Laser spectroscopy of $^{248-250}\mathrm{Fm}$ and Lr level search

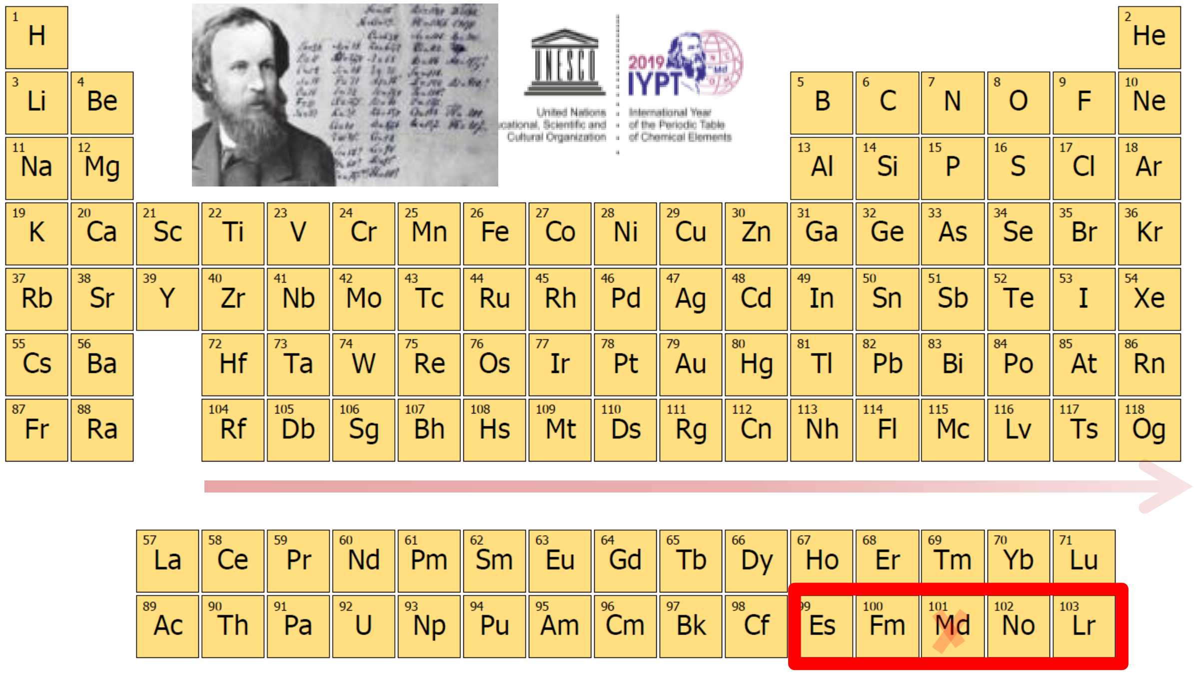
E. Rickert for the RADRIS Collaboration

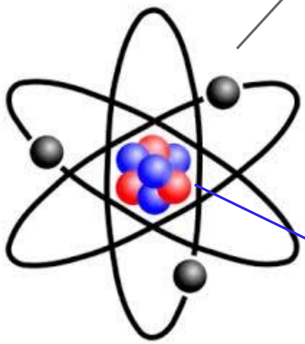
NUSTAR Annual Meeting

Properties of the heaviest elements

Laser spectroscopy for fundamental properties

- Understanding of atomic structure & chemical behaviour
- What is nuclear structure of SHE: e.g. shape and size ?





Electron shell

atomic structure

chemical properties

defines the element

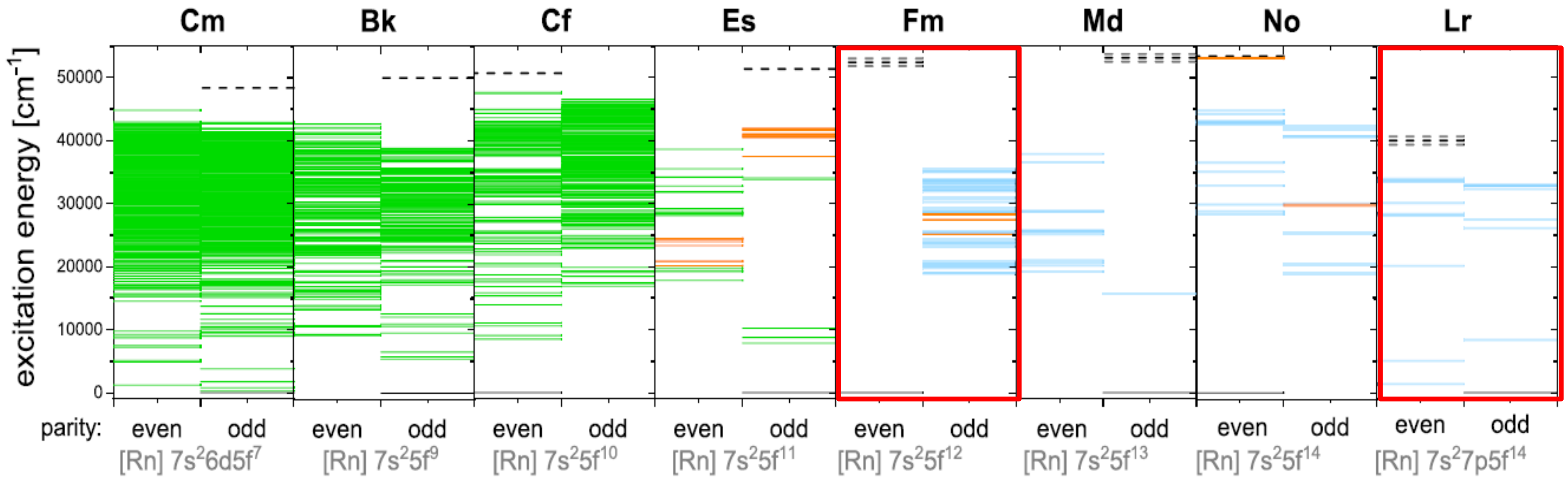
Nucleus

nuclear structure

stability of elements

Overview of known Atomic Levels in the Actinides

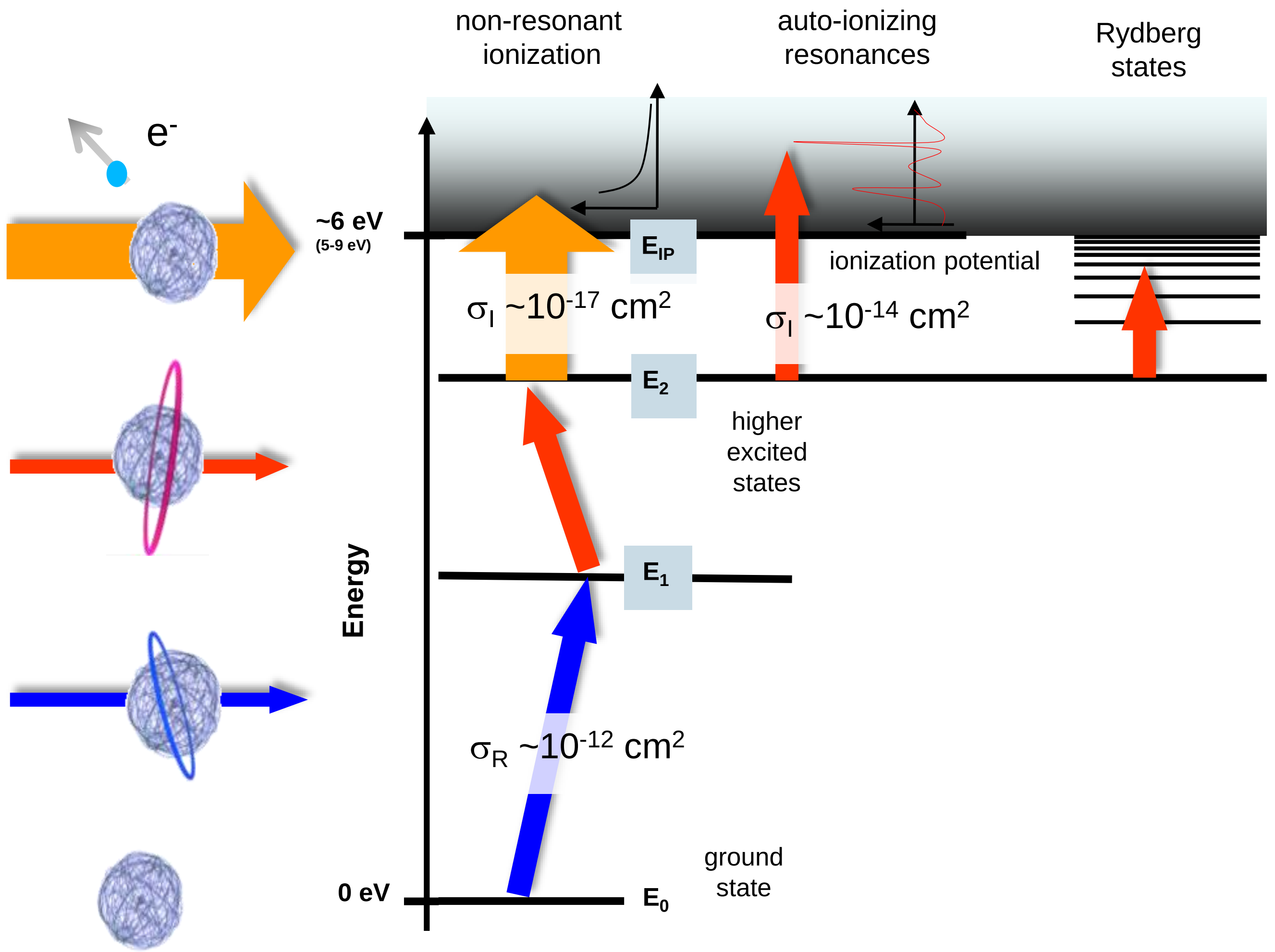
Overview on atomic levels reported for the heavy actinides



- Atomic structure still to be investigated
- Sparse for heavier element
- For Z ≥ 100 only calculations are available

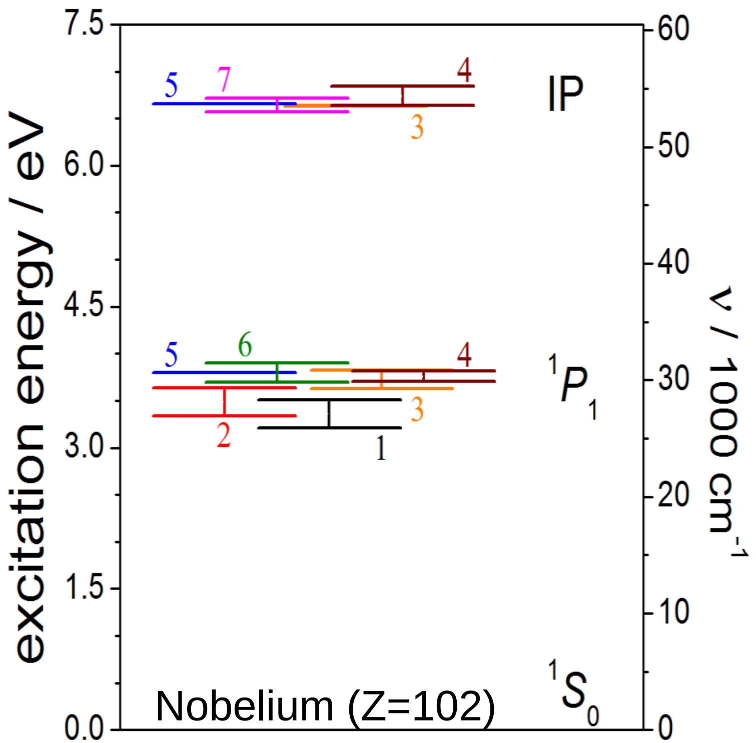
Experimental levels Blaise 1992
Experimental levels
Theory – calculated levels

