Laser Spectroscopy of Fermium isotopes:

Weakening of shell effects in the heaviest nuclei

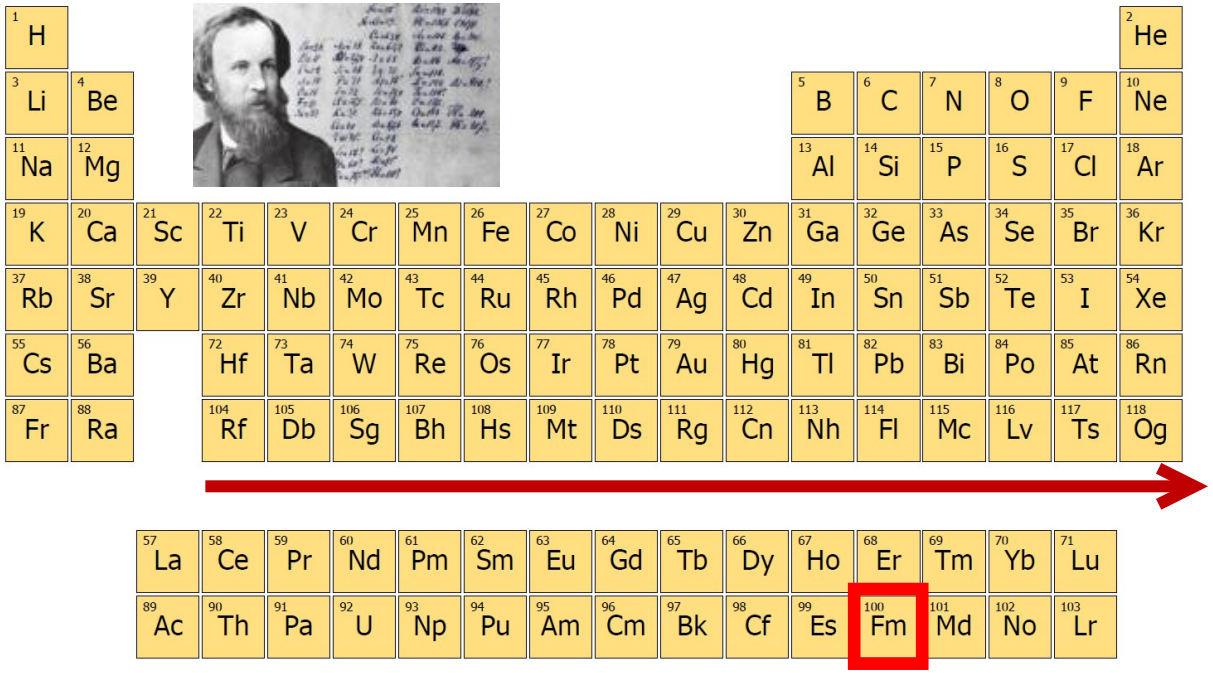
E. Rickert for the Fermium Collaboration

GSI Helmholtzzentrum für Schwerionenforschung GmbH & Helmholtz Institut Mainz

Properties of the Heaviest Actinides

Laser spectroscopy: a powerful tool to understand

- Atomic structure & chemical behavior
- Nuclear structure: stability, shape and size

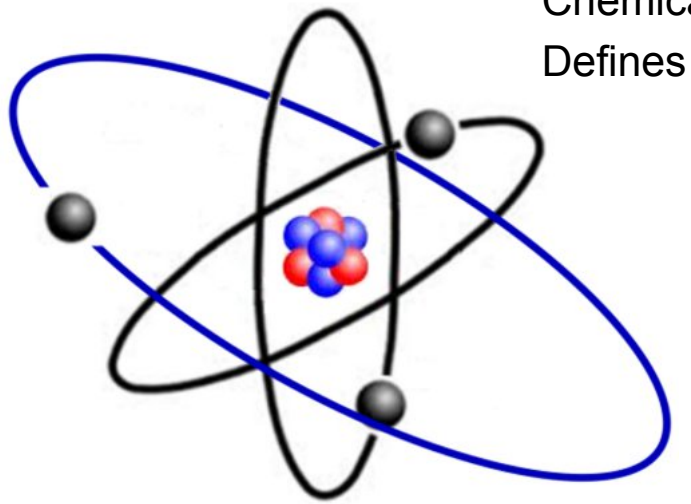


Electron shell

Atomic structure

Chemical properties

Defines the element



Nucleus

Nuclear structure

Stability of elements

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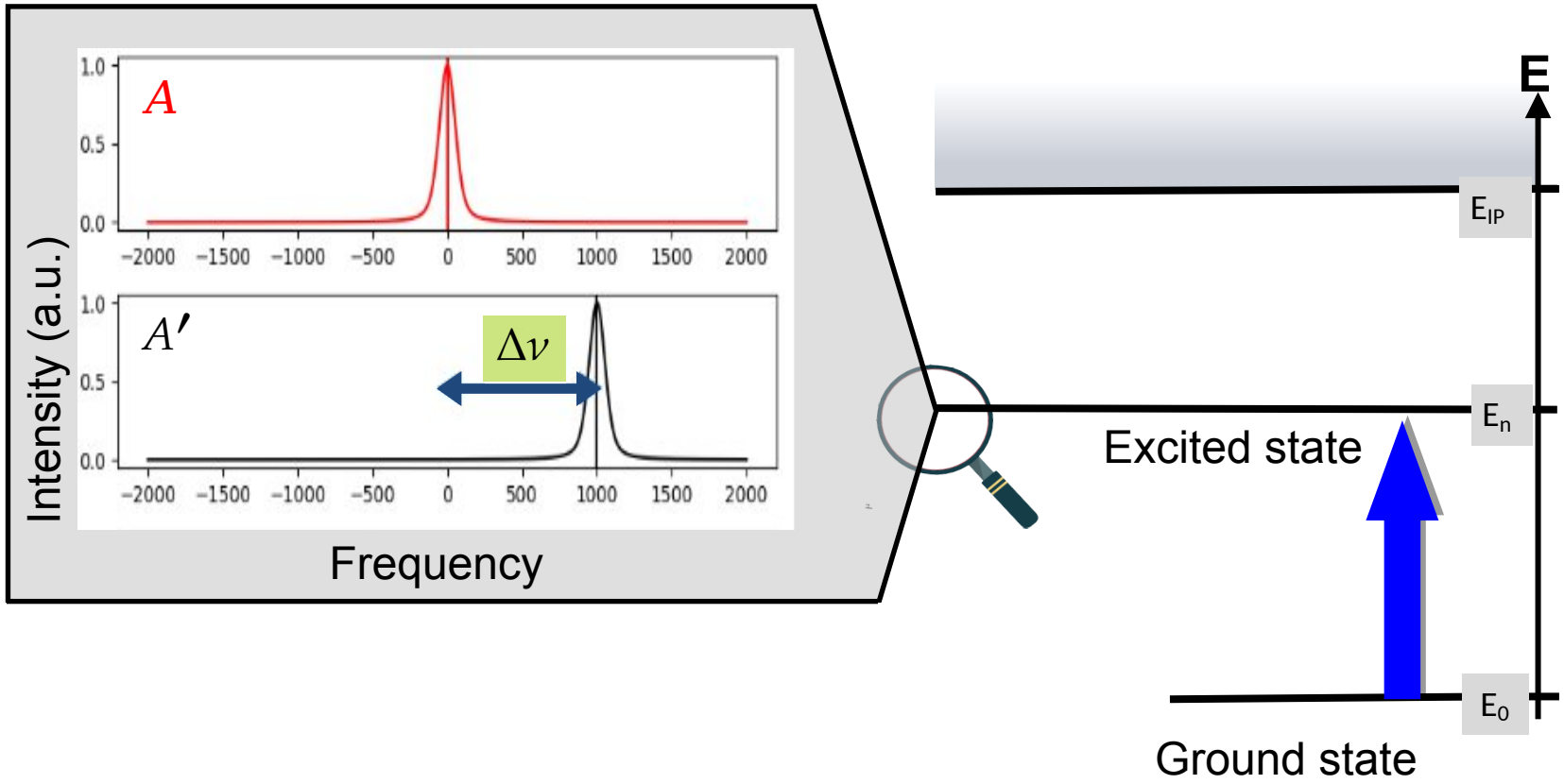
Spectroscopy for Nuclear Property Investigation

Obtain isotope shift and $\delta\langle r^2\rangle$

→ Nuclear shape, deformation

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

Experiment Theory



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RIS for Nuclear Property Investigation

Obtain isotope shift and $\delta\langle r^2\rangle$

→ Nuclear shape, deformation

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

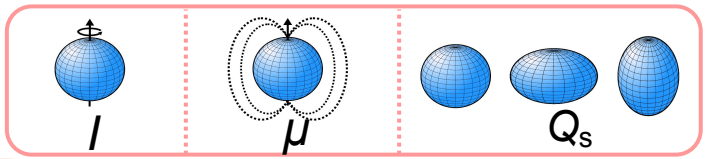
Experiment Theory

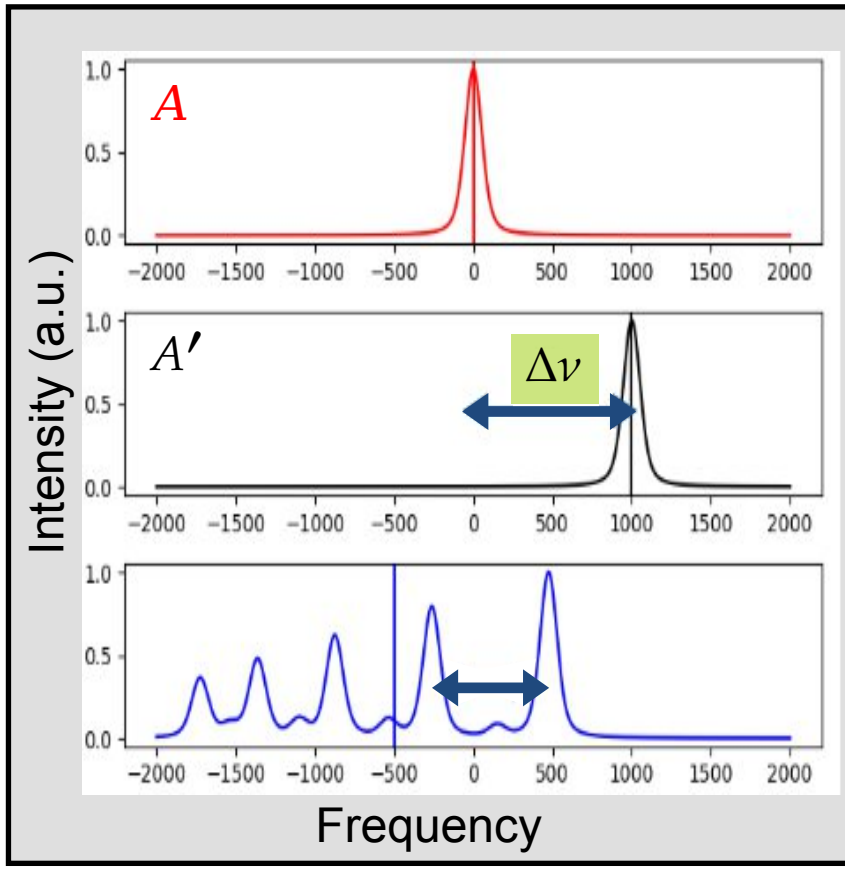
Hyperfine structure

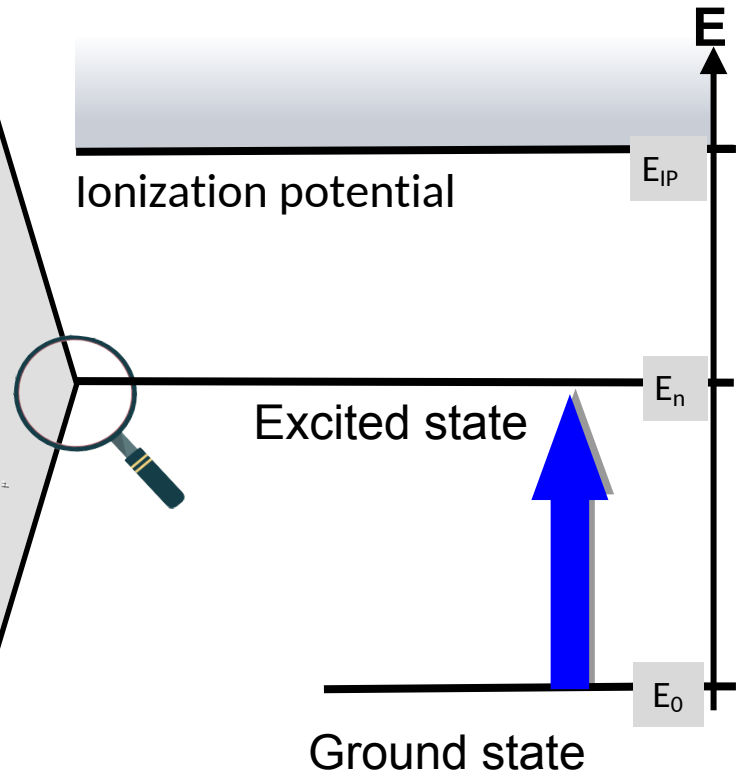
→ Spin, nuclear moments

$$A = \mu\frac{B_e(0)}{I\cdot J} \qquad B = eQ_s\left\langle\frac{\delta^2 V}{\delta z^2}\right\rangle$$

Nuclear information: Atomic







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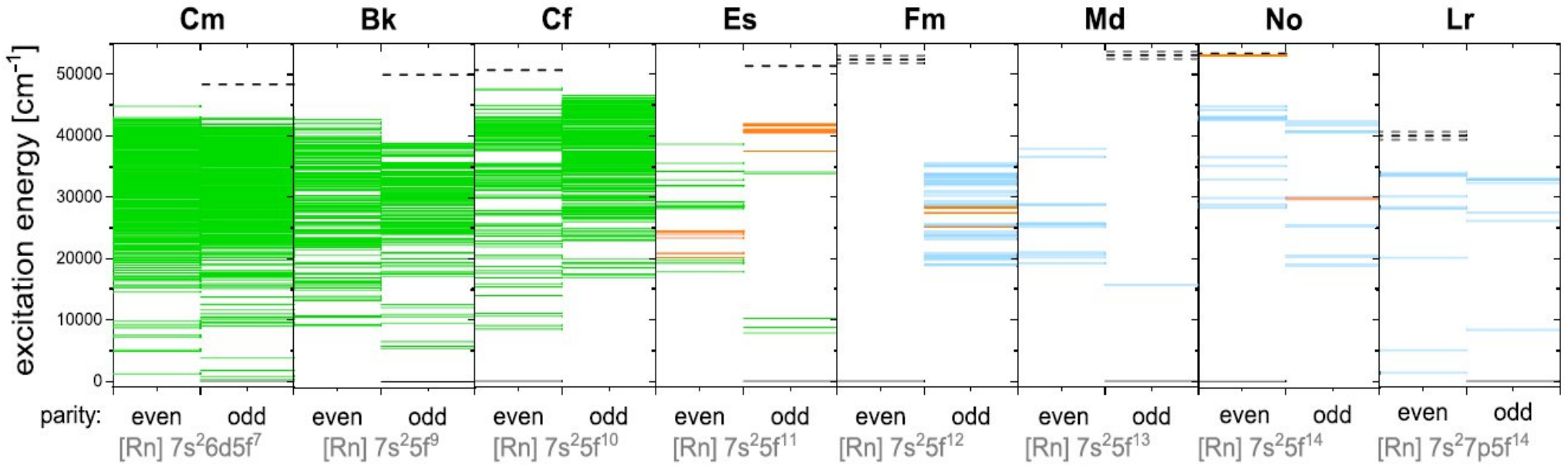
Laser Spectroscopy of the Heaviest Actinides

