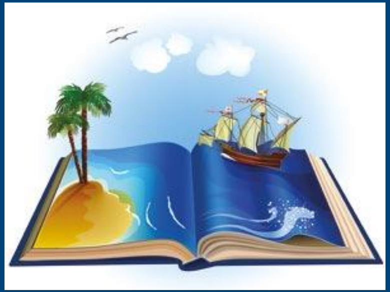
STFC Summer School 2026 - Aberdeen

Ground-State Properties from Laser Spectroscopy
Part III: Examples from Recent Experiments



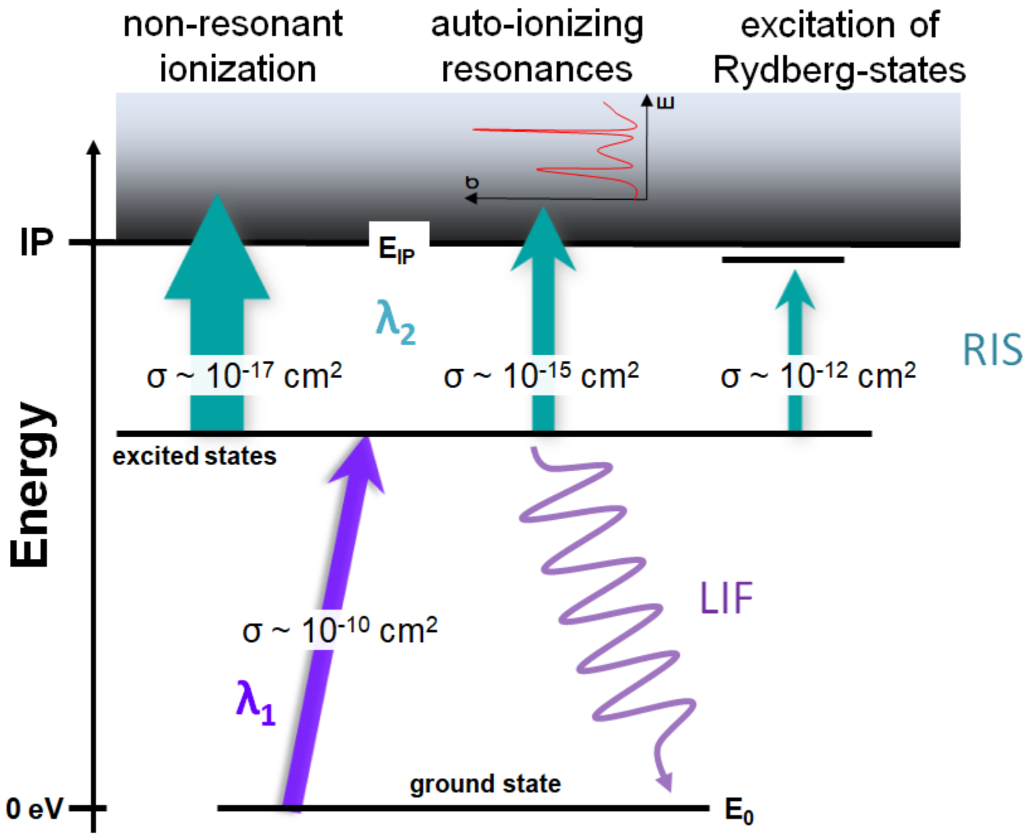
Michael Block

GSI Darmstadt, Germany
Helmholtz Institut Mainz (HIM), Germany
Department Chemie, Universität Mainz, Germany

Part II – Laser Spectroscopy for Nuclear Physics

- laser spectroscopy of fermium, nobelium, and lawrencium at GSI
- laser spectroscopy of actinides at RISIKO Mainz
- comparison of different techniques

Principles of Resonant Ionization Laser Spectroscopy



- ion detection more efficient than fluorescence photon detection
- low-background conditions, particularly for detection via decay
- sensitive method applied in ultra-trace analysis and in laser-ion sources

Ionization Probability vs. Excess Energy in RIS

Near threshold ($E \gtrsim IP$)

- Photoionization cross section follows Wigner threshold law:

  $$\sigma \propto (E - IP)^{(l+1/2)} \quad (\approx \sqrt{(E-IP)} \text{ for s-wave electrons})$$