Resonance Ionization Spectroscopy



- 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]$5f^{14}7s^2$ $^1S_0$

- Zα ~ 1:

  Large relativistic effects & QED contribution

- 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

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

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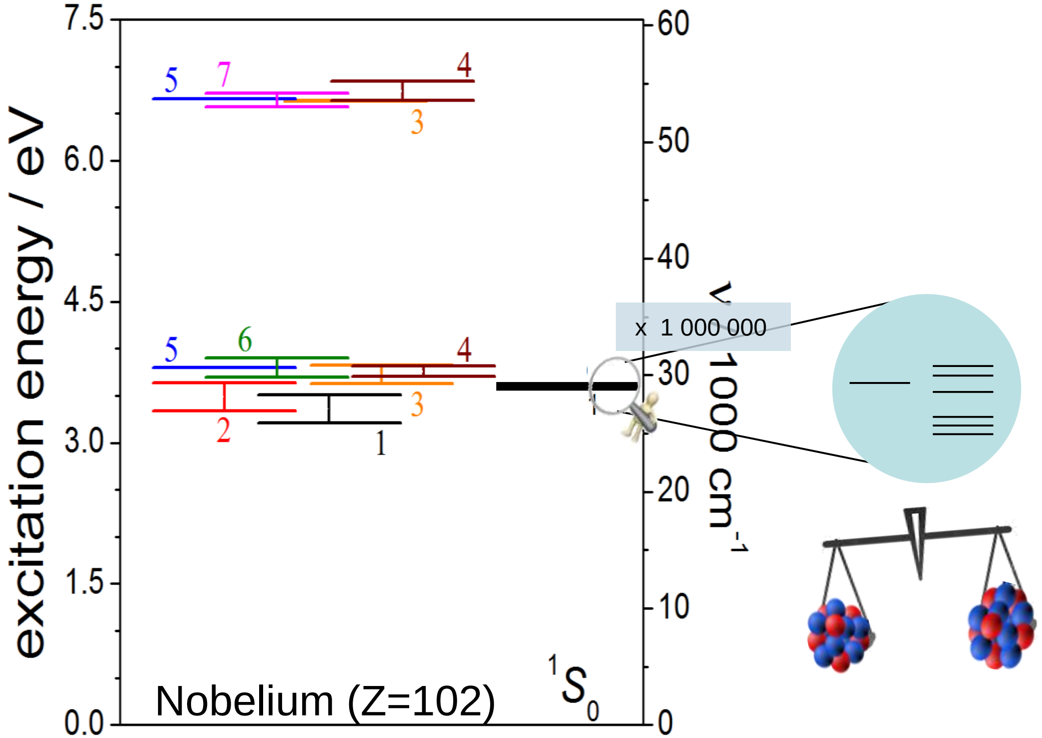
Motivation – Nuclear Properties



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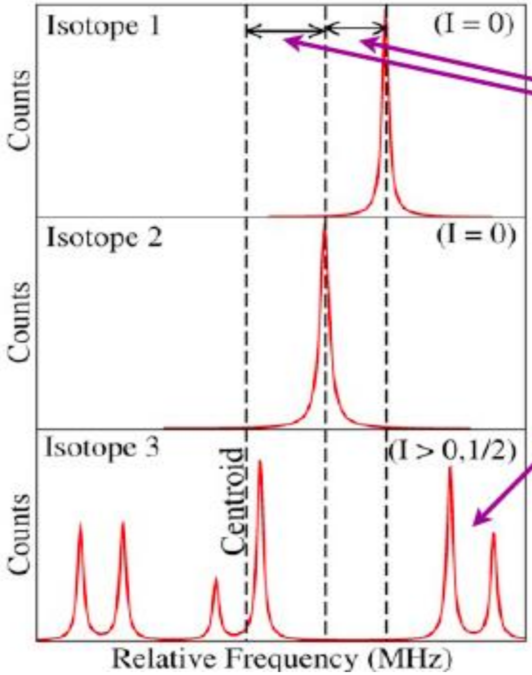

Isotope shift

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)

- 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

Model calculations

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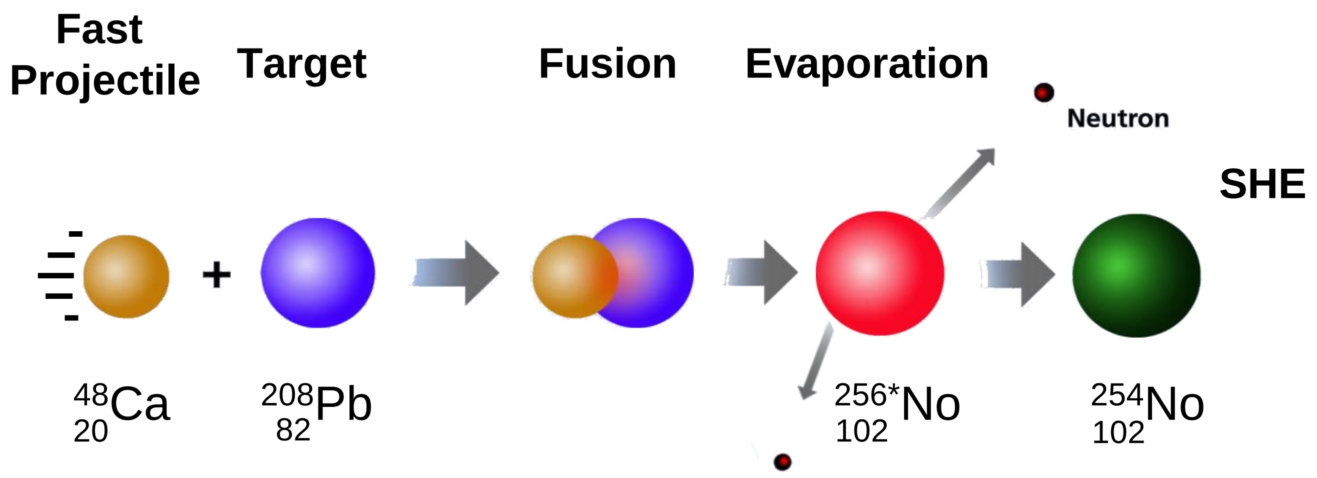
Production of SHE

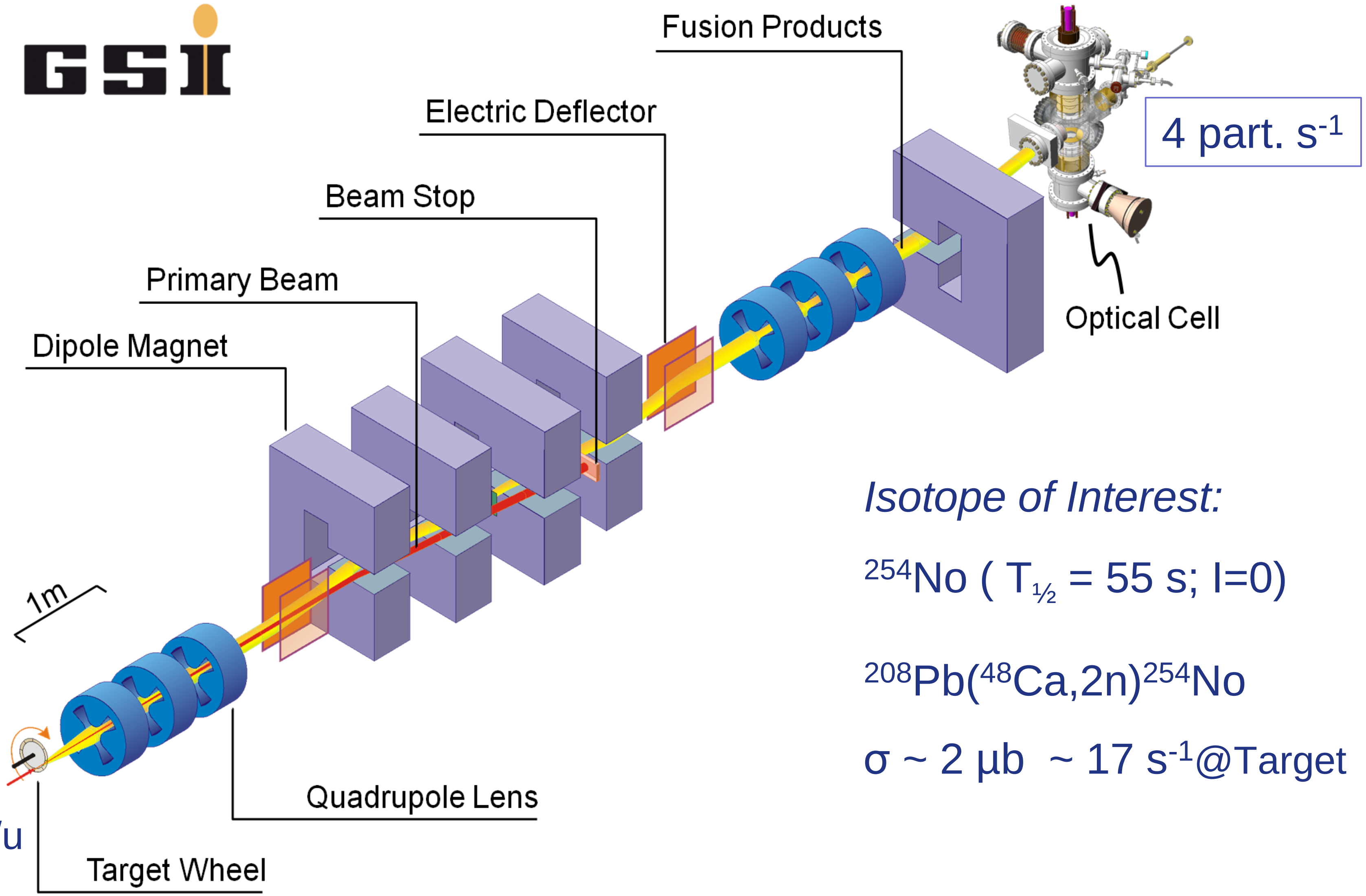
Production of heavy elements (Z ~100)

Accelerator based in “single-atom-quantities”



- Intense primary beam
- Thin and high-quality targets
- Separation of SHE from intense projectile beam

Production: Velocity Filter SHIP



^{48}Ca
4.55 MeV/u
1 pμA

Isotope of Interest:

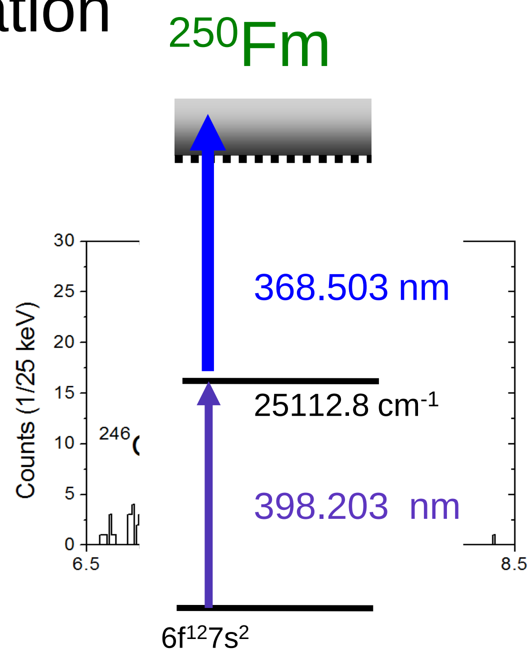
^{254}No ($T_{½}$ = 55 s; I=0)