Laser spectroscopy on heaviest actinides:

- Reported atomic levels sparse
- For Z ≥ 102 only calculations available
- Benchmark atomic structure calculations

Blaise 1992
Recent experimenal levels
Theoretic prediction



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

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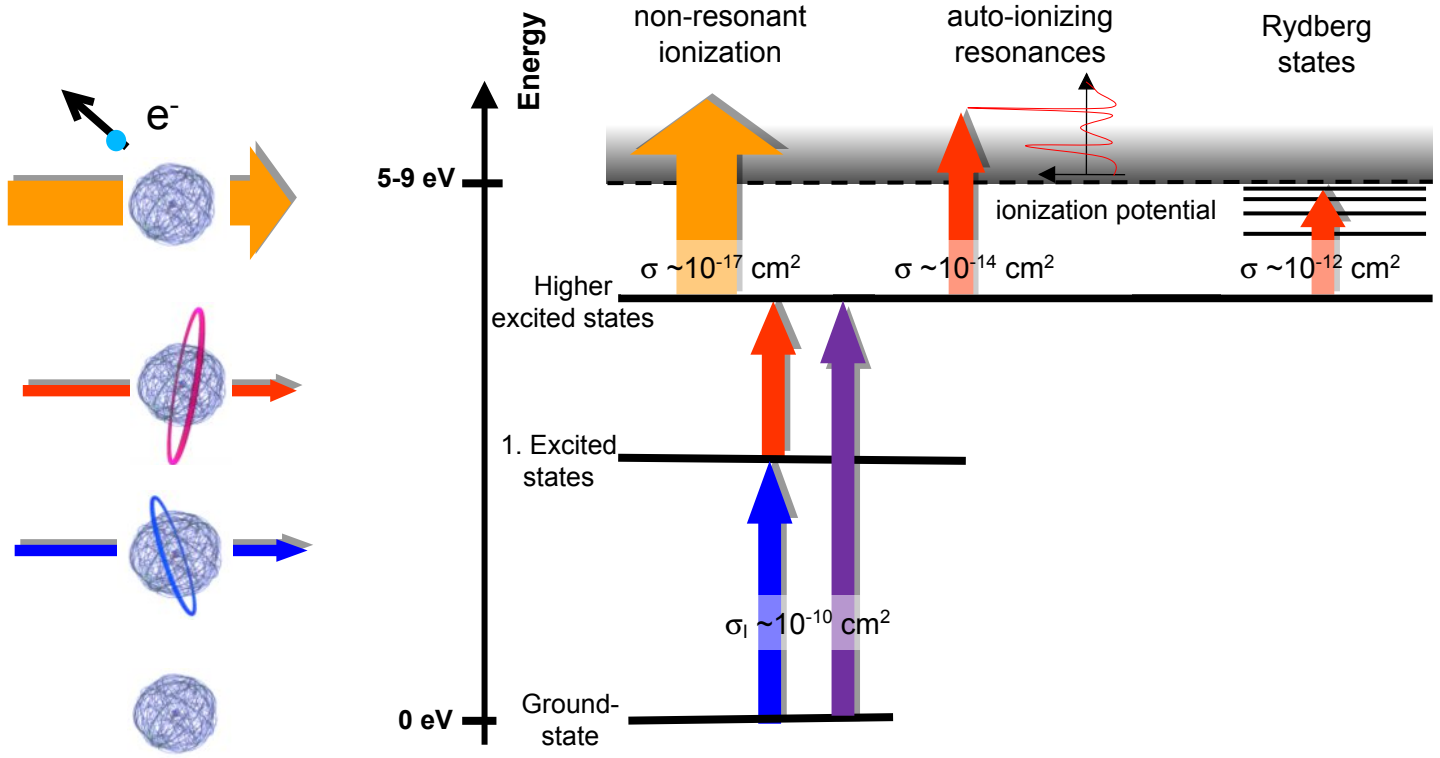
Resonance Ionization Spectroscopy



- Extract atomic and nuclear properties by RIS → Sensitive
- Characteristic level scheme for every element → Efficient
- Exploit resonant transitions → Selective

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Deformed shell gap N=152

Known heavy nuclei around Z=100, N=152 deformed

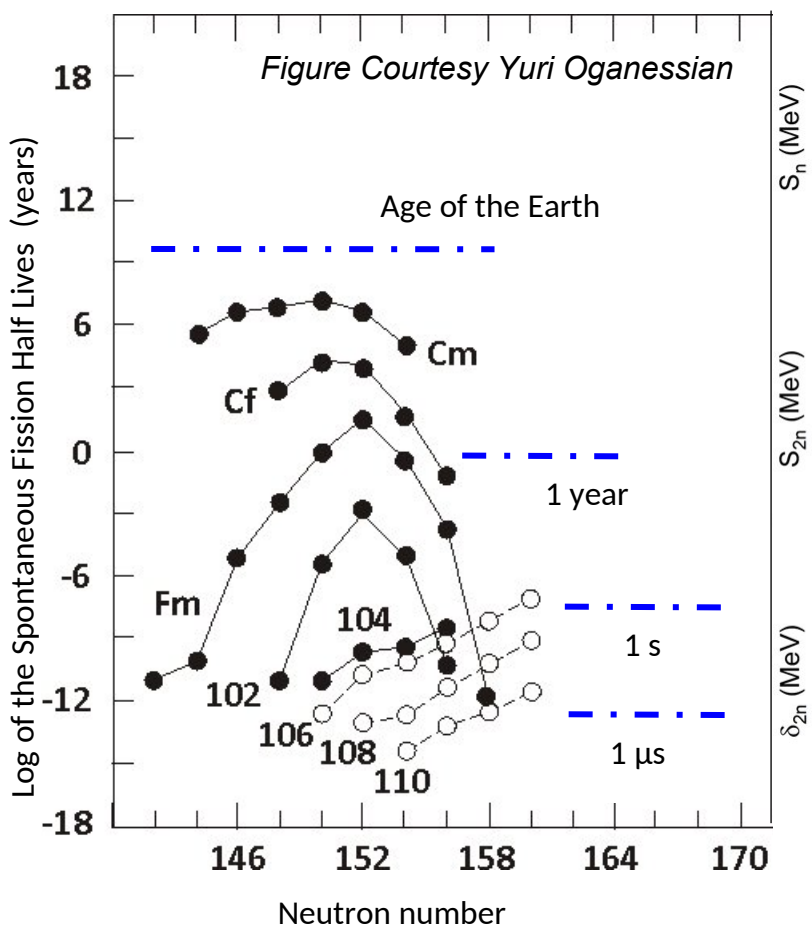
- Quadrupole deformation parameter $\beta_2 \approx 0.3$

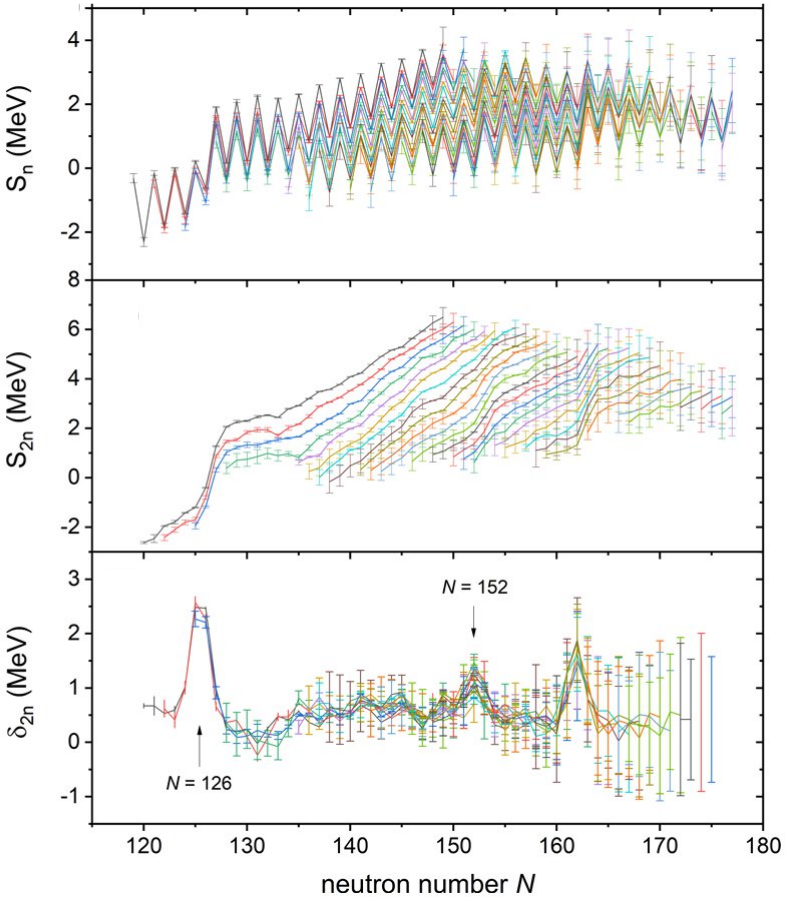
Deformed shell gap at N=152

- Mass measurements
- SF half lives
- α decay energy Q_α
- Two-n separation energies
- Shell gap parameter δ_{2n}

How pronounced in $\delta\langle r^2 \rangle$?

→ Perform Laser spectroscopy in heavy actinides





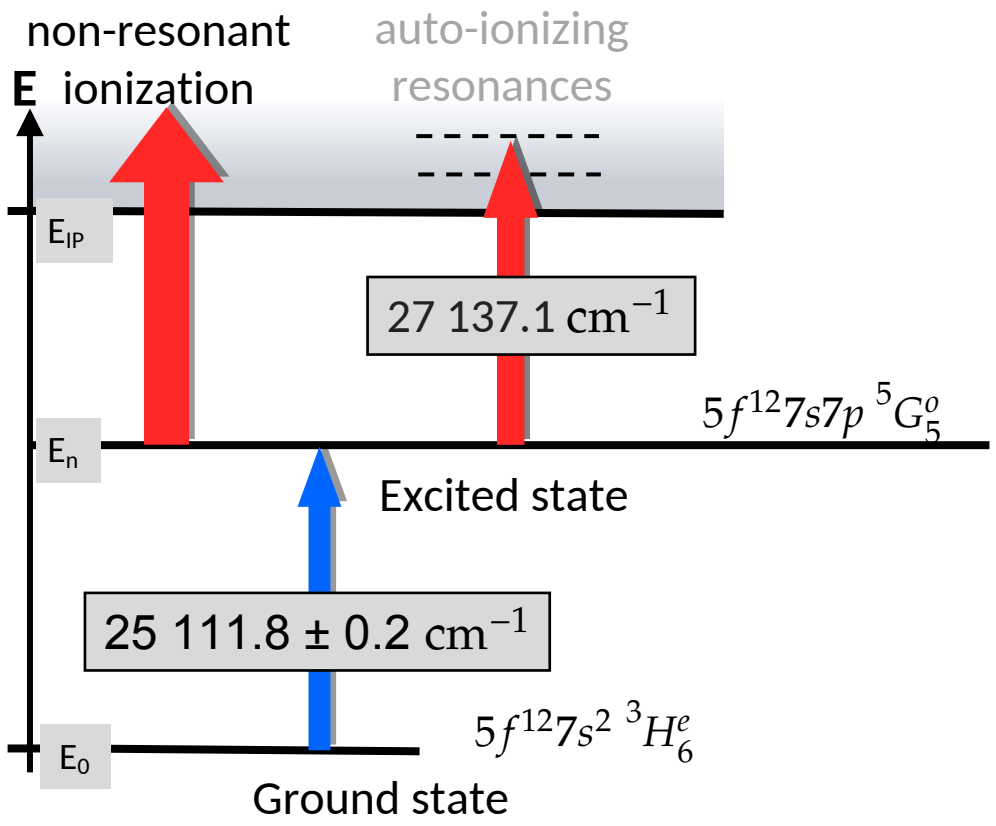
O. Kaleja., PhD Thesis, University Mainz (2020)