- Ionization probability initially rises slowly

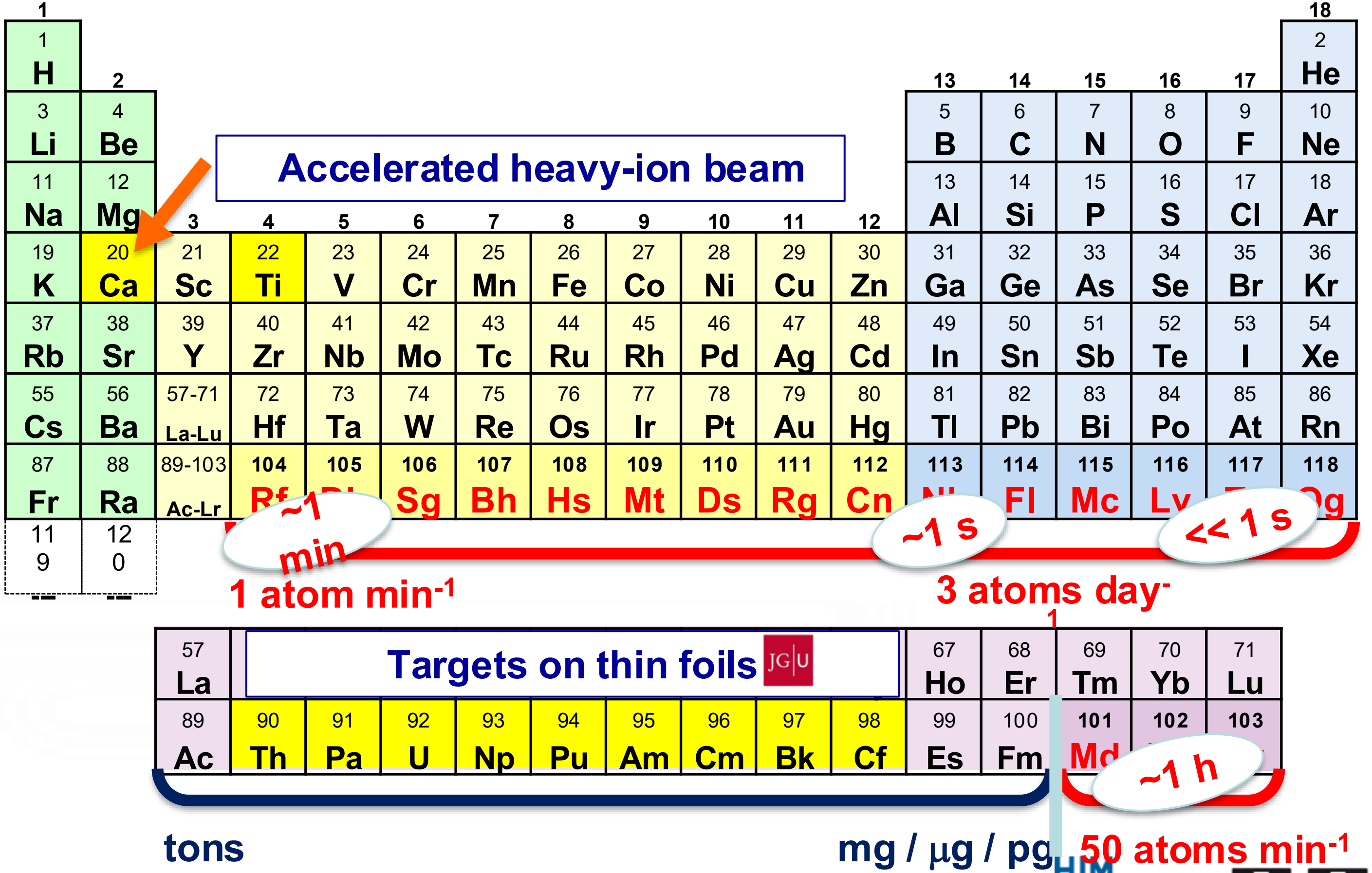
Intermediate excess energy

- Cross section typically reaches a maximum
- $P = 1 - \exp(-\sigma F)$; saturation when $\sigma F \gg 1$.

Far above threshold

- Cross section generally decreases ($\sim E^{-3}$).
- More excess energy does not necessarily increase efficiency.