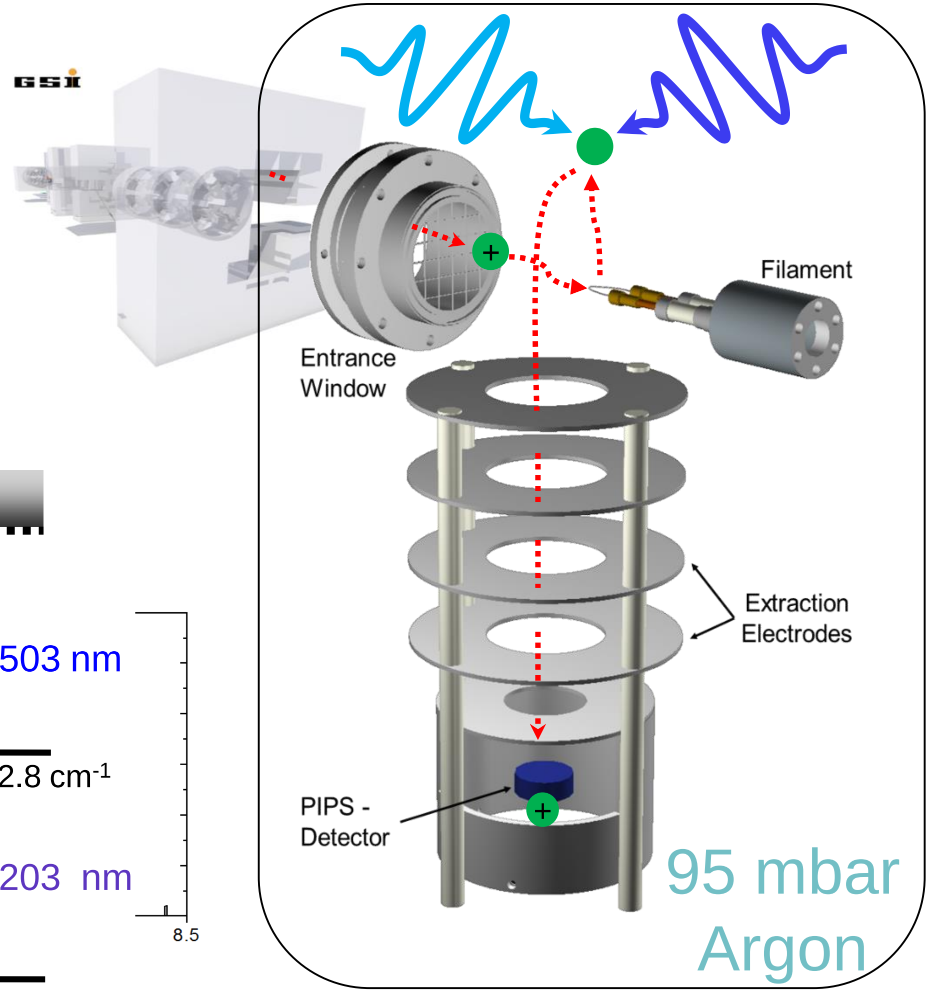
^{208}Pb(^{48}Ca,2n)^{254}No

σ ~ 2 μb ~ 17 s^{-1}@Target

RADRIS Method:

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





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

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

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On-line Laser Spectroscopy of Fm Isotopes

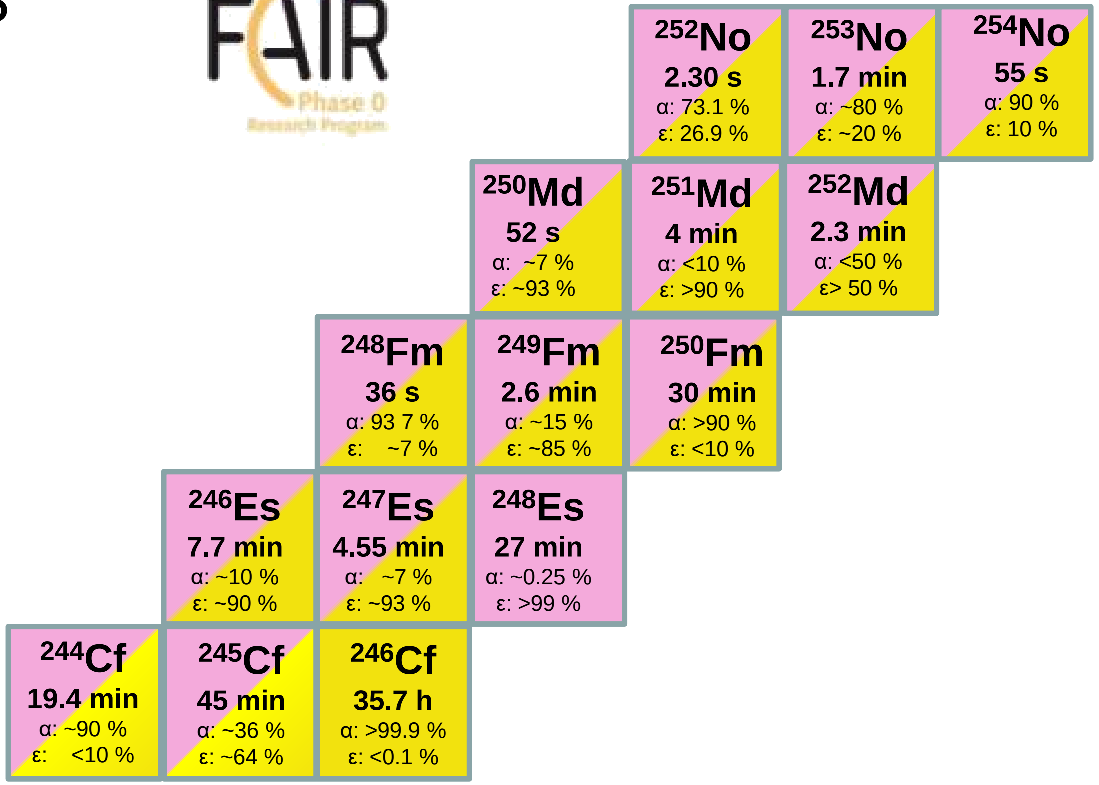
Fm (Z=100) - A new element for RADRIS

- Collection of No-mother on the filament
- Letting it decay

  $\longrightarrow$ Accessing daughter nuclides

Reactions:

- $^{208}\mathrm{Pb}\left(^{48}\mathrm{Ca}, 2\mathrm{n}\right)^{254}\mathrm{No} \xrightarrow{\alpha} {}^{250}\mathrm{Fm}$
- $^{207}\mathrm{Pb}\left(^{48}\mathrm{Ca}, 2\mathrm{n}\right)^{253}\mathrm{No} \xrightarrow{\alpha} {}^{249}\mathrm{Fm}$
- $^{206}\mathrm{Pb}\left(^{48}\mathrm{Ca}, 2\mathrm{n}\right)^{252}\mathrm{No} \xrightarrow{\alpha} {}^{248}\mathrm{Fm}$

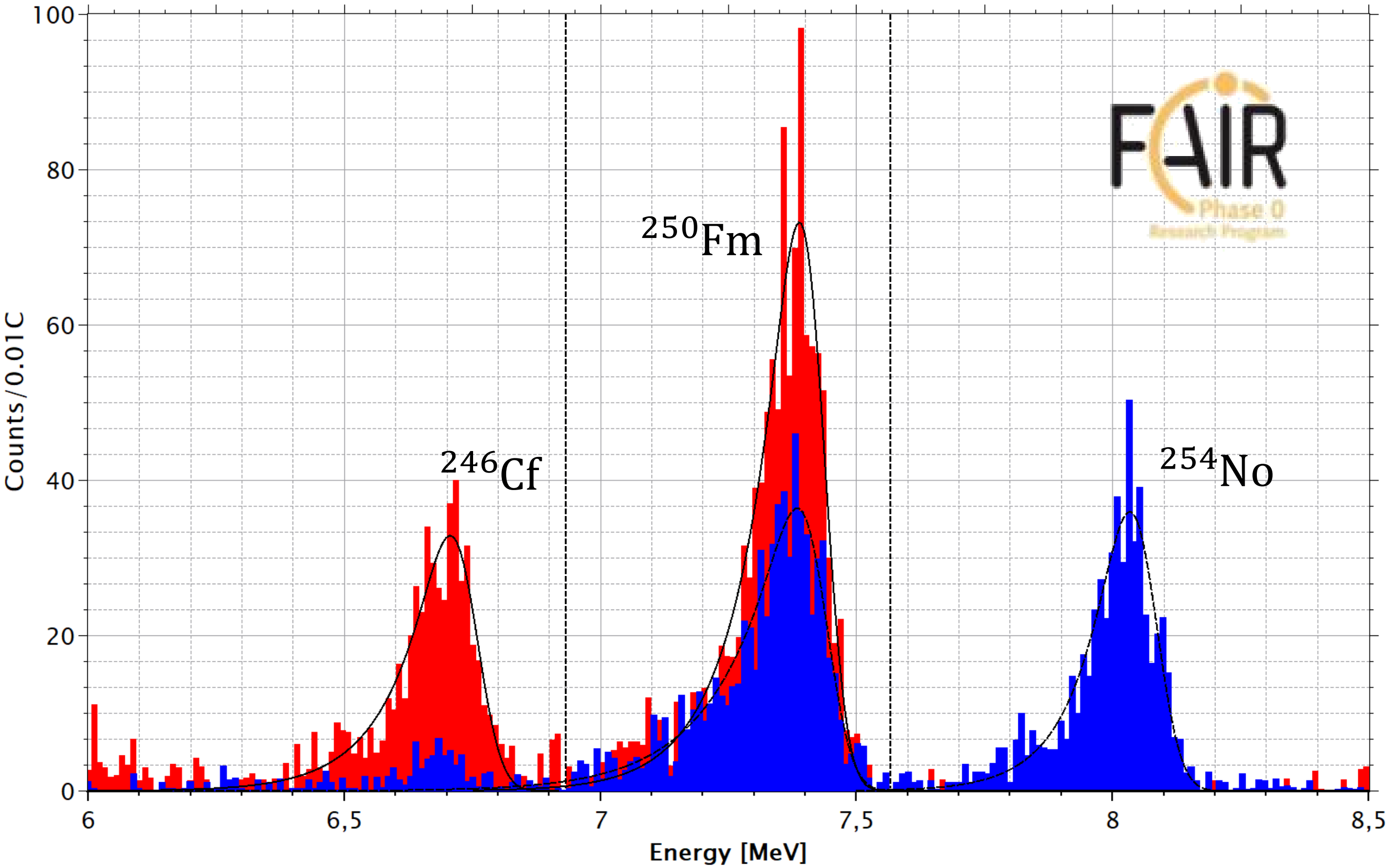


On-line Laser Spectroscopy of Fm Isotopes

- Alpha spectrum:
  - Direct guiding to detector: Blue
    - $^{254}\mathrm{No}$, $^{250}\mathrm{Fm}$
  - Scanning: Red
    - $^{250}\mathrm{Fm}$, $^{246}\mathrm{Cf}$