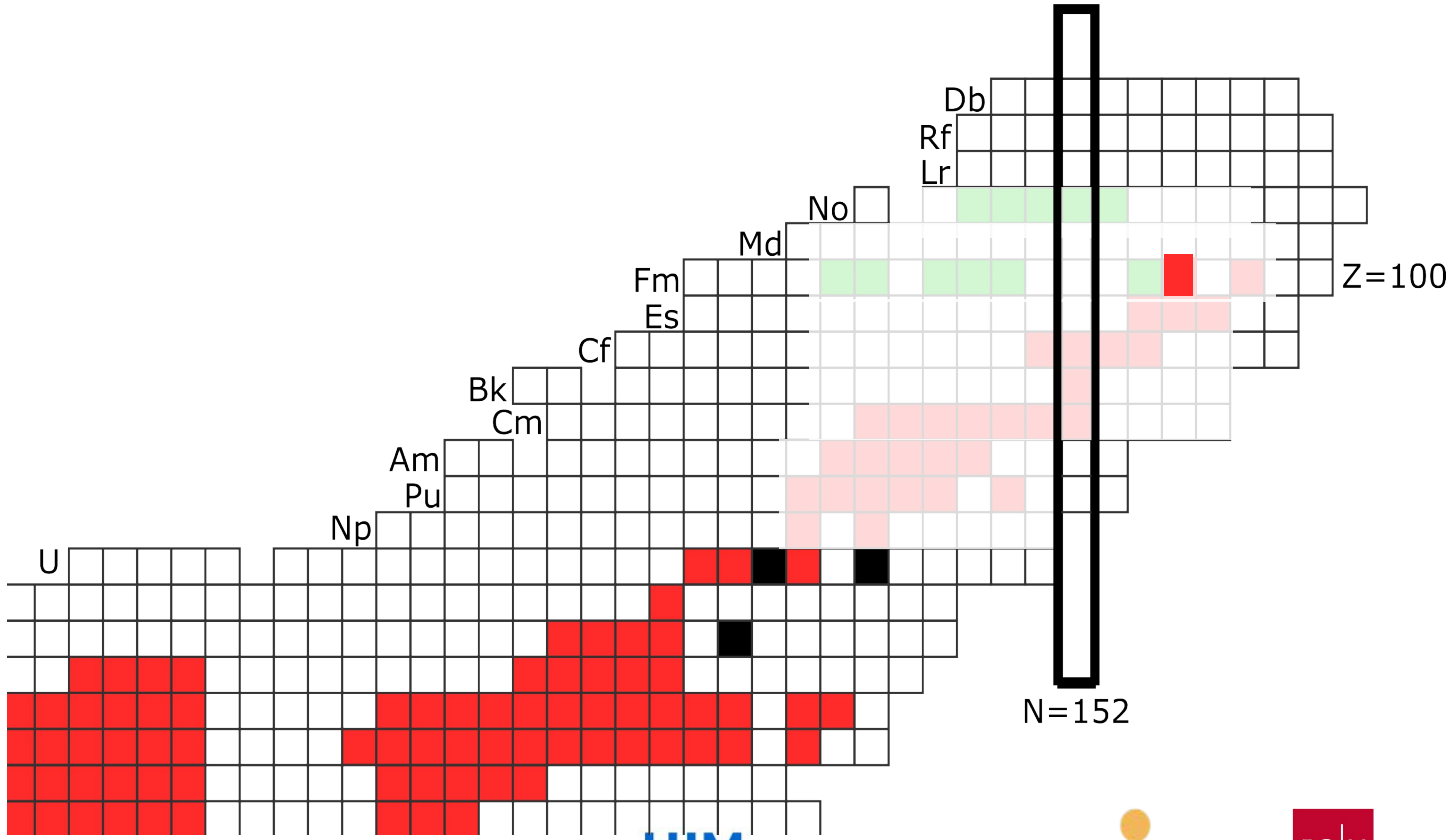
Spectroscopy for atomic structure investigations

Fm atomic transition: 2003 from offline studies of ^{255}Fm

M. Sewtz et al., Physical Review Letters 90 (2003)
H. Backe et al., Hyperfine Interactions 162 (2005)

First offline measured heavy actinide in gas





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RIS on Heavy Elements

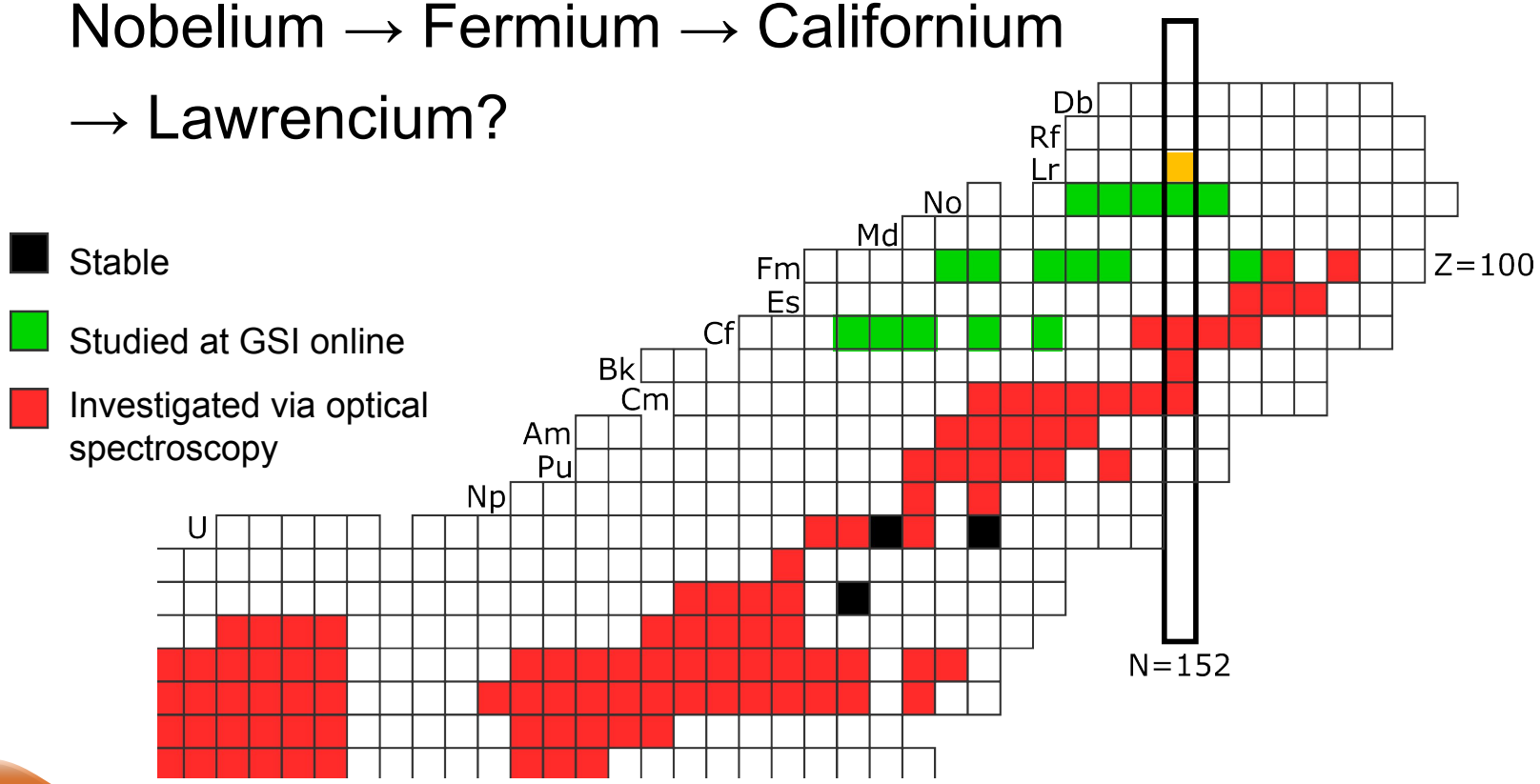
Element specific experimental setup required

Online investigation: high production cross section needed

Spectroscopy in gas cell: RADRIS

Nobelium → Fermium → Californium

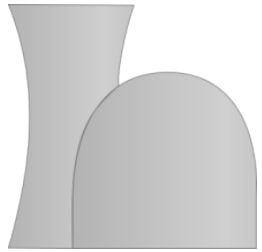
→ Lawrencium?





Accelerator based production

- Low yield ≤ 1/s
- Short lifetimes



Reactor breeding

Macroscopic samples for offline measurements

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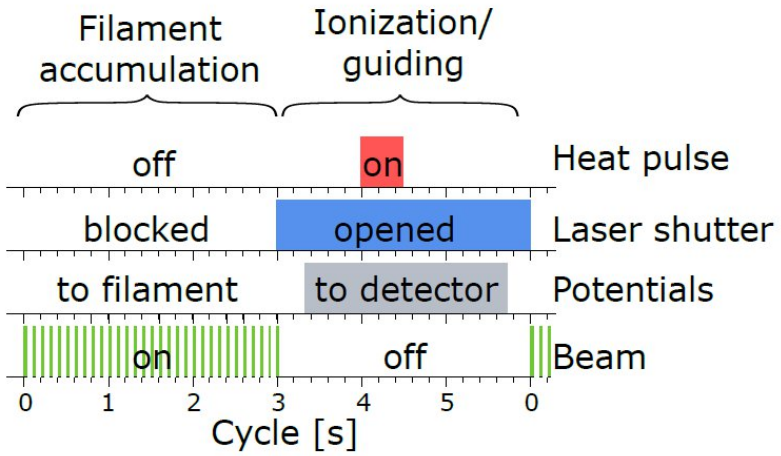
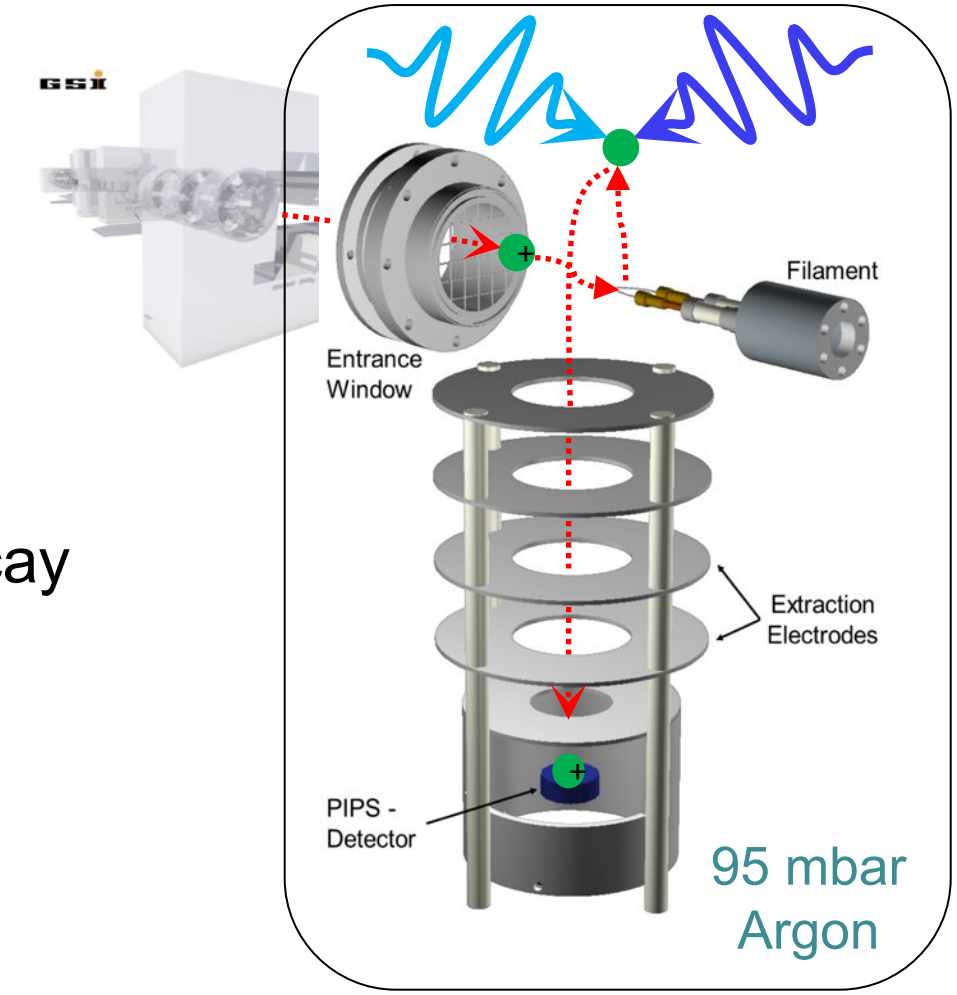
Radiation Detected Resonance Ionization Spectroscopy

RADRIS Method:

- Thermalizing of incoming fusion products
- Collecting onto thin hafnium filament
- Evaporation
- Two-step photoionization process
- Transport to detector and detection of alpha decay



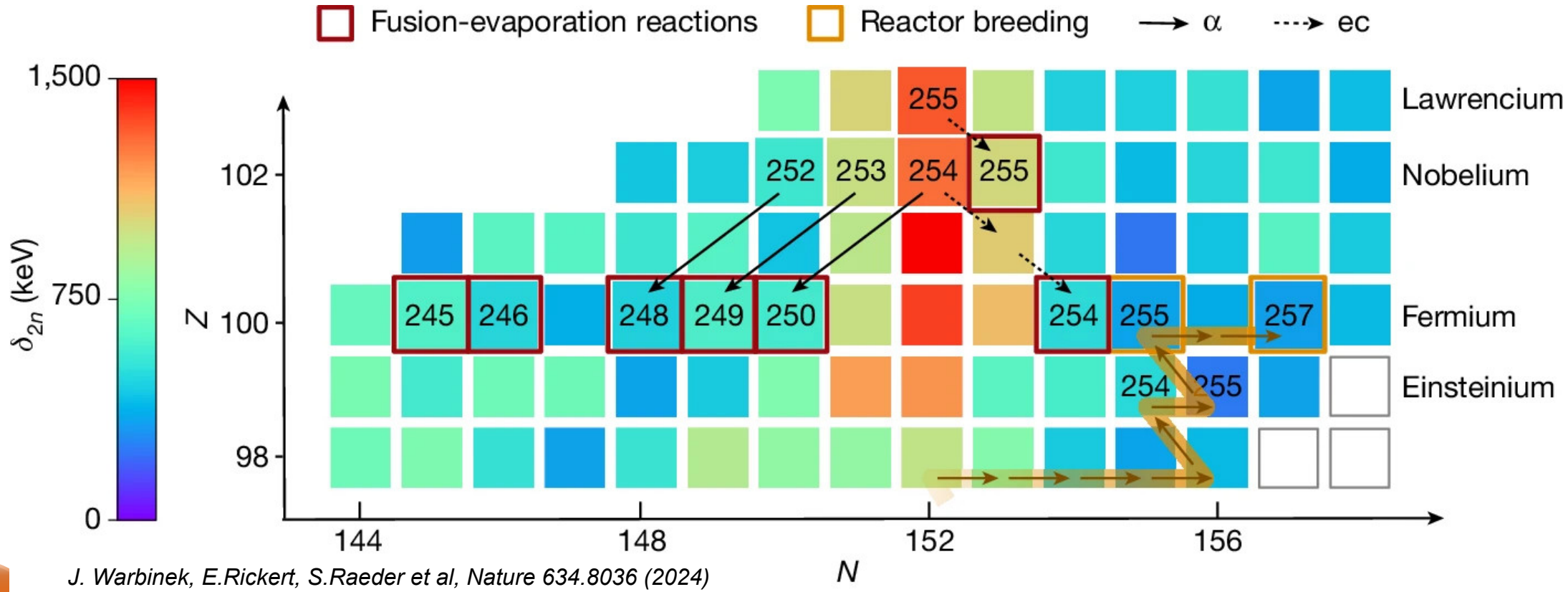
J. Warbinek et al., Atoms 10, 41 (2022)



M. Laatiaoui et al., Nature 2016, 538, 495–498

Fm laser spectroscopy

- Combine on-line and off-line spectroscopy of 8 Fm isotopes from different production mechanisms around N=152 shell gap
- On-line: RADRIS
- Off-line: RISIKO