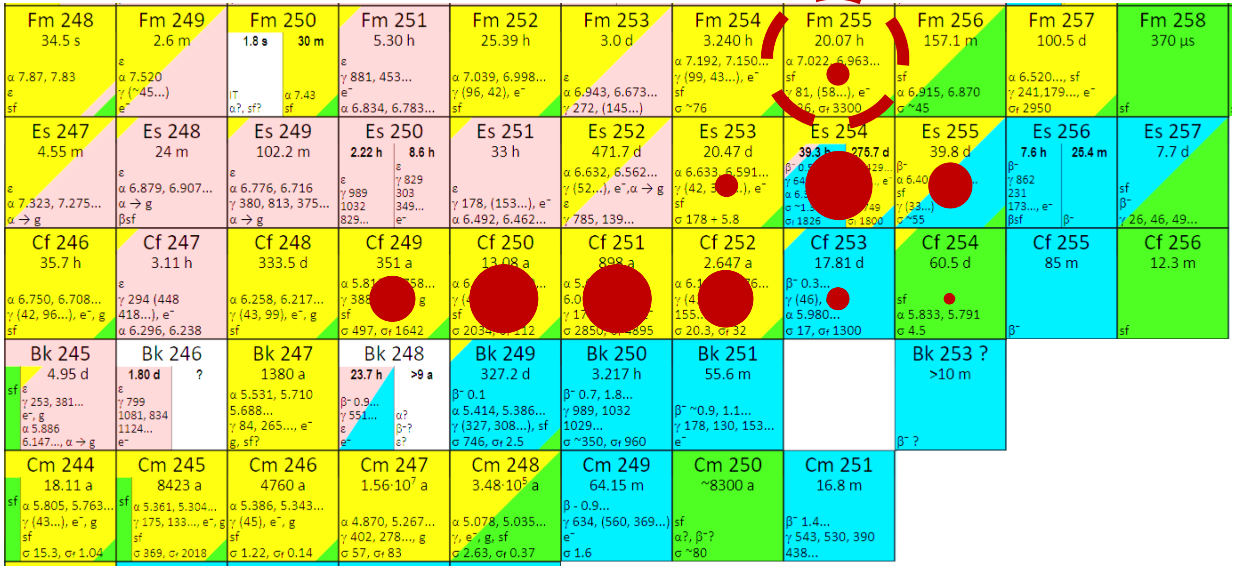
Availability of Superheavy Elements



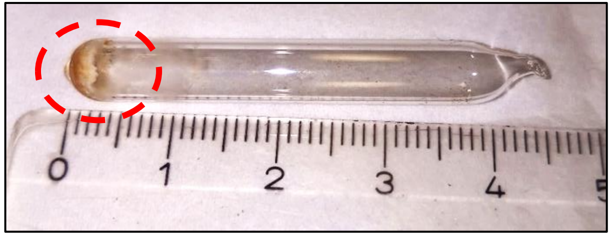
Courtesy
Ch. Düllmann

Production of Heavy Actinides for Off-line Studies

First analytics of the unseparated Fm sample 7 days after irradiation at ILL



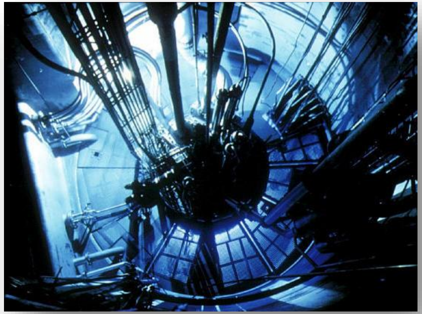
- 10^{14} atoms
- 10^{13} atoms
- 10^{12} atoms
- 10^{11} atoms
- 10^{10} atoms
- 10^{9} atoms
- 10^{8} atoms
- 10^{7} atoms
- 10^{6} atoms



NEUTRONS FOR SOCIETY

Courtesy S. Berndt

High Flux Reactor at ILL



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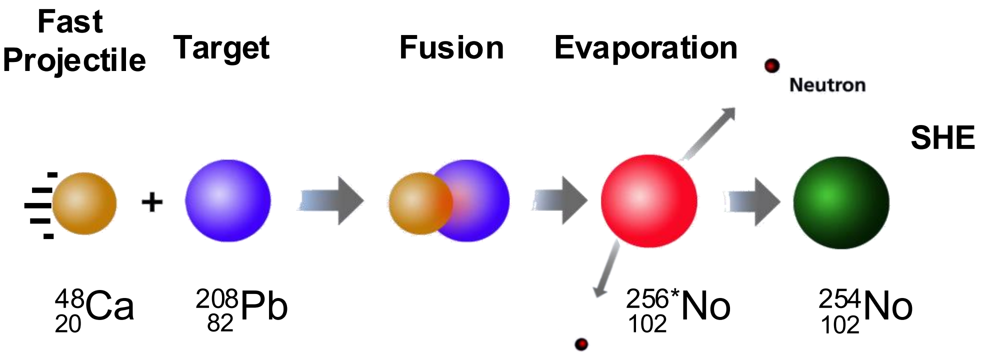
Production in Fusion-Evaporation Reactions

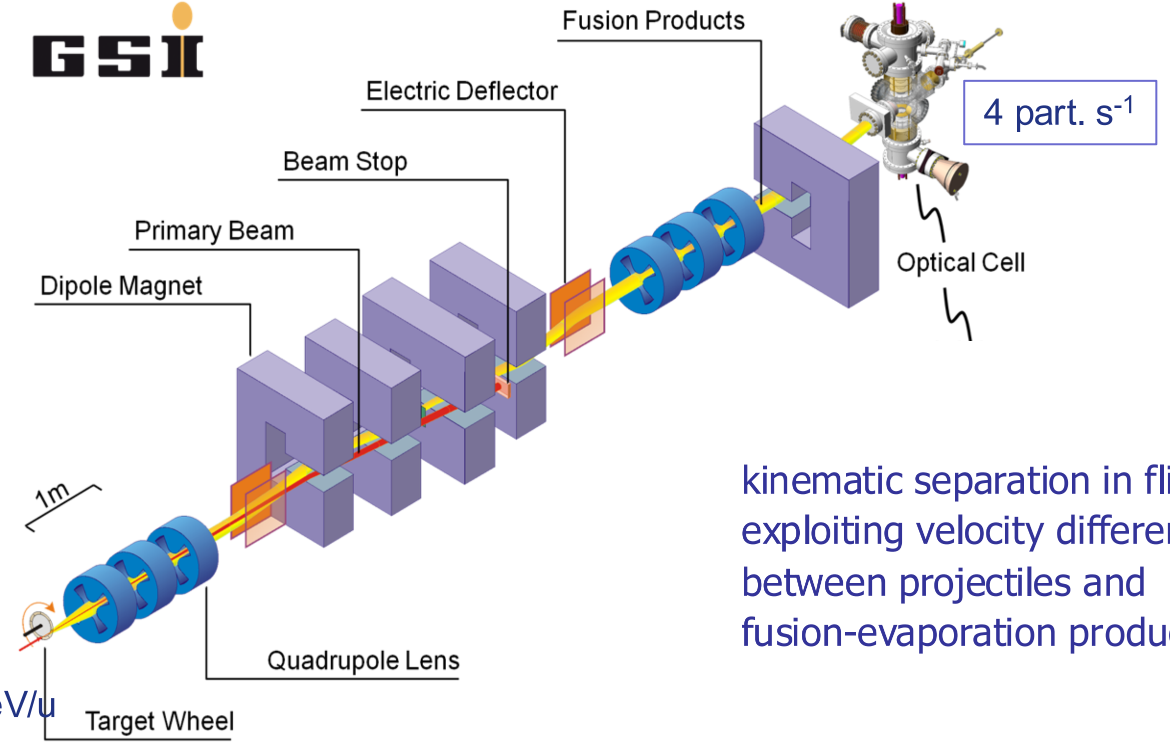
high-intensity beam:
6 x 10^{12} particles
per second