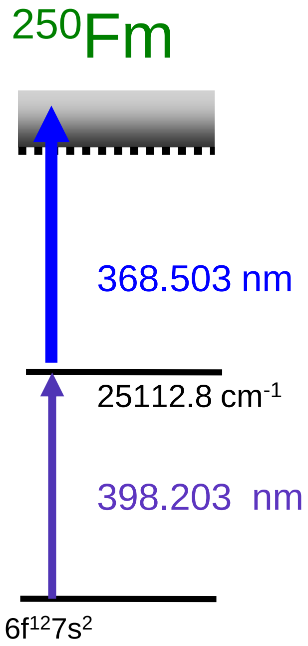
- Set gates for Fm isotopes
  - Normalize to collected charge

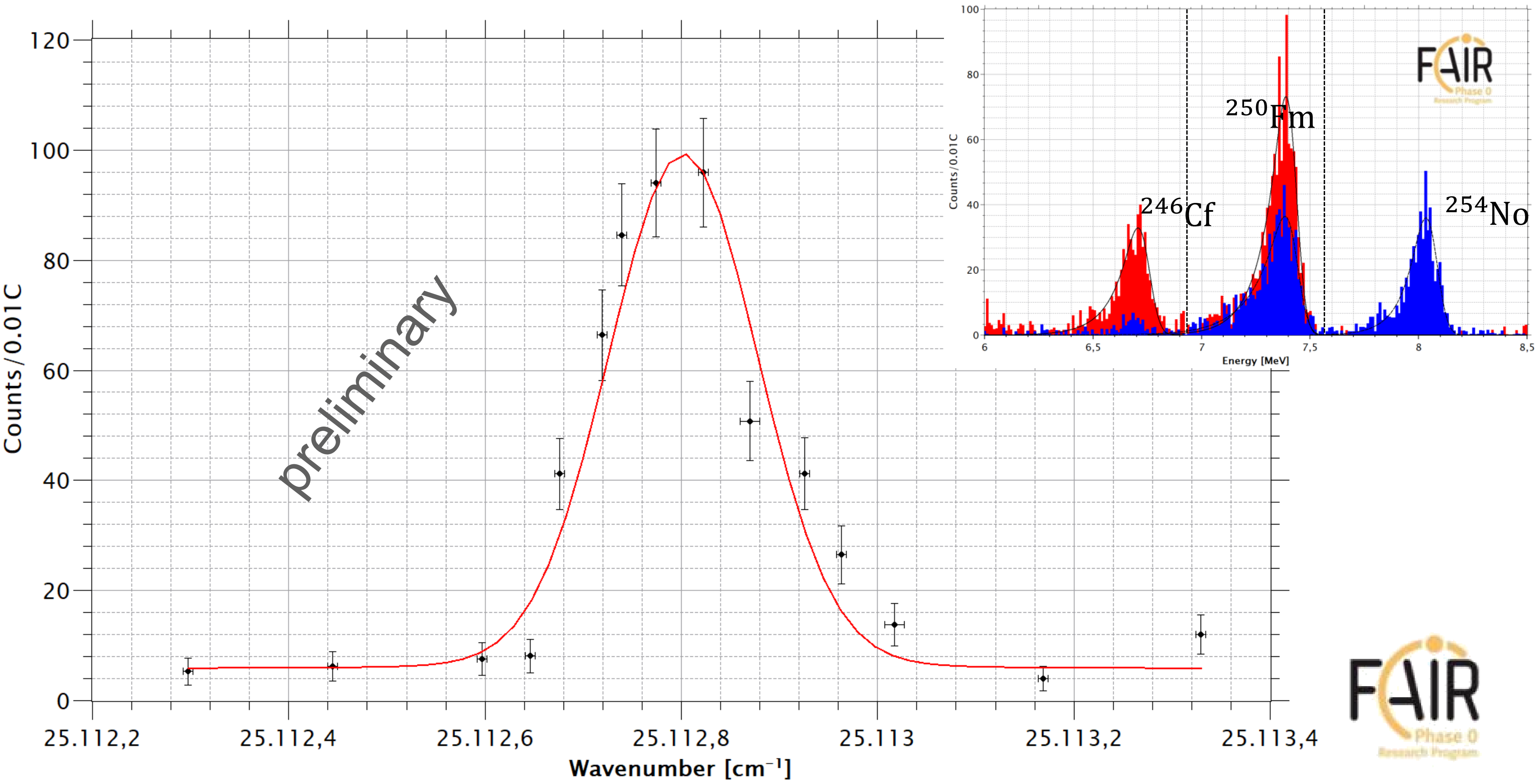
$$f(x) = \frac{A}{2\tau} \cdot \exp\left(\frac{x-x_c}{\tau} + \frac{\sigma^2}{2\tau^2}\right) \cdot \mathrm{erfc}\left(\frac{1}{\sqrt{2}} \frac{x-x_c}{\sigma} + \frac{\sigma}{\tau}\right) \quad [1]$$



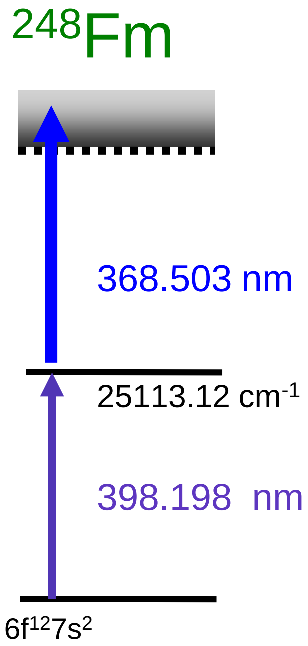
[1]: G. Bortels, P. Collaers, Appl. Rad. Isot. 38 (1987) 831