J. Warbinek, E.Rickert, S.Raeder et al, Nature 634.8036 (2024)

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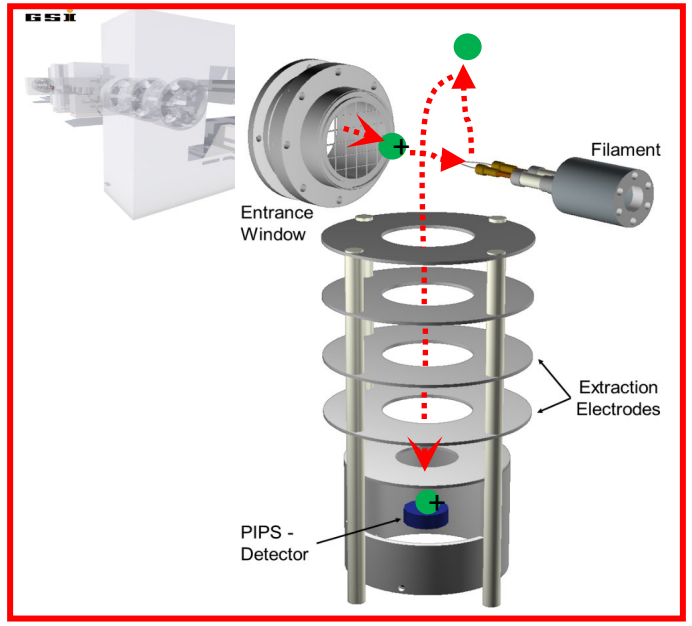
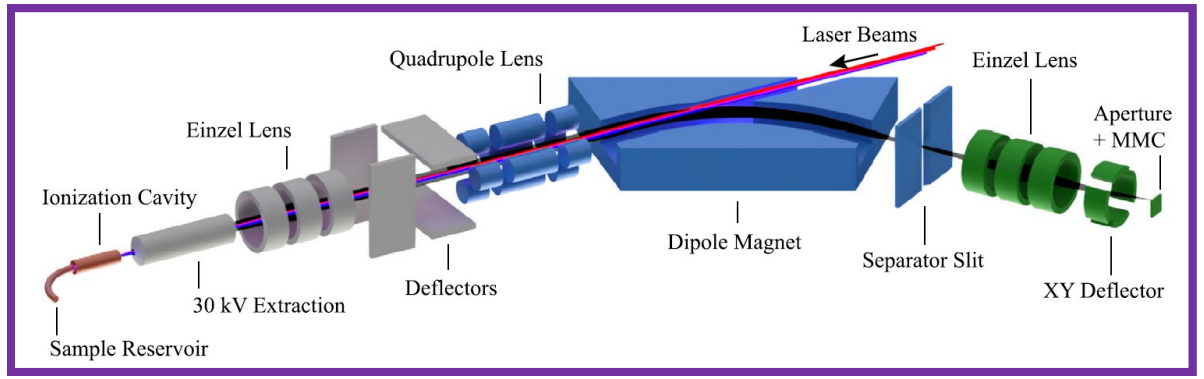
Fermium spectroscopy

- Combine on-line and off-line spectroscopy of 8 Fm isotopes from different production mechanisms around N=152 shell gap
- On-line: RADRIS (in gas)
- Off-line: RISIKO (in hot cavity)

241 Fm	242 Fm	243 Fm	244 Fm	245 Fm	246 Fm	247 Fm	248 Fm	249 Fm	250 Fm	251 Fm	252 Fm	253 Fm	254 Fm	255 Fm	256 Fm	257 Fm	258 Fm	259 Fm
0.73ms	0.8 ms	231 ms	3.21ms	4.2 s	1.54 s	31 s	34.5 s	2.6 min	30 min	5.3 h	25.39 h	3 d	3.24 h	20.07 h	157min	100.5 d	370 µs	1.2 s



N=152



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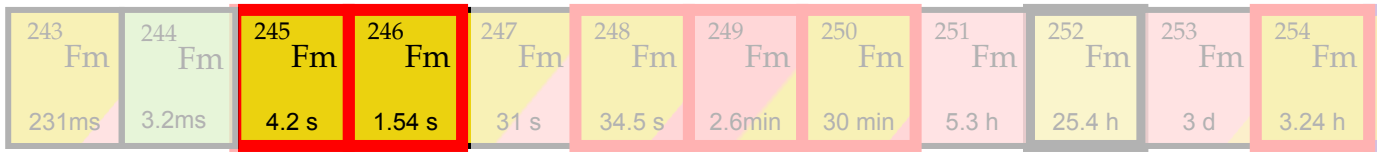
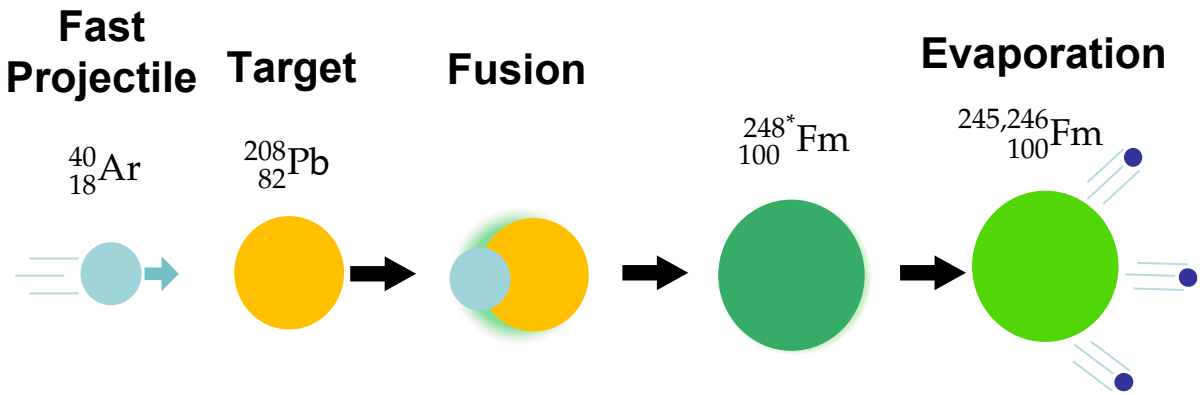
^{245,246}Fm spectroscopy

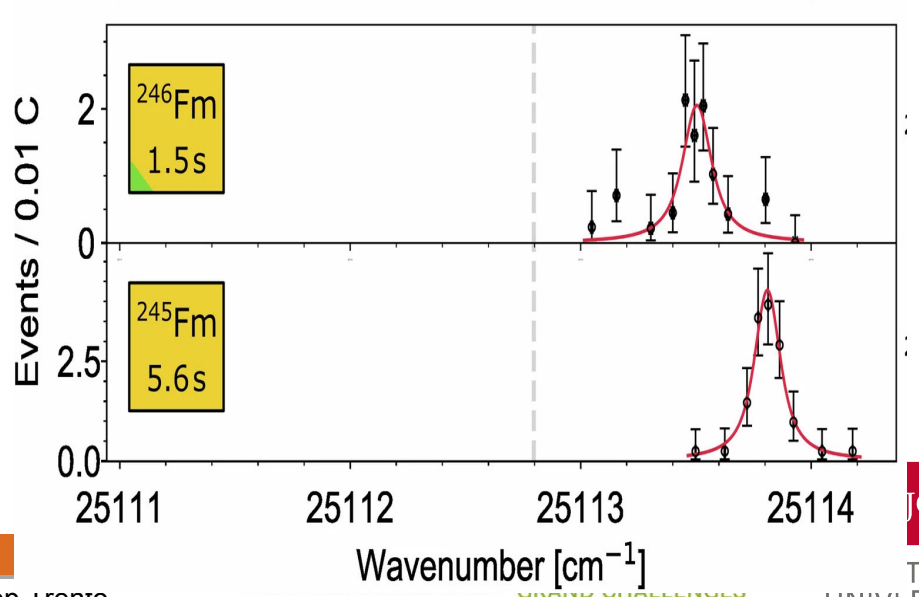
^{245,246}Fm on-line spectroscopy @ RADRIS, direct production @SHIP

Low production (4/min @ target)

Short $t_{1/2}$ → fast RADRIS cycle developed with fast potential switching

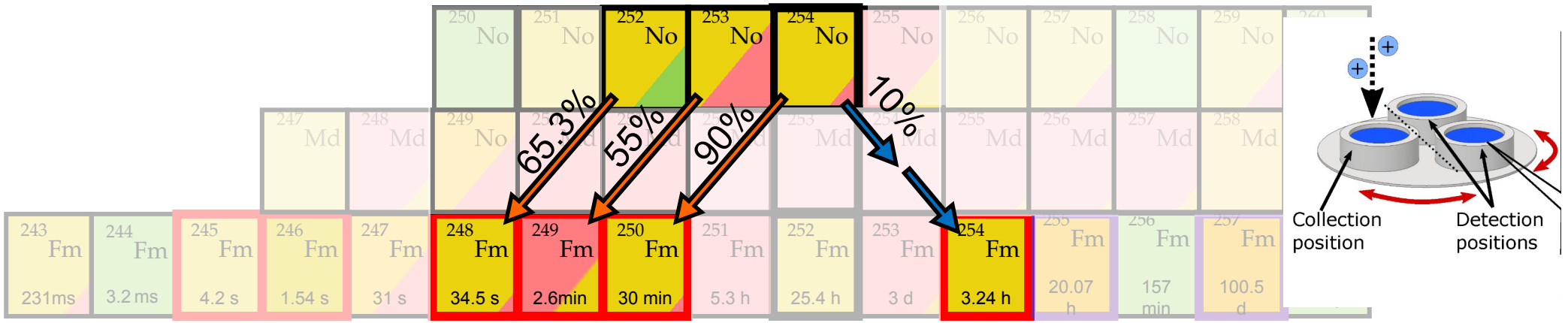






$^{248\text{-}250,254}$Fm spectroscopy

^{248,249,250}Fm and ^{254}Fm: on-line spectroscopy @ RADRIS, indirect production @SHIP



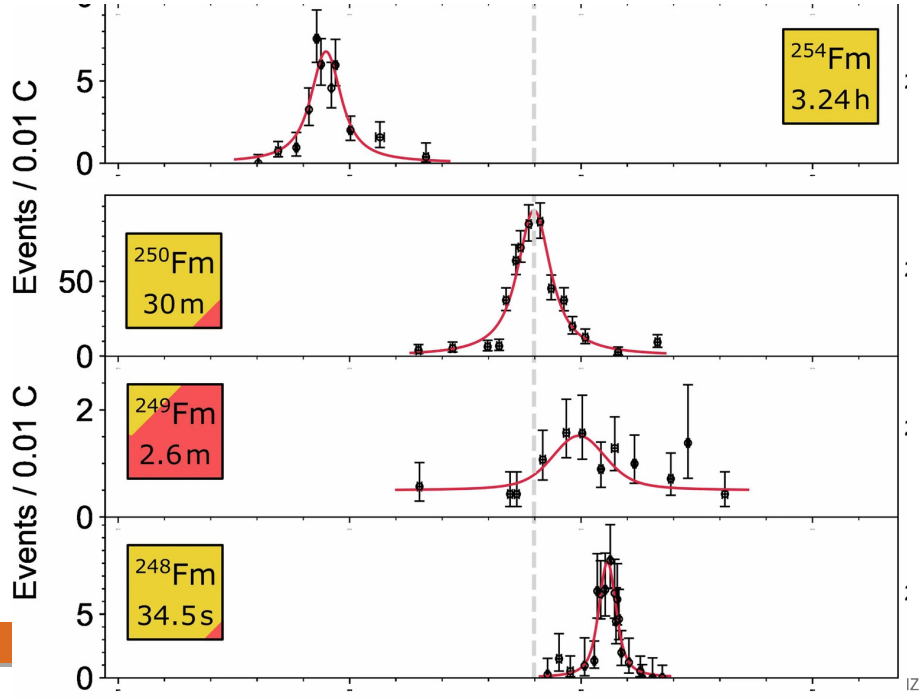
Collection of No-mother on the filament

Access Fm nuclides over decay → decay losses

Accumulation on filament based on $t_{1/2}$

^{254}Fm: 1 day per datapoint/wavenumber

Rotatable detector setup

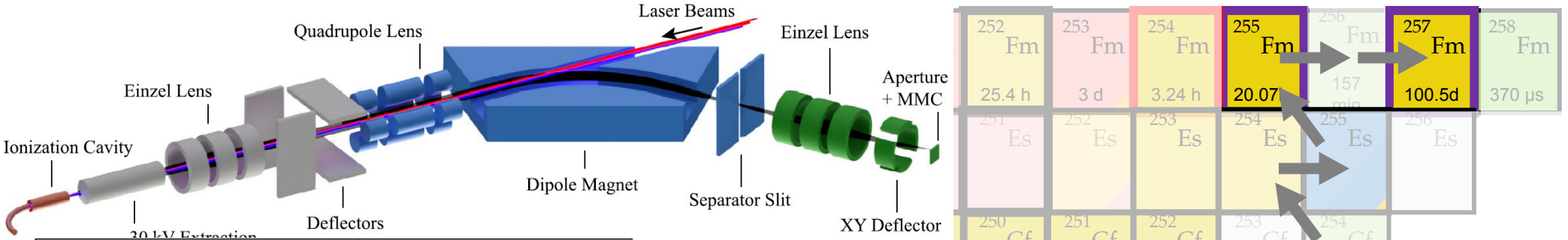


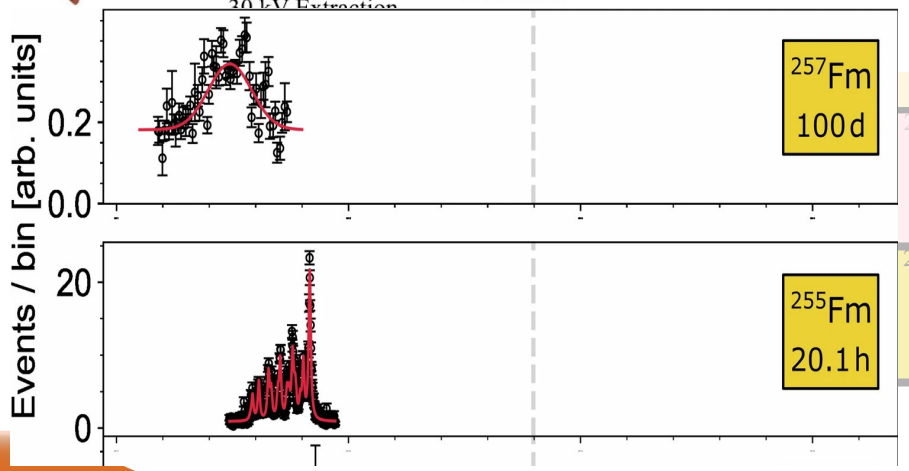
^{255,257}Fm spectroscopy

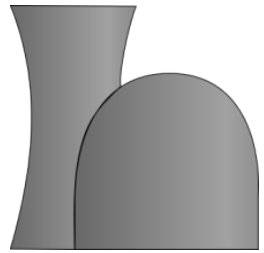
^{255,257}Fm : off-line hot cavity RIS @ RISIKO

