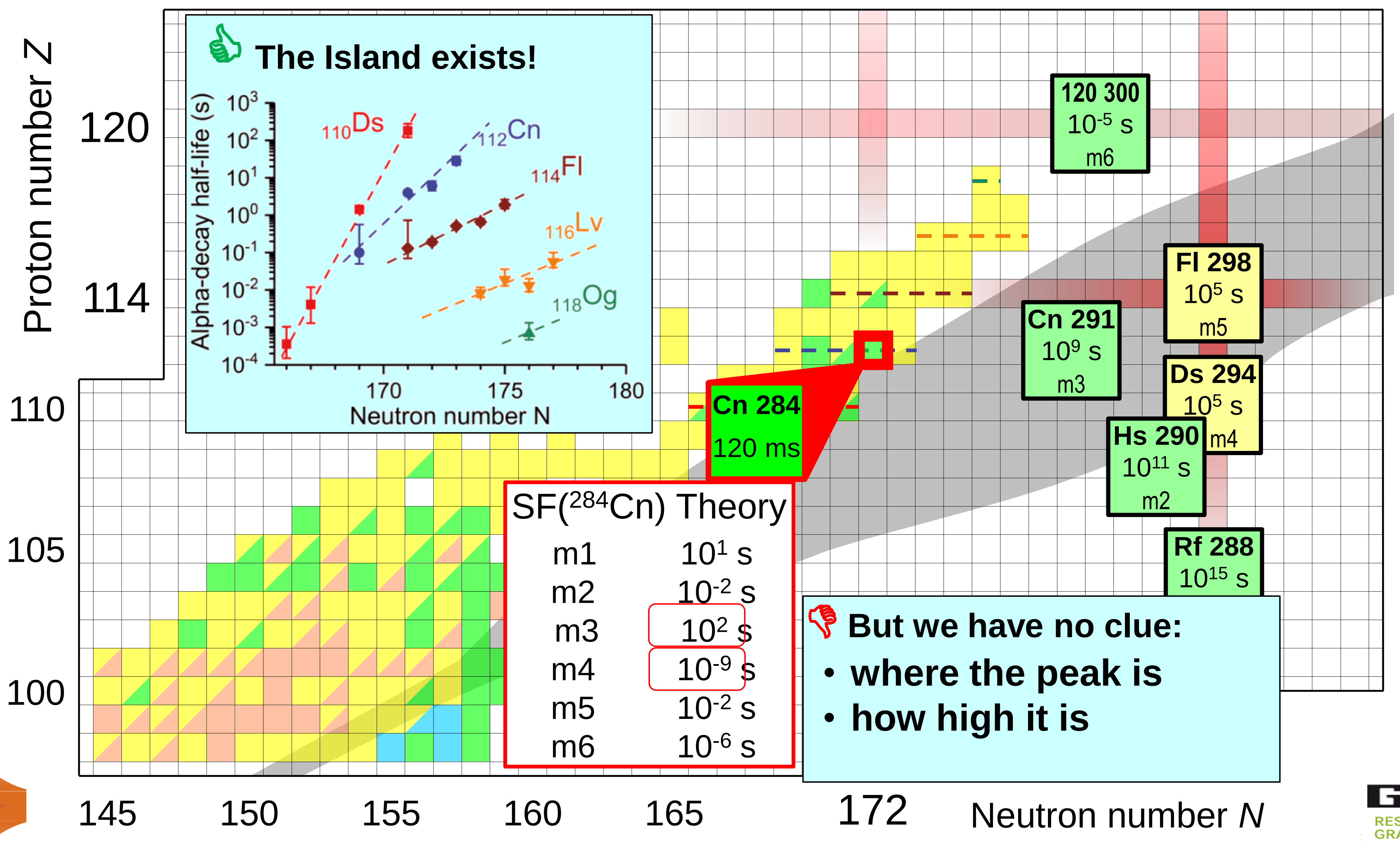
Superheavy Elements – Present Status



Courtesy of Ch. Düllmann

Island of Stability – Status 2023



β-stability line

Often predicted spherical shells

Known nuclei decaying by

- α-decay
- β⁻-decay
- β⁺/EC-decay
- SF

Predicted longest-lived nuclei decaying by

- α-decay
- β⁻-decay

O. Smith et al, Nat Rev Phys **6**, 86–98 (2024)

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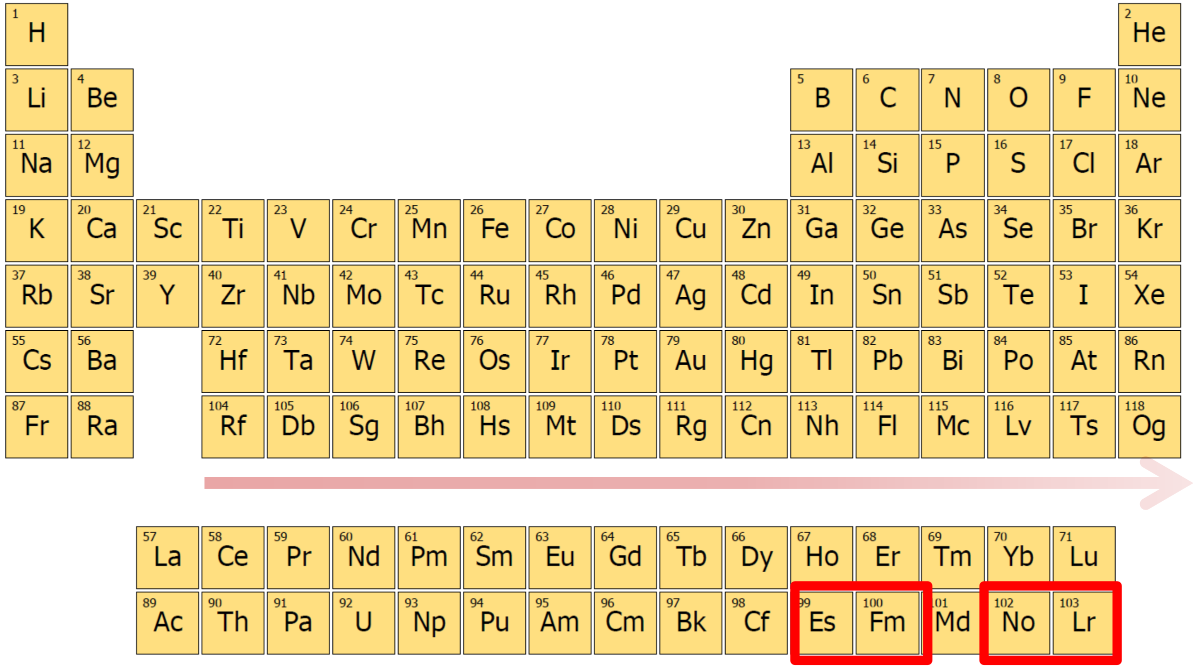
Properties of the heaviest elements

Laser spectroscopy for fundamental properties

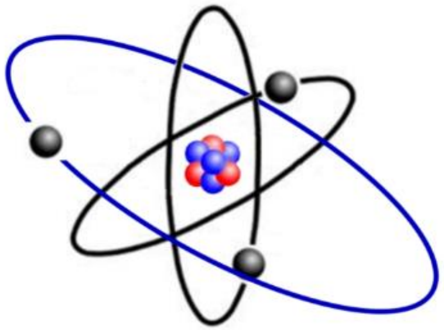
- Understanding of atomic structure & chemical behaviour
- What is nuclear structure: what is their shape and size ?

Atomic structure is linked to light



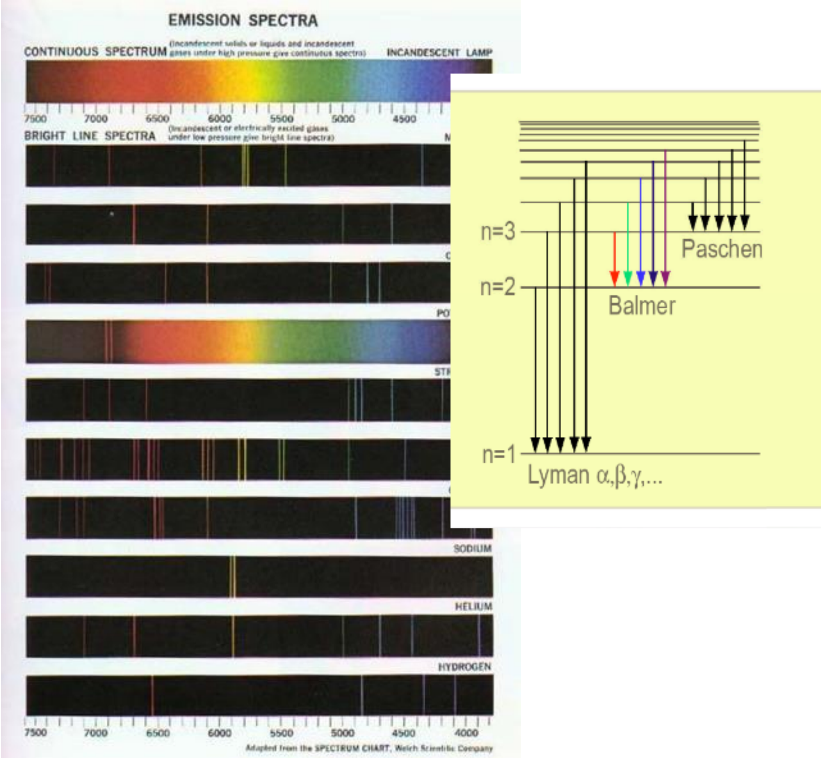
Electron shell

atomic structure
chemical properties
→ defines the element



Nucleus

nuclear structure
stability of elements



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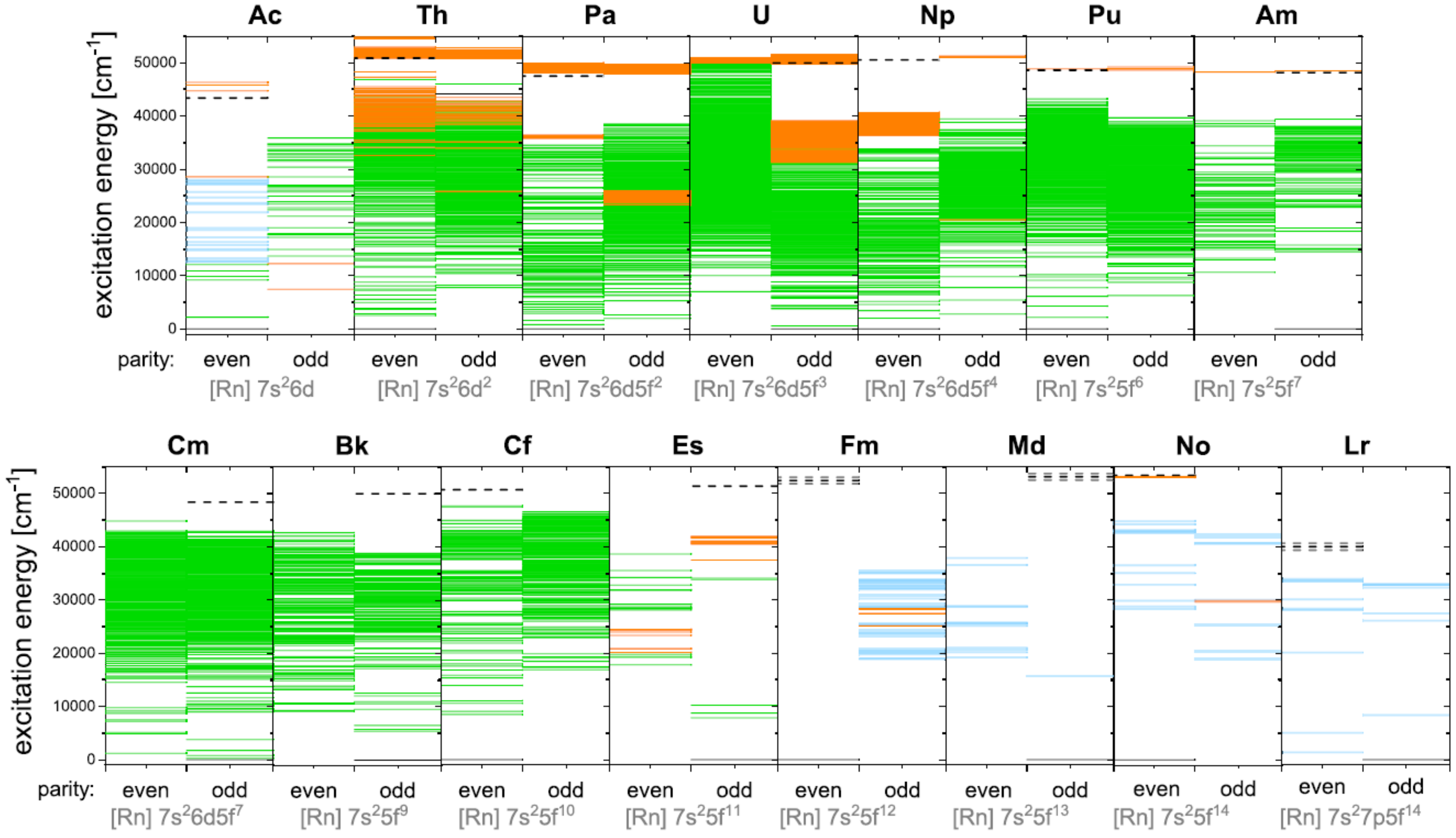
Density of Atomic Levels in the Actinides

Overview on atomic levels reported for the heavy actinides



- Atomic structure
- Sparse for heavier element
- For Z ≥ 100 only calculations are available

Blaise 1992

Experimental levels

Theory – calculated levels

Block, M. et al, *Progress in Particle and Nuclear Physics* (2020): 103834.

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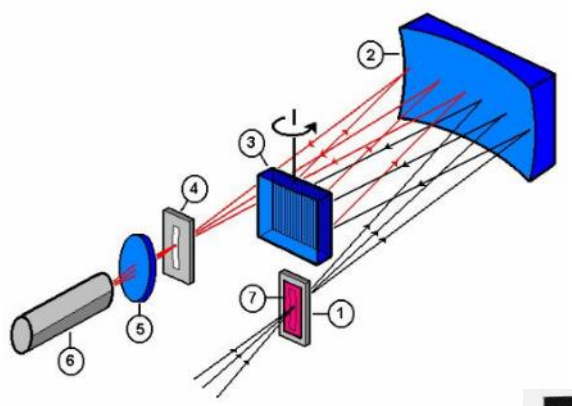
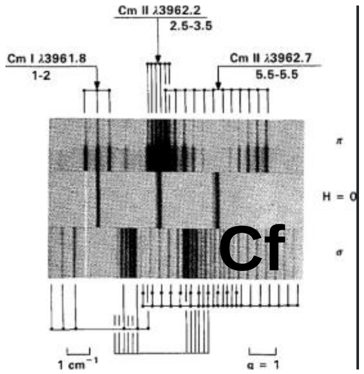
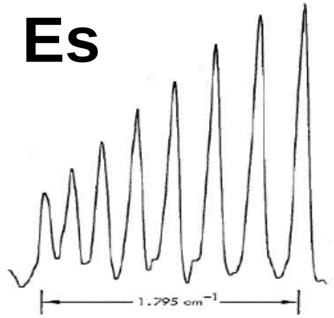
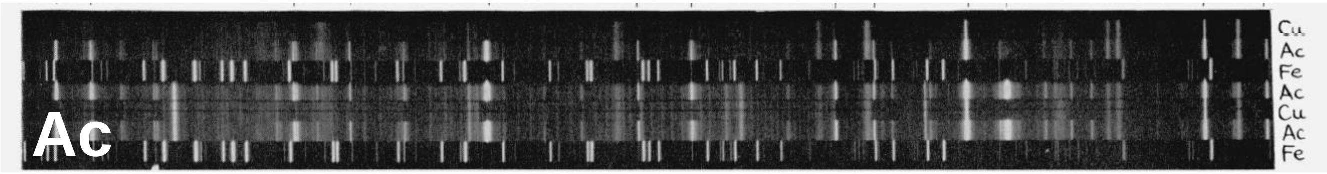
^{99}Es – analysis of fluorescence light

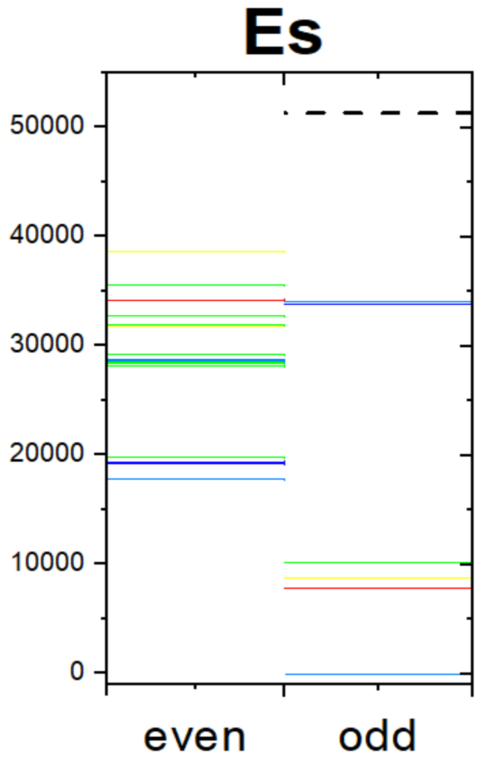
Spectrometry of light from discharge











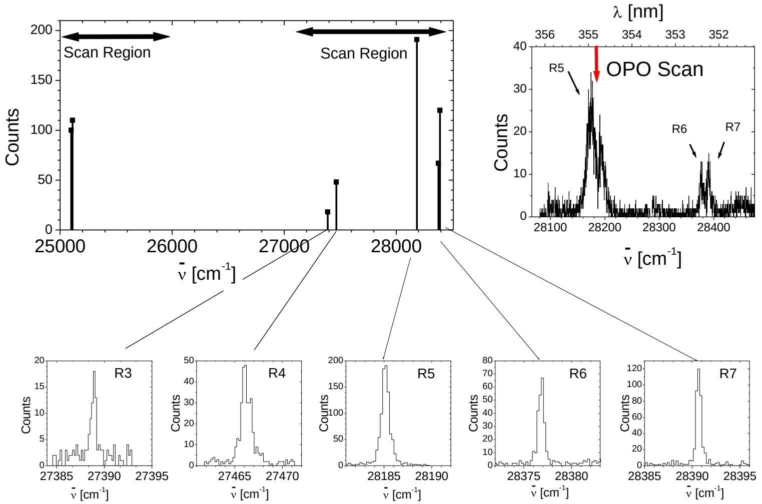
- 0.6 µg – 48 µg ^{253}Es (10^{16} atoms) – 1970's
  - – report of ~300 optical lines (Es I & Es II)
  - – level assignment from analysis
  - – magnetic moment of ^{253}Es from HFS
  - – too little material for Zeemann splitting

[Wor74] Worden E.F., et al. " Hyperfine structure in the 253Es emission spectrum, III: Extension of the line list, levels of Es i and Es ii, nuclear magnetic-dipole and quadrupole moments* " *J.Opt. Soc.Am.* 64.1 (1974): 77.