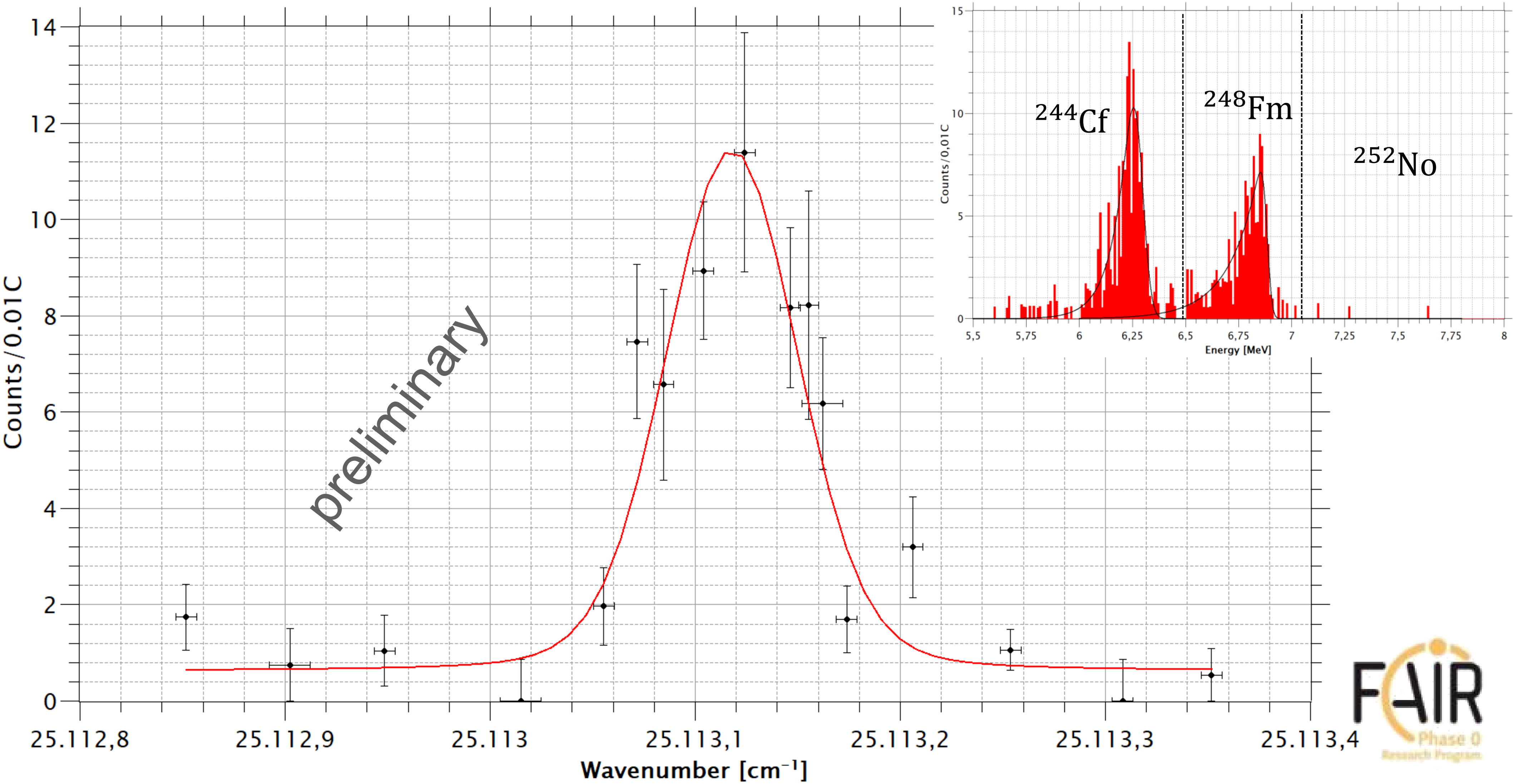
On-line Laser Spectroscopy of ^{250}Fm



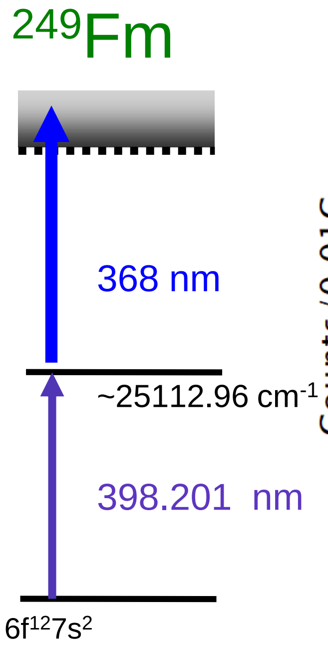


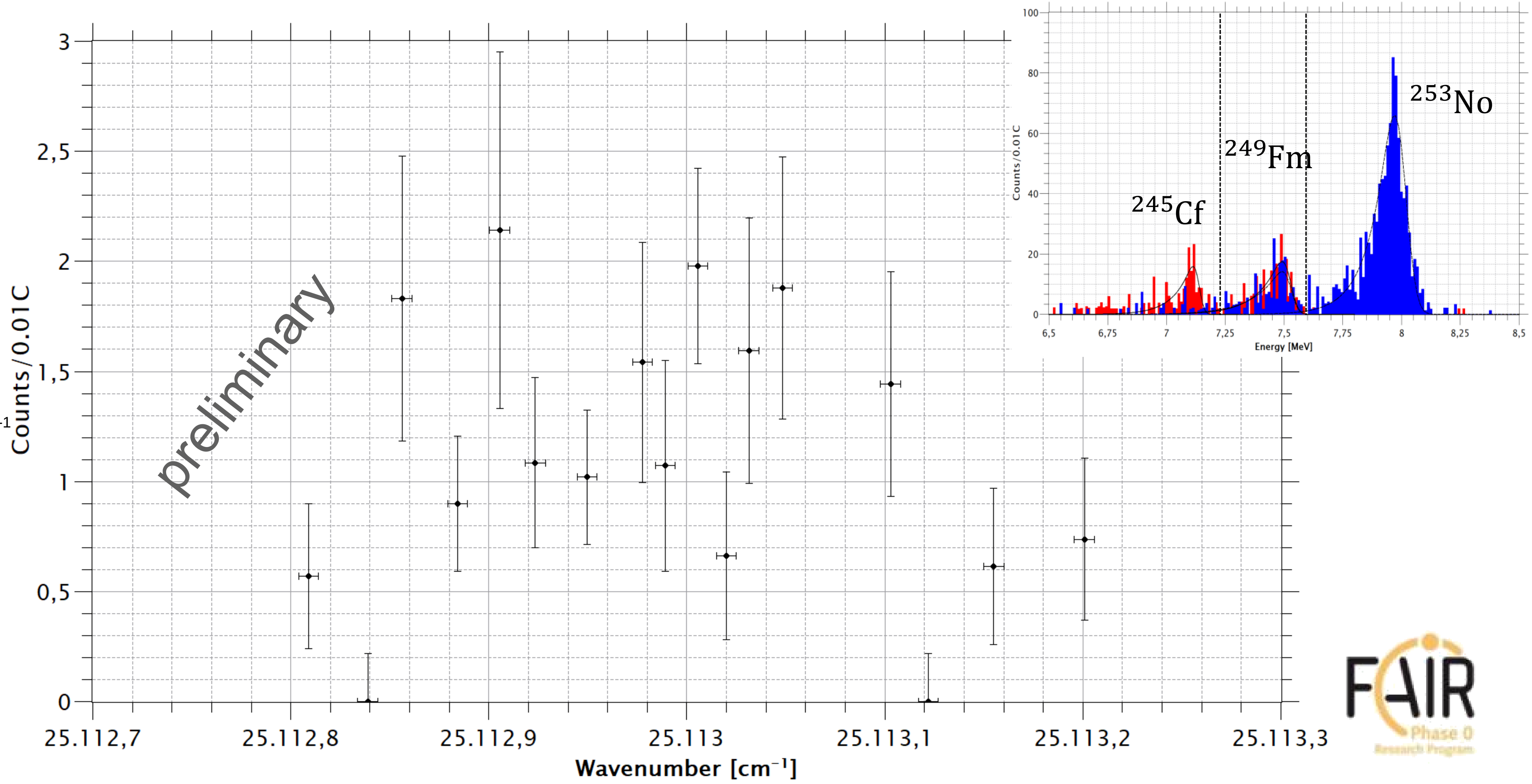
On-line Laser Spectroscopy of ^{248}Fm





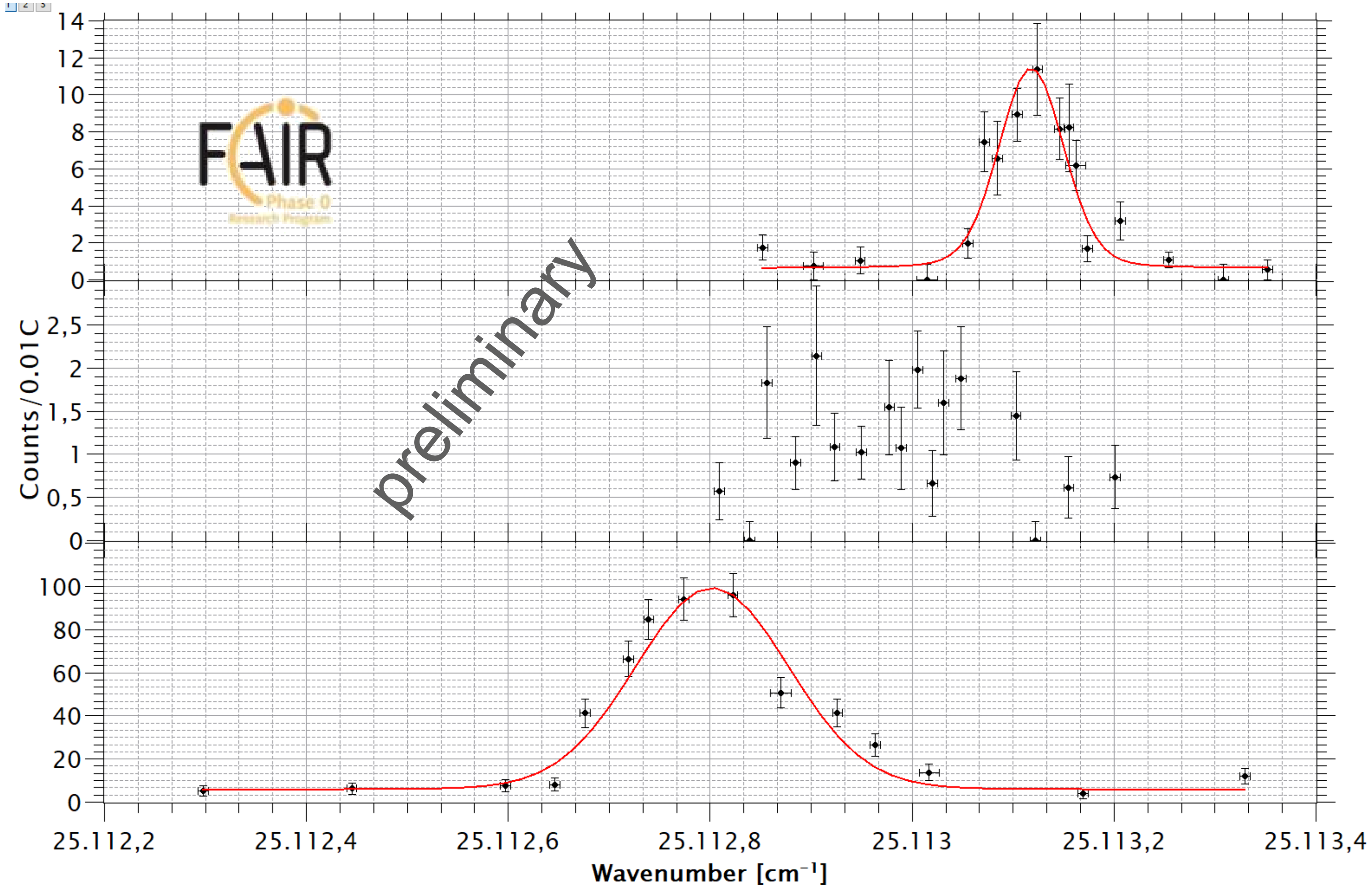
On-line Laser Spectroscopy of ^{249}Fm





Fm – Isotope Shifts

Laser spectroscopy of $^{248\text{-}250}$Fm → large range of isotopes across *N*=152 in reach



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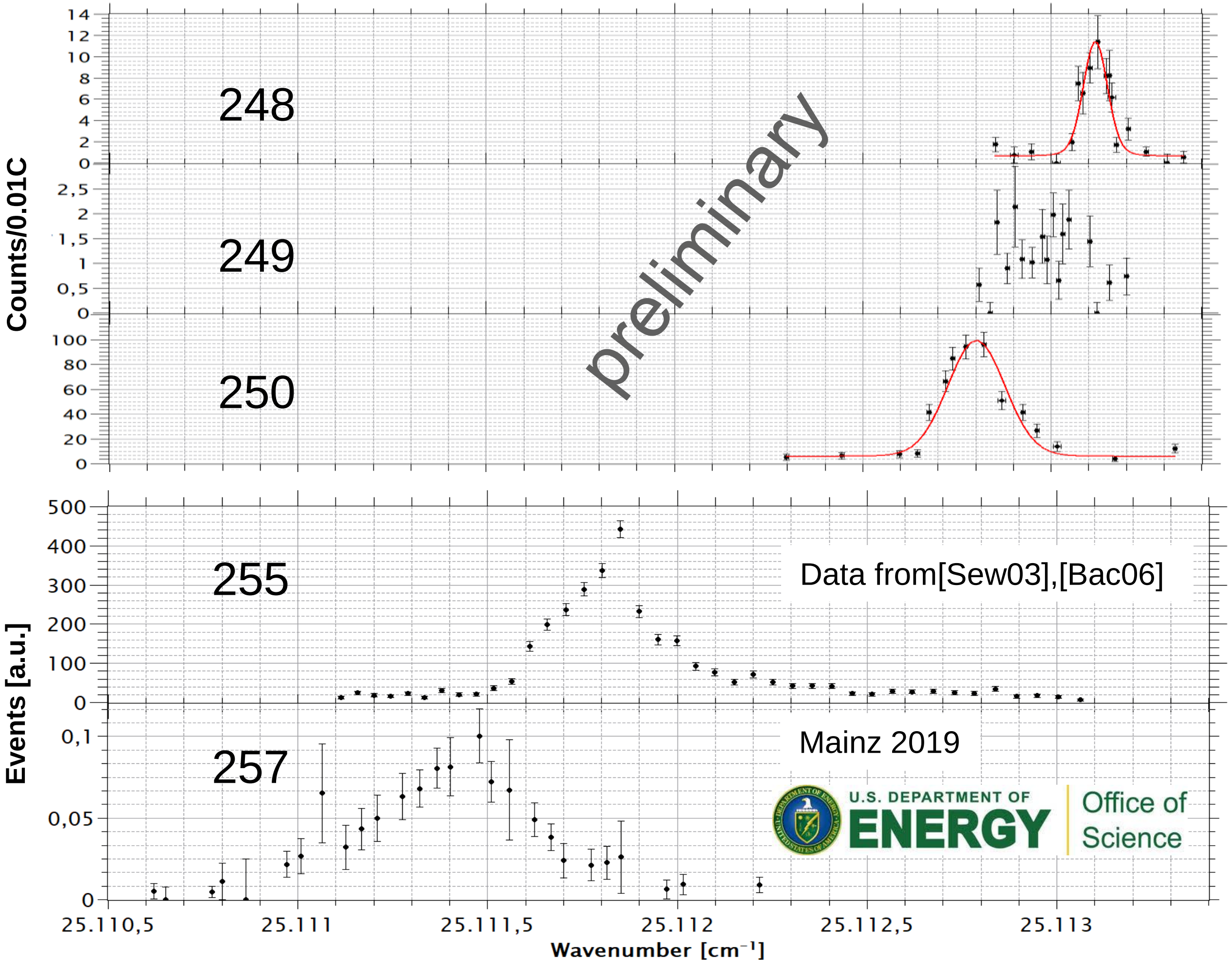
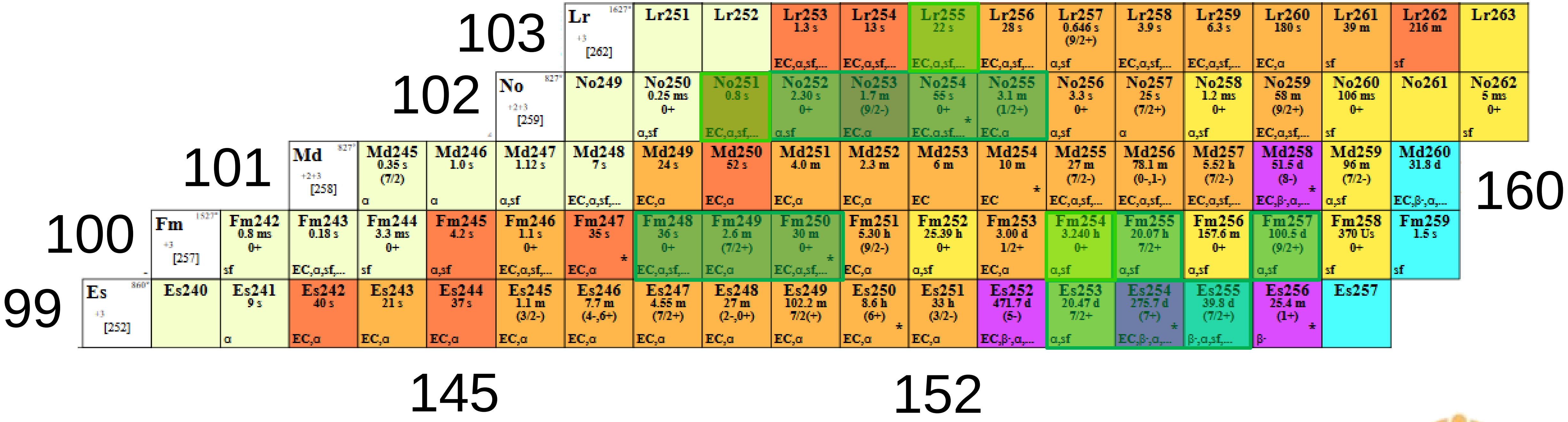