Yields:
1 /s (Z≈102)
to
< 1 /week (Z≥112)

- production in heavy-ion induced fusion-evaporation reactions
- besides low production rates, high energy of reaction products poses challenges for mass spectrometry and laser spectroscopy
- utilizing buffer-gas stopping cells for slowing down and thermalizing ion beams

Production and Separation with Velocity Filter SHIP

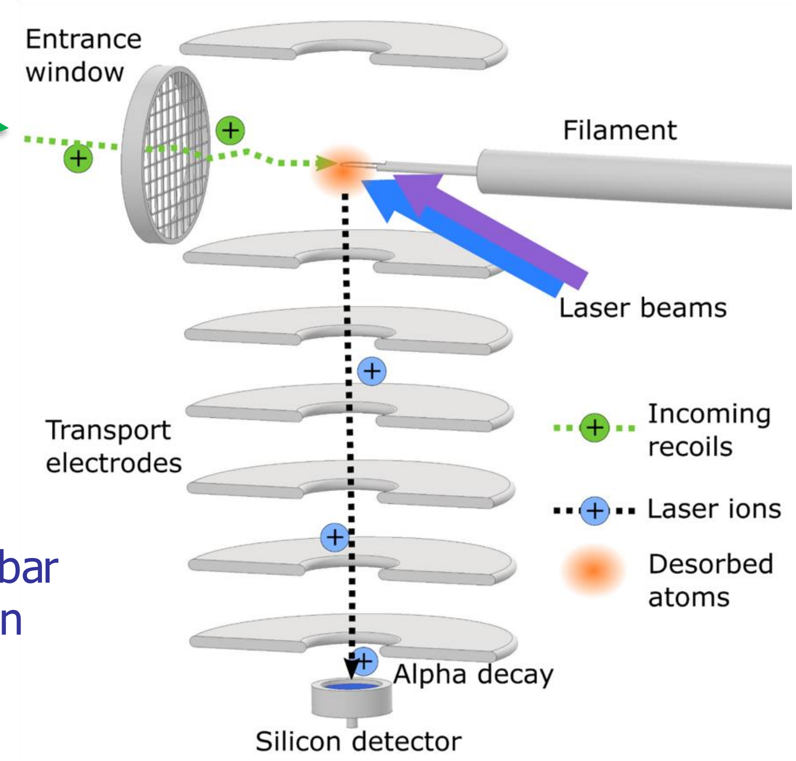


^{48}Ca
4.55 MeV/u
1 pμA

kinematic separation in flight exploiting velocity difference between projectiles and fusion-evaporation products

Radiation Detected Resonance Ionization Spectroscopy

incoming beam



100 mbar argon

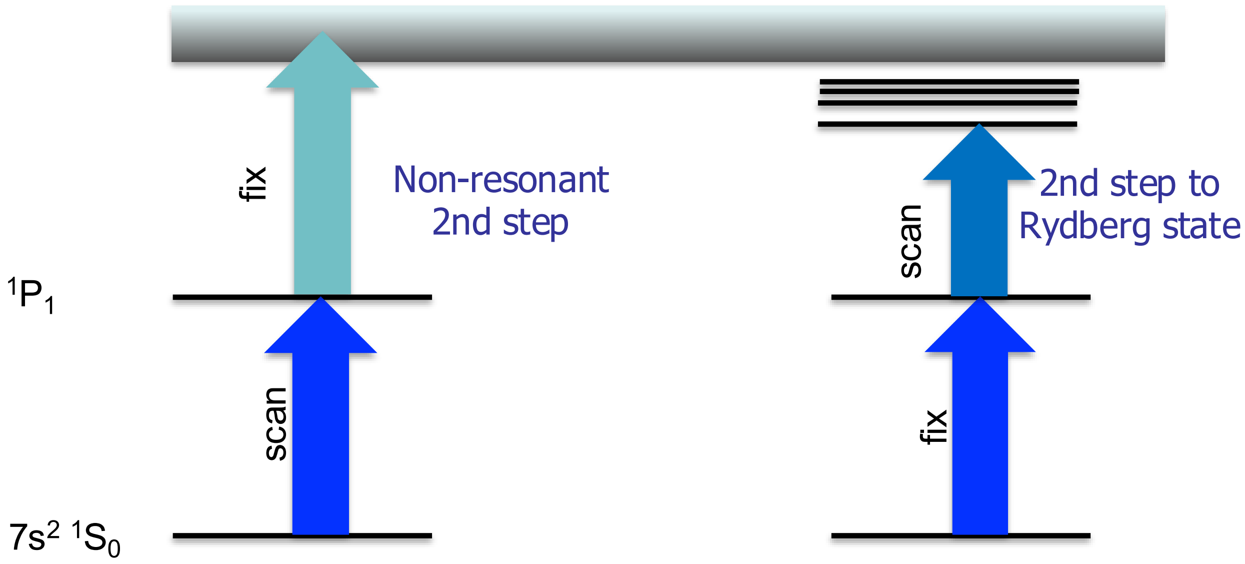
tailored method for measurements of actinide isotopes produced by fusion reactions with lowest rates:

- slow down ions in Ar gas
- neutralize on filament
- re-evaporate atoms
- two-step photo-ionization
- transport laser ions to detector and register radioactive decay

H. Backe et al. Eur. Phys. J. D, 45 (1) (2007), 99
F. Lautenschläger et al. Nucl. Instrum. Meth. B, 383 (2016), 115
J. Warbinek et al., Atoms (2022)