^{100}Fm – only possible with laser spectroscopy

2003: First atomic information on Fm

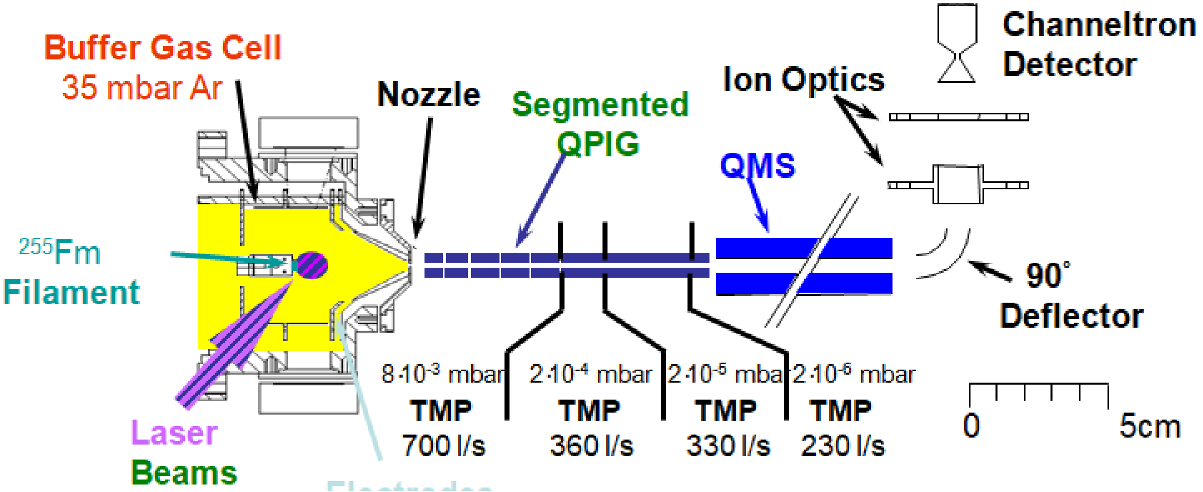
Mainz: Institut für Kernphysik, Institut für Kernchemie



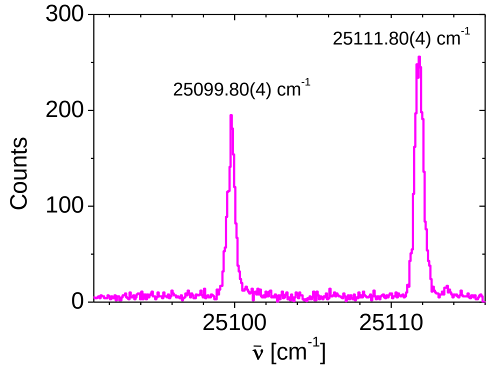
breeding of ^{255}Es
at Oak Ridge, USA

$\Phi_n = 2.6 \cdot 10^{15}/cm^2 \cdot s$
T = 1 a

4 ng ^{255}Fm ($t_{1/2}$= 20 h)
(10^{12} atoms)



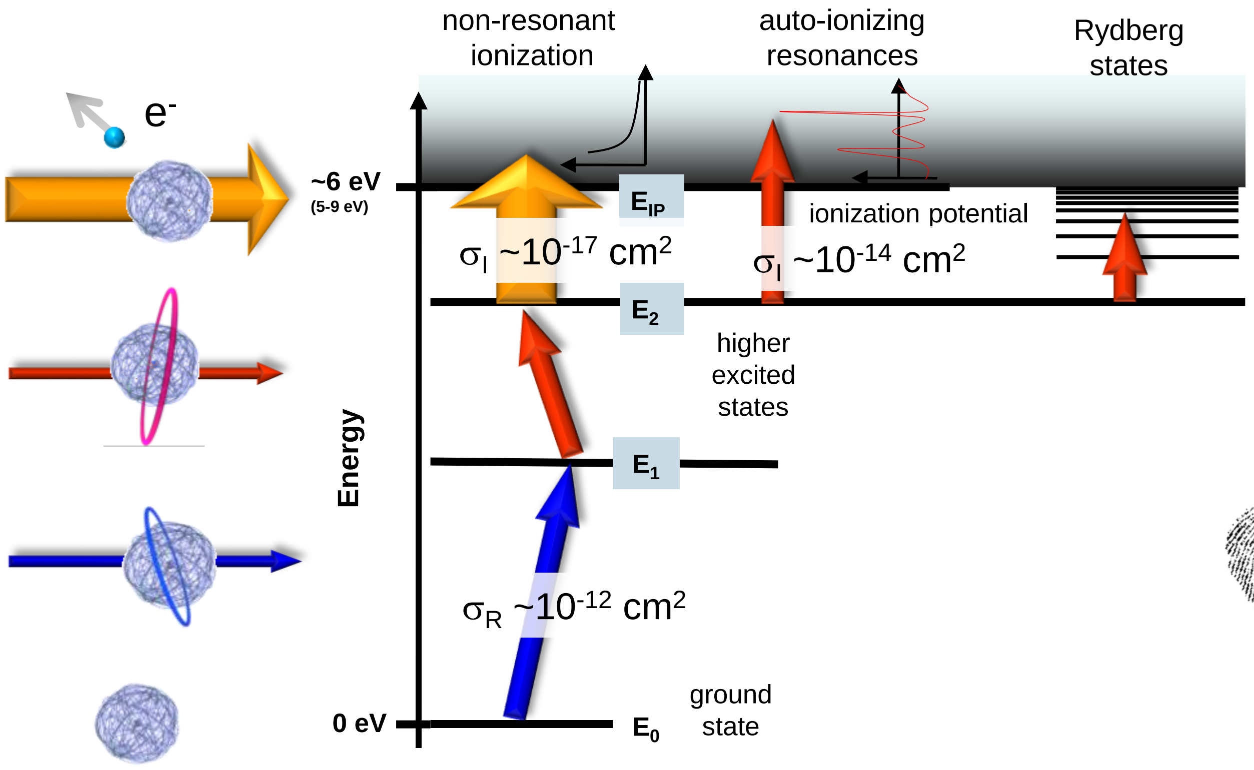
7 atomic transitions



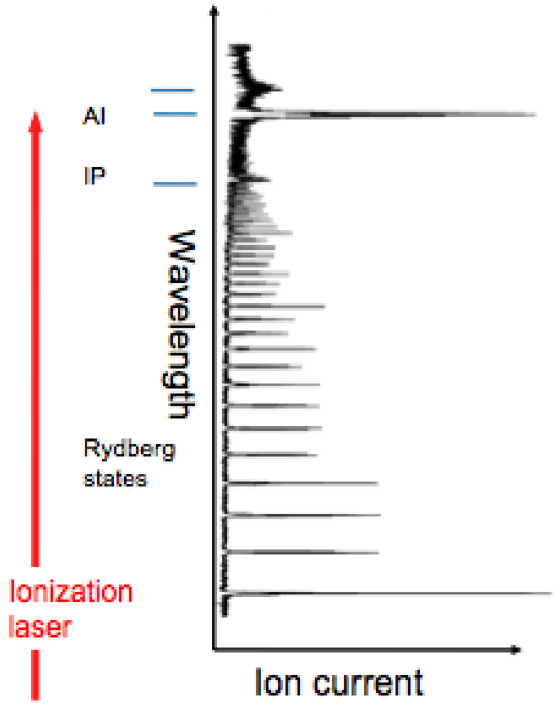
Laser system: 100 Hz, Excimer pumped Dye laser + 50 Hz OPO

[Sew03] Sewtz, M., et al. "First observation of atomic levels for the element fermium (Z= 100)." *Phys. Rev. Lett.* 90.16 (2003): 163002.
[Bac06] Backe, H., et al. "Laser spectroscopic investigation of the element fermium (Z= 100)." Laser 2004. (2006). 3-14.

Resonance Ionization Spectroscopy

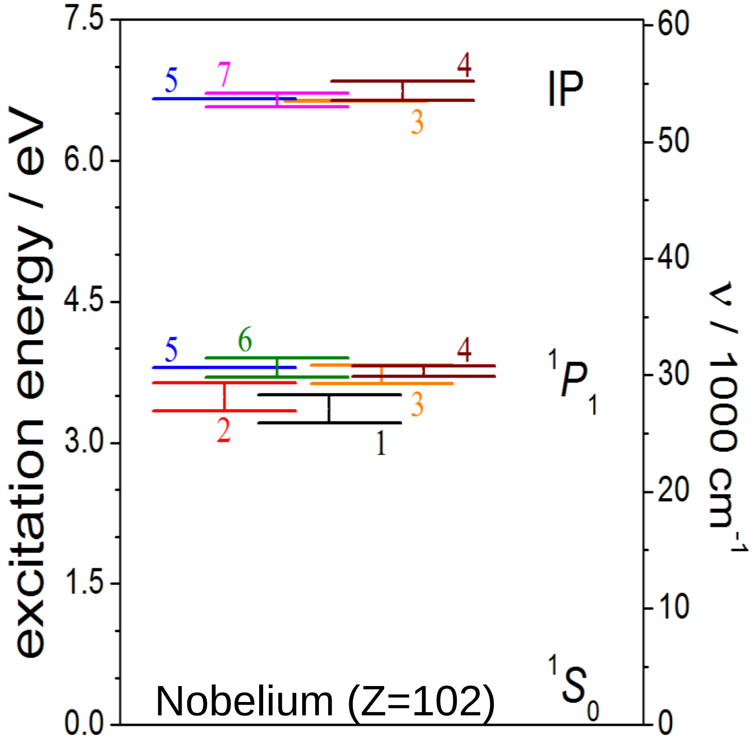


Atomic properties



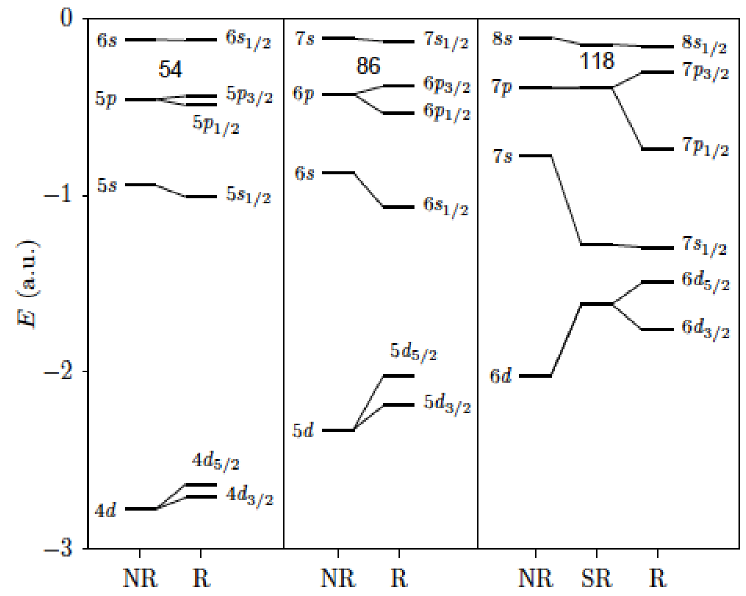
- Resonant laser excitation – selective & efficient
- Efficient excitation schemes generally exist for every element
- Atomic spectra incomplete – development often necessary

Motivation - Atomic Structure



Atomic ground state: [Rn]$5f^{14}7s^{2}$ $^{1}S_{0}$

- Zα → 1: large QED contribution & relativistic effects in the electronic structure



P. Jerabek et al., PRL **120,** 053001 *(2018)*

Model calculations

1, 2 (MCDF): S.Fritzsche, Eur. Phys. J. D 33 (2005) 15

3 (IHFSCC): A.Borschevsky et al., Phys. Rev. A 75 (2007) 042514

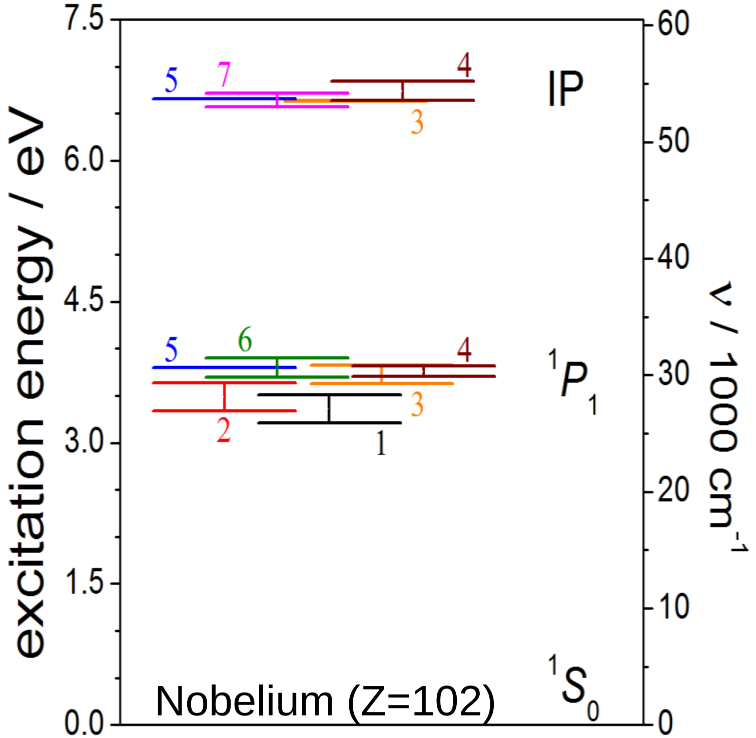
4 (RCC): V.A.Dzuba et al., Phys. Rev. A 90 (2014) 012504

5 (MCDF): Y.Liu et al., Phys. Rev. A 76 (2007) 062503

6 (MCDF): P.Indelicato et al., Eur. Phys. J. D 45 (2007) 155

7 (extrapolation): J.Sugar, J. Chem. Phys. 60 (1974) 4103

Motivation - Atomic Structure



Atomic ground state: [Rn]$5f^{14}7s^{2}$ $^{1}S_{0}$

- Zα → 1: large QED contribution & relativistic effects in the electronic structure
- Strong electron correlations
- Benchmark predictive power of atomic theory
- Ionization potential (IP) → chemical properties
- Determination of nuclear properties

Model calculations

1, 2 (MCDF): S.Fritzsche, Eur. Phys. J. D 33 (2005) 15

3 (IHFSCC): A.Borschevsky et al., Phys. Rev. A 75 (2007) 042514

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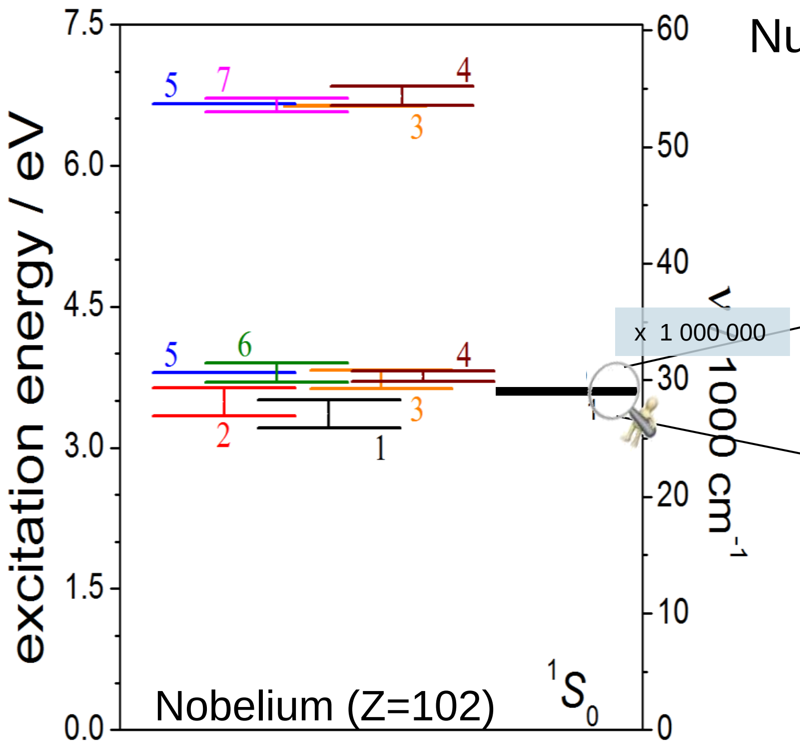
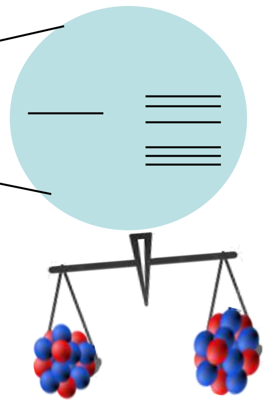
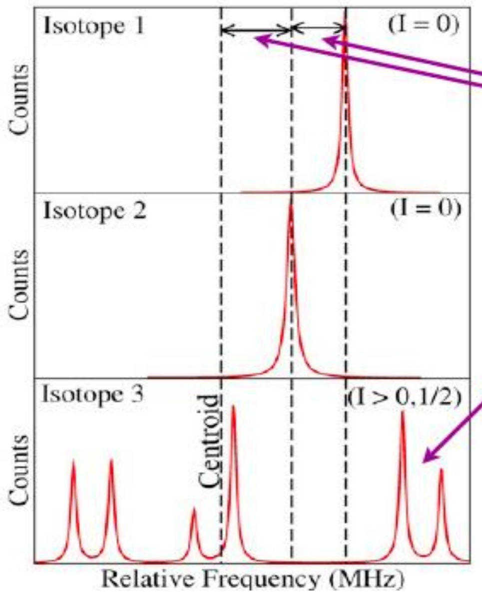
Motivation – Nuclear Properties



Atomic ground state: [Rn]$5f^{14}7s^2$ $^1S_0$



Nuclear ground state properties from



Isotope shift

Δr^2 Nuclear Shape, deformation

$$\delta\langle r^2\rangle^{AA'} = \left(\Delta\nu^{AA'} - \frac{A-A'}{AA'}M\right)\frac{1}{F}$$

Hyperfine splitting (HFS)

Ground state parameters

- μ
- $Q_S \rightarrow \langle\beta_2\rangle$
- I

$$A = \mu\frac{B_e(0)}{IJ} \quad ; \quad B = eQ_s\left\langle\frac{\delta^2 V}{\delta z^2}\right\rangle$$

Model calculations

1, 2 (MCDF): S.Fritzsche, Eur. Phys. J. D 33 (2005) 15

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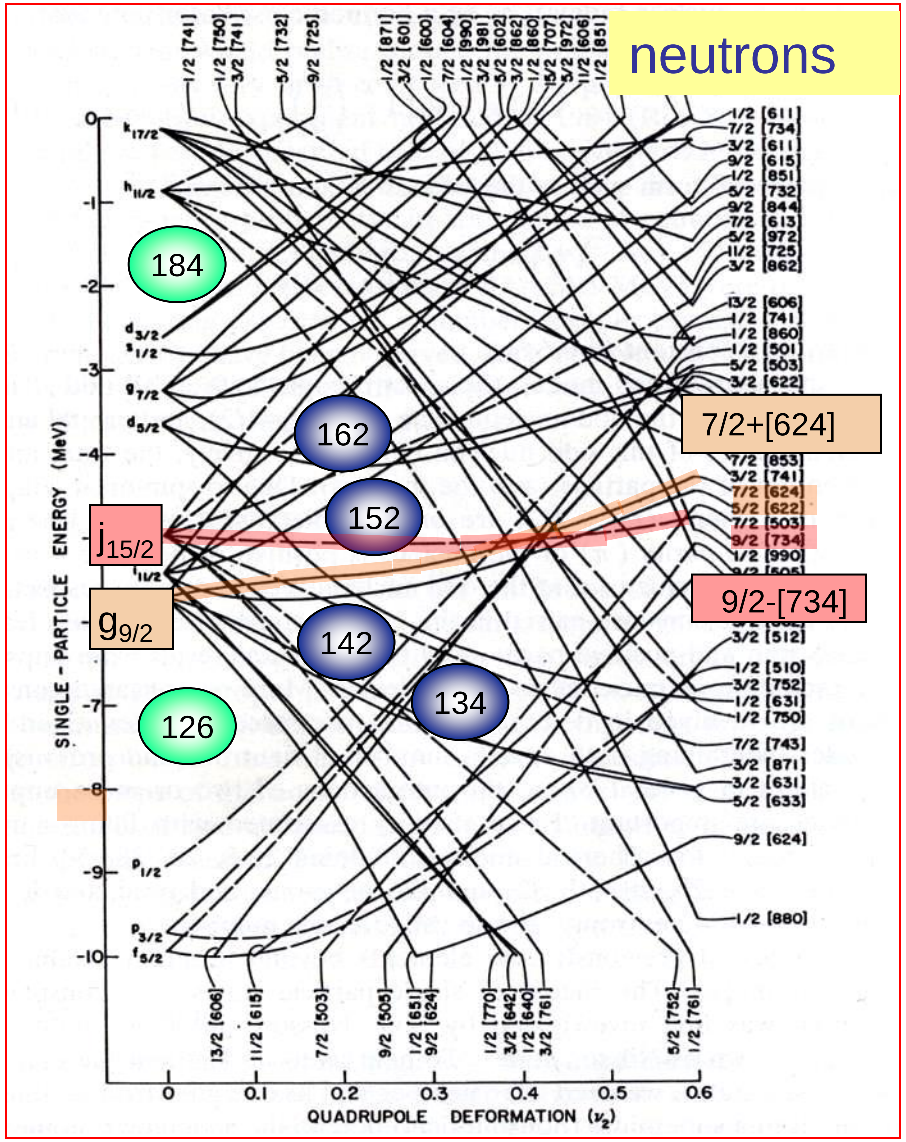
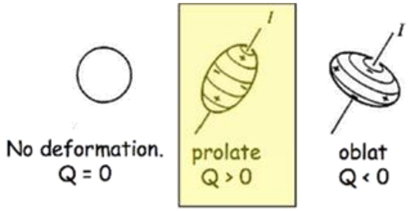
Nuclear Information from Laser Spectroscopy



Orbital energy changes with deformation – Nilsson model

Hyperfine structure:

- Deformation (Q, β_2) from HFS



- Magnetic moments $\mu = g \cdot I$

  Provides g-factors of unpaired nucleon characteristic for the wavefuctions

- Assignment of nuclear Spin I

Charge radii:

- Change in deformation

Optical Investigation of Heavy Elements

Laser spectroscopy for fundamental properties

- Understanding of atomic structure & chemical behaviour
- Nuclear structure: what is their shape and size ?