[Sew03] Sewtz, M., et al. *Phys. Rev. Lett.* 90.16 (2003): 163002. -- *[Bac06] Backe, H., et al. " Laser 2004. (2006). 3-14.*

On-line Laser Spectroscopy of SHE Isotopes

Access further SHE isotopes with Laser spectroscopy

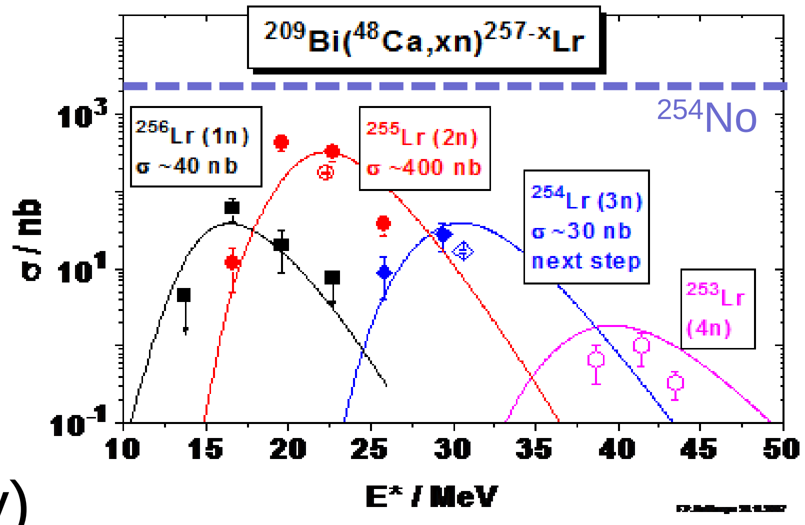


Already performed

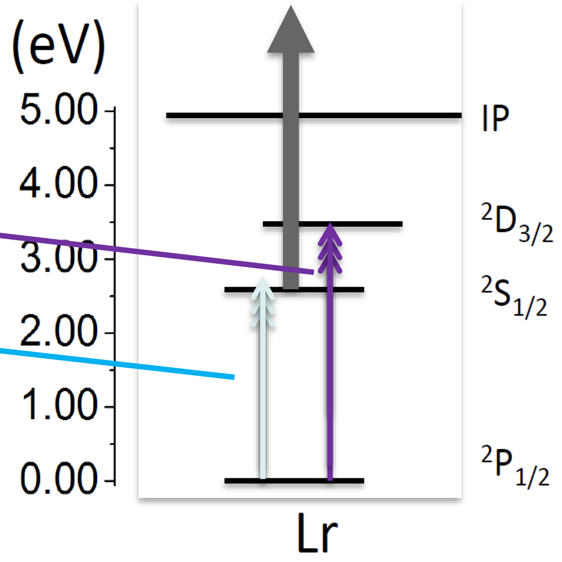
To be performed in BT2021

Laser Spectroscopy of Lr

Search for resonance in Lawrencium (Lr, Z=103)



- Cross section known - production rate of 1 ions/s
- Search for 2 different states (predictions from theory)
  - 28,000 cm^{-1}
  - 20,000 cm^{-1}



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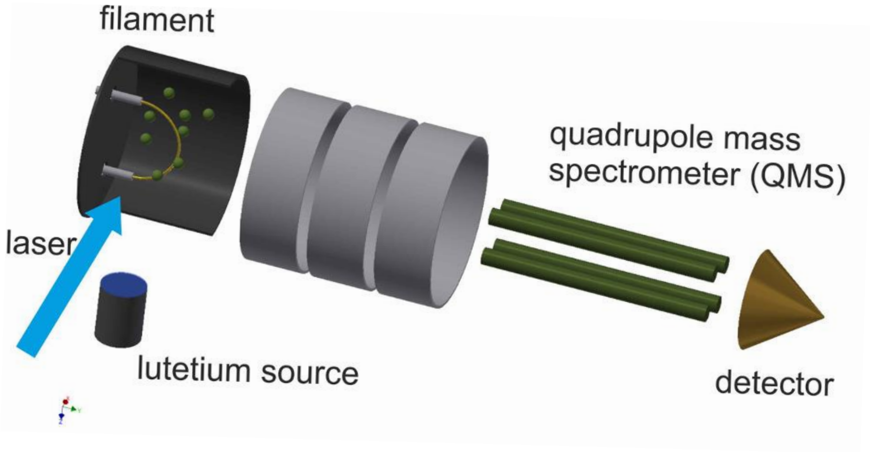
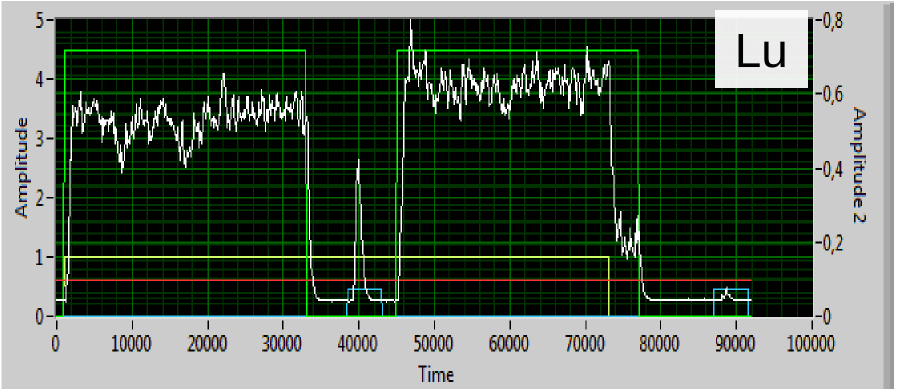
Developments for Lr Spectroscopy

RADRIS technique relies on filament capture and release

- Filament requirements (tested in off-line studies)
  - Low work function (low BG from surface ions)
  - High melting point (stability)
  - Low desorption temperature (no turbulences in gas cell)



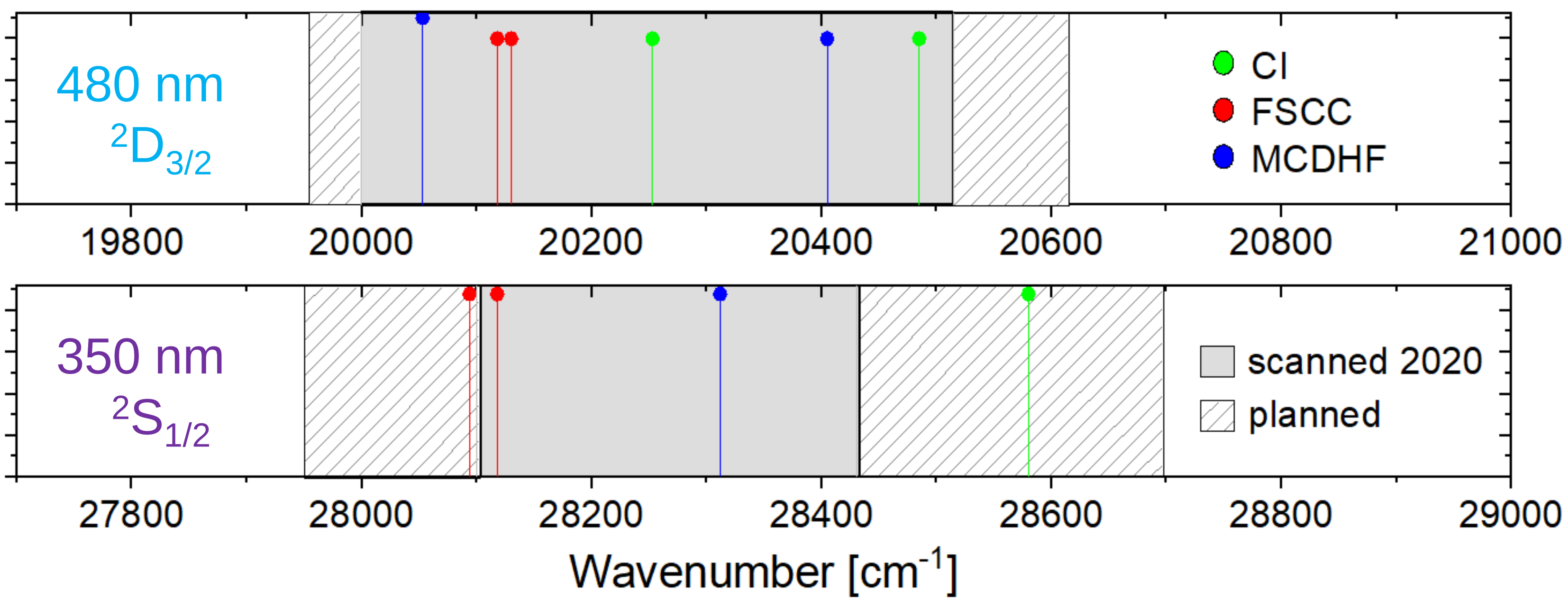


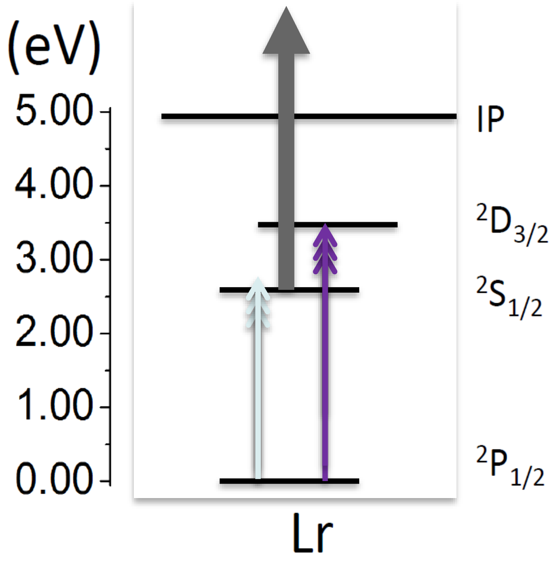
Hafnium is suitable for Lr - ~1800°C

Level Search in Lawrencium (Z=103)

- Beamtime 2020: level search started, about 850 cm^{-1} scanned
  - So far no resonance observed
  - More theoretical predictions available, but larger discrepancy