Pioneered at Mainz/GSI

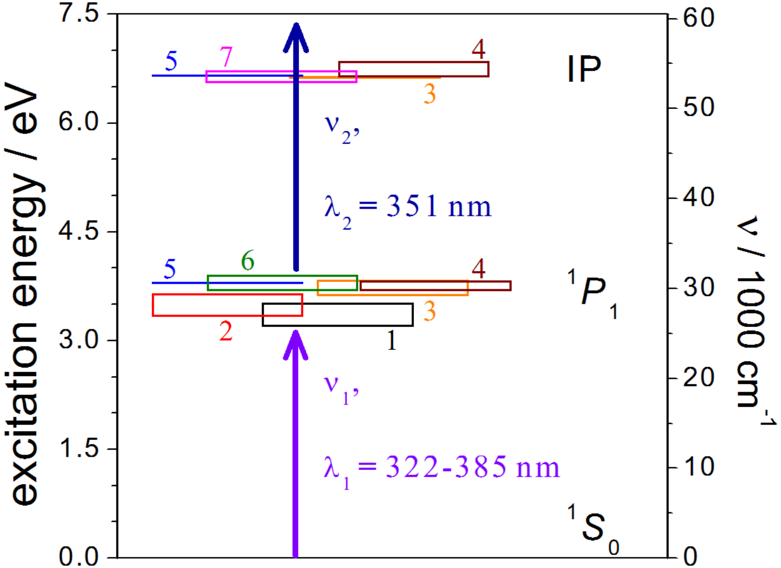
Resonant Laser Ionization – Nobelium Excitation Schemes



High power in 2nd step (>30mJ/pulse) for high efficiency

Two pulsed (dye) lasers, temporal overlap important

Predictions for Atomic Transitions in Nobelium



Z=102 atomic ground state: [Rn]$5f^{14}7s^2$ $^1S_0$

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

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

- **theoretical uncertainty corresponds to a scan range of about 5.000 steps**
- **depending on atomic properties, one step may take several minutes**

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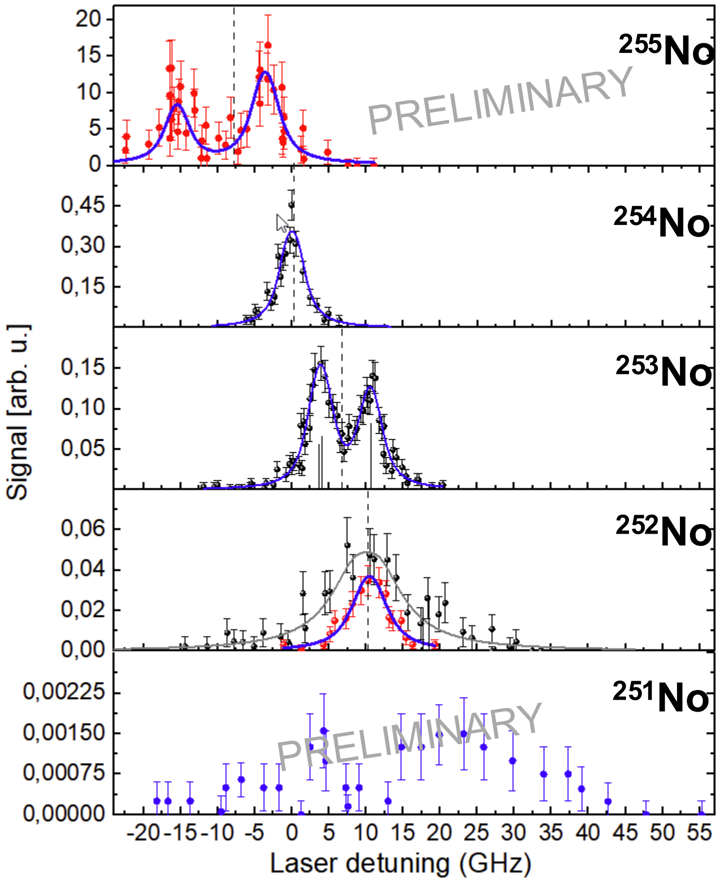
Laser Spectroscopy of Nobelium (Z=102) Isotopes



Experiment: S. Raeder *et al*.

Theory: A. Borschevsky V. Dzuba, S. Fritzsche, B. Schütrumpf, W. Nazarewicz *et al.*

- first laser spectroscopy spectroscopy beyond Z=100
- yield as low as 0.05 particles per second
- changes in mean-square charge radii of No isotopes around N = 152 from isotope shift
- magnetic dipole and electric quadrupole moment of ^{253,255}No obtained from hyperfine splitting