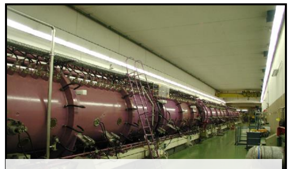
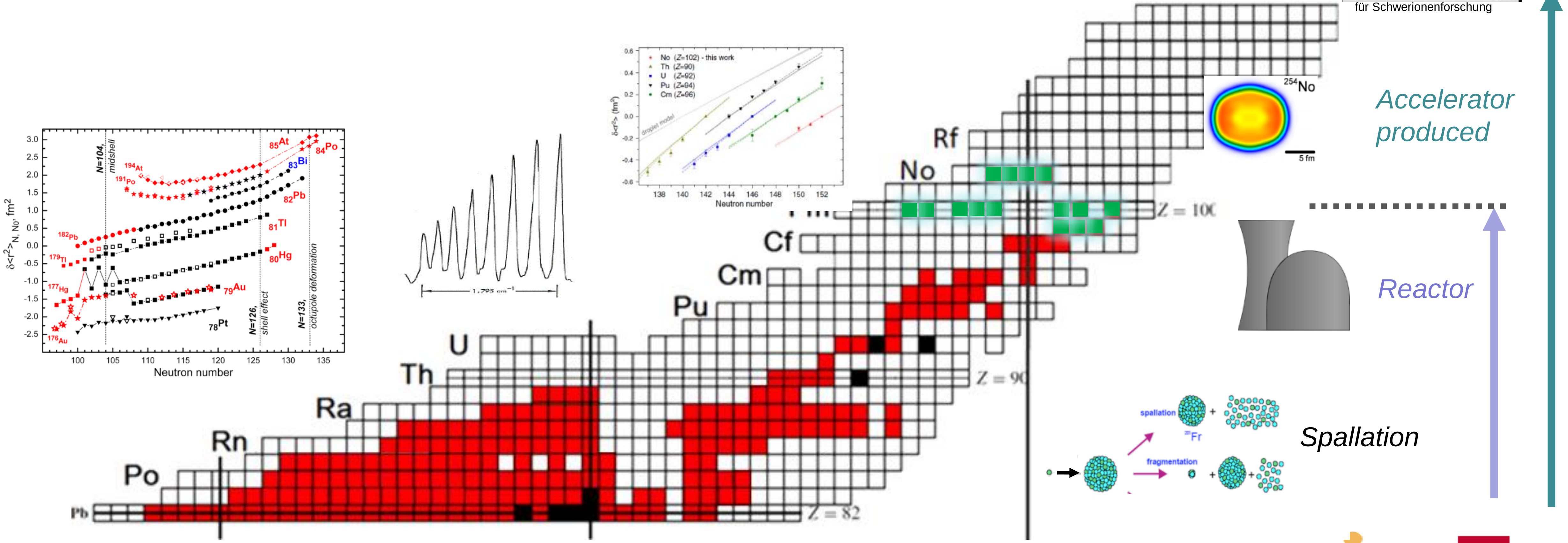


Bild: GSI Helmholtzzentrum für Schwerionenforschung



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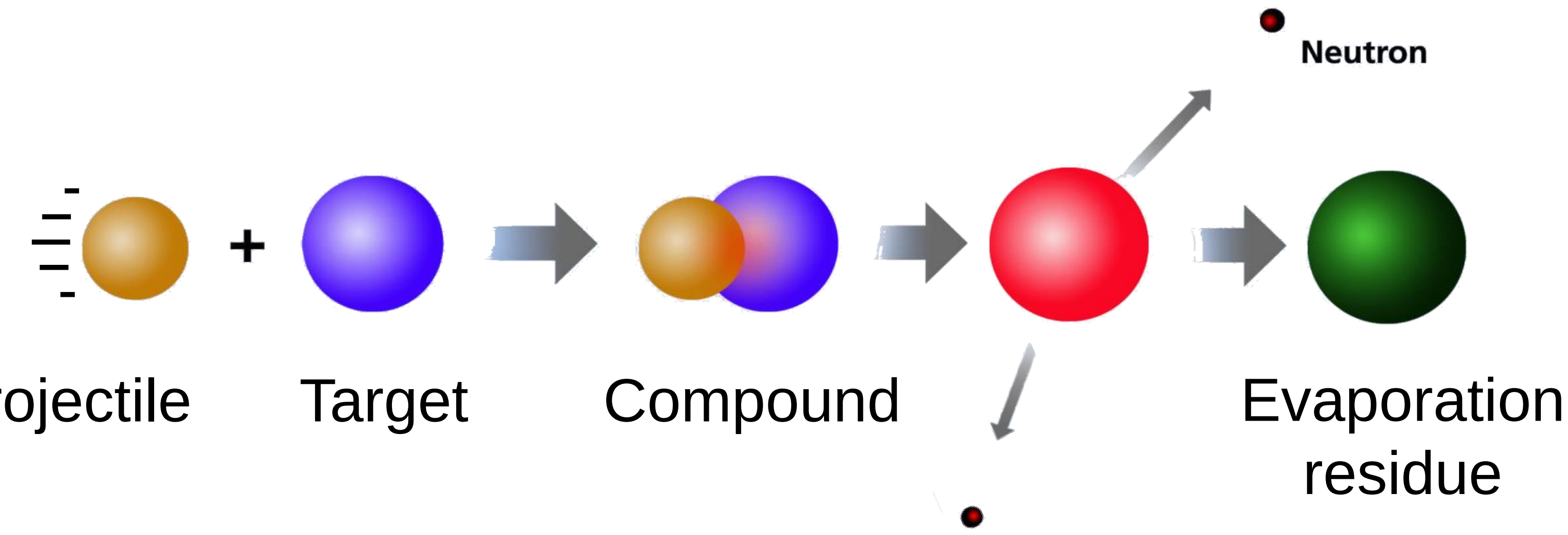
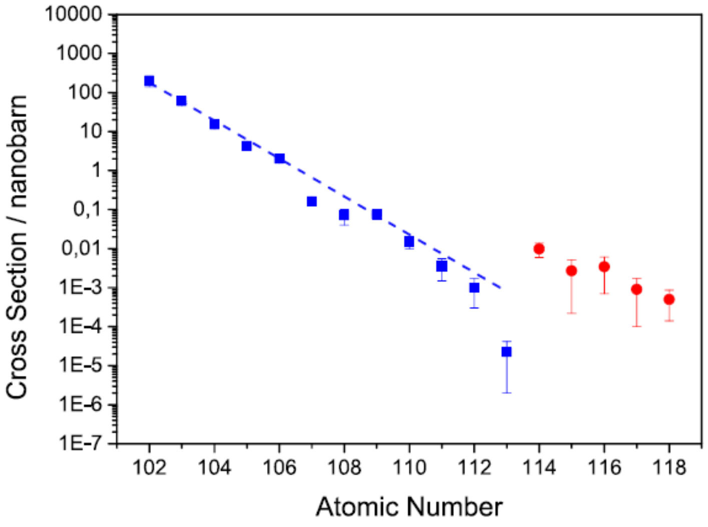
Production of SHE at GSI

$$^{48}_{20}\mathrm{Ca} \rightarrow {}^{244}_{94}\mathrm{Pu} \longrightarrow {}^{289}_{114}\mathrm{Fl} + 3n$$

Production through fusion-evaporation reactions

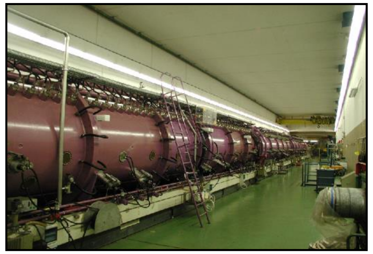




Production cross section

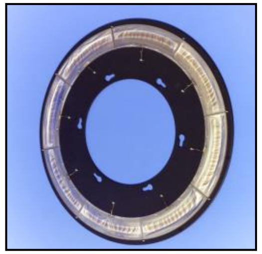
Production of SHE at GSI

$$^{48}_{20}\mathrm{Ca} \rightarrow \, ^{244}_{94}\mathrm{Pu} \rightarrow \, ^{289}_{114}\mathrm{Fl} + 3n$$



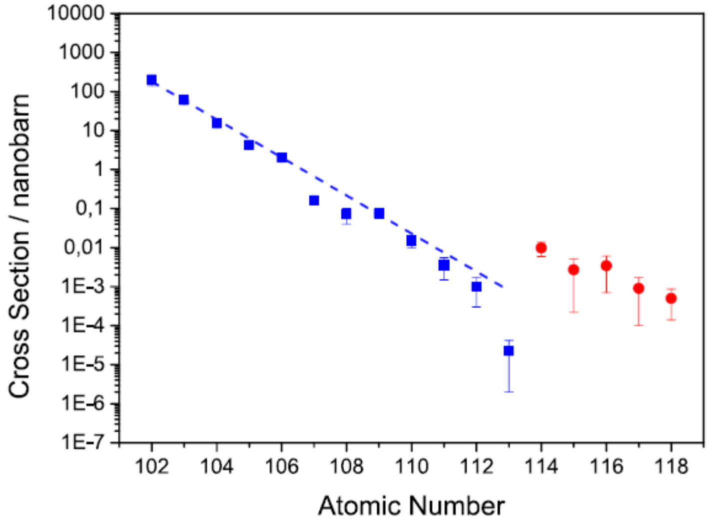
UNILAC

Intensity
10^{13} $^{48}Ca^{10+}$ s^{-1}

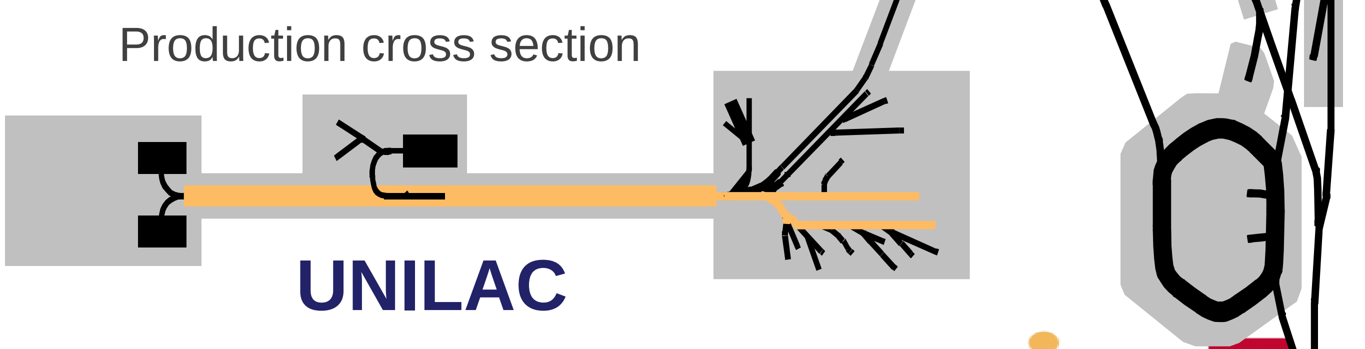


Target

Thickness
0.4 -1 µm

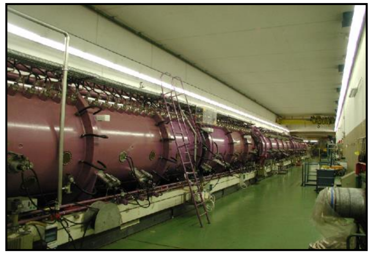


Production cross section



Production of SHE at GSI

$^{48}_{20}Ca \rightarrow ^{244}_{94}Pu \rightarrow ^{289}_{114}Fl + 3n$



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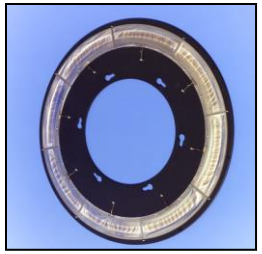
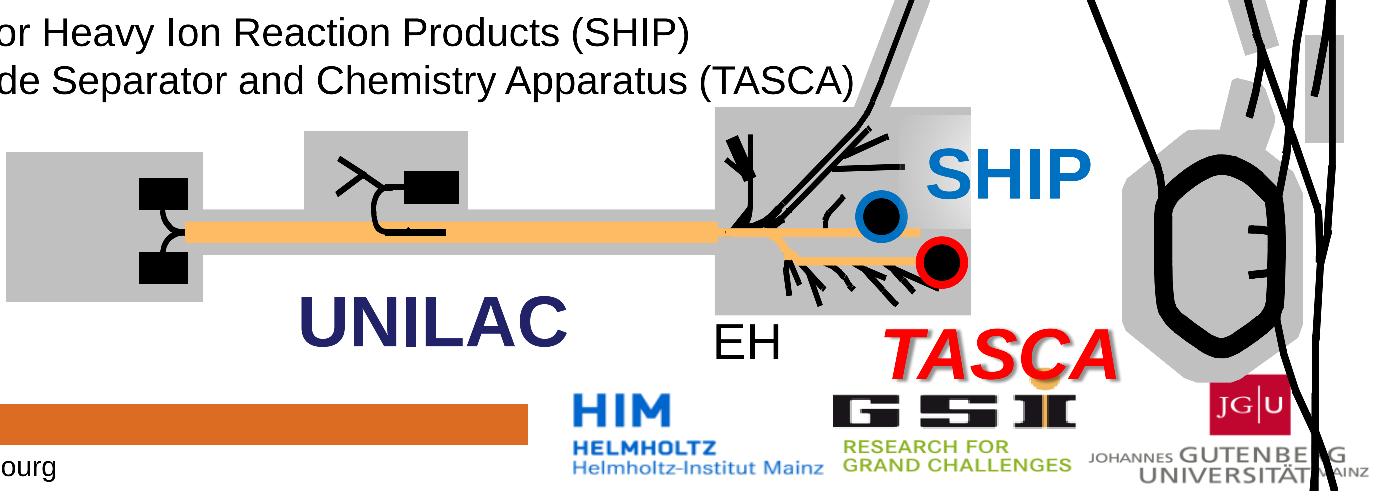


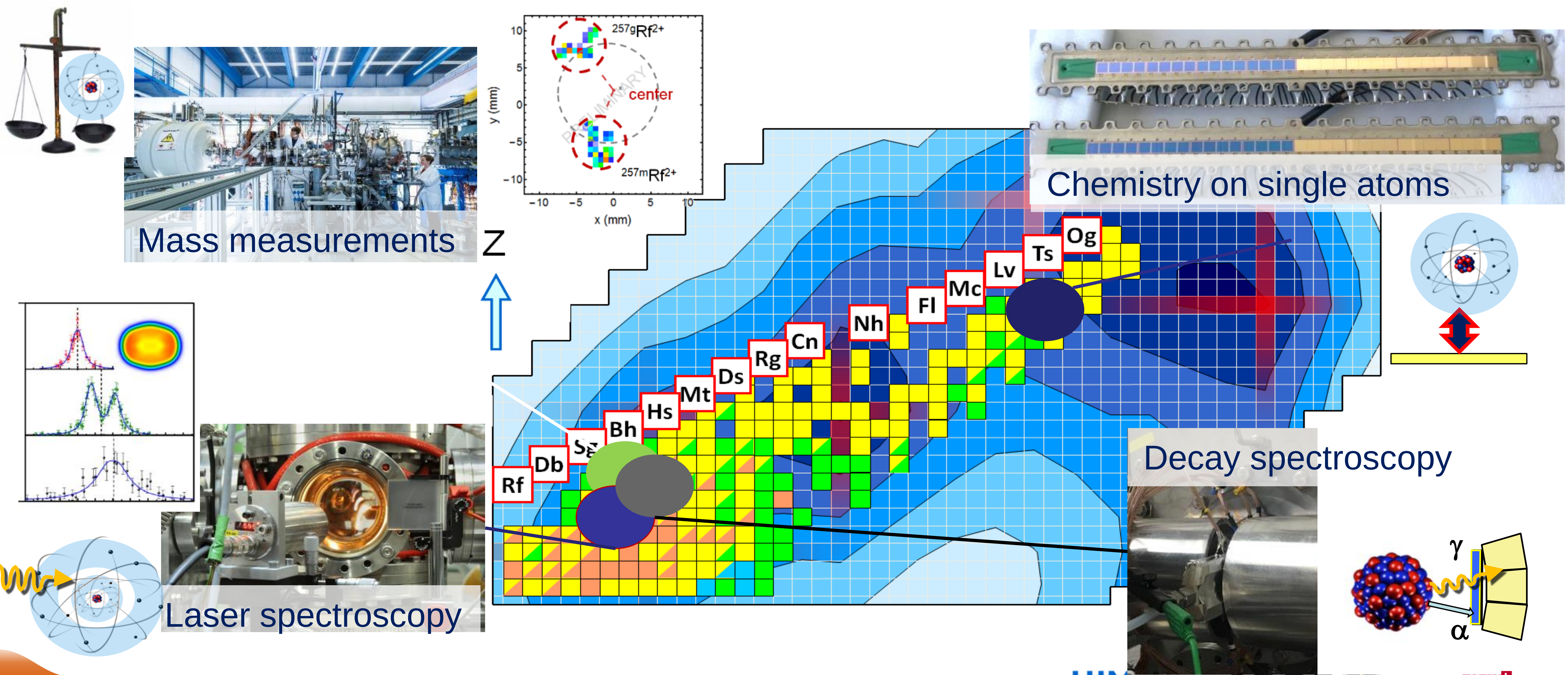
Target

Thickness
0.4 -1 µm

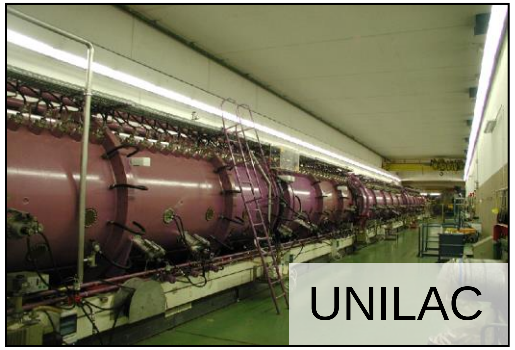
Separator for Heavy Ion Reaction Products (SHIP)
TransActinide Separator and Chemistry Apparatus (TASCA)

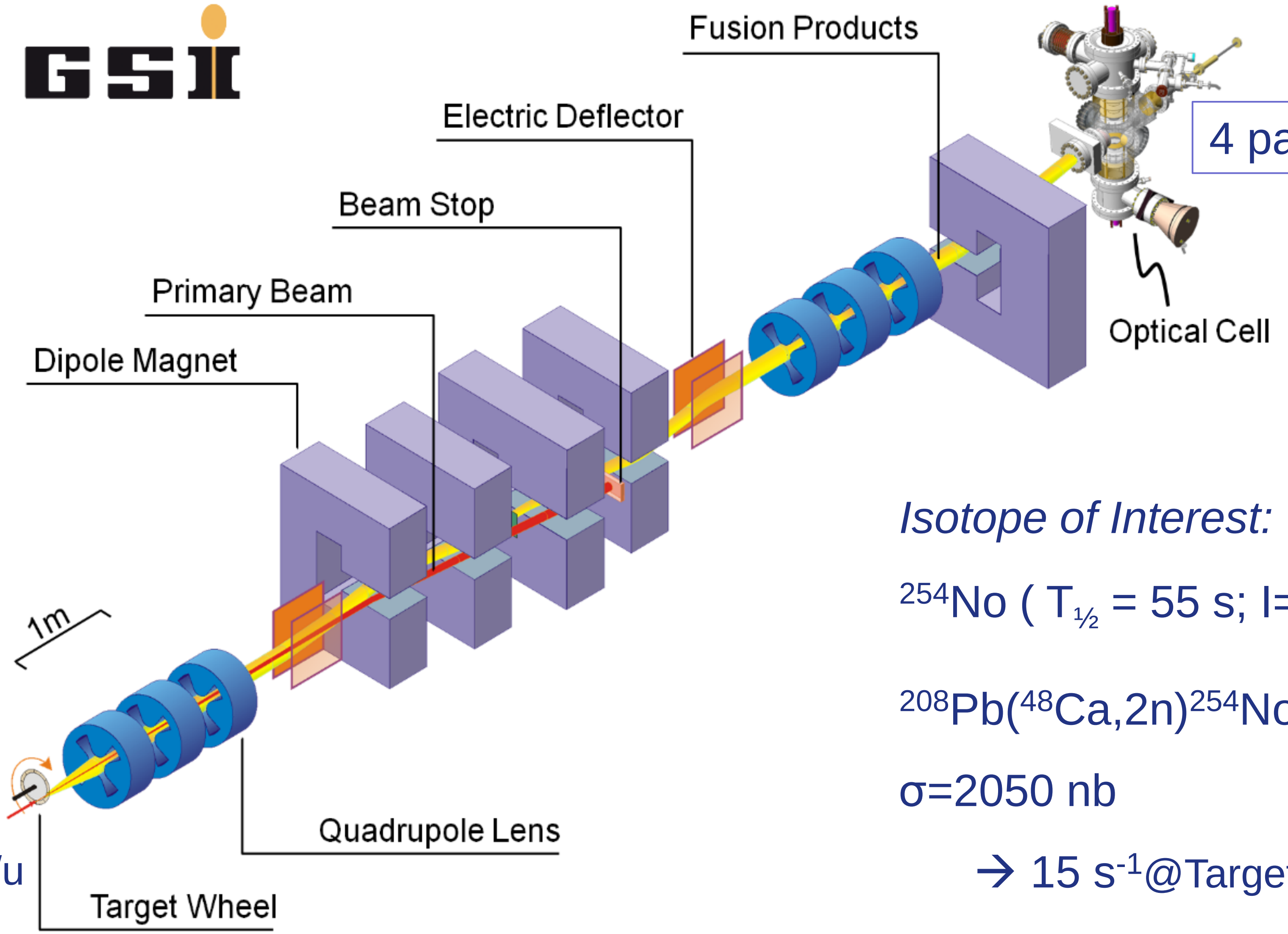


Superheavy Experiments at GSI



Production: Velocity Filter SHIP





4 part. s^{-1}

^{48}Ca
4.55 MeV/u
1 pµA

Isotope of Interest:

^{254}No ($T_{½}$ = 55 s; I=0)

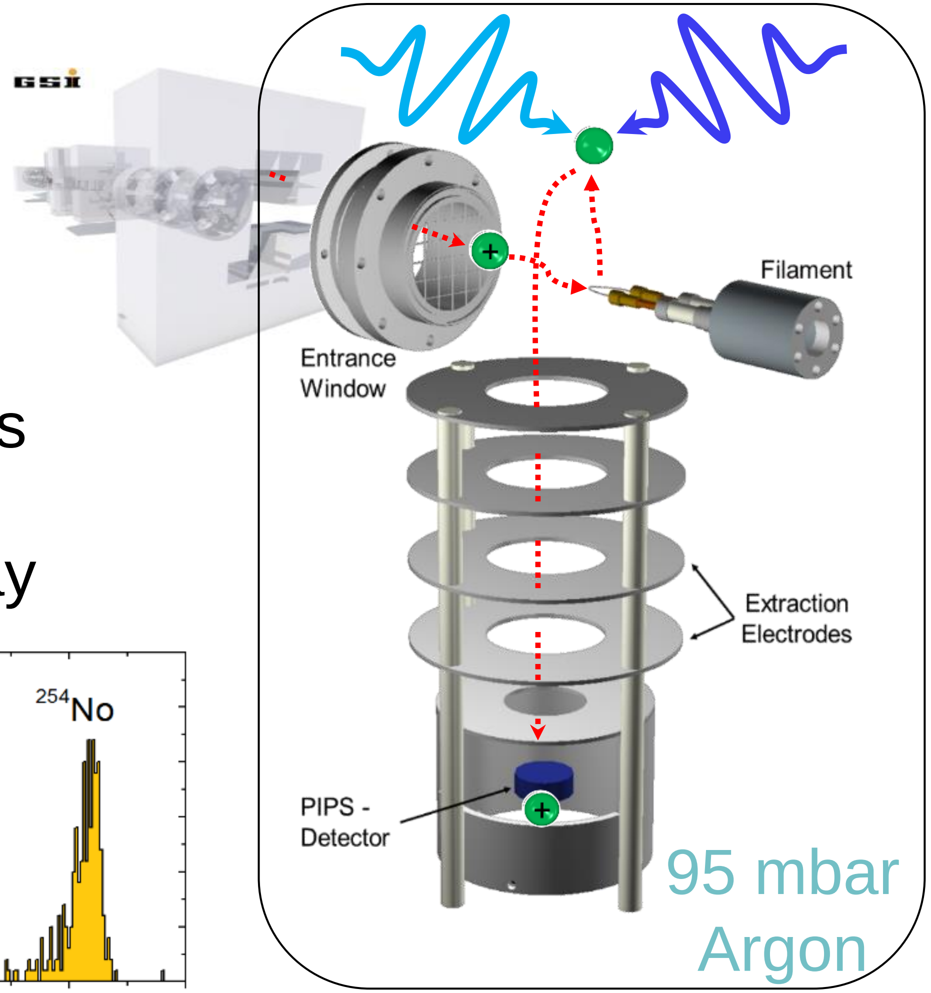
^{208}Pb(^{48}Ca,2n)^{254}No

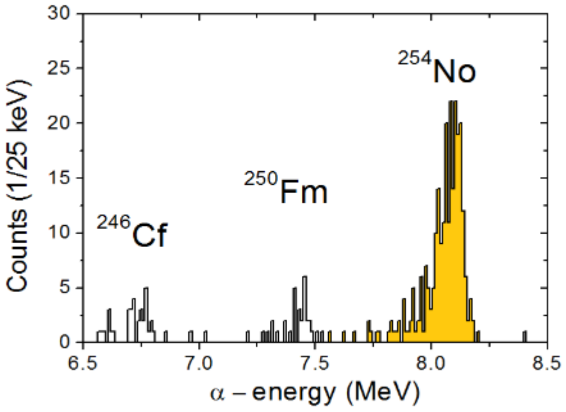
σ=2050 nb

→ 15 s^{-1}@Target

RADRIS Method:

- Thermalizing of incoming fusion products
- Collecting onto thin tantalum wire
- Evaporation and two-step photoionization process
- Transport to detector and detection of alpha decay
- High power 100 Hz Laser system



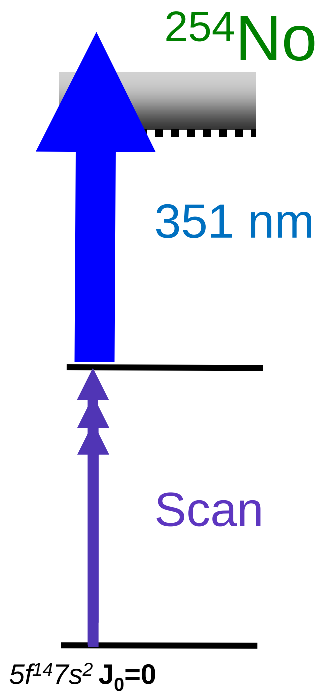


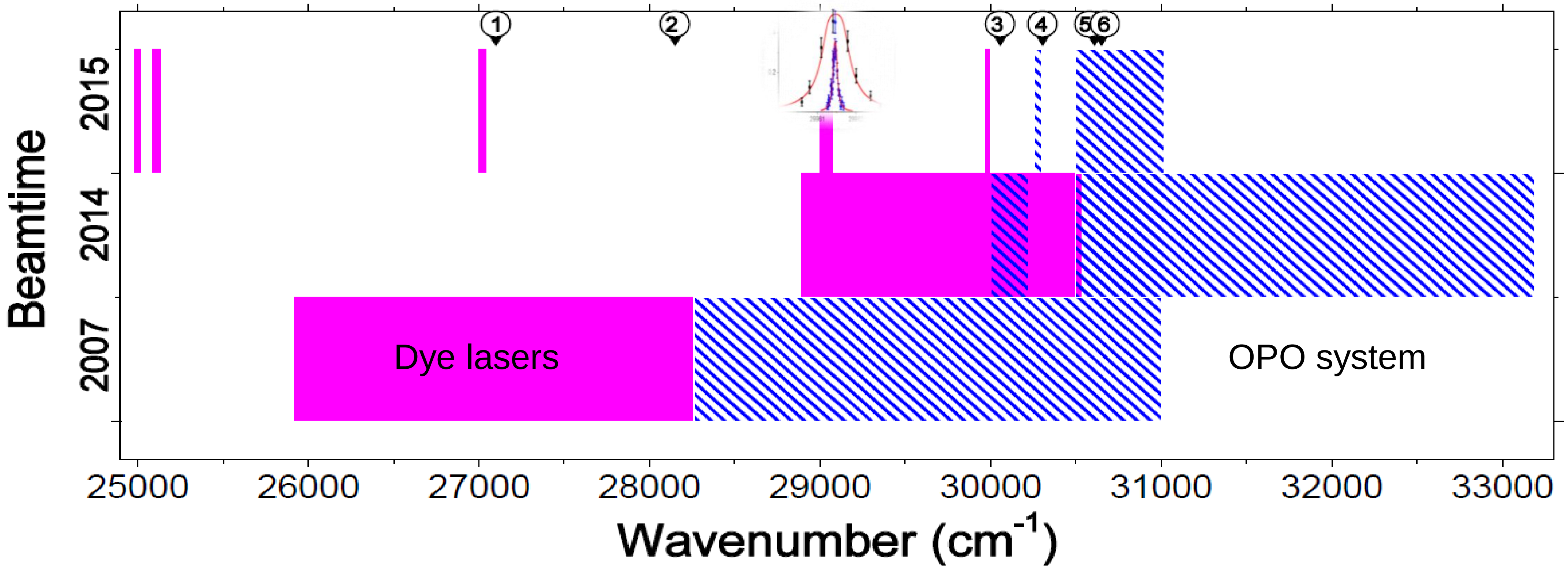
*H. Backe et al., Eur. Phys. J. D **45**, 99 (2007)*

*F. Lautenschläger et al., NIMB **383**, 115 (2016)*

Level Search in ^{254}No

Year	2007	2014
Scan range (cm^{-1})	25920 – 31001	28887 – 33191
Net scan time (h)	39	67





1: MCDF (2005), 2: MCDF (2005), 3: IHFSCC (2007), 4: RCC (2014), 5: MCDF (2007), 6: MCDF (2007)

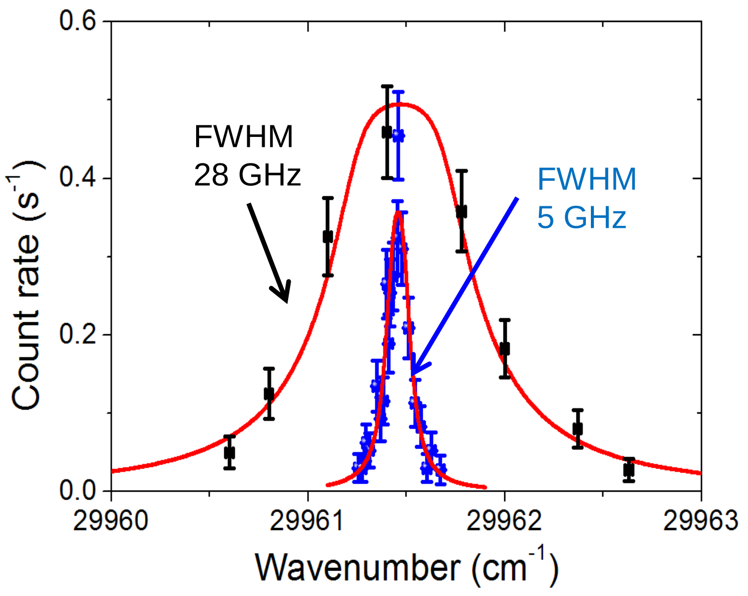
Nobelium: The Ground-State Transition

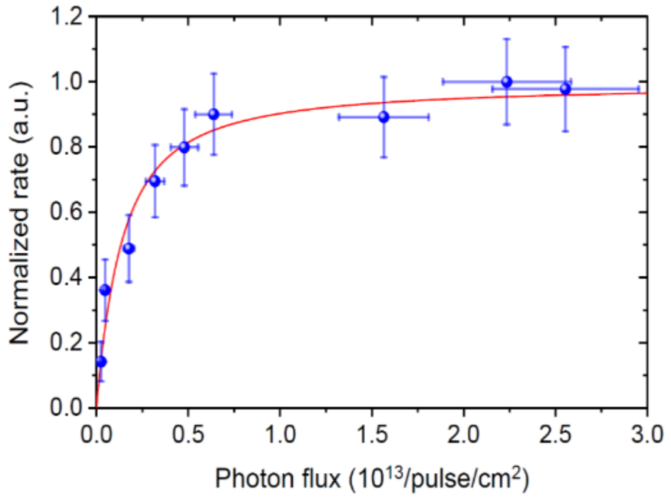
Observed strong atomic ground state transition

- Resolution 5 GHz
- A total efficiency of 6.4(10) % for ^{254}No
- Less than 30 000 atoms were delivered to the cell
- Saturates at low photon fluxes

	ν_1 (cm^{-1})	A_{ki} (s^{-1}) x 10^8
Experiment [1]	29,961.457(7)$_{stat}$	4.2 (2.6)$_{stat}$
IHFSCC [2]	30,100(800)	5.0
MCDF [3]	30,650(800)	2.7

Agrees with predicted $^1S_0 \rightarrow {}^1P_1$ transition





[1] *M. Laatiaoui et al., Nature* 538 (2016) 7626 [2] *A. Borschevsky et al., Phys. Rev. A* ***75*** *(2007) 042514*
[3] *P. Indelicato et al., Eur. Phys. J. D* ***45****, (2007) 155*

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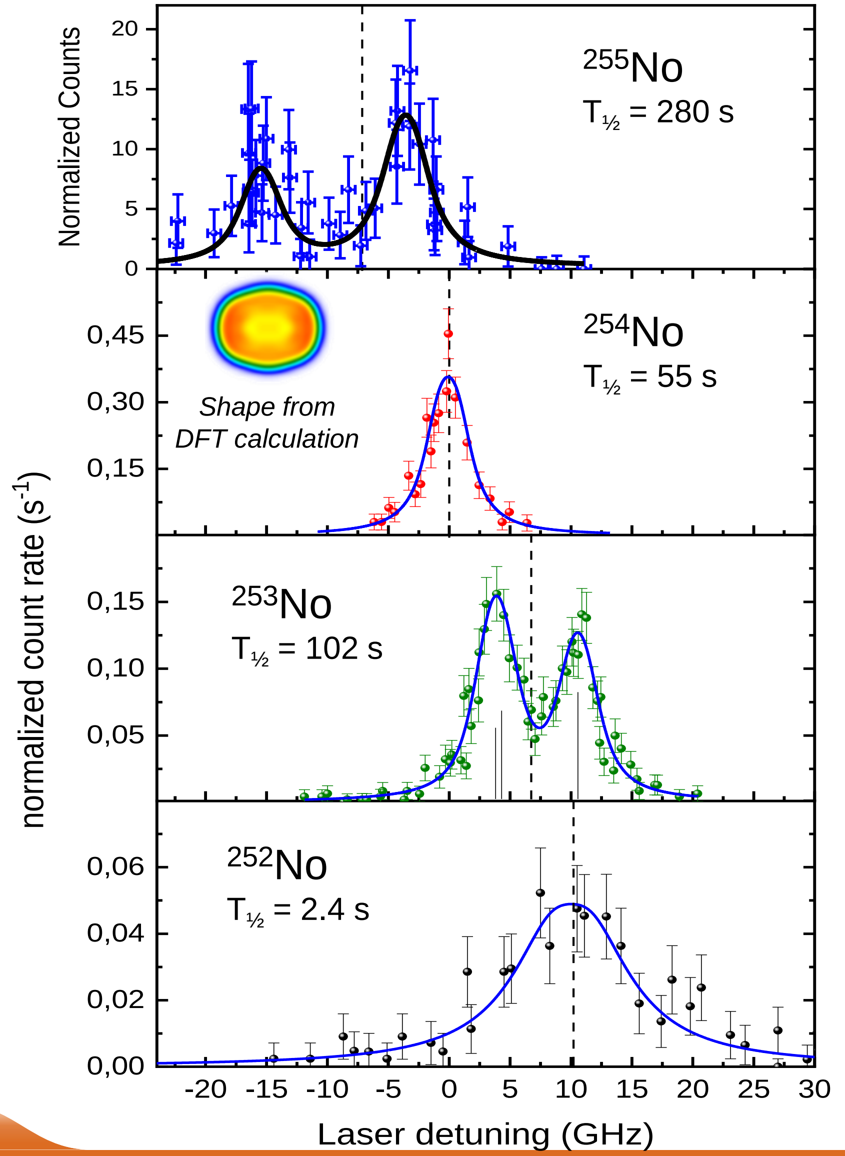
Isotope Shift of $^{252\text{-}254}$No & HFS in ^{253,255}No



- Isotope shift for $^{252\text{-}254}$No measured
- Change in charge radii: Input from atomic theory
  - Mass-shift constant: 1044 GHz u
  - Field-shift parameter: -95.8(7.0) GHz/fm

(R. Beerwerth & S. Fritzsche (MCDF), V. Dzuba, M. Safranove (CI), A. Borschevsky (RCC))

nuclear — atomic — properties

$$\delta\langle r^2\rangle^{AA'} = \left(\Delta\nu^{AA'} - \frac{A-A'}{AA'}M\right)\frac{1}{F}$$

experiment

Note: requires high precision atomic calculations !

S. Raeder et al., Phys. Rev. Lett. ***120*** *(2018) 232503*

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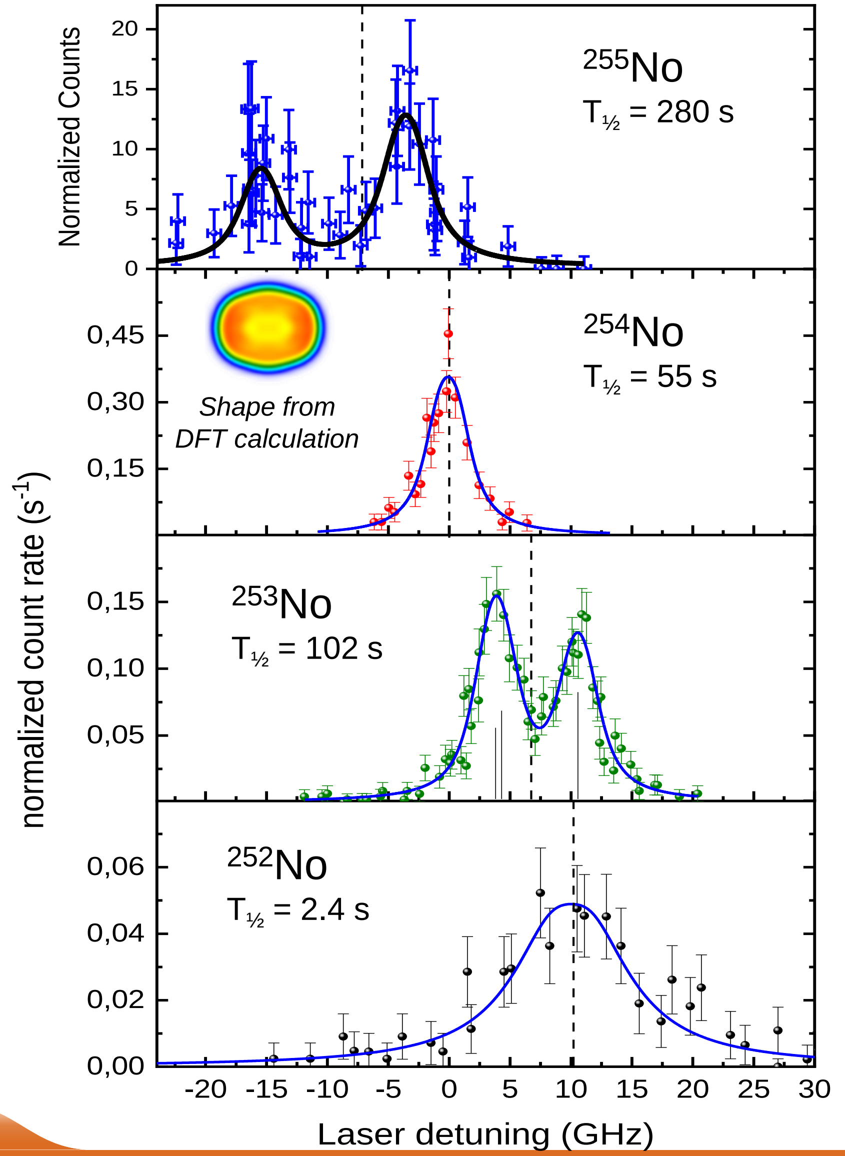
Isotope Shift of $^{252-254}$No & HFS in ^{253,255}No



- Isotope shift for $^{252-254}$No measured
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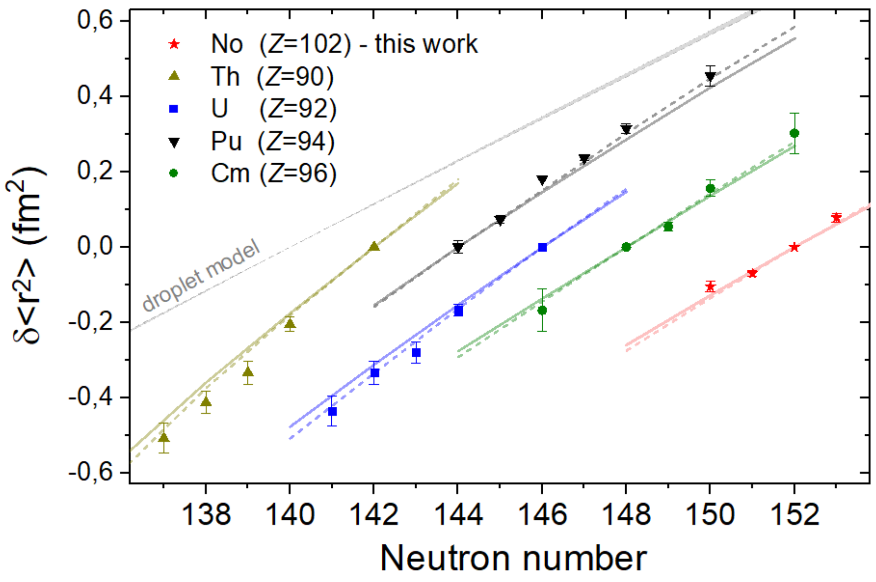
(R. Beerwerth & S. Fritzsche (MCDF), V. Dzuba, M. Safranove (CI), A. Borschevsky (RCC))



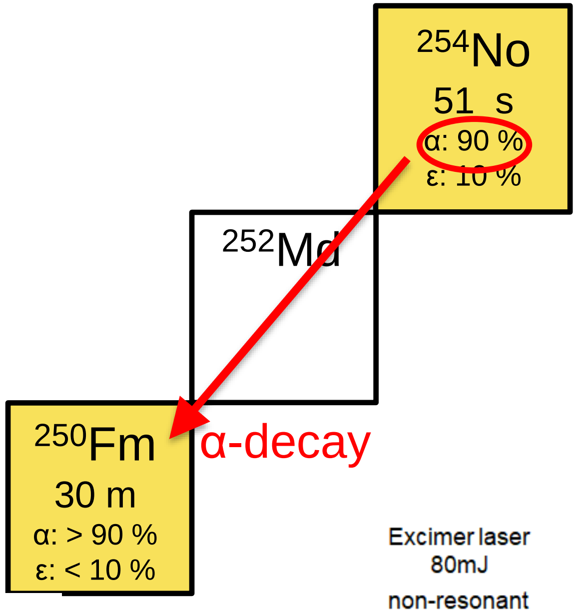
Agrees well with nuclear DFT calculations

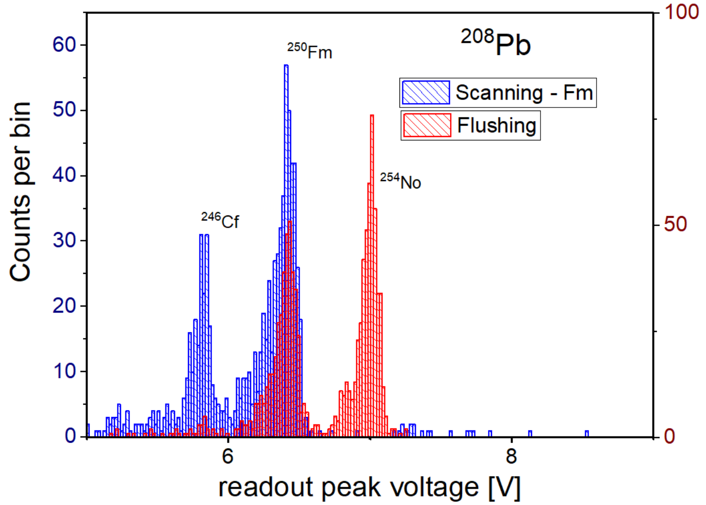
S. Raeder et al., Phys. Rev. Lett. ***120*** *(2018) 232503*

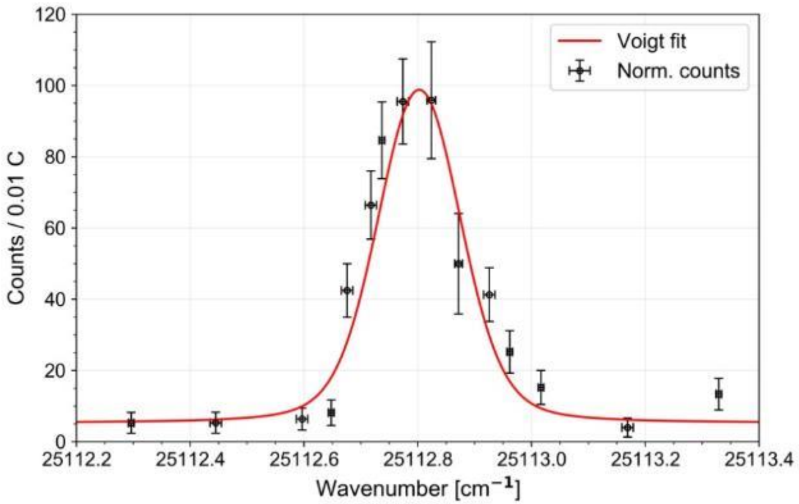
On-line Laser Spectroscopy of Fm Isotopes

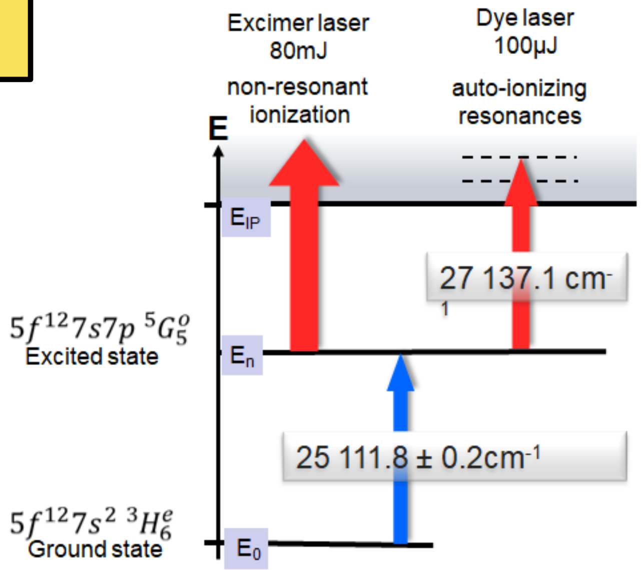
Fm (Z=100) - A new element for RADRIS

- Collection and decay on the filament
  - Direct production difficult
    - → Accessing daugher nuclides from No
  - Fm: few atomic levels are known









[Sew03] M. Sewtz, et al., *Phys. Rev. Lett.* 90.16 (2003): 163002.