☐ Continuation of the level search with high sensitivity next beamtime

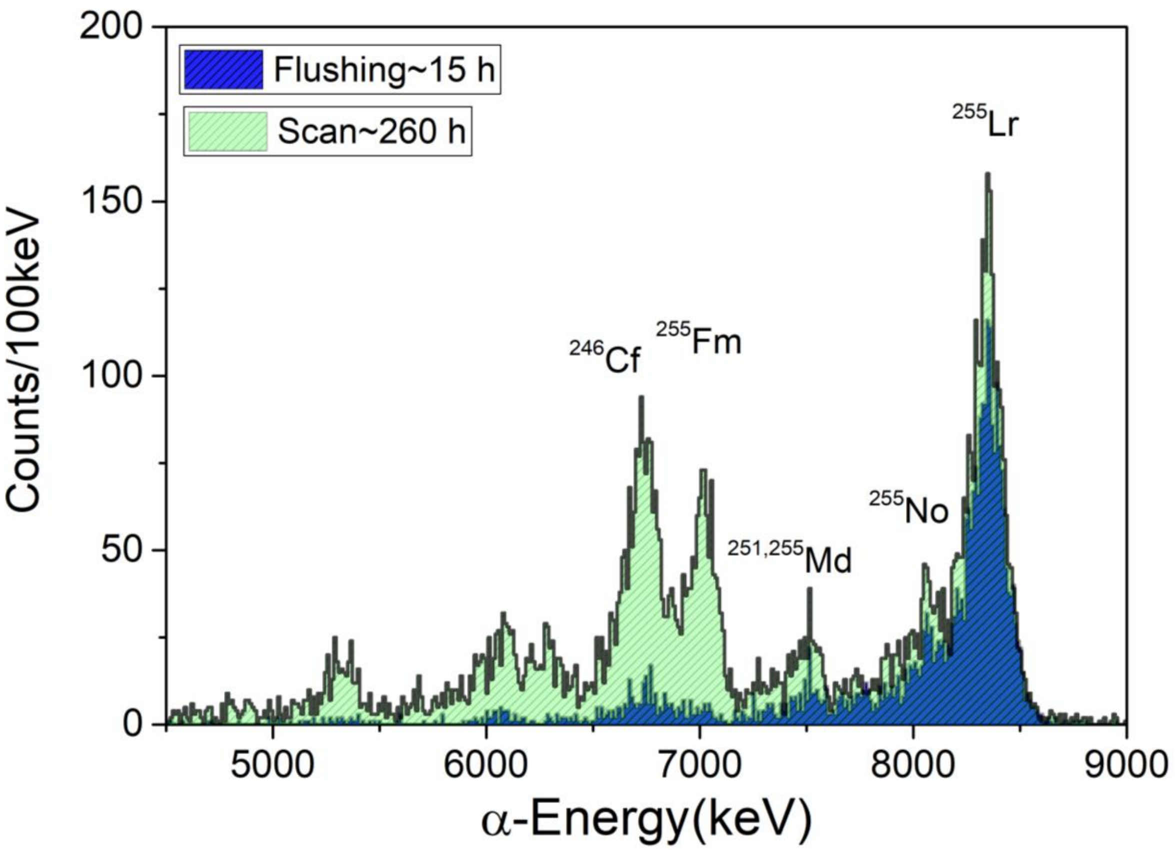




Level Search in Lr

- $^{255}\mathrm{Lr}$ ($t_{1/2}$ = 31 s) Production: $^{209}\mathrm{Bi}\left(^{48}\mathrm{Ca}, 2\mathrm{n}\right)^{255}\mathrm{Lr}$ (200 nb)
- 600 s per wavelength
- 19 days of main beam

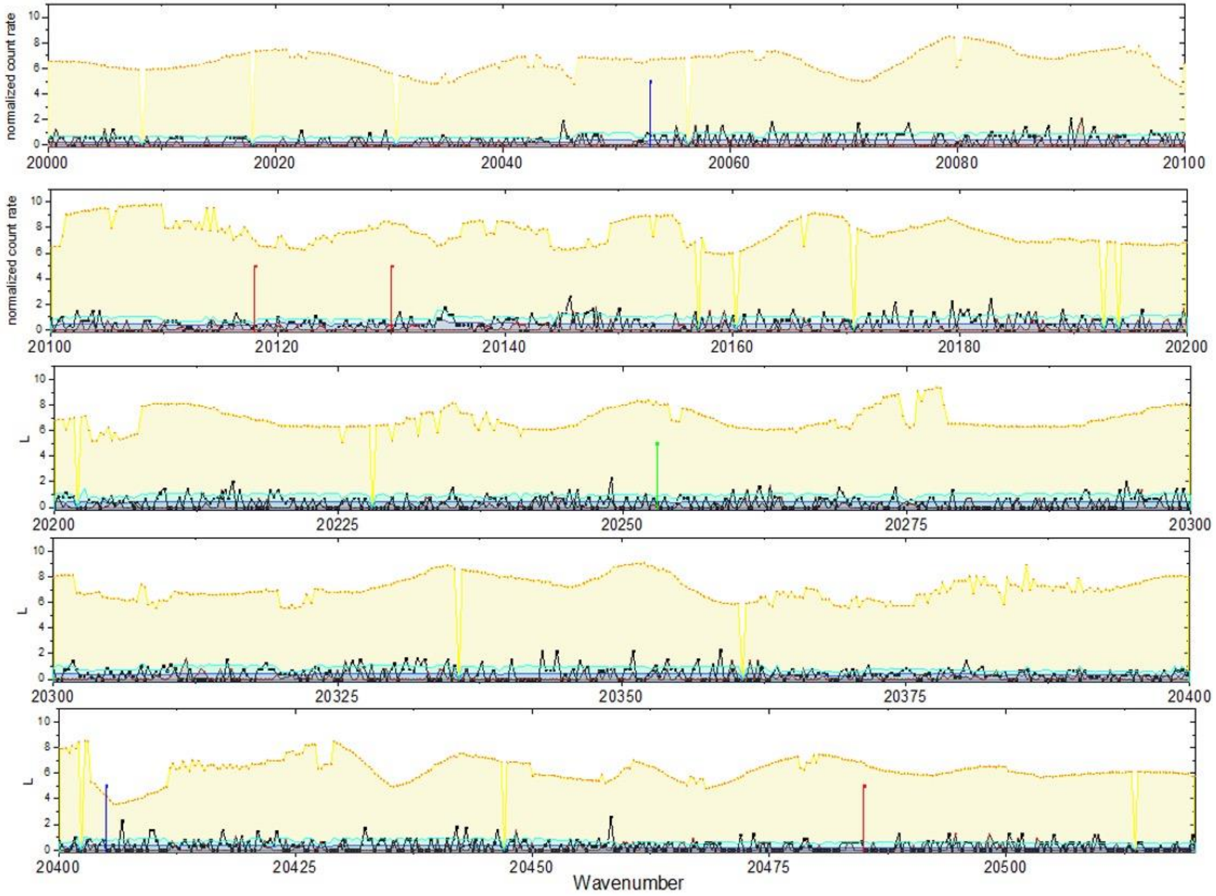
Lr 1627° +3 [262]	Lr251	Lr252	Lr253 1.3 s EC,α,sf,...	Lr254 13 s EC,α,sf,...	Lr255 22 s EC,α,sf,...	Lr256 28 s EC,α,sf,...
No249	No250 0.25 ms 0+ α,sf	No251 0.8 s EC,α,sf,...	No252 2.30 s 0+ α,sf	No253 1.7 m (9/2-) EC,α	No254 55 s 0+ * EC,α,sf,...	No255 3.1 m (1/2+) EC,α
Md248 7 s EC,α,sf,...	Md249 24 s EC,α	Md250 52 s EC,α	Md251 4.0 m EC,α	Md252 2.3 m EC,α	Md253 6 m EC	Md254 10 m * EC
Fm247 35 s * EC,α	Fm248 36 s 0+ EC,α,sf,...	Fm249 2.6 m (7/2+) EC,α	Fm250 30 m 0+ * EC,α,sf,...	Fm251 5.30 h (9/2-) EC,α	Fm252 25.39 h 0+ α,sf	Fm253 3.00 d 1/2+ EC,α
Es246 7.7 m (4-,6+) EC,α	Es247 4.55 m (7/2+) EC,α	Es248 27 m (2-,0+) EC,α	Es249 102.2 m 7/2(+) EC,α	Es250 8.6 h (6+) * EC,α	Es251 33 h (3/2-) EC,α	Es252 471.7 d (5-) EC,β-,α,...
Cf245 45.0 m (5/2+) EC,α	Cf246 35.7 h 0+ EC,α,sf,...	Cf247 3.11 h (7/2+) EC,α	Cf248 333.5 d 0+ α,sf	Cf249 351 y 9/2- α,sf	Cf250 13.08 y 0+ α,sf	Cf251 898 y 1/2+ α