FAIR Phase 0 Research Program
SHIP

M. Laatiaoui *et al*., Nature 538, 495 (2016)
S. Raeder *et al*., Phys. Rev. Lett. 120 (2018) 232503

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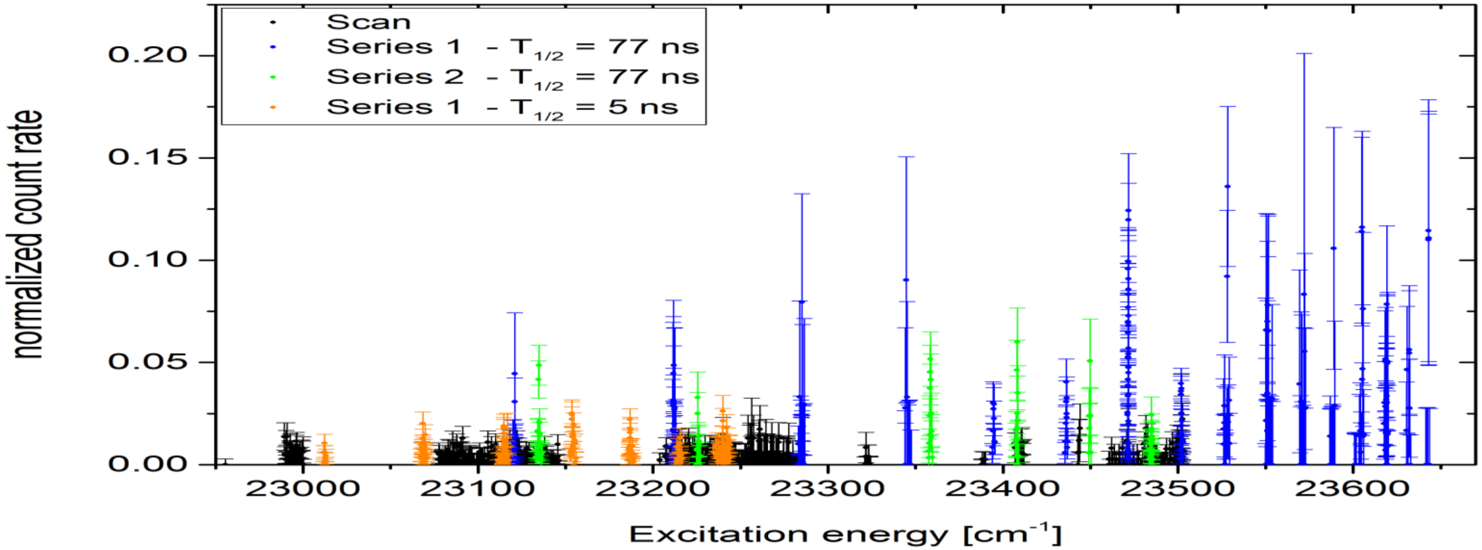
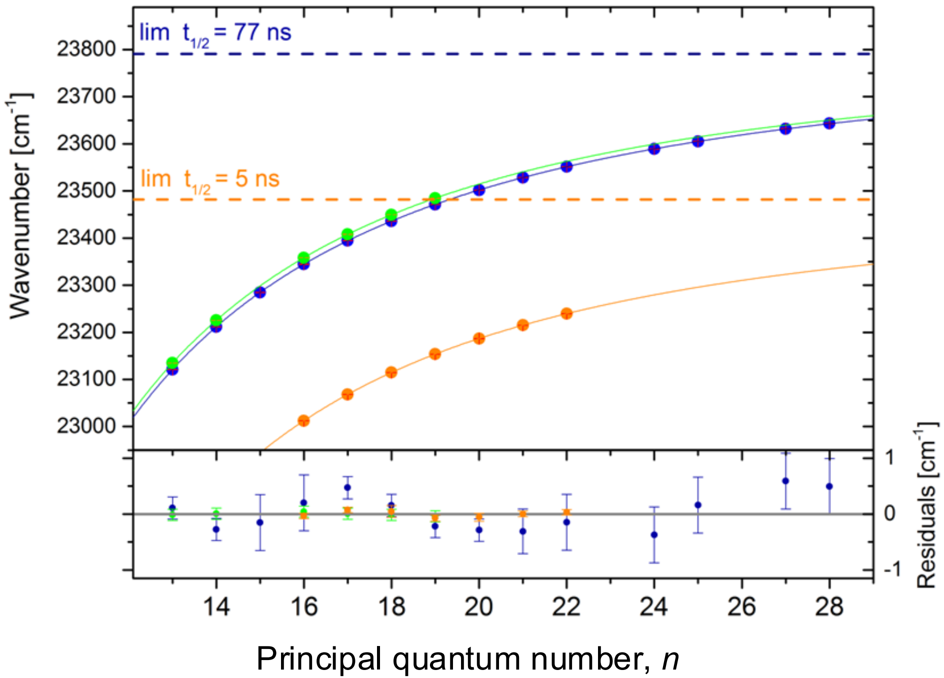
Search for Rydberg States in ^{254}No

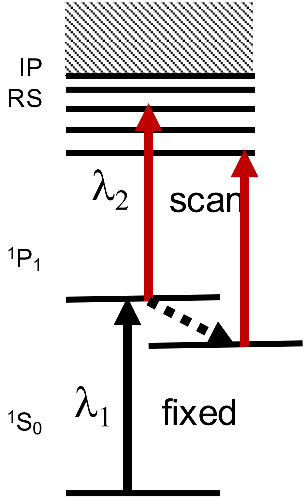


- Rydberg series starting from different states observed and identified
- IP and energy difference of D state can be determined accurately