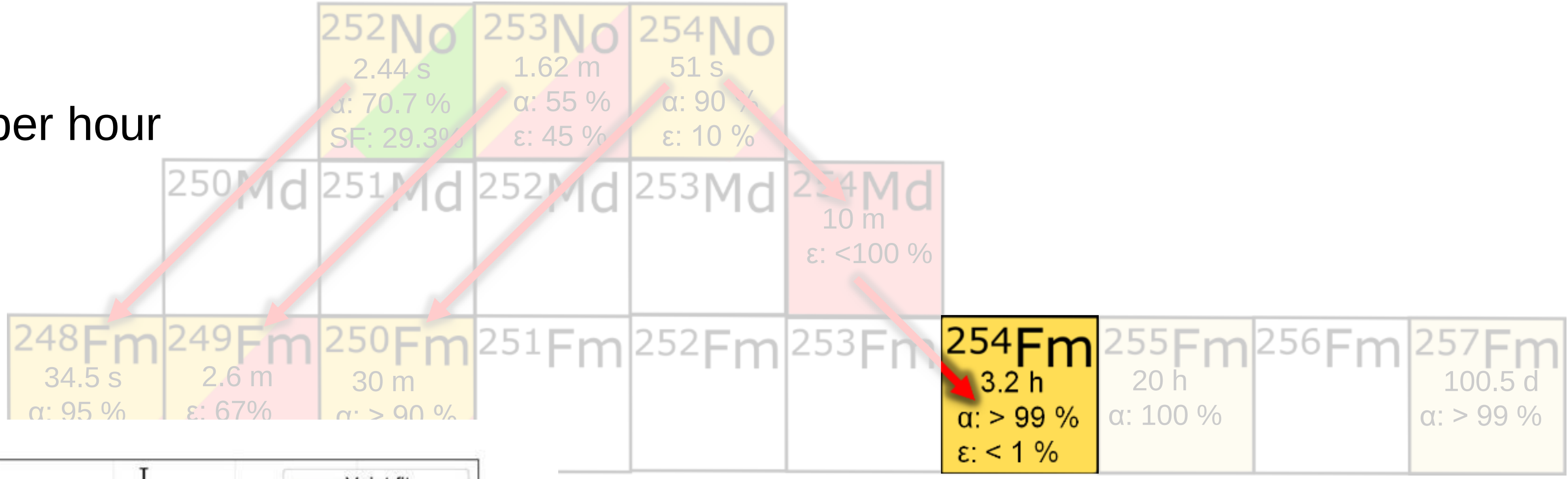
Accessible Fm isotopes

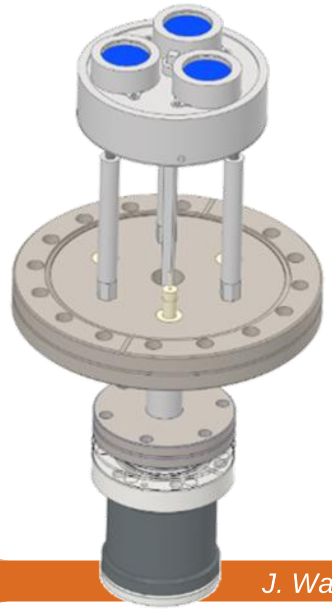
More Fm isotopes in reach from different No isotopes

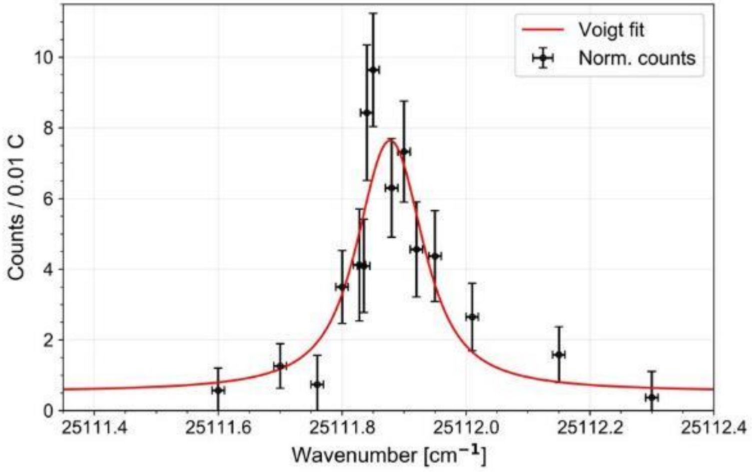
<u>Particular challenge: ^{254}Fm</u>

- Count rates of only few events per hour
- Half life of >3 h

→ Dedicated detector setup







- <u>21 h</u> per data point

  7 h collection – 14 h decay

Longest-lived isotope studied with RADRIS so far with $T_{1/2}$=3.2 h

J. Warbinek et al., Atoms 10(2), 41 (2022)

Es – Fm Sample available from Oak Ridge

2019: contact from Florida: Fm sample available

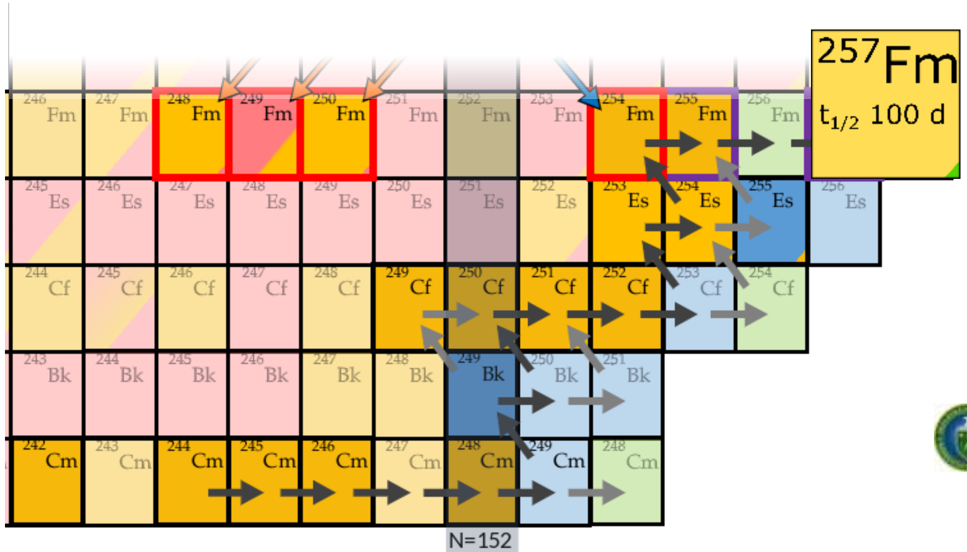
„waste“ in the ^{252}Cf production process

- breeding of ^{252}Cf

  $\Phi_n = 2.6 \cdot 10^{15}/cm^2 \cdot s$

  T = 3 months

High Flux Isotope Reactor
Oak Ridge National Laboratory



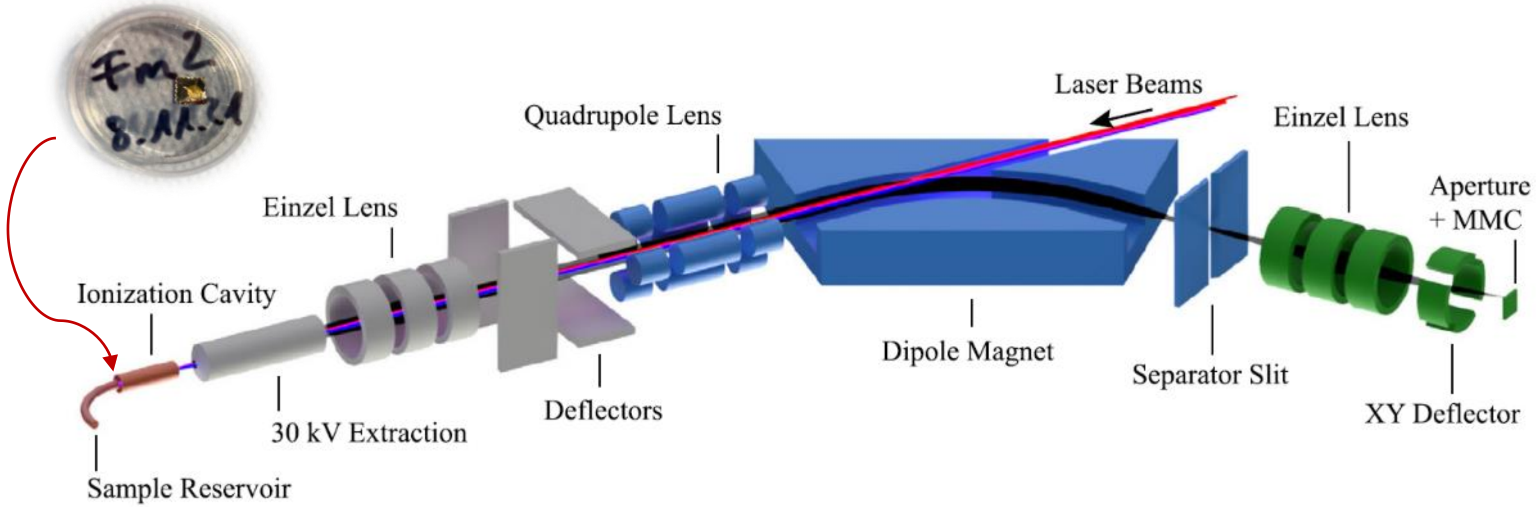
REDC-2606-B		
Cf-249	5.10E-03	µg.
Es-253	2.29E-03	µg.
Es-254	4.02E-03	µg.
Fm-257	1.38E-06	µg.

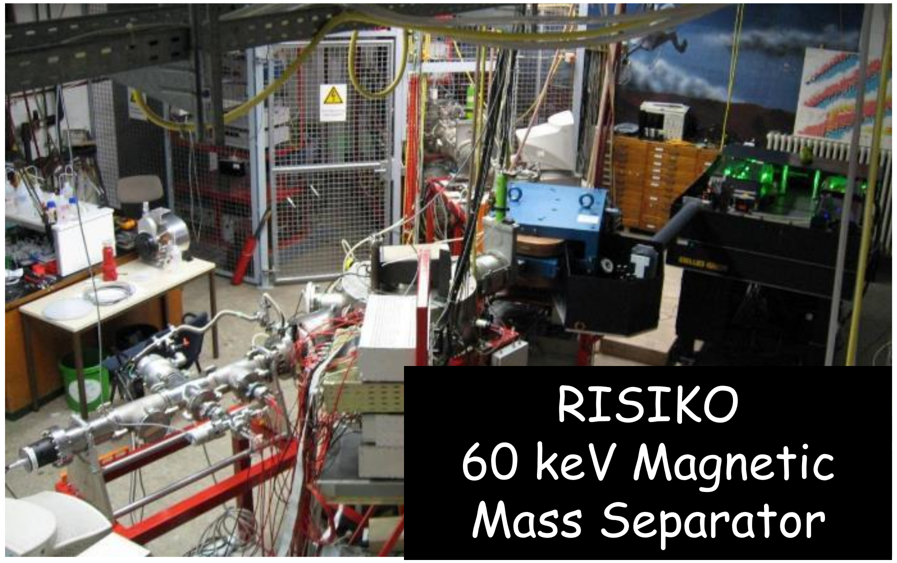
$T_{1/2}$ = 30 d
$T_{1/2}$ = 175 d
$T_{1/2}$ = 100 d

10^9 atoms

Radiochemical separation required → JGU - nuclear chemistry

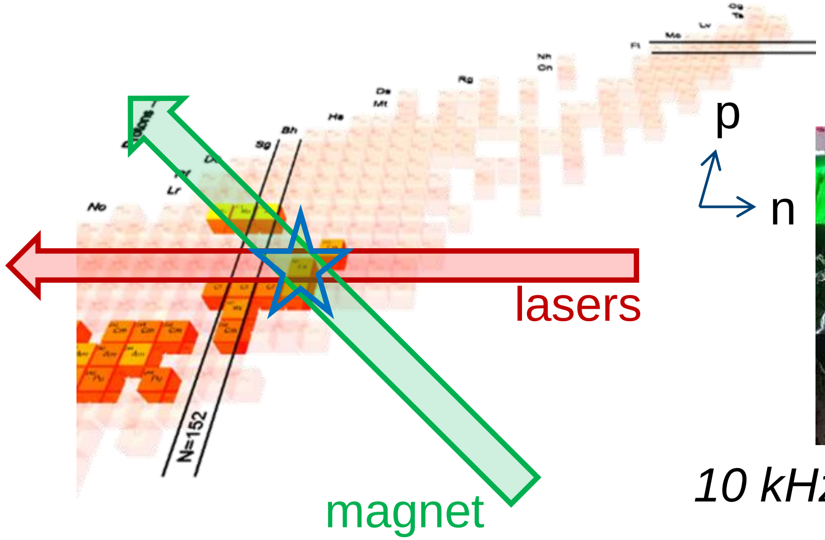
Hot Cavity Resonance Ionization Spectroscopy





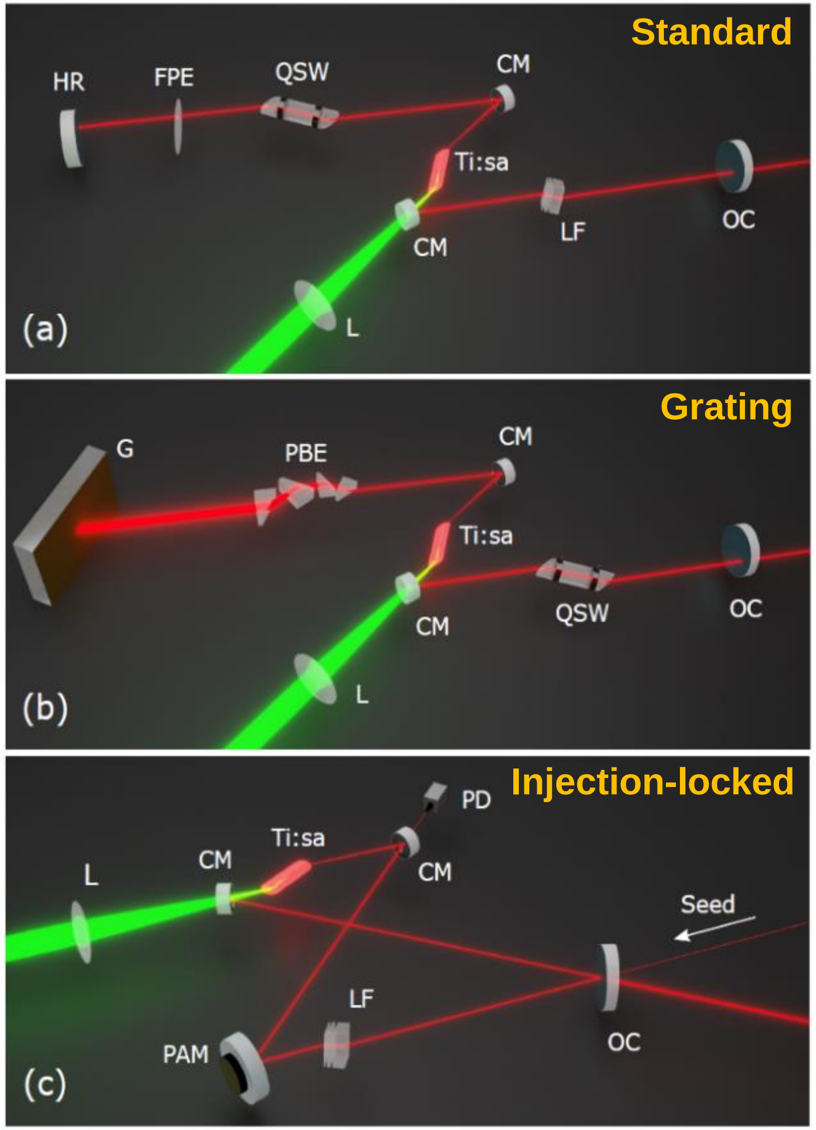
- Used for production of radioactive ion beams
- Laser spectroscopy with high efficiency
- Background from surface ionization
- Resolution limited by

  source temperature and laser bandwidth



10 kHz Laser system

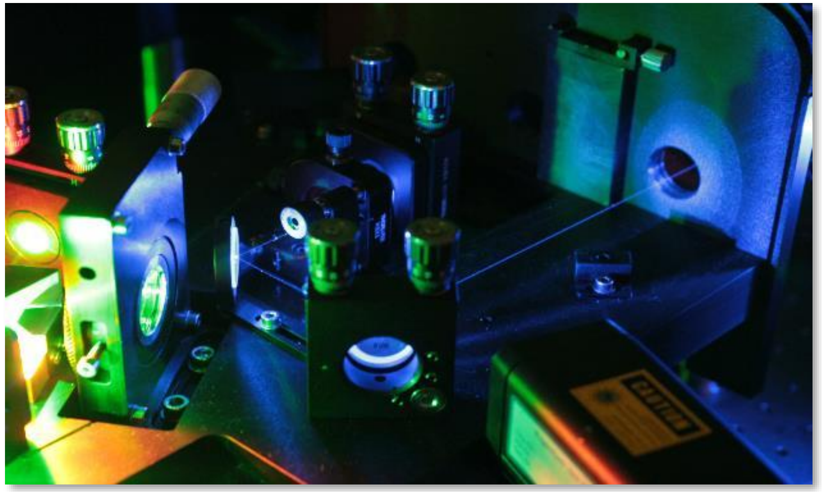
Ti:sapphire laser system



Three laser types for different applications

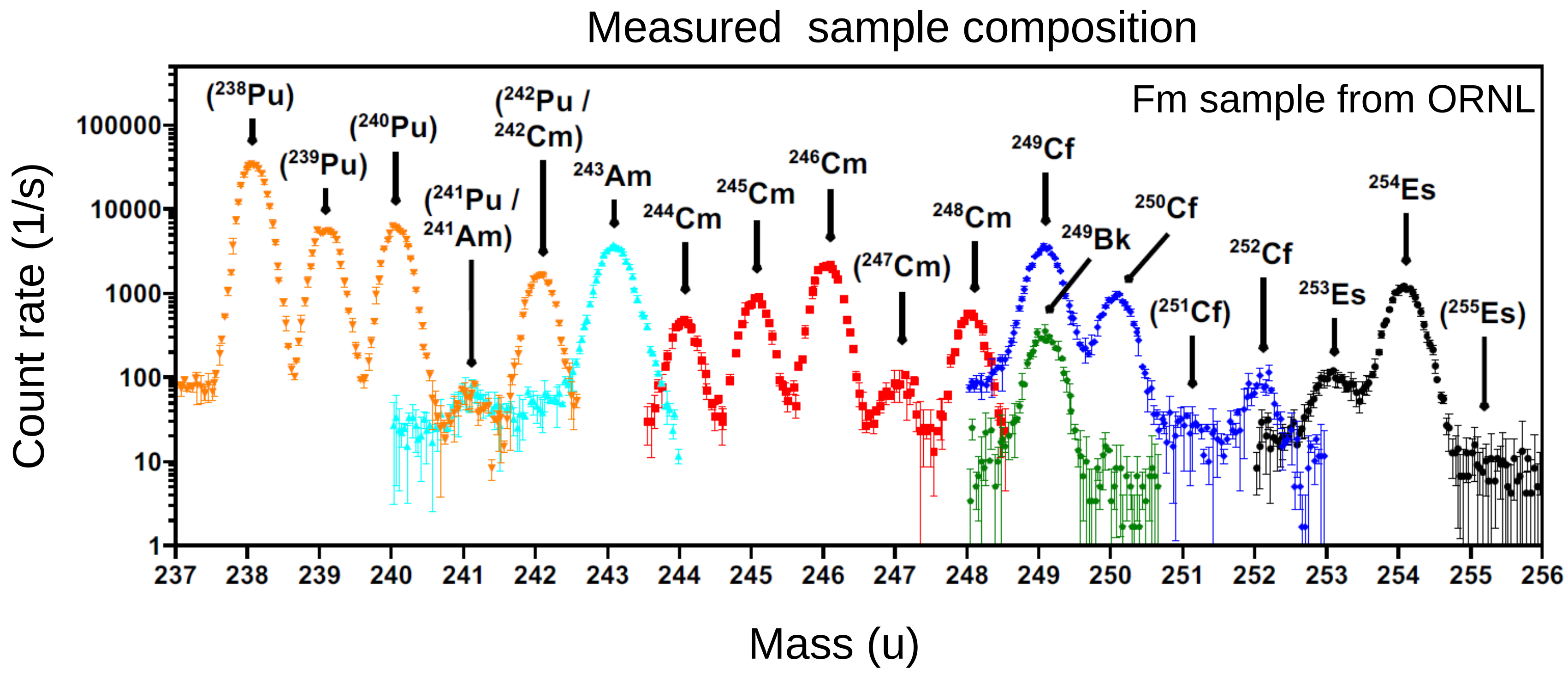
	Standard	Grating	Injection-locked
Repetition rate	10 kHz		
Pulse width	40 to 60 ns		
Avg. Power	**3 – 5 W**	1 – 2 W	2 – 3 W
Output range	700 – 1020 nm		seed source
Tuning range	100 GHz	**700 – 1020 nm**	typ. 20 GHz
Spectral bandwidth	1 to 10 GHz	1 to 3 GHz	**20 MHz**
Application	Laser ion source	BB spectroscopy	HR spectroscopy