^{255}Fm: ORNL + ILL (booster): 2-9 $\cdot 10^6$ atoms , ^{257}Fm: ORNL: 5 $\cdot 10^7$ atoms

RISIKO: Off-line resonance ionization spectroscopy in hot cavity









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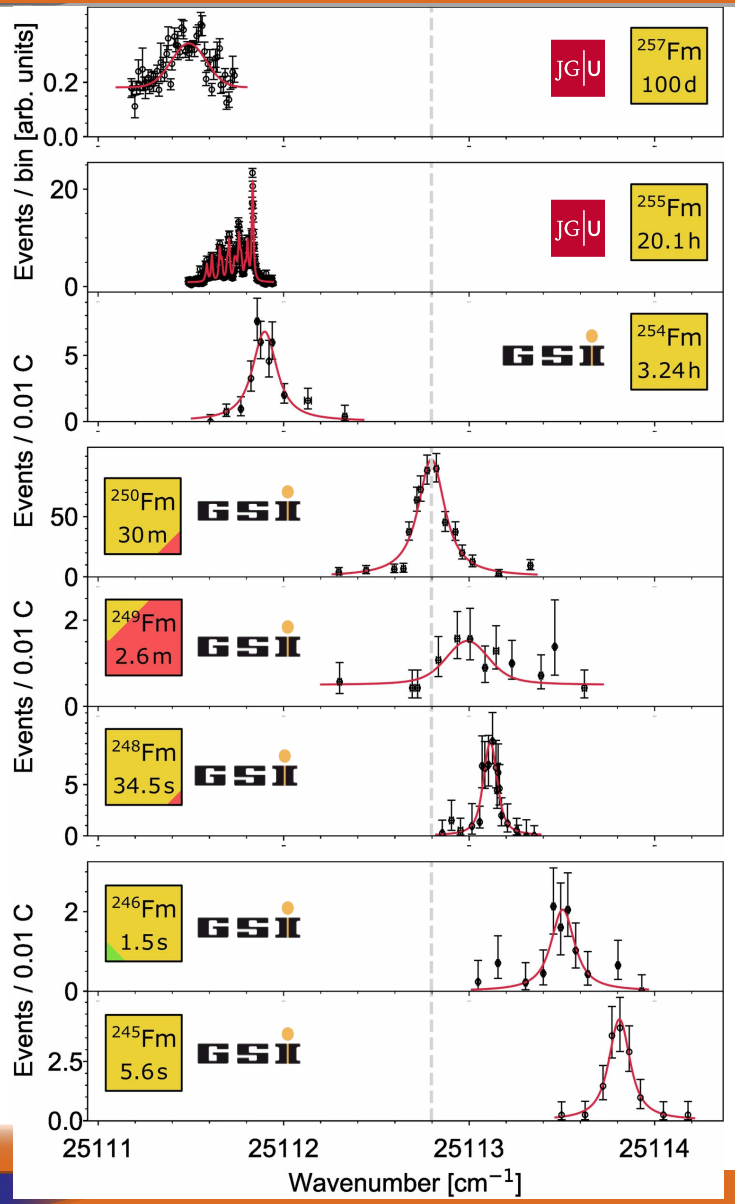
Isotope Shift in Fermium



- Obtained isotope shift and $\delta\langle r^2\rangle$ of a long chain across the deformed N=152 neutron shell gap
- Extended RADRIS method to measure both short and long lived Fm isotopes (1.54 s – 3.2 h)
  - Short RADRIS cycle for ^{245,246}Fm, low cross sections
  - Customized, rotatable detector for ^{254}Fm
- Offline measurements in hot cavity:
  Spectroscopy at limit of detection at RISIKO for ^{255,257}Fm
- HFS resolved, extraction of μ and Q_s by M. Urquiza et al, PRL, 136.19 (2026)

J. Warbinek, E.Rickert, S.Raeder et al, Nature 634.8036 (2024)

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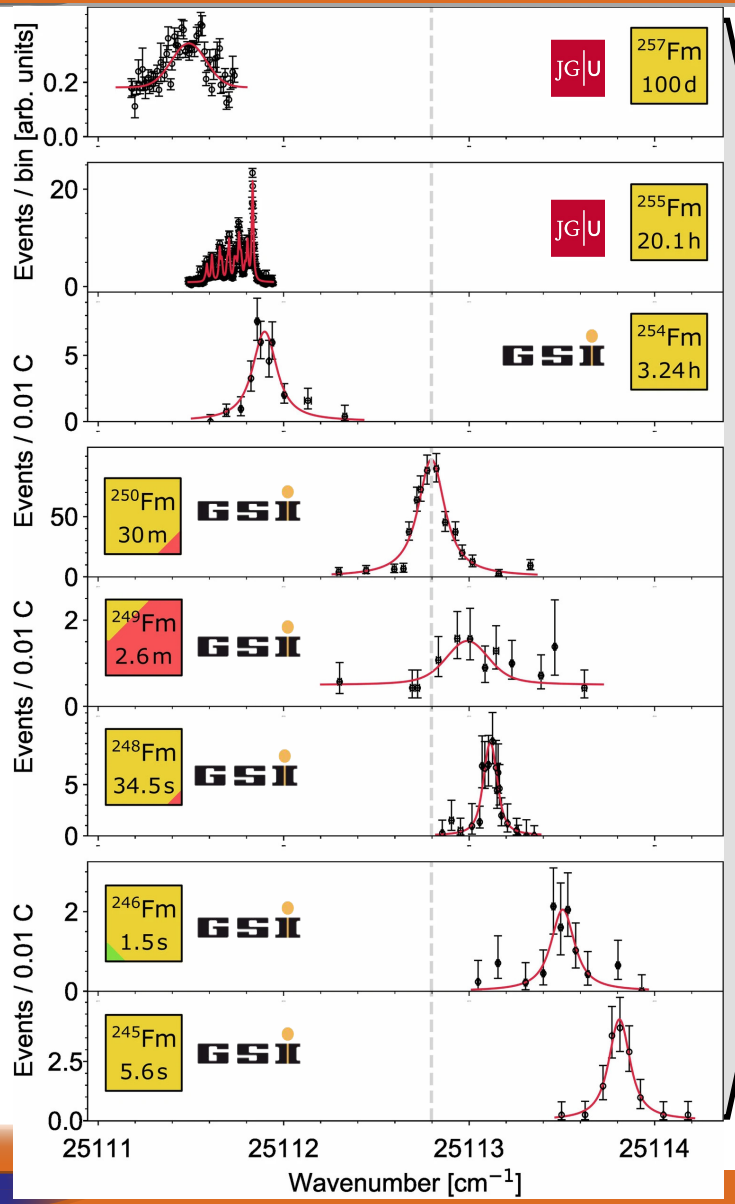
Isotope Shift in Fermium



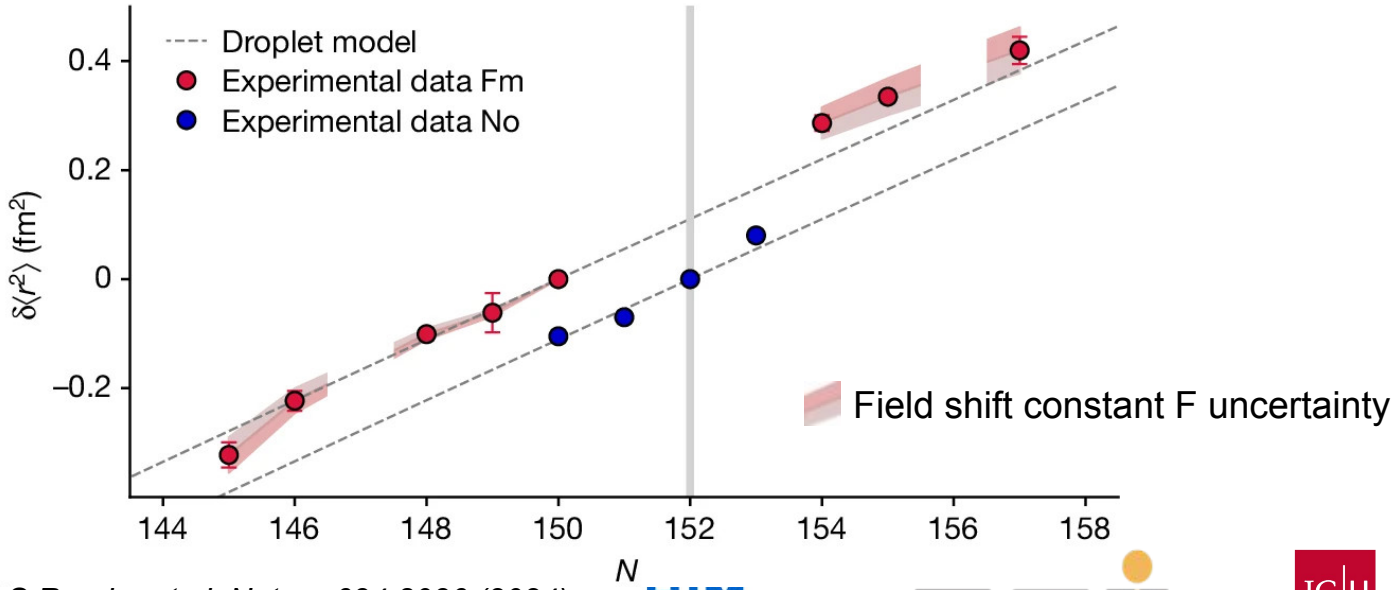
Theory input to extract changes in charge radii

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

Theory

F factor provided by *S.O. Allehabi,* *JQSRT, 253, 107137 (2020)*

→ Compare to different theoretical approaches



J. Warbinek, E.Rickert, S.Raeder et al, Nature 634.8036 (2024)

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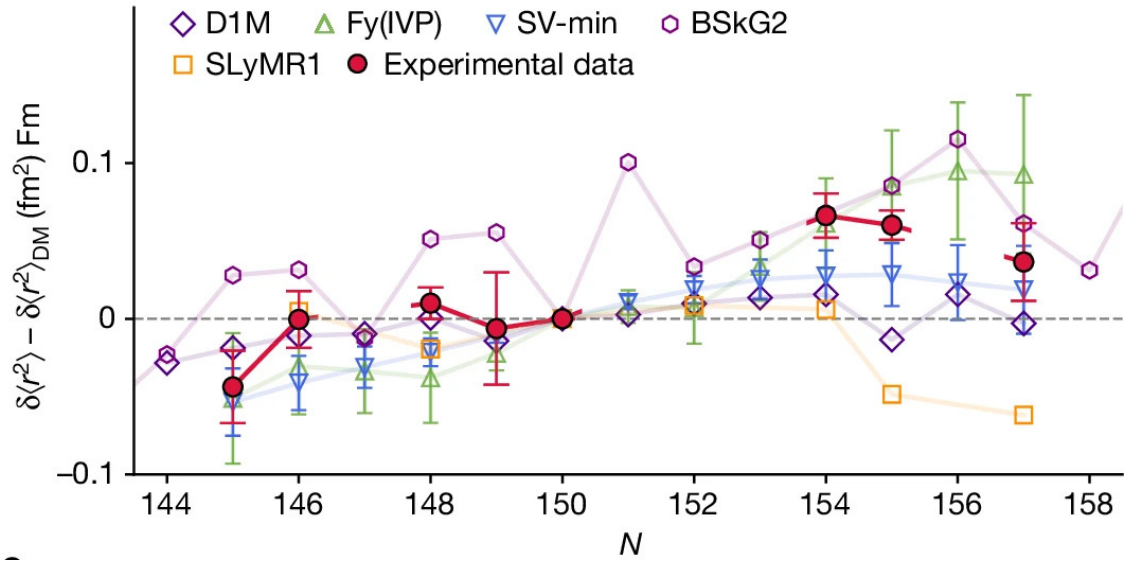
$\delta < r^2 >$ in Fermium and Nobelium

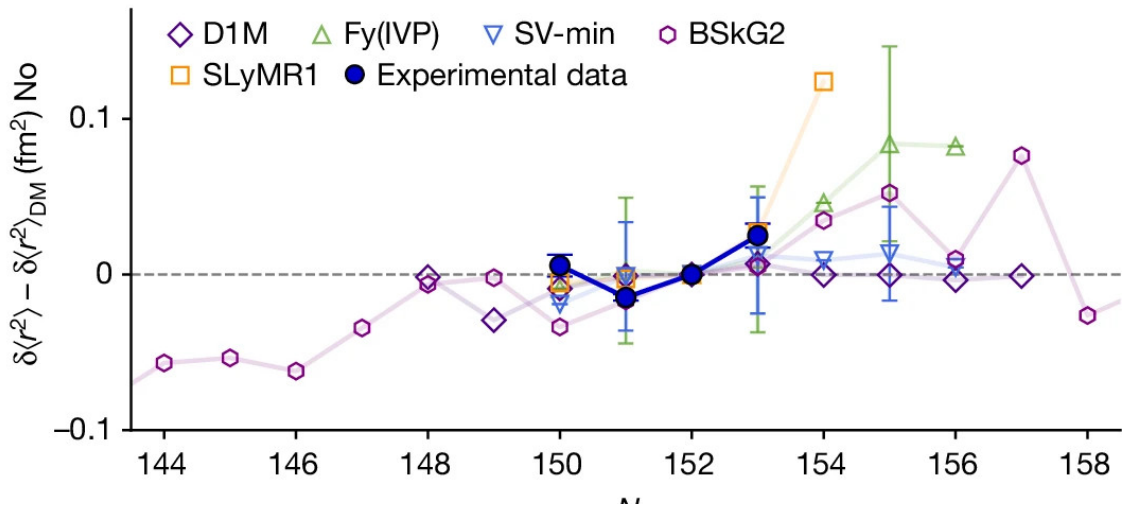
Substract spherical droplet model for better comparison

Different theoretical calculations (MREDF, HFB, Fy(IVP)) in overall good agreement

Nuclear energy density functional theory with different single particle handling

→ Weak shell effects in heavy actinides don‘t influence charge radii





J. Warbinek, E.Rickert, S.Raeder et al, Nature 634.8036 (2024)

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High resolution spectroscopy on ^{255}Fm