Ionization limits

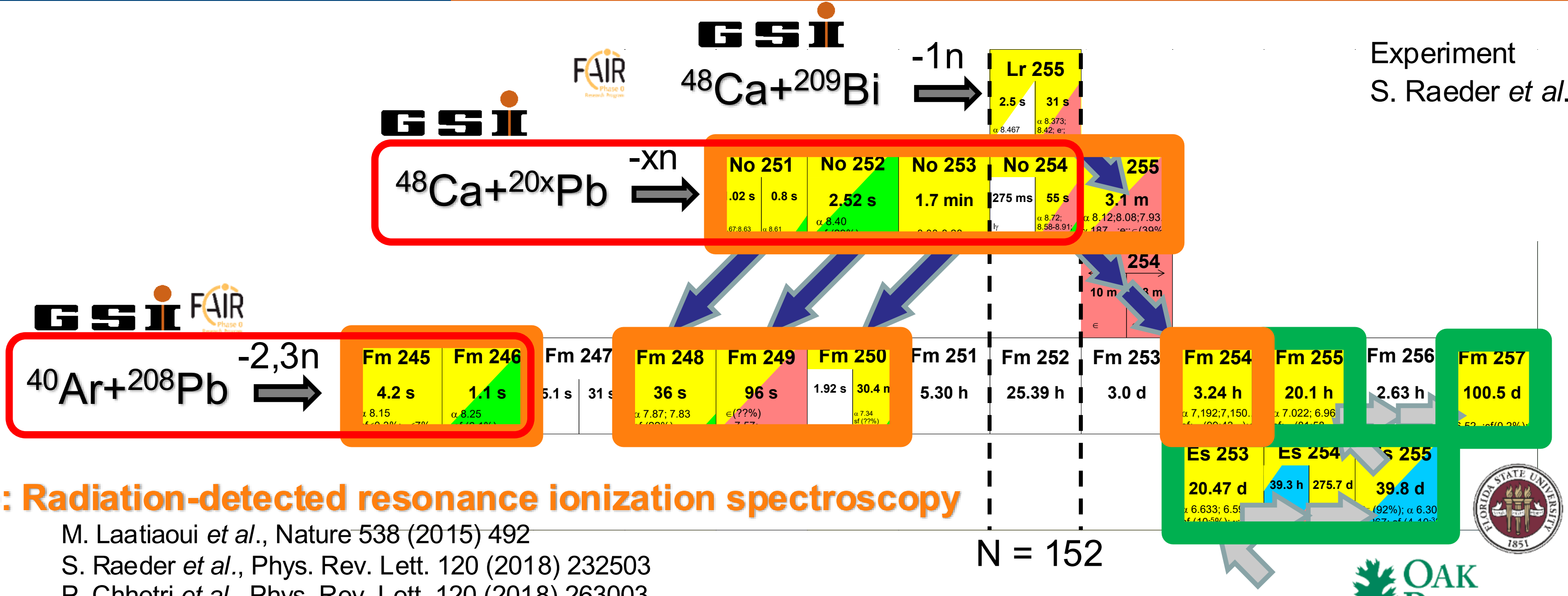


	IP (eV)
This work	6.6261(3)
Theory (Borschevsky et al.)	6.632
Extrapolation (Sugar)	6.65(7)



Production of $_{99}$Es, $_{100}$Fm, and $_{102}$No nuclei

Experiment
S. Raeder *et al.*



Online: Radiation-detected resonance ionization spectroscopy

M. Laatiaoui *et al.*, Nature 538 (2015) 492
S. Raeder *et al.*, Phys. Rev. Lett. 120 (2018) 232503
P. Chhetri *et al.*, Phys. Rev. Lett. 120 (2018) 263003

Offline: Resonance ionization spectroscopy of Es

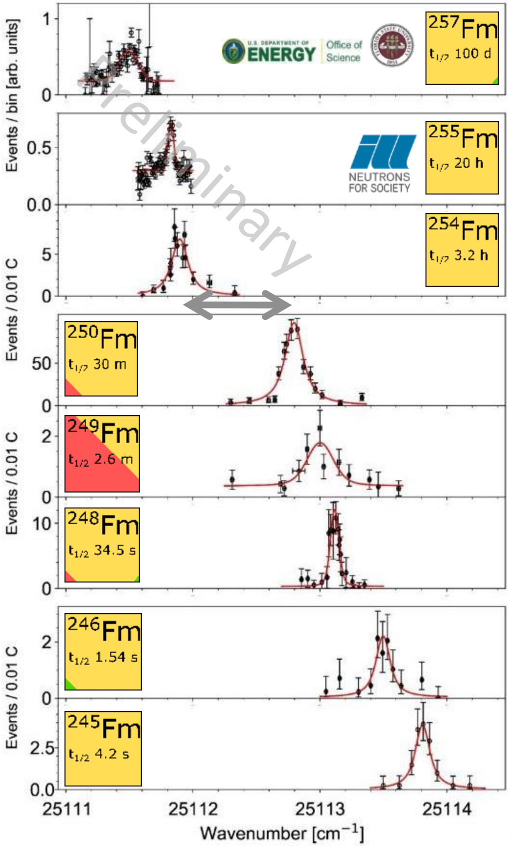
S. Nothhelfer *et al.*, PRC 105 (2022) L021302
F. Weber *et al.*, PRR 4 (2022) 043053

From HFIR

Es reirradiated at

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.

Laser Spectroscopy of Fm (Z=100) Isotopes



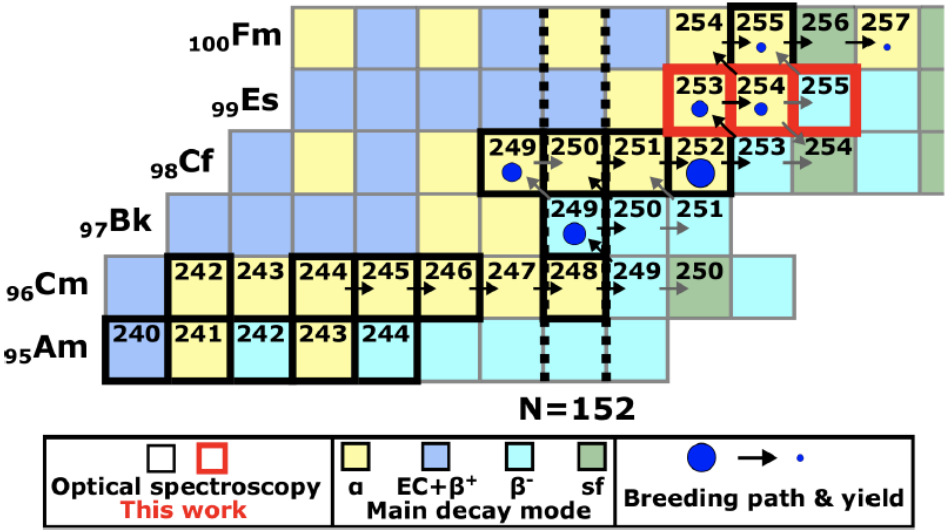
Smooth trends in fermium charge radii and the impact of shell effects