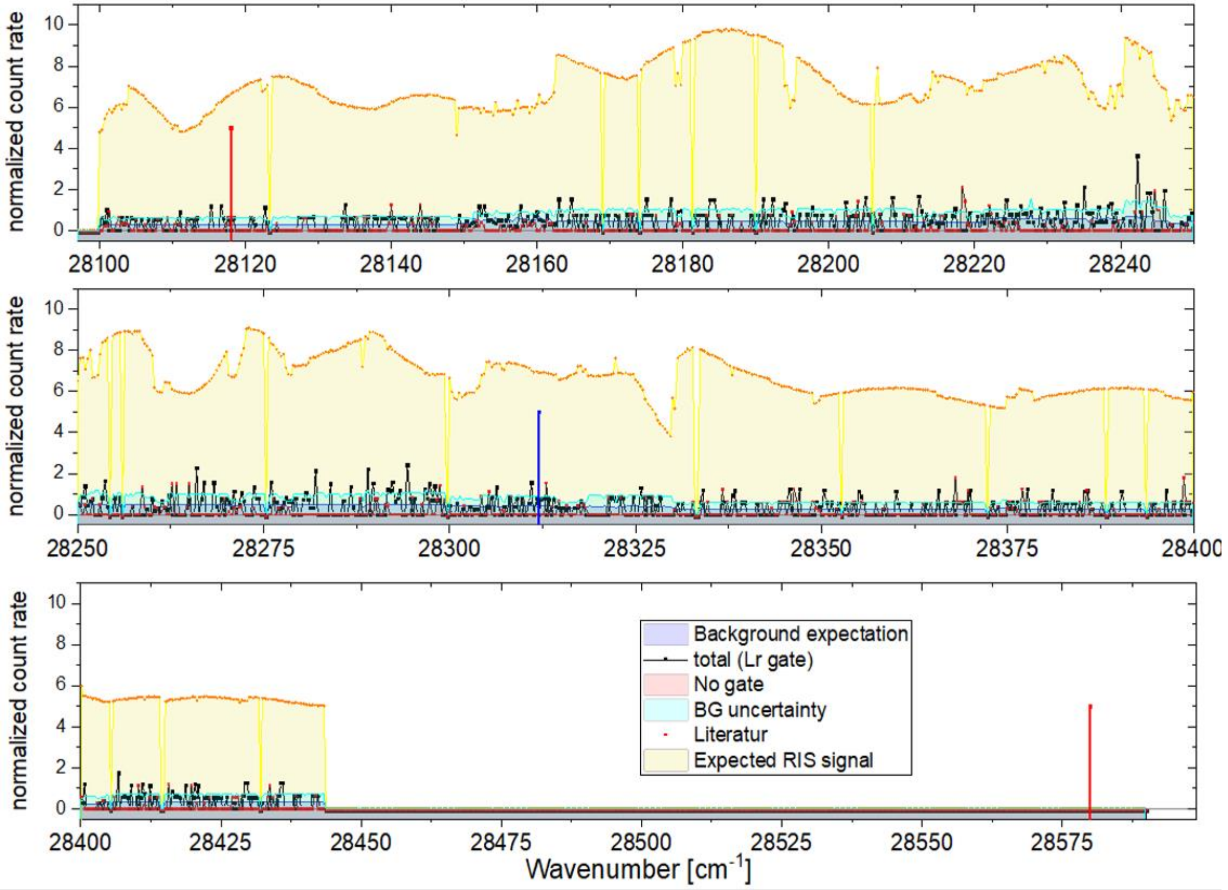
Level Search in Lr

- Beamtime 2020: level search started, about 850 cm^{-1} scanned

VIS range - 480 nm $^2D_{3/2}$



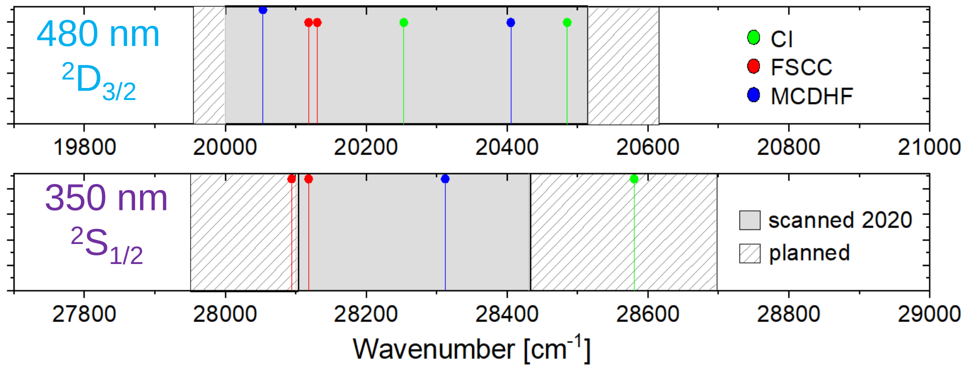
UV range - 350 nm $^2S_{1/2}$



RADRIS – Perspectives

Beamtime period 2021/22

- Continuation of Lr level search
- ^{251}No and ^{254}Fm isotopes

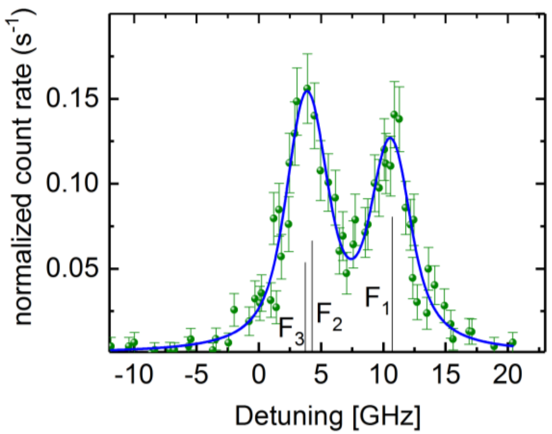


- Improvements: adding detectors to improve the efficiency

Limitations of the RADRIS technique

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

→ In Gas Spectroscopy setup is beeing developed



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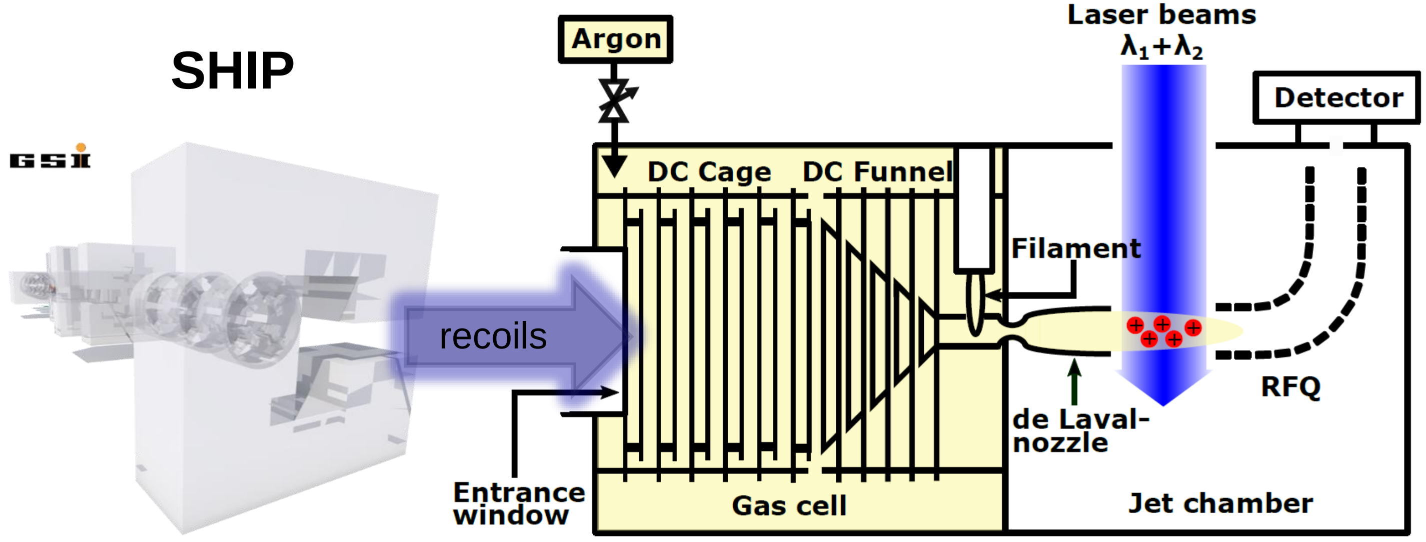
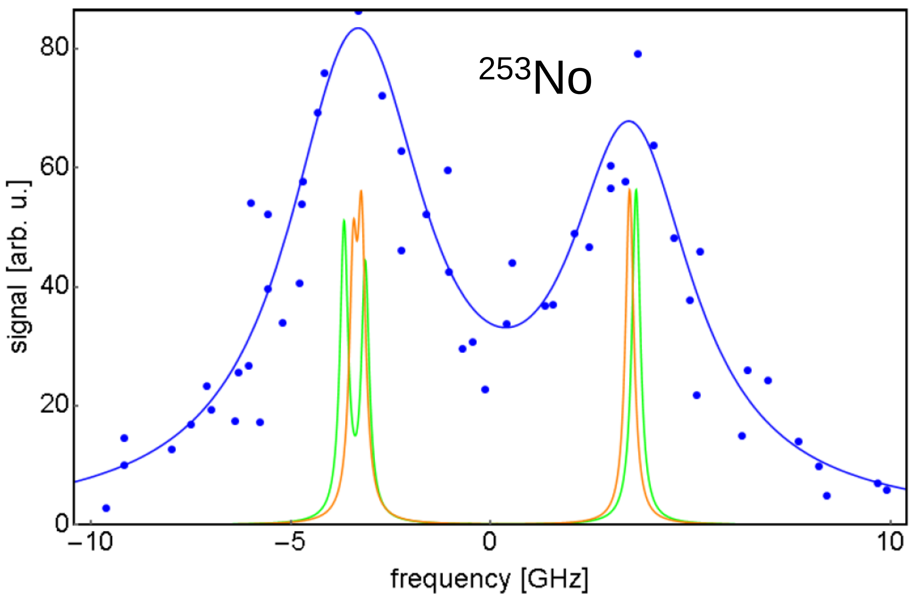
In Gas Jet Spectroscopy – Tailored Setup for GSI





- Gas jet spectroscopy at SHIP
    - Electric guiding of incoming ions
    - Filament neutralization @ RADRIS

- High resolution HFS enables unambiguous nucleon configuration assignment

[1] S. Raeder et al., NIMB, 463, 272-276 (2020)

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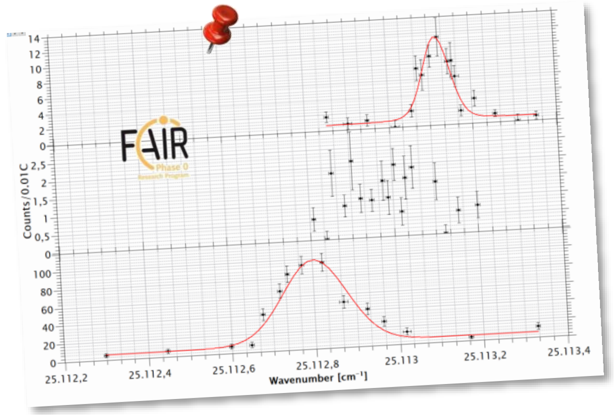
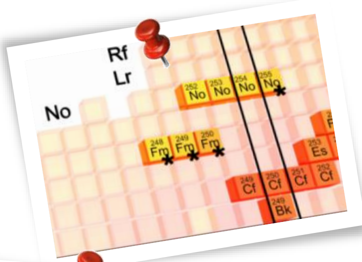
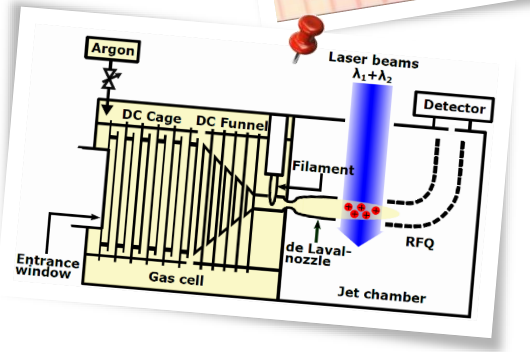
Summary

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

- RADRIS: First on-line measurements of Fm-isotopes
- Competitive laser spectroscopy program will continue
- RADRIS beamtime approved
- Gas jet: development for improved resolution
- LRC: new approach to extend the realm of laser spectroscopy







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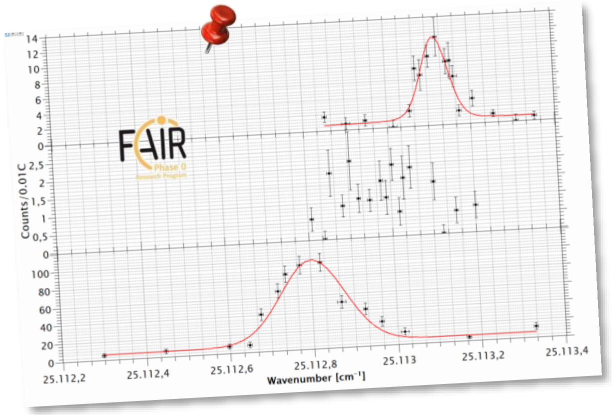
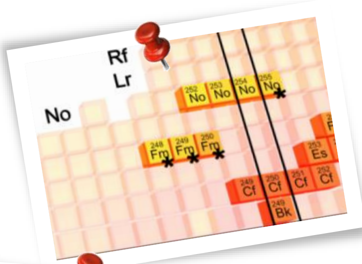
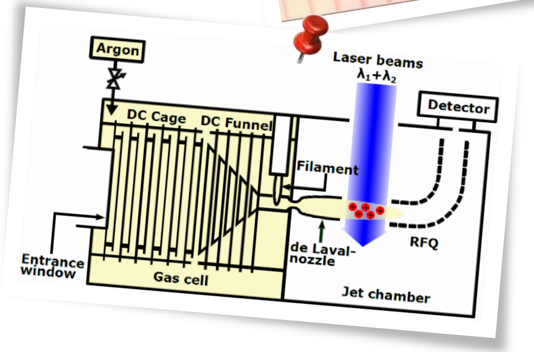
Thank You!







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