^{255}Fm: 2003 spectroscopy in gas ~10^{10} atoms

High resolution spectroscopy ^{255}Fm in source at RISIKO

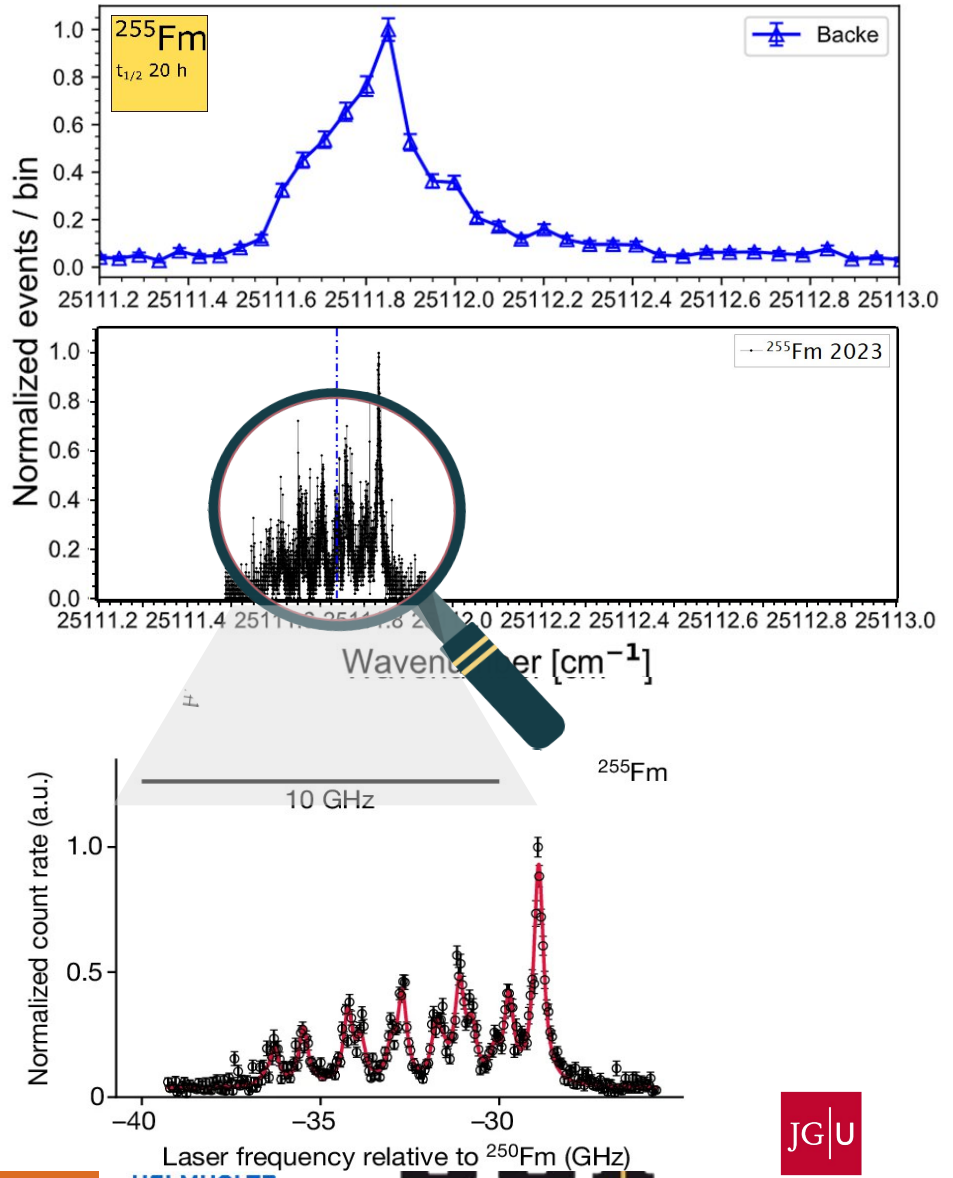
Hyperfine structure resolved in perpendicular illuminated trap with ~10^{6} atoms

Hyperfine structure observed → Extraction of μ and Q_s

M. Urquiza-Gonzalez et al, PRL, 136.19 (2026)

- μ = - 0.75(5) μ_N
- Q_s = + 5.84(13) eb

→ prolate deformated nucleus



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Further steps towards heavy element spectroscopy

Expand RADRIS technique to further actinide isotopes:

- Implementation of 8-detector array (PhD thesis K. van Beek)

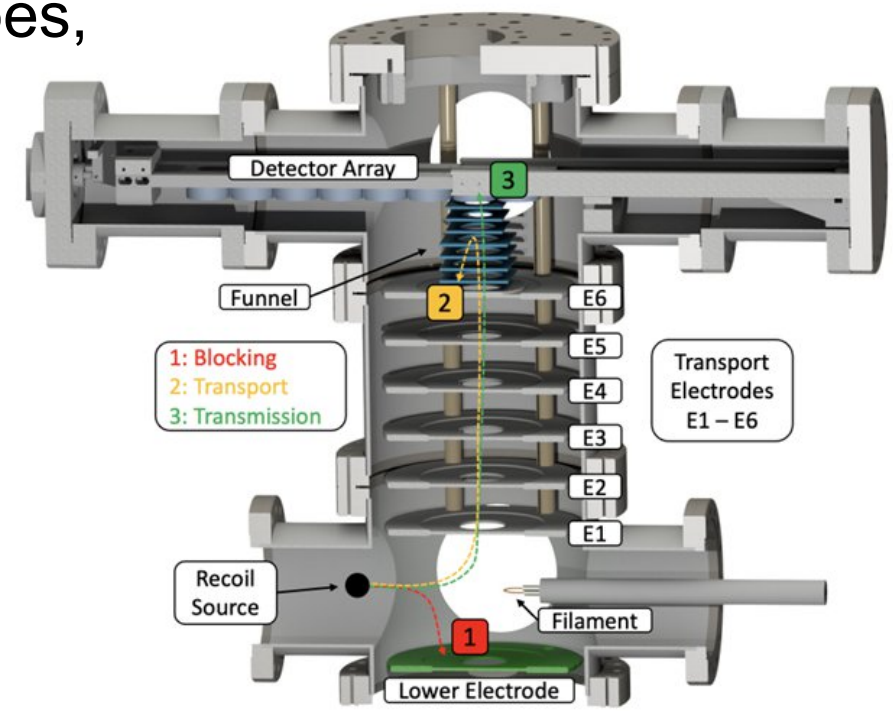
  → use for spectroscopy of α-decaying Cf isotopes,

  $T_{1/2}$ between 57 s to 35 h (!)

  → Obtained results for

  ^{240}Cf, ^{241}Cf, ^{242}Cf, ^{244}Cf and ^{246}Cf

240 Cf	241 Cf	242 Cf	243 Cf	244 Cf	245 Cf	246 Cf	247 Cf	248 Cf	249 Cf	250 Cf
0.96 m	3.78 m	3.5 m	10.7 m	19.4 m	45 m	35 h	3.1 h	333 d	351 y	13 y



Only possible due to prior offline studies at RISIKO

→ Isotope shifts will be published soon, stay tuned

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High resolution spectroscopy

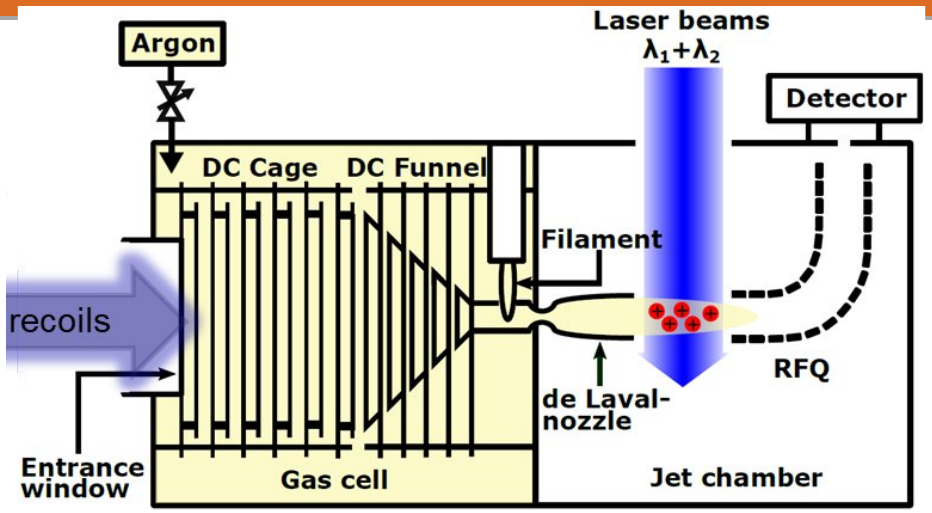
JetRIS setup at GSI: Combination of RADRIS and Gas Jet

Production of heavy elements at SHIP

Stopping of ions in gas cell

Neutralization of ions at filament

Spectroscopy in gas jet → low pressure and temperature regime

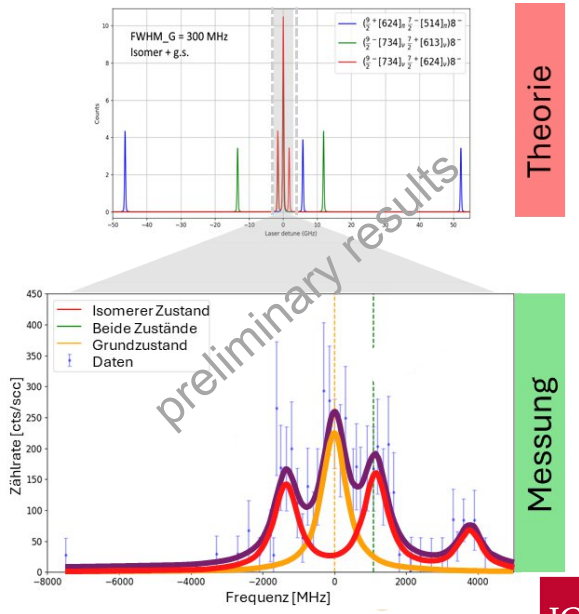


In ^{254}No K-isomer with unknown configuration ($K=8^-$, $T_{1/2}=259(7)$ ms)

→ Test of different nuclear models

Resolved hyperfine structure enables independent determination of

- magnetic dipole moment electric
- quadrupole moment and isomer shift → Publication in progress

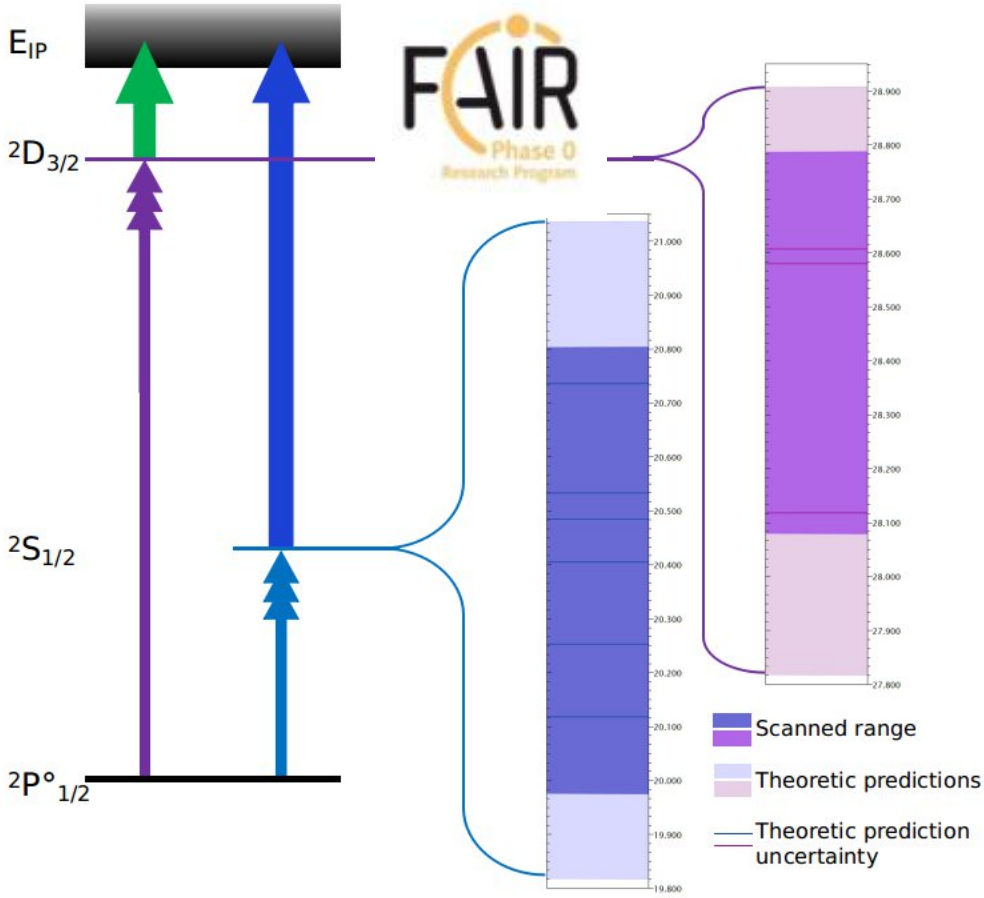


Level Search in Lawrencium (Z=103)

Search for 2 different states

- Predictions from theory:

  20500 cm^{-1} ($^2S_{1/2}$) & 28500 cm^{-1} ($^2D_{3/2}$)
- Extensive level search campaigns during beamtimes in 2020 and 2022
- Exclusion for ~ 800 cm^{-1} in each region with high confidence
- Uncertainty of atomic predictions ~300 cm^{-1}
- Increased sensitivity with RADRIS upgrade



E. Rickert et al. EPJ D 80.6 (2026): 88.

Kahl, E. V., et al. arXiv preprint arXiv:2103.11287 (2021).
A. Borschevsky et al., Eur. Phys. J. D 45, 115 (2007).
V.A. Dzuba et al., Phys. Rev. A 90, 012504 (2014).
S. Fritzsche et al., Eur. Phys. J. D 45, (2007) 107-113.