Extension of output range by SHG, frequency mixing possible



Sample Analysis with Laser Ionization

Lasers tuned to resonantly ionize different actinide elements



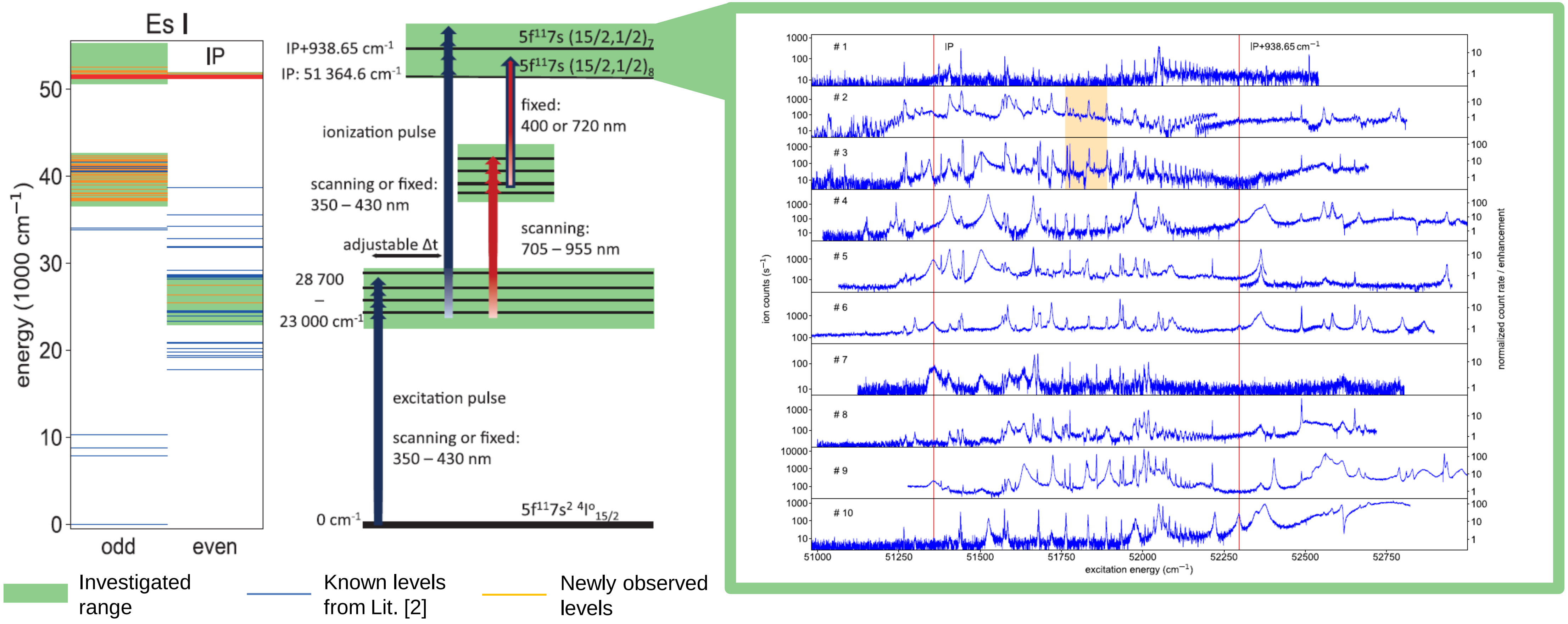
Stated sample composition

REDC-2606-B		
Cf-249	5.10E-03	μg.
Es-253	2.29E-03	μg.
Es-254	4.02E-03	μg.
Fm-257	1.38E-06	μg.

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

Es Laser Ionization Spectroscopy

Idendification of ionization schemes: Investigation of atomic struture in Einsteinium



Characterization of 10 Levels using only 10^{10} atoms (10 pg), revised ionization potential

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

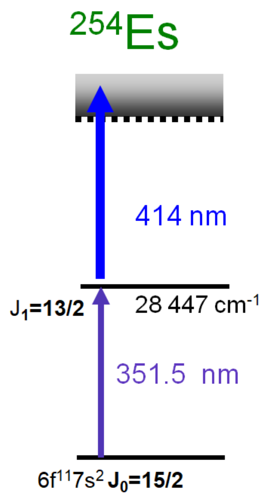
F. Weber et al., Phys. Rev. Res. 4, 043053 (2022)

Hyperfine Structure of Es Isotopes

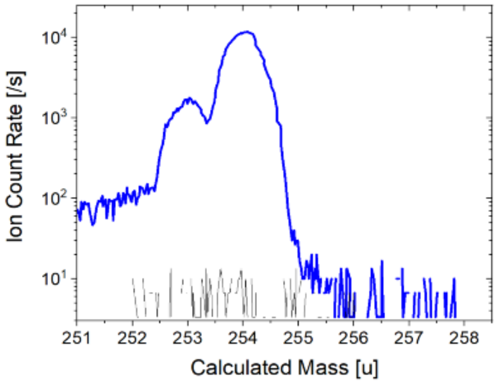
Atomic structure investigation with 10 pg samples (10^{10} atoms)

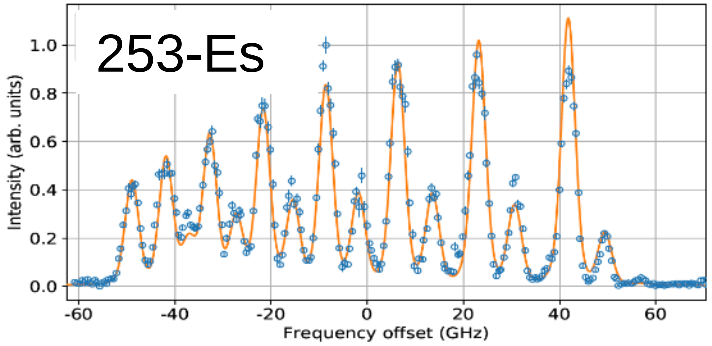
Hyperfine structure measurements

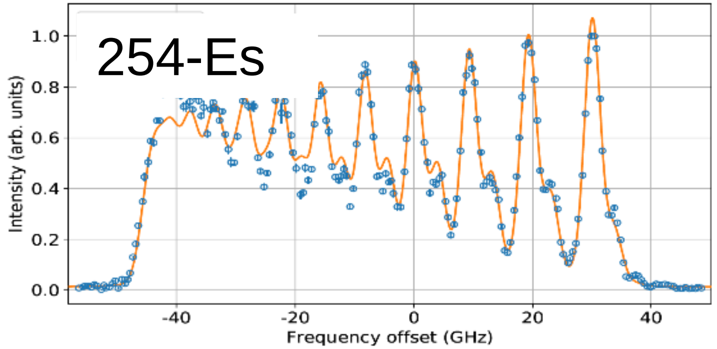
- Fixed ionization scheme
- Nuclear moments deduced

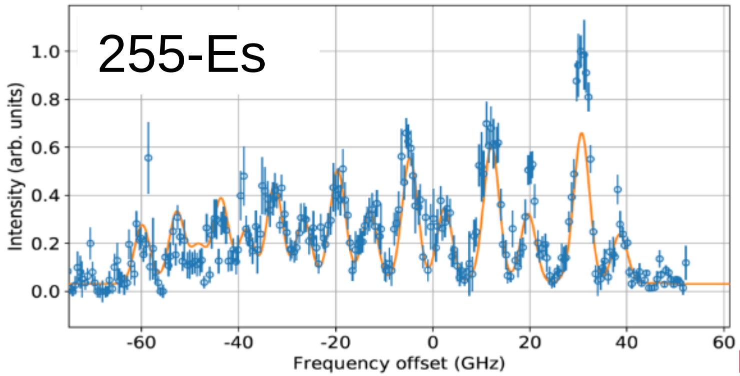


		This work		Literature	
Isotope	I	μ_I (μ_N)	Q_s (eb)	μ_I (μ_N)	Q_s (eb)
^{253}Es	7/2			4.10(7) [12]	6.7(8)[a] [12]
^{254}Es	7	3.42(7)	9.6(1.2)	4.35(41) [15]	
^{254m}Es	2			2.90(7) [12]	3.8(5) [12]
^{255}Es	7/2	4.14(10)	5.1(1.7)		









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S. Nothhelfer et al., Phys. Rev. C 105.L021302 (2022), F. Weber et al., Phys. Rev. Res. 4.4 (2022): 043053.

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Nuclear Properties of Cf Isotopes

PI-LIST ensures higher resolution

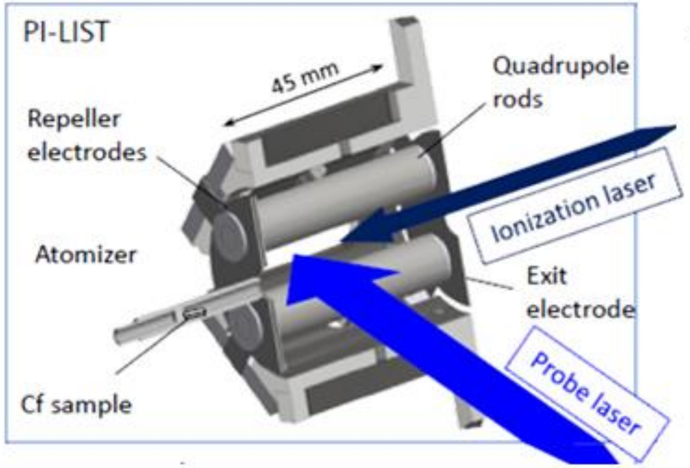
Cf samples as low as 5•10^7 atoms !

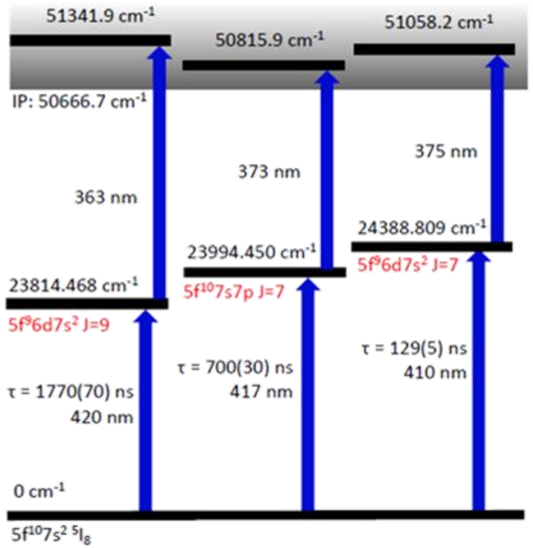
Hyperfine structure measurements

- Fixed ionization scheme
- Nuclear moments deduced

→ **input from atomic theory**

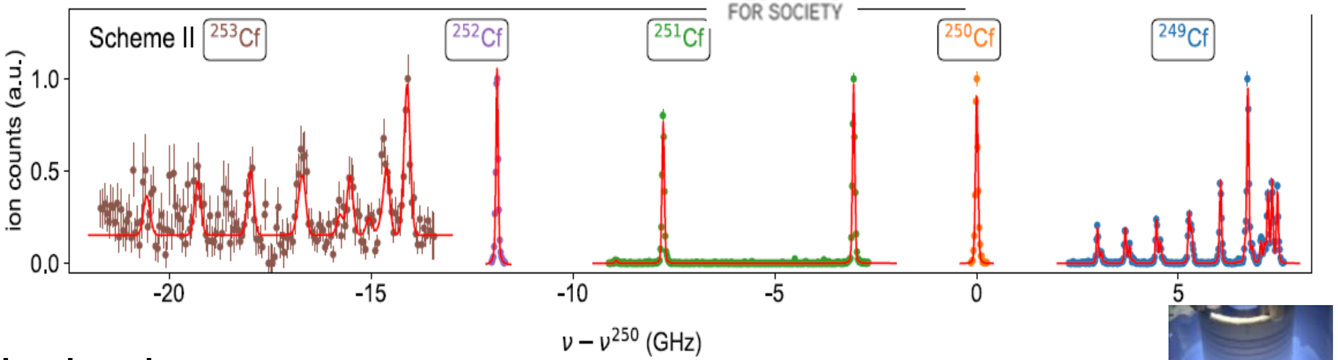
(V. Dzuba et al., CIPT)

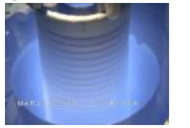




Isotope	I	μ_I (μ_N)	$\mu_{I,HFB}$ (μ_N)	Q_S (eb)	$Q_{S,HFB}$ (eb)
^{249}Cf	9/2	-0.395(18)†	-0.731	6.27(31)	6.86
^{251}Cf	1/2	-0.571(26)	-1.015		
^{253}Cf	7/2	-0.731(33)	-0.755	5.53(28)	5.40

† Literature value: 0.28(6) [2]



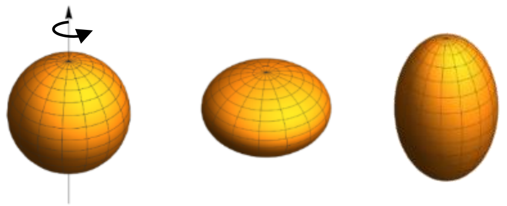


First values for Q_S and comparision to HFB calculations *(S. Hilaire, S. Goriely, S. Peru)*

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

[1] F. Weber et al., Phys. Rev. C 107, 034313 (2023) [2] N. Edelstein, D. G. Karraker, J. Chem. Phys. 62, 938 (1975)

Deformation of the Actinides



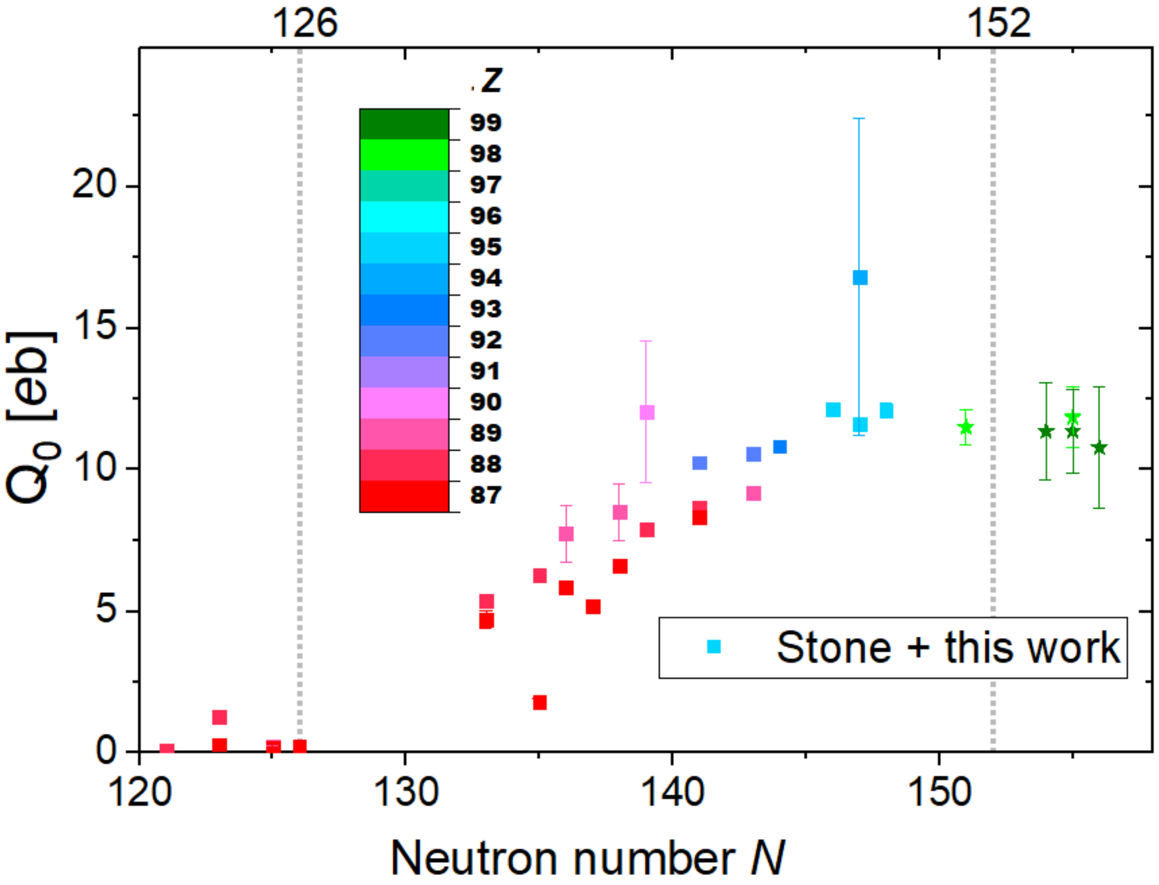
Spectroscopic Quadrupole Q_S moment
from Laser spectroscopy (and other techniques)

$$Q_0 = \frac{(I+1)(2I+3)}{3K^2 - I(I+1)} Q_S, \qquad \beta = \frac{\sqrt{5\pi}}{3R_0^2 Z} Q_0$$

For well-deformed nuclei

Evaluating the evolution of deformation

- Access to nuclei beyond N=152
- Region of large, stable deformation



N.J. Stone , IAEA INDC(NDS)-0594 (2015)

Deformation of the Actinides

Spectroscopic Quadrupole Q_S moment

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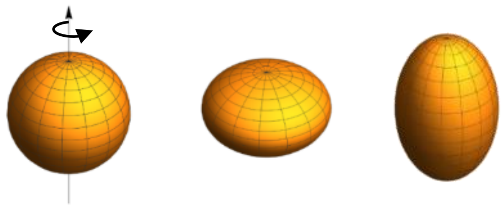
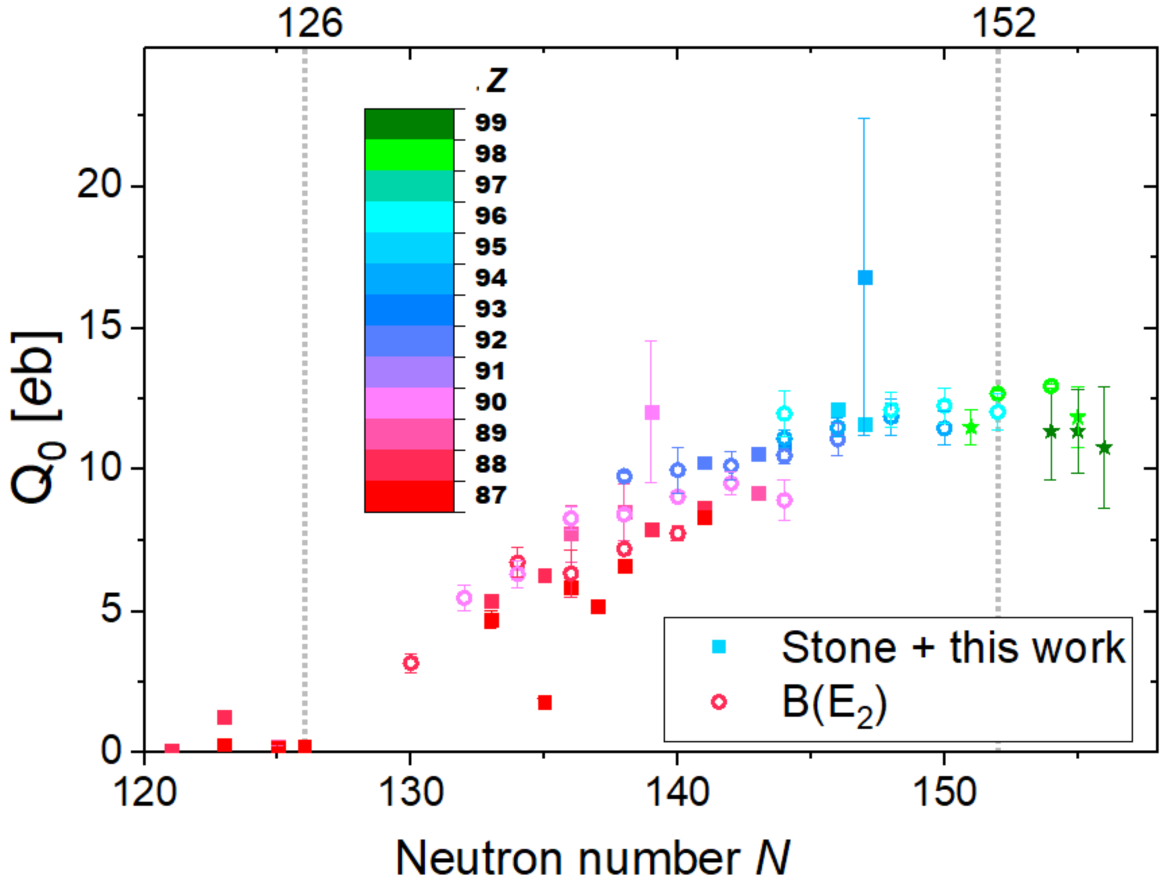


$$Q_0 = \frac{(I+1)(2I+3)}{3K^2 - I(I+1)} Q_S, \qquad \beta = \frac{\sqrt{5\pi}}{3R_0^2 Z} Q_0$$

For well-deformed nuclei



Evaluating the evolution of deformation

- Access to nuclei beyond N=152
- Region of large, stable deformation

N.J. Stone , IAEA INDC(NDS)-0594 (2015) - B. Pritychenko et al , Atom. Dat.Nucl.Dat.Tab.107, 1-139 (2016)

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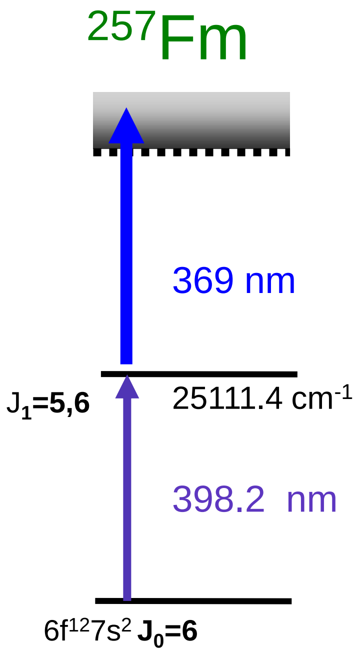
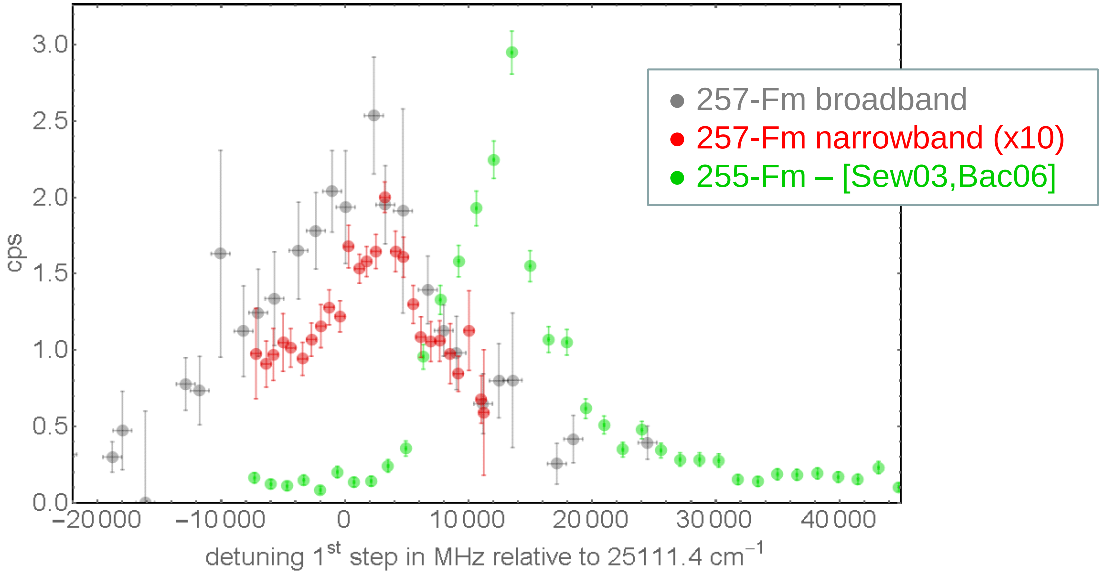
What about Fermium?