J. Warbinek et al., Nature 634, 1075 (2024) **nature**

- Determination of change in nuclear charge radii from isotope shifts for a long chain of Fm isotopes produced in different reactions
- comparison to several nuclear EDF calculations

Es – Fm Sample available from Oak Ridge

- Small amount of Es/Fm as „leftovers“ in the ^{252}Cf production process
- 2019: Fm sample available from Florida
- Radiochemical separation of Es/Fm



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.

10^9 atoms

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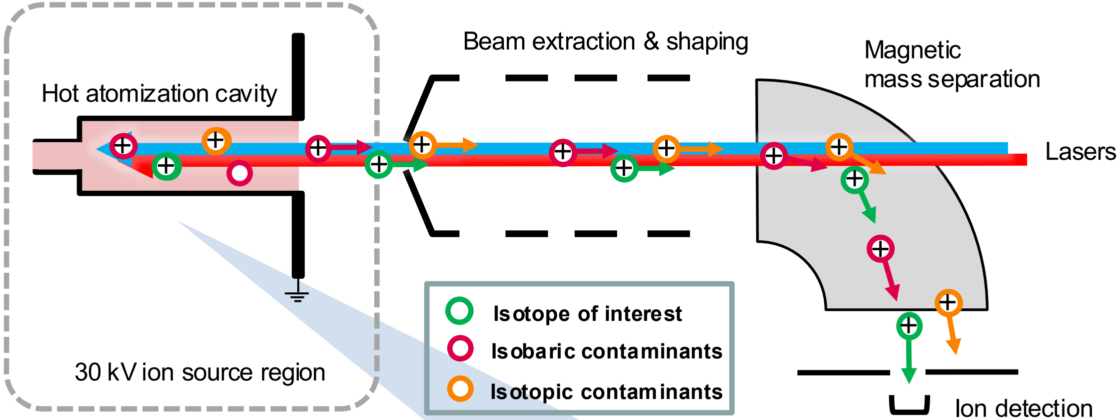
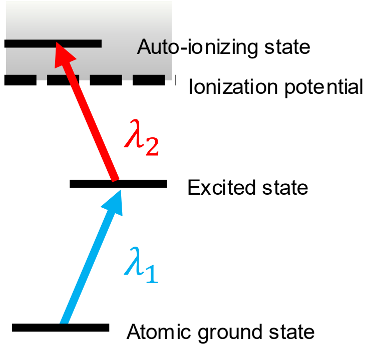
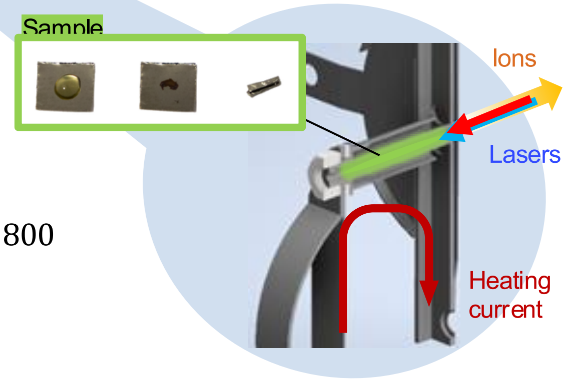
FLORIDA STATE UNIVERSITY 1851

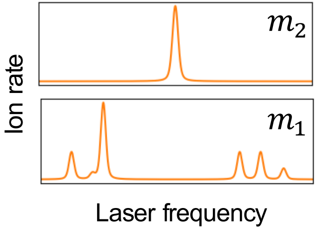
RISIKO Setup at Mainz University





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





RISIKO

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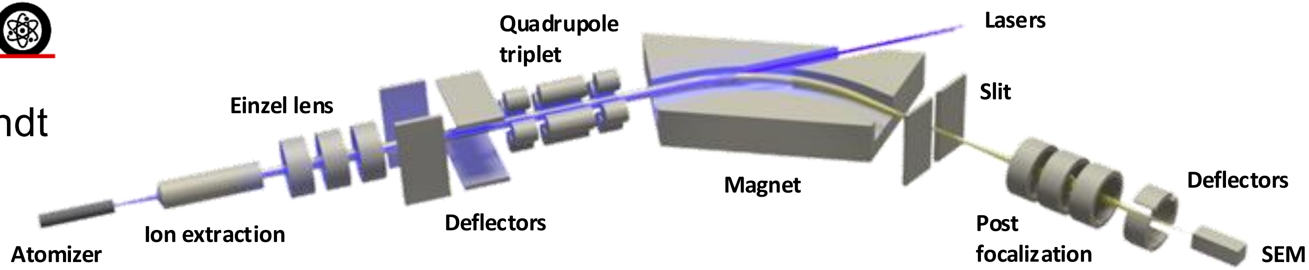