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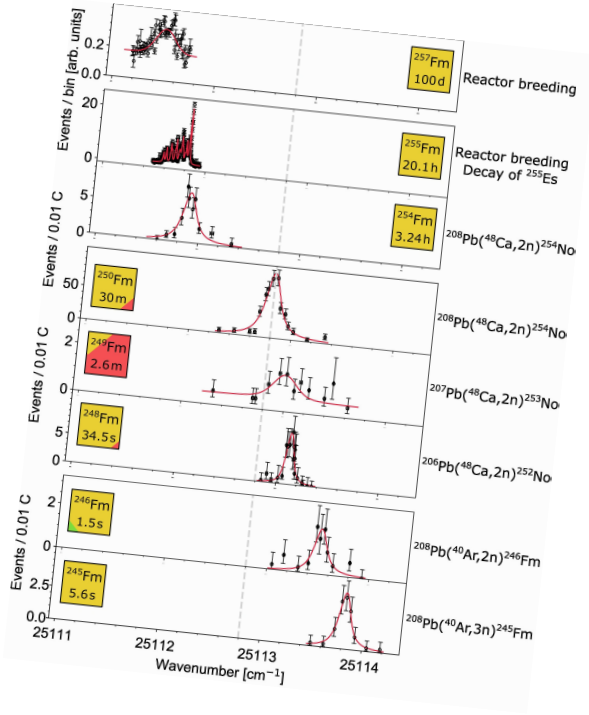
Summary and Outlook

Laser spectroscopy to investigate nuclear structure in heavy elements

Achievements in laser spectroscopy of fermium:

- Extended RADRIS to measure short and long lived Fm isotopes (1.54 s – 3.2 h)
  - Spectroscopy at limit of detection at RISIKO for ^{255,257}Fm
  - Extracted $\delta\langle r^2\rangle$ of eight Fm isotopes $^{245,246,248\text{-}250,254}$Fm and ^{255,257}Fm
  - Very recently: High resolution spectroscopy on ^{255}Fm



Weak shell effects in heavy actinides don‘t influence charge radii

→ Extend spectroscopy on further isotopic chains around N=152

Recent results on Cf chain (RADRIS) and ^{254}No K-isomer (JetRIS)

→ Extend spectroscopy on further Fm isotopes (e.g. ^{252}Fm)

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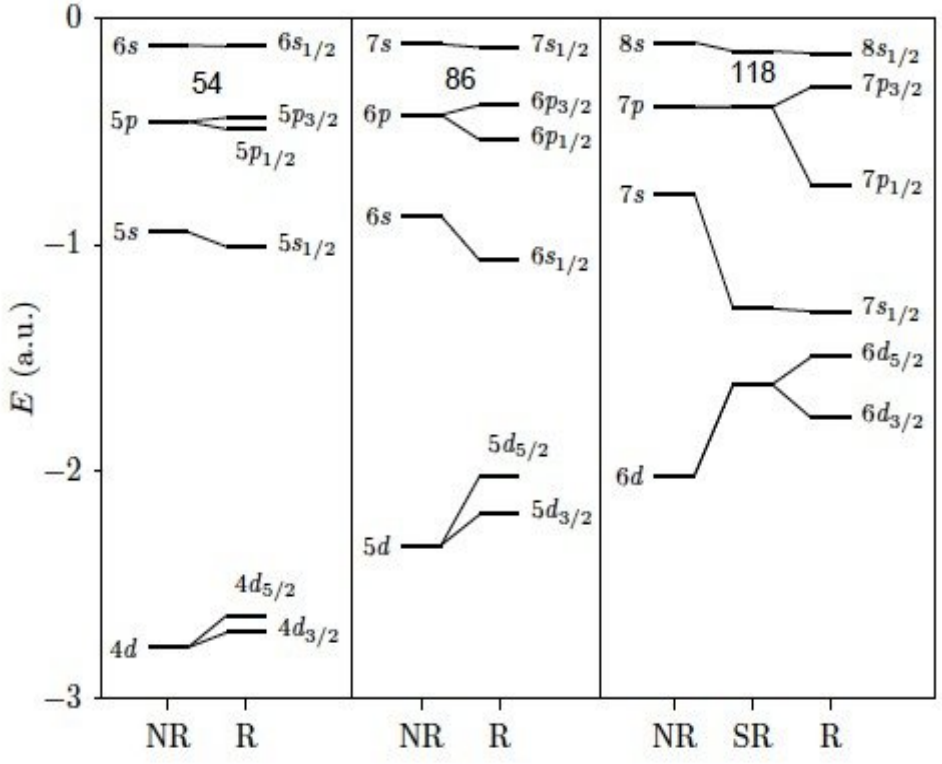
Spectroscopy for Atomic Structure Investigations

- Relativistic effects strongly affect valence electron shells
- Significant deviations in chemical behaviour compared to lighter homologues
- Examine chemical properties (IP)
- Benchmark atomic theory predictions



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

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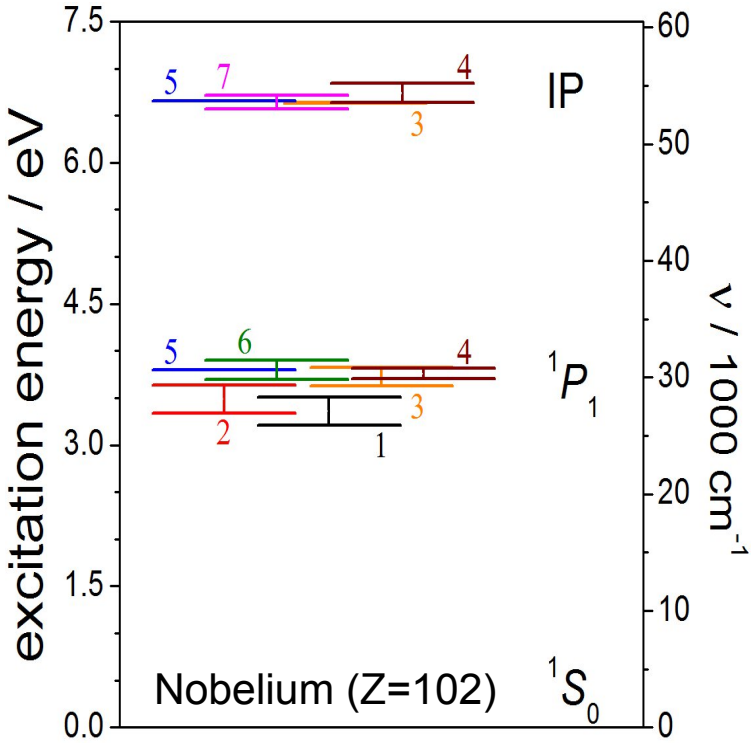
Model calculations



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

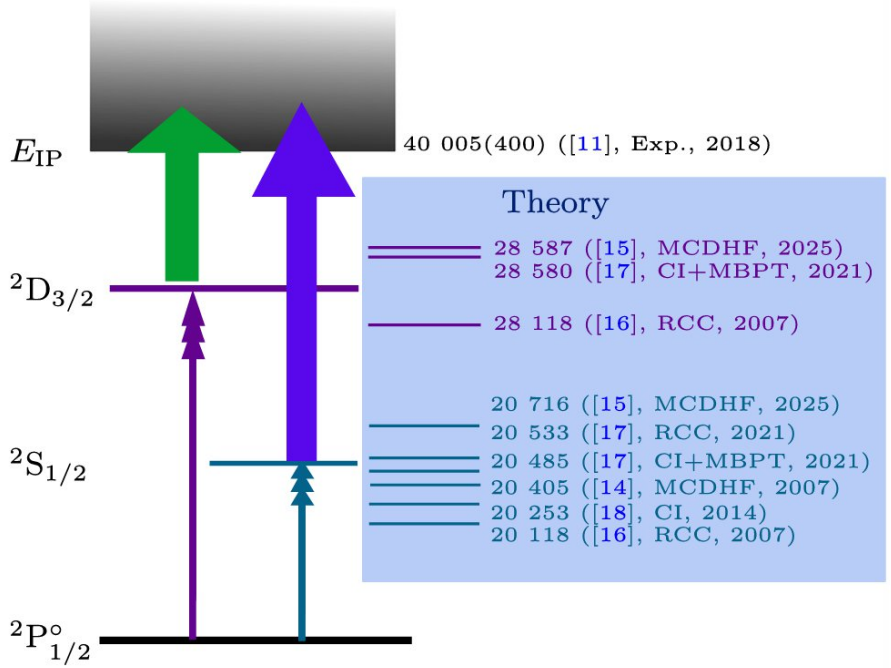
3 (IHFSCC): A.Borschevsky et al., Phys. Rev. A 75 (2007) 042514

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

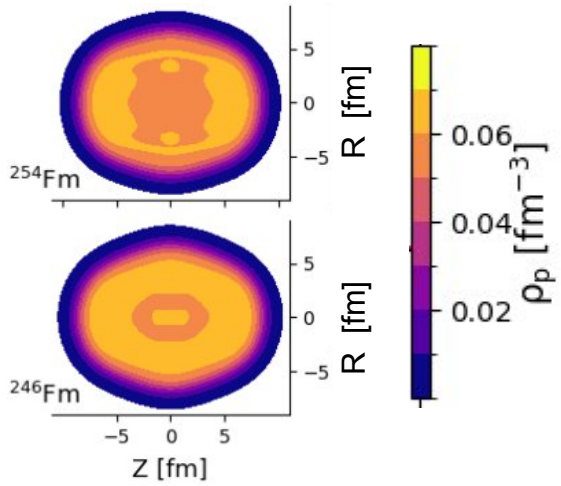
7 (extrapolation): J.Sugar, J. Chem. Phys. 60 (1974) 4103

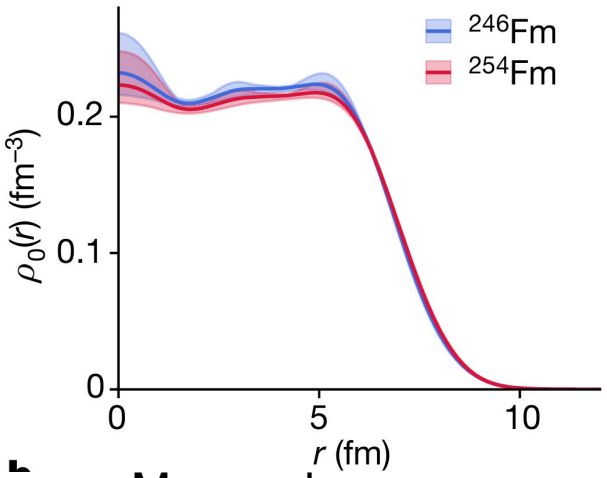


Average radial proton densities

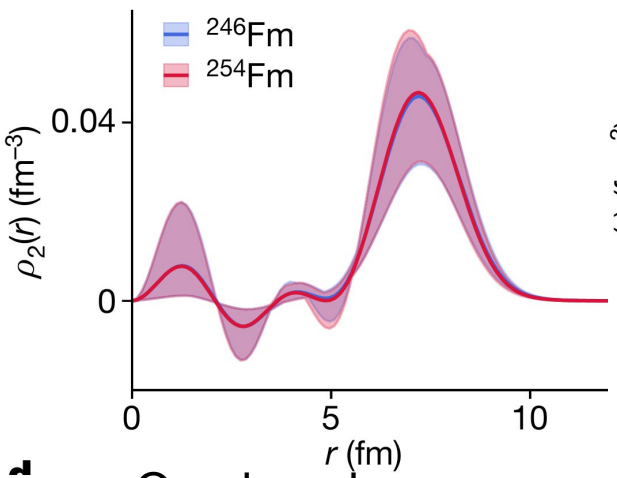
Radial proton densities in very similar for ^{246}Fm and ^{254}Fm

- Models indicate negligible changes in quadrupole deformation
- Influence of higher order deformations increased (e.g. hexadecupole)