- Preparation: Chemical separation to increase the fermium content





REDC-2606-B		
Cf-249	5.10E-03	µg.
Es-253	2.29E-03	µg.
Es-254	4.02E-03	µg.
Fm-257	1.38E-06	µg.

→ first laser spectroscopy of ^{257}Fm

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

[Sew03] Sewtz, M., et al. *Phys. Rev. Lett.* 90.16 (2003): 163002. -- *[Bac06] Backe, H., et al. " Laser 2004. (2006). 3-14.*

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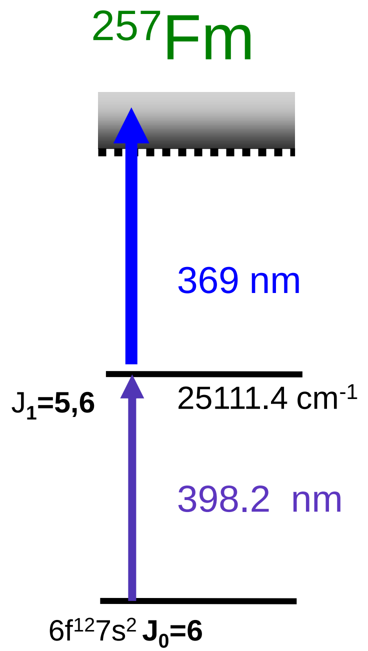
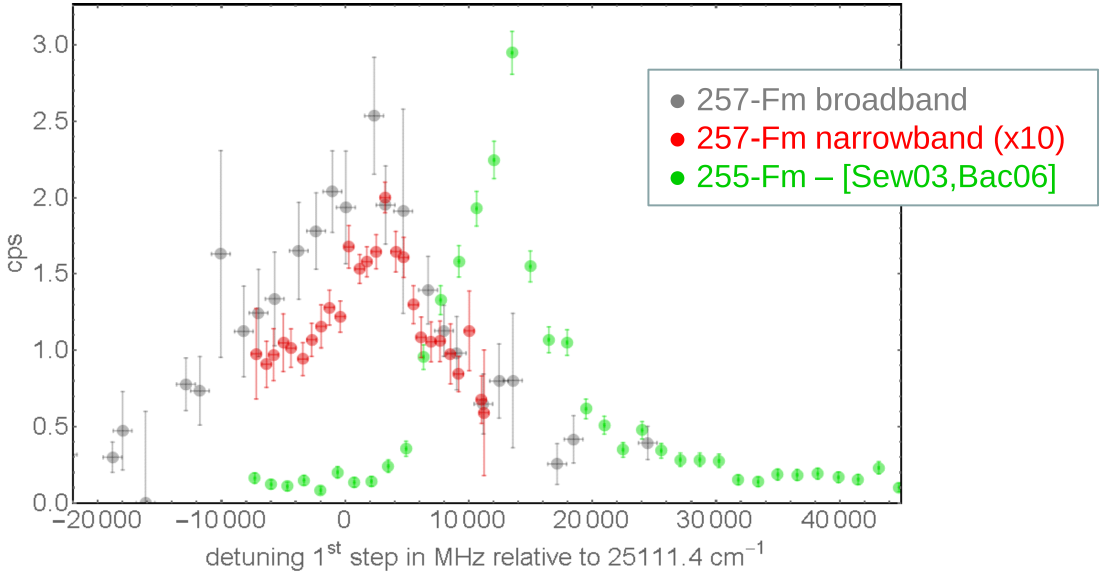
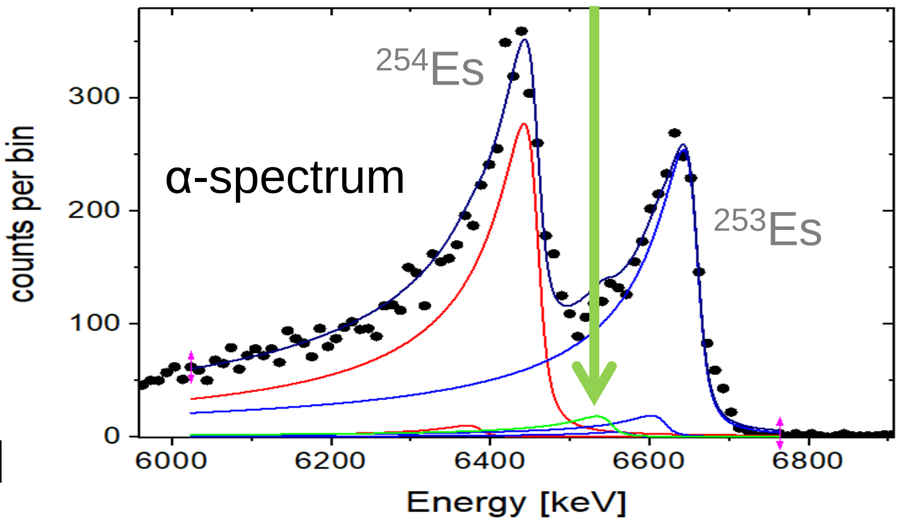
Laser spectroscopy of Fm-257

- Preparation: Chemical separation to increase the fermium content





5x10^7 atoms ^{257}Fm



→ first laser spectroscopy of ^{257}Fm

despite a much lower sample size then expected

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

[Sew03] Sewtz, M., et al. *Phys. Rev. Lett.* 90.16 (2003): 163002. -- *[Bac06] Backe, H., et al. " Laser 2004. (2006). 3-14.*

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Fm-255 – boostered sample from ILL

^{254}Es

Breeding at ILL
Grenoble, France

NEUTRONS
FOR SOCIETY

^{255}Es

$t_{1/2}$ = 40 d

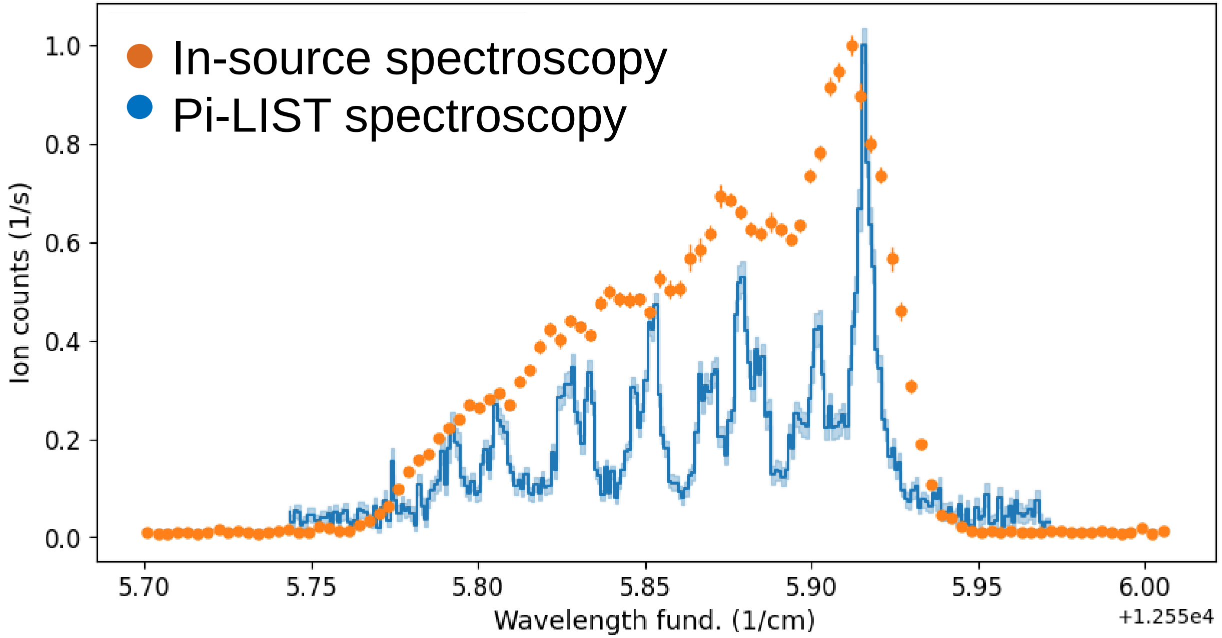
β^-

^{255}Fm
$t_{1/2}$ 20 h

Chemical separation:

- Increase purity
- Enable muliple separation
- ^{255}Fm generator system
- 2023: 13 samples (10^8 atoms)!

More data available → under analysis



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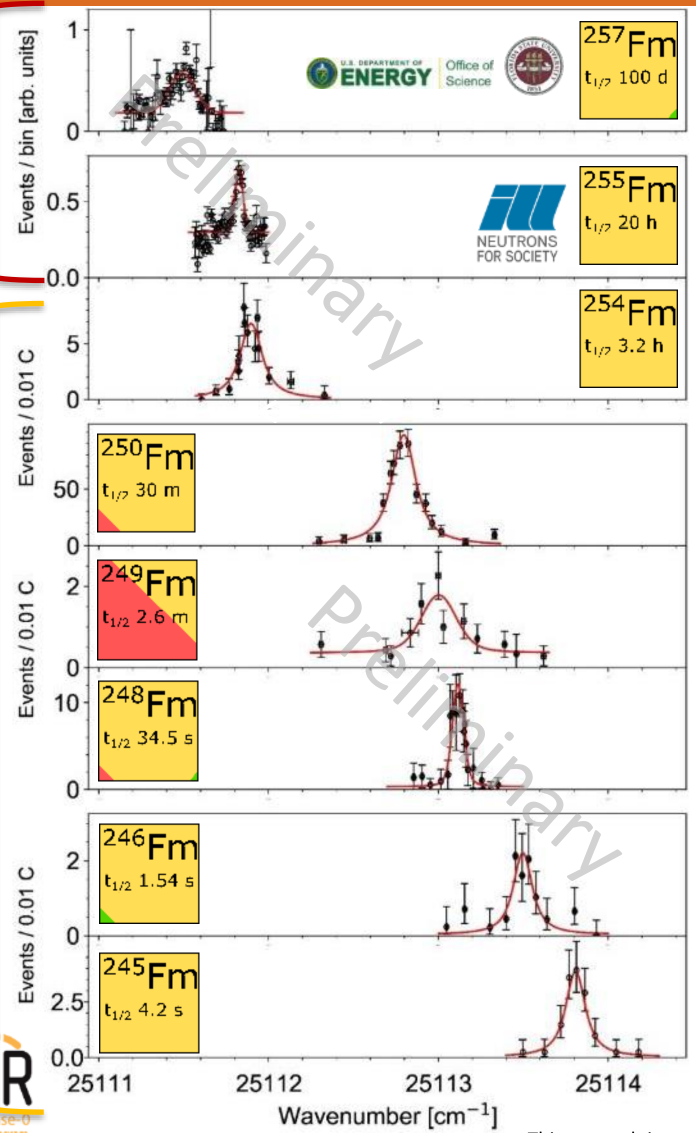
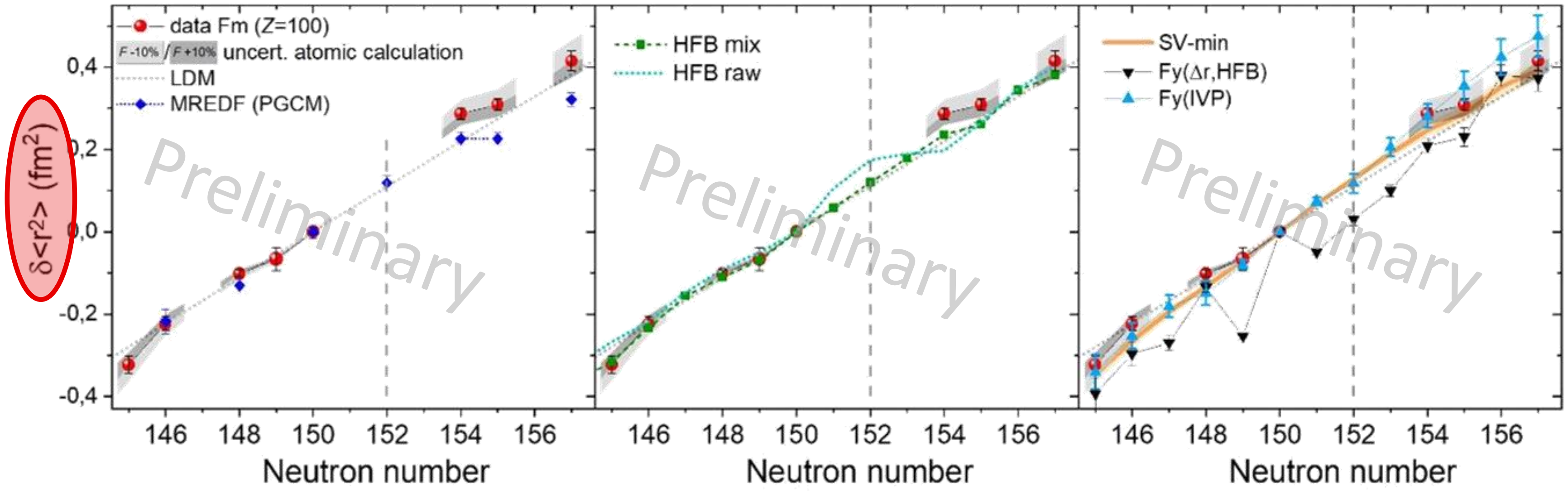
Fm isotopic chain – change in rms charge radii



Nuclear EDF calculations performed within collaboration by B. Bally, M. Bender, S. Goriely, S. Hilaire, W. Nazarewicz, S. Peru, P.G. Reinhard, W. Ryssens



Isotope shift measured to reference ^{250}Fm

Atomic parameters from theory available:

$$\delta\langle r^2\rangle^{AA'} = \left(\Delta\nu^{AA'} - \frac{A - A'}{AA'} M\right)\frac{1}{F}$$

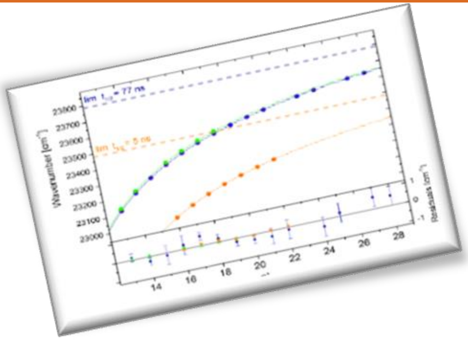
S. Allehabi et al., J. Quant. Spec. Rad. Transfer 253, 107137 (2020).

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

RADRIS – Perspectives

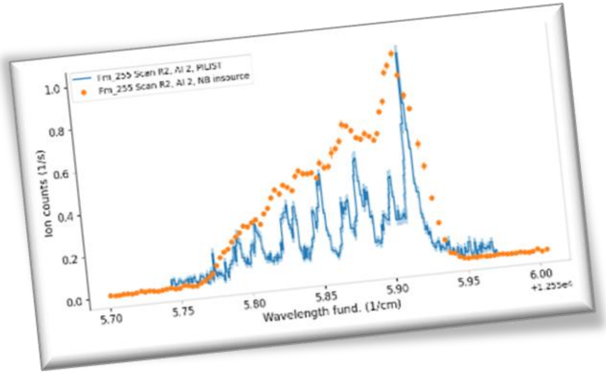
Achievements in Laser spectroscopy:

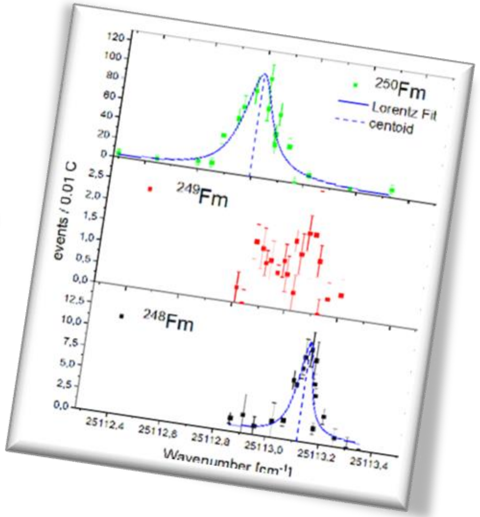
- ✓ a sensitive & versatile tool for investigating atomic & nuclear properties
- ✓ Many atomic levels observed in ^{254}No
- ✓ Differential mean square charge radii extracted for $^{252\text{-}255}$No & $^{248\text{-}250,254,255,257}$Fm
- ✓ Complementary off-line laser spectroscopy
- ✓ Exotic Cf isotopes accessible online ….