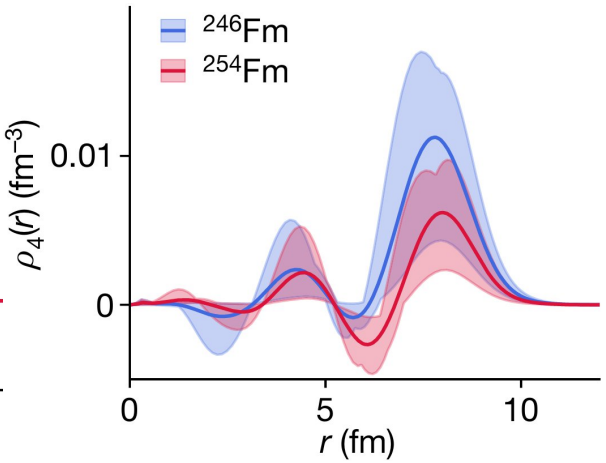




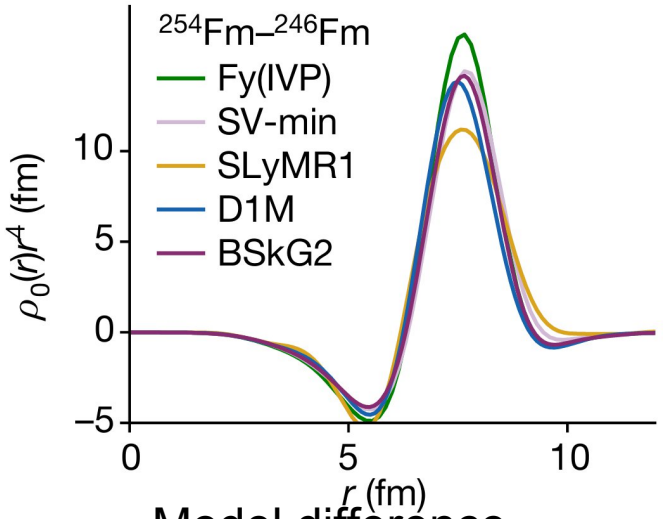
Monopole



Quadrupole



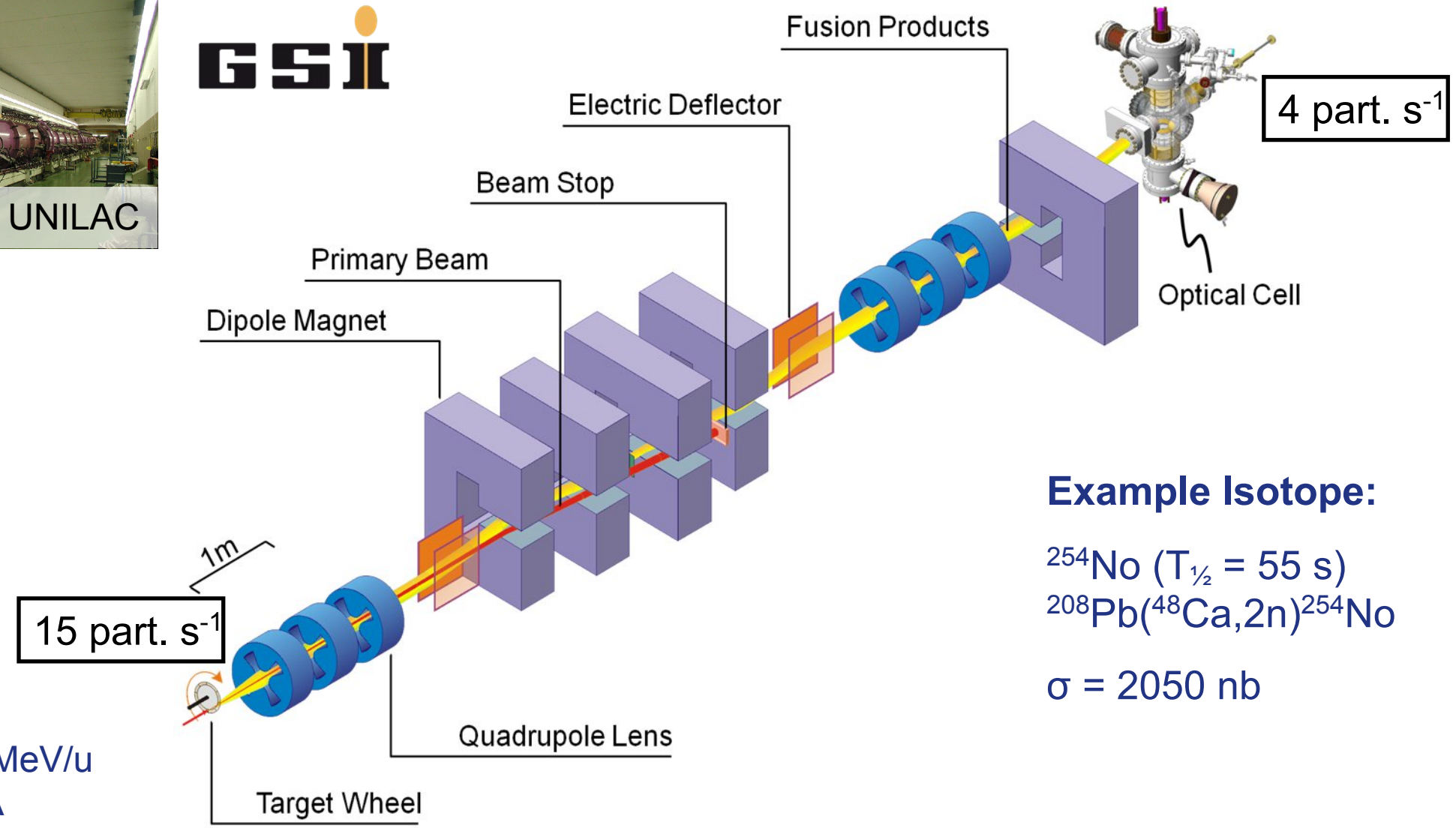
Hexadecupole



Model difference

Production: Velocity Filter SHIP





^{48}Ca
4.55 MeV/u
1 pμA

Example Isotope:

^{254}No ($T_{½}$ = 55 s)
^{208}Pb(^{48}Ca,2n)^{254}No

σ = 2050 nb

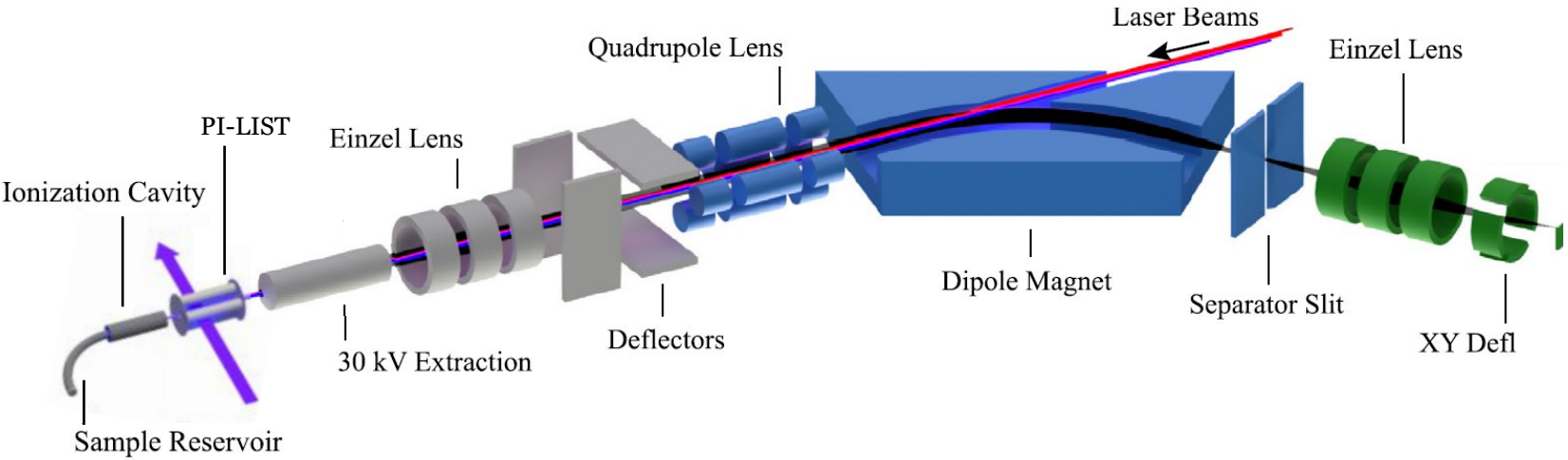
High resolution spectroscopy on ^{255}Fm

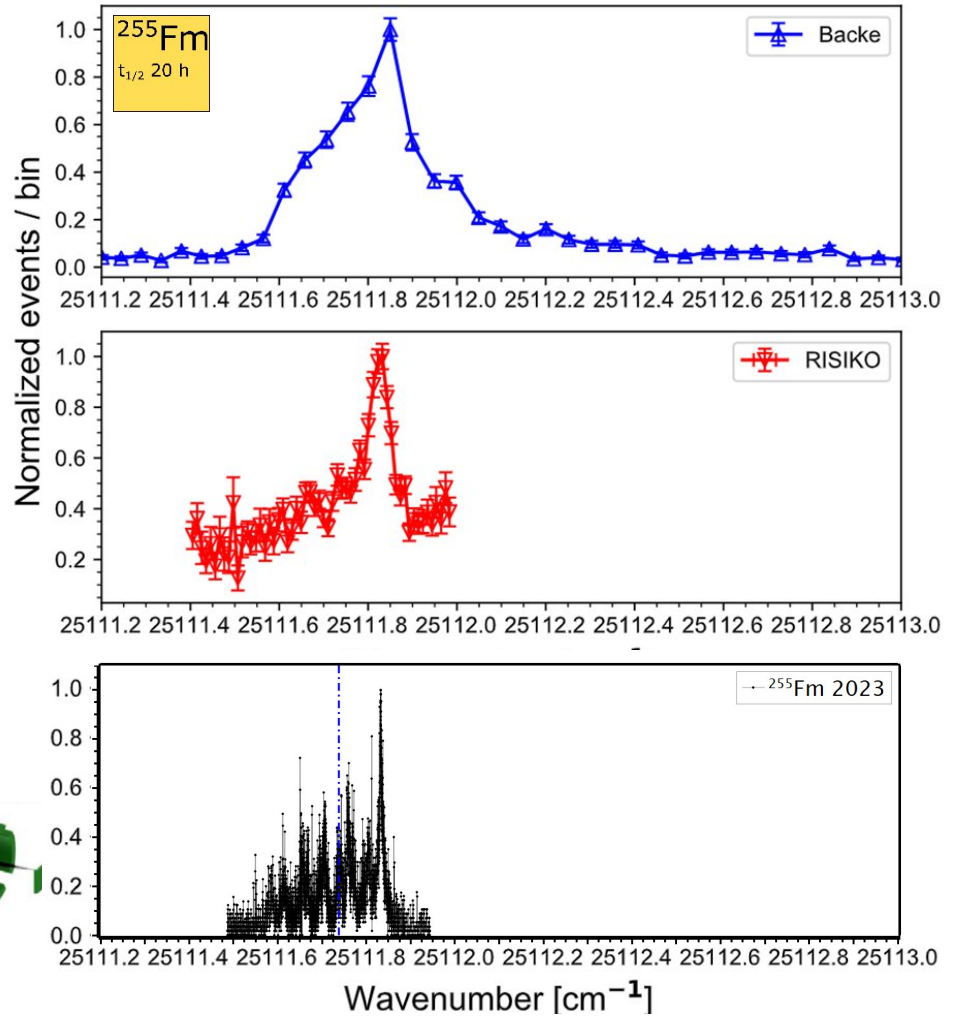
For high resolution spectroscopy ^{255}Fm in PI-LIST

- Starting activity: 12 kBq≈10^9 atoms

→ Low efficiency (factor ~100)

- Hyperfine structure observed





Resonance Ionization Spectroscopy in Collinear Geometry

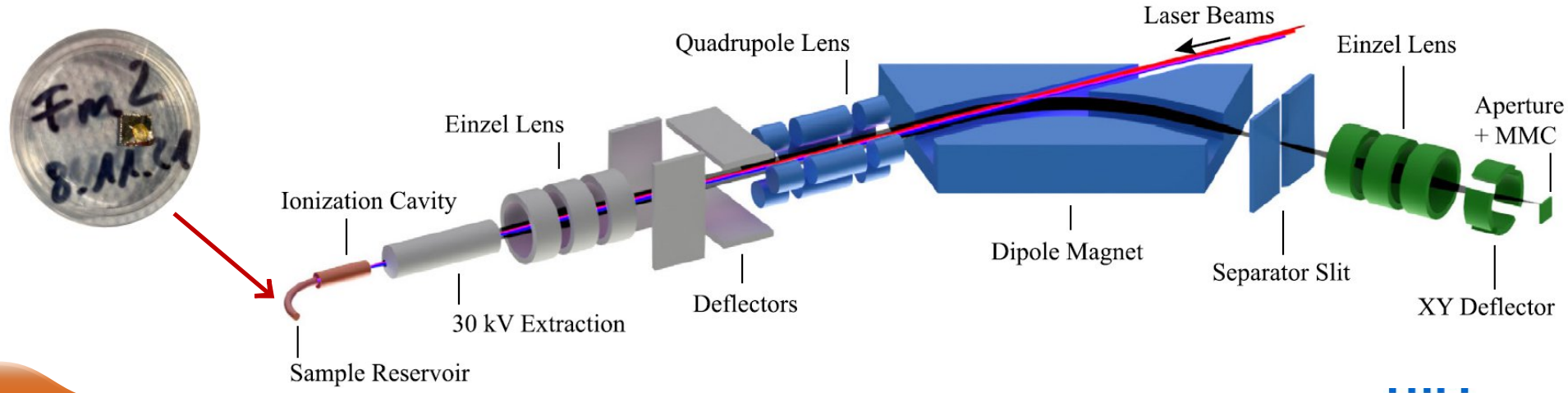
RISIKO: Off-line resonance ionization spectroscopy in hot cavity

Operated by Larissa Collaboration in Mainz (K. Wendt)

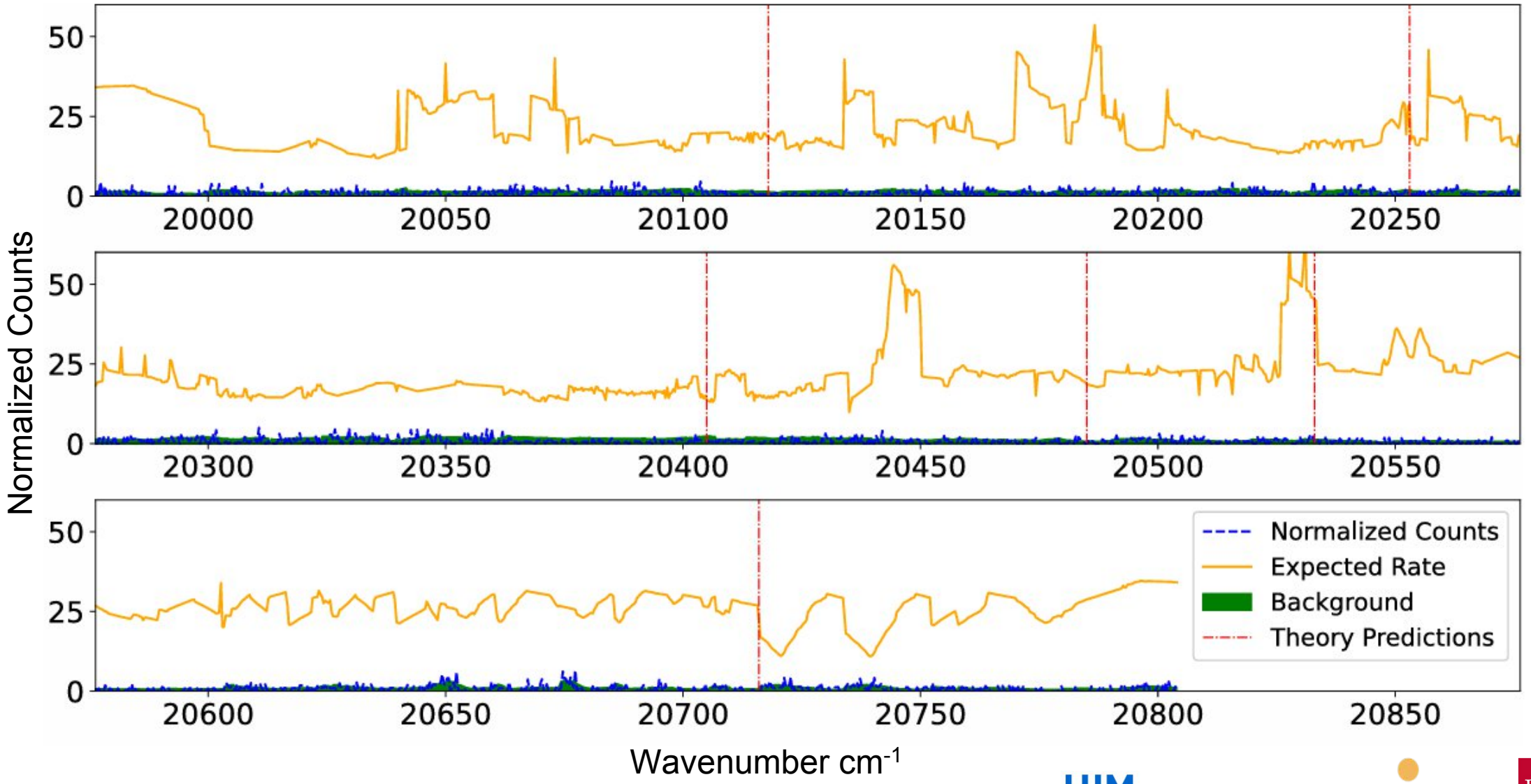
- Development of RIS excitation schemes and laser spectroscopy of long-lived actinides

Spectral resolution limited by source temperature and laser bandwidth

- Background from surface ionization



Vis Level Search in Lawrencium (Z=103)



UV Level Search in Lawrencium (Z=103)