Limitations of the RADRIS technique

- Collection cycle limits short lifetimes
- Radiation detection difficult for long-lived nuclides
- Gas environment limits the spectral resolution





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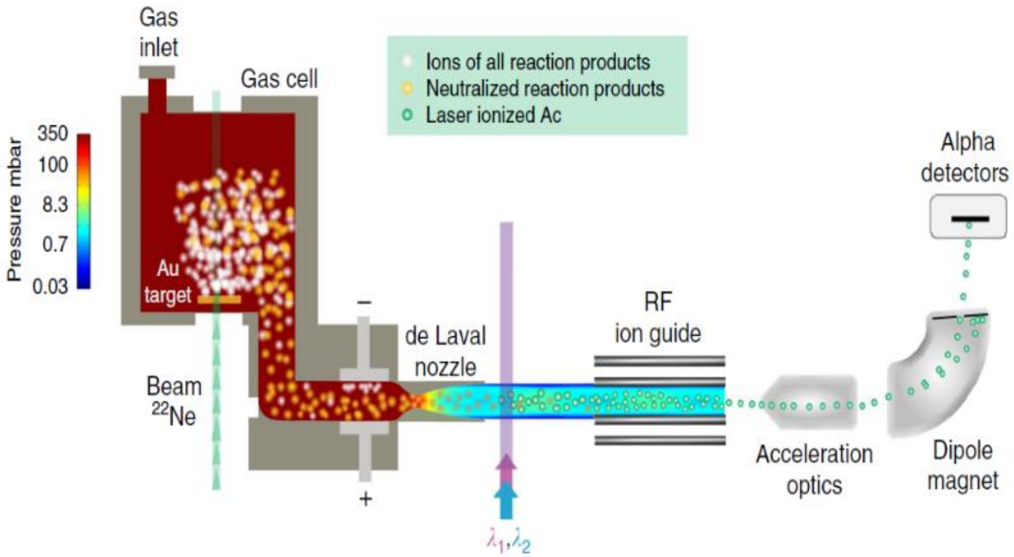
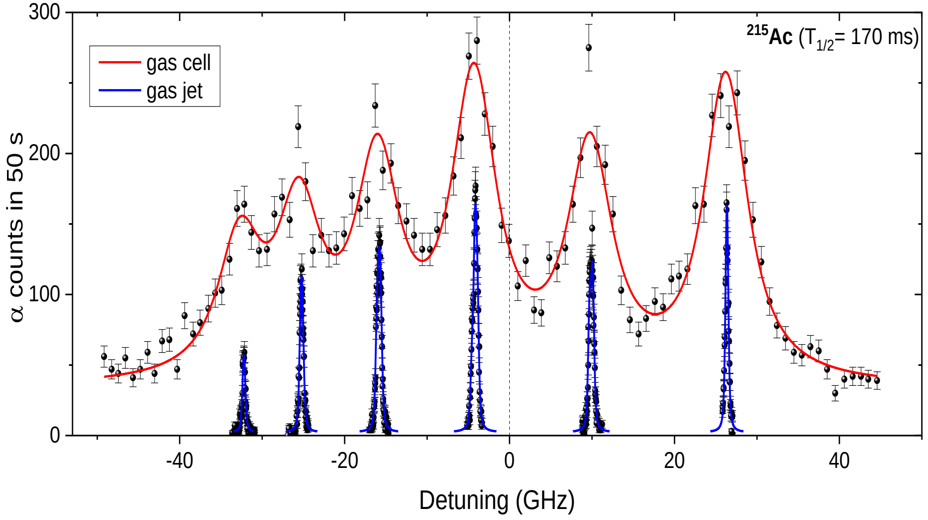
Gas jet – High Resolution & High Efficiency



Gas jet schematic used on-line @ LISOL

In-Cell vs In-Jet Spectroscopy - ^{215}Ac

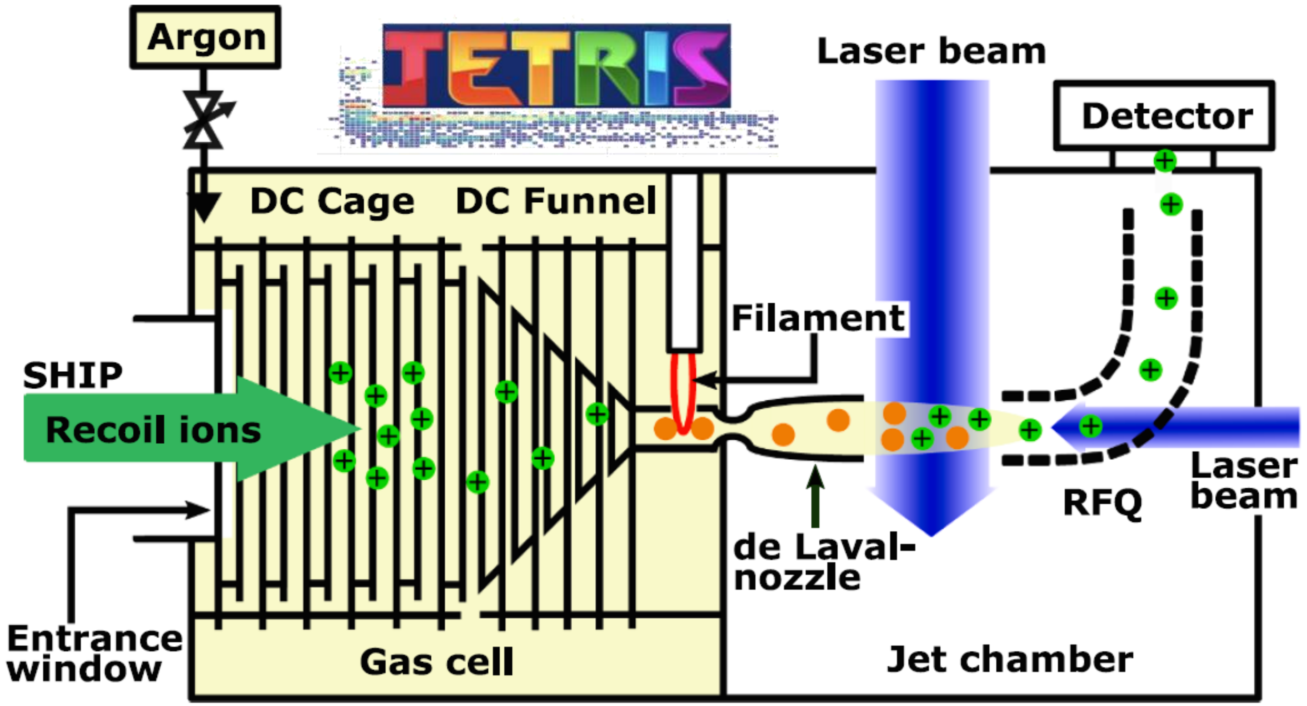


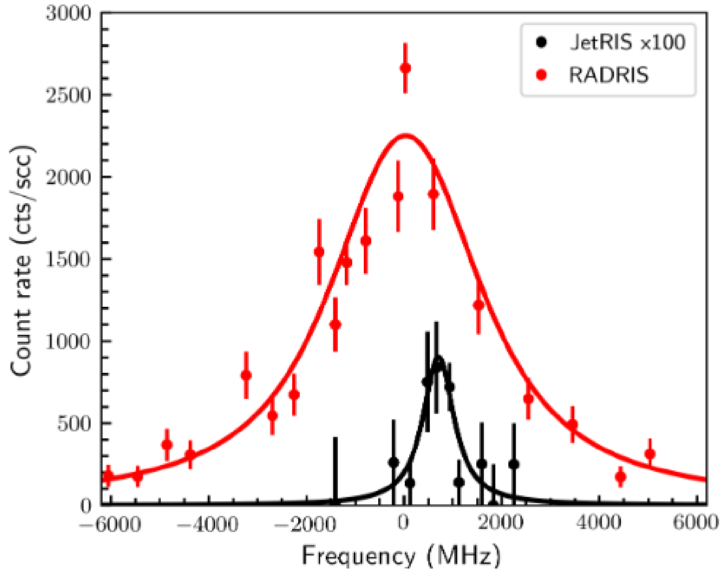
- Low temperature & low density supersonic gas jets are ideal environments for laser spectroscopy experiments of (trans)actinides

[1] R. Ferrer, et al., Nature Commun., 8, 2017.

In-gas-jet laser spectroscopy on ^{254}No at GSI

Combination of high-efficiency RADRIS with high resolution in-jet methods





Beamtime 2022

- First in-gas-jet laser spectroscopy on ^{254}No with improved resolution

S. Raeder et al., NIM B 463 (2020)(2019) 272 M. Laatiaoui et al., Nature (London) 538, 495 (2016),
J. Lantis et al, Pys Rev Rese. Accepted

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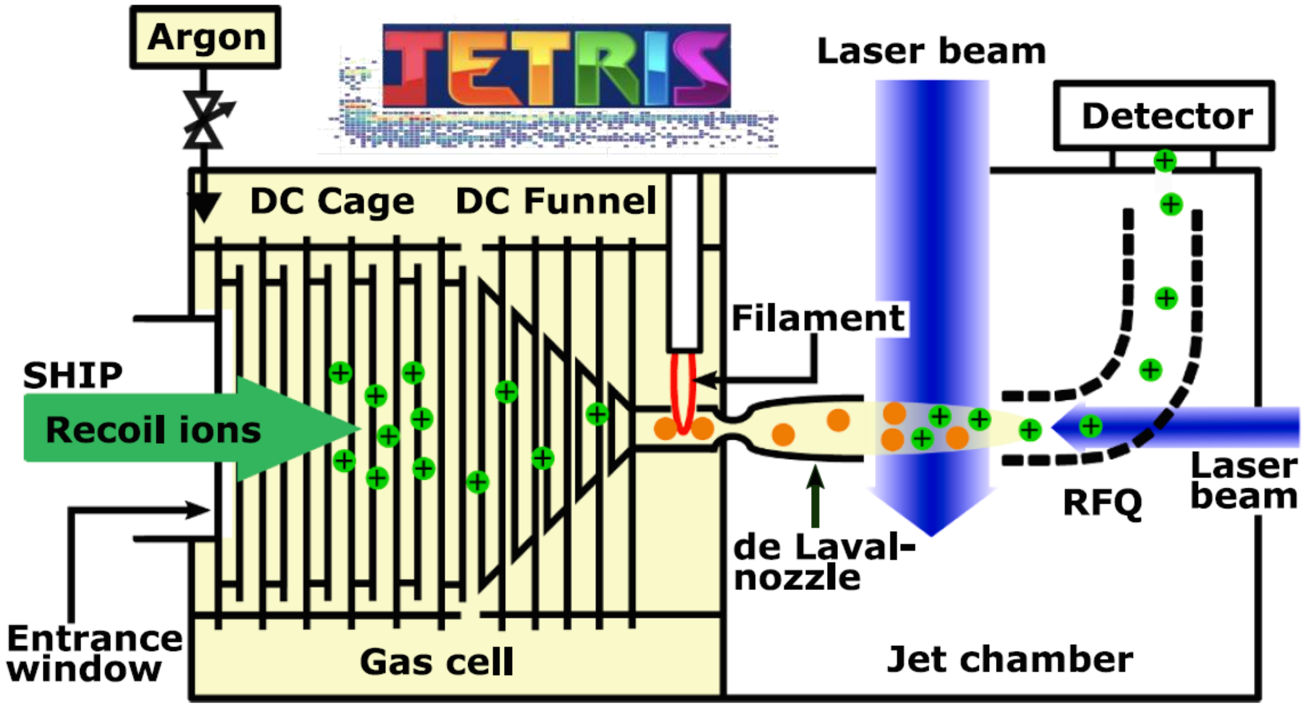
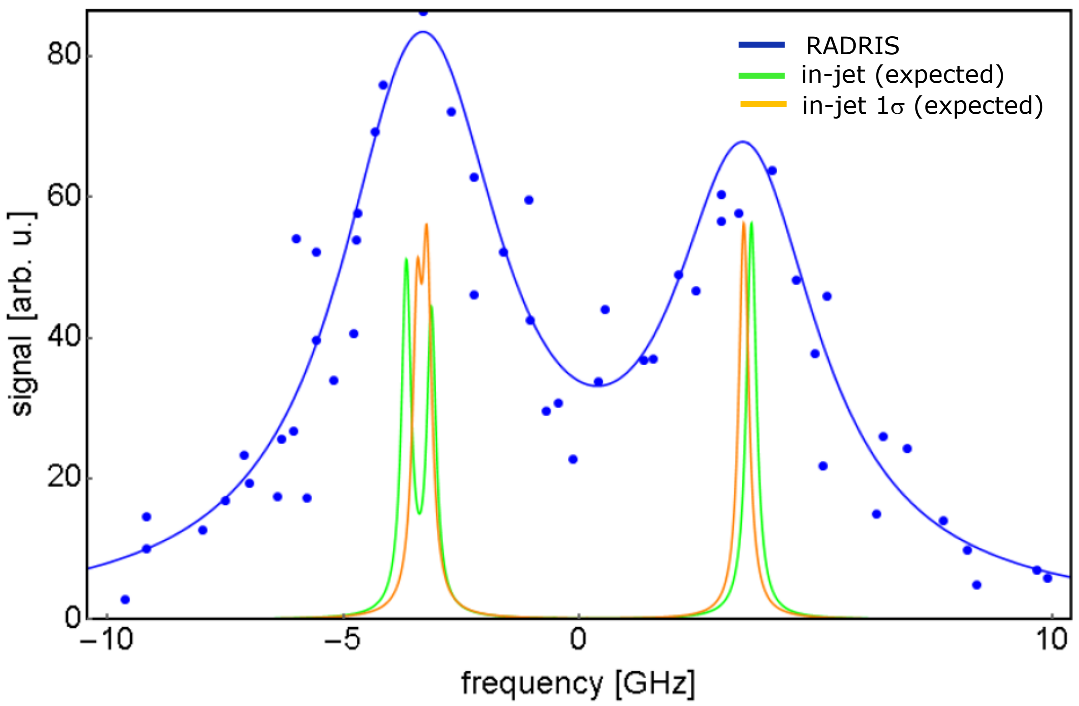
In-gas-jet laser spectroscopy on ^{253,254m,255}No at GSI

Combination of high-efficiency RADRIS with high resolution in-jet methods



HFS of ^{253}No



- In-gas-jet laser spectroscopy on ^{253,255}No will enable improved precision in nuclear deformation to assign Nilsson orbital→ validation nuclear models

M. Laatiaoui et al., Nature (London) 538, 495 (2016), S. Raeder et al., Phys.Rev.Lett. 120, 232503 (2018)
S. Raeder et al., NIM B 463 (2020)(2019) 272 R.-D. Herzberg, et al., Nature, 442(7105) 896, 2006

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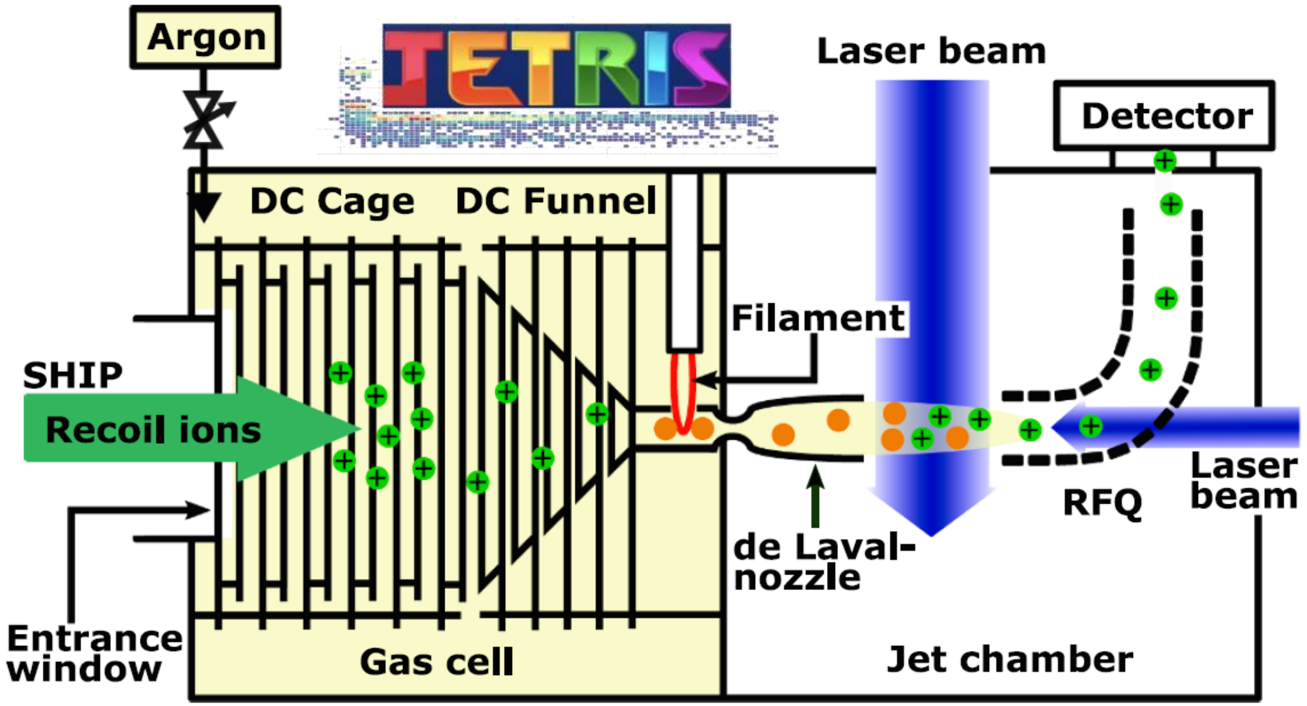
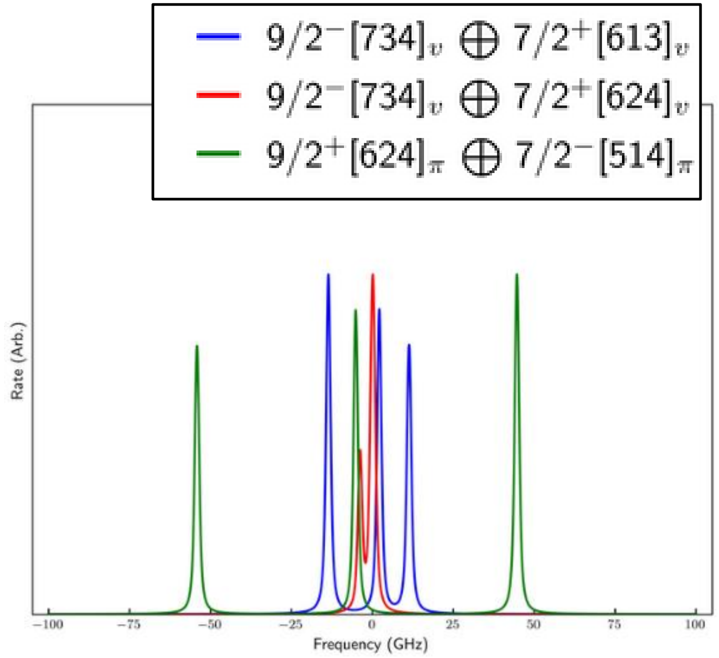
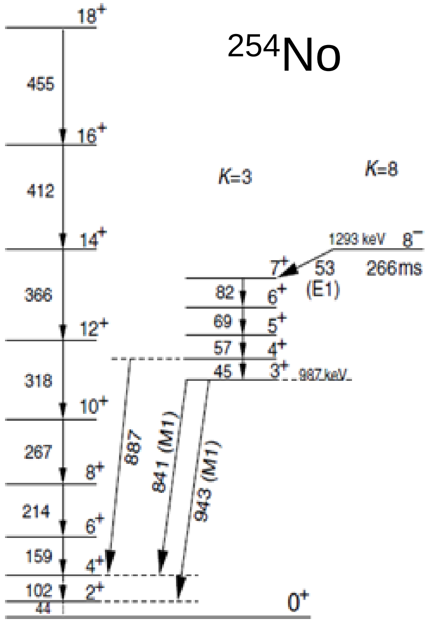
In-gas-jet laser spectroscopy on ^{253,254m,255}No at GSI

Combination of high-efficiency RADRIS with high resolution in-jet methods







- For ^{254}No in-jet-spectroscopy will enable to study the nature of the low lying 8^- *K*-isomer

M. Laatiaoui et al., Nature (London) 538, 495 (2016), S. Raeder et al., Phys.Rev.Lett. 120, 232503 (2018)
S. Raeder et al., NIM B 463 (2020)(2019) 272 R.-D. Herzberg, et al., Nature, 442(7105) 896, 2006

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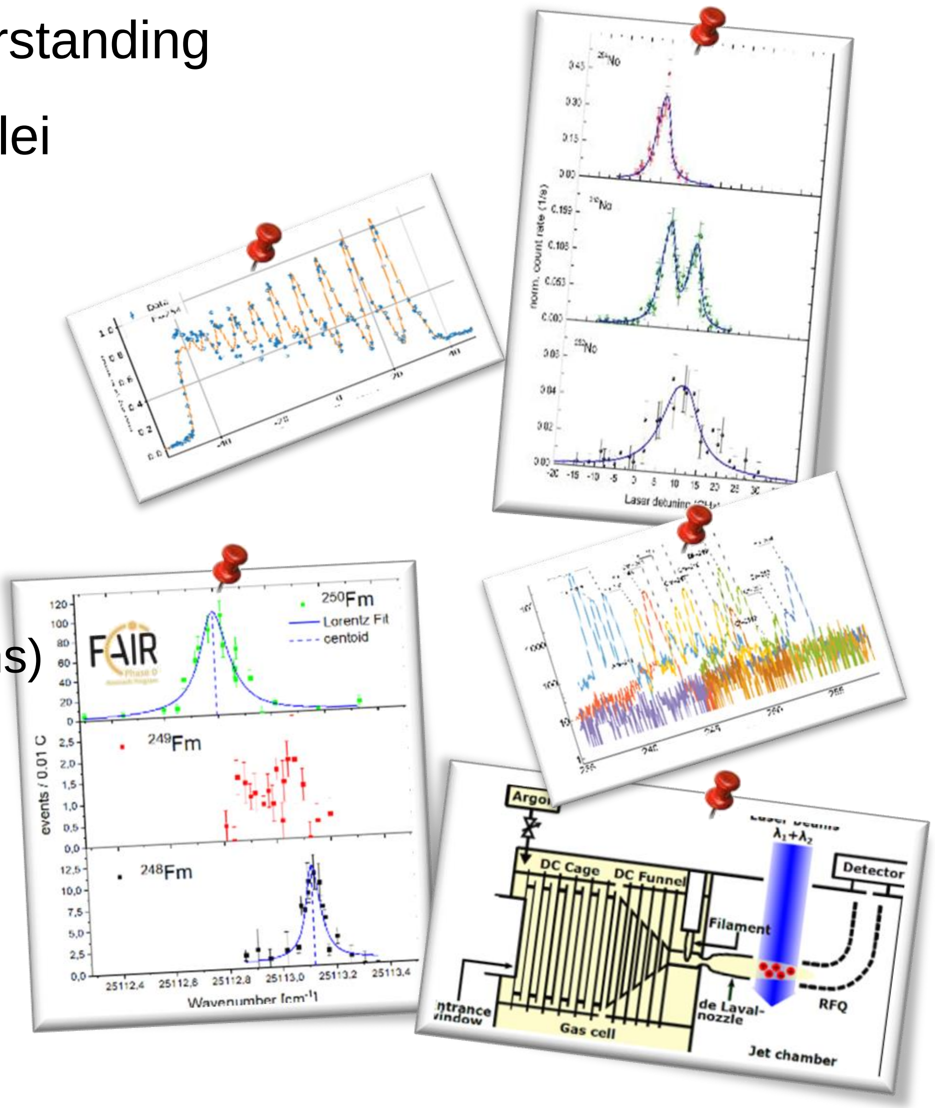
Summary

Laser spectroscopy on heavy elements is important for the understanding of atomic/chemical character and for investigations of the nuclei

- RADRIS: First optical transistion in a transfermium element
  - ✓ Differential mean square charge radii extracted ($^{252-254}$No)
  - ✓ First on-line measurements of Fm isotopes
- Insoure laser spectroscopy of actinides
  - ✓ Laser spectroscopy with Es (10^{10} atoms) and ^{255,257}Fm (10^{7} atoms)

Competitive laser spectroscopy program will continue

- ❖ RADRIS & gas jet beamtime running
- ❖ Gas jet: development for improved resolution
- ❖ LRC: new approach to extend the realm of laser spectroscopy



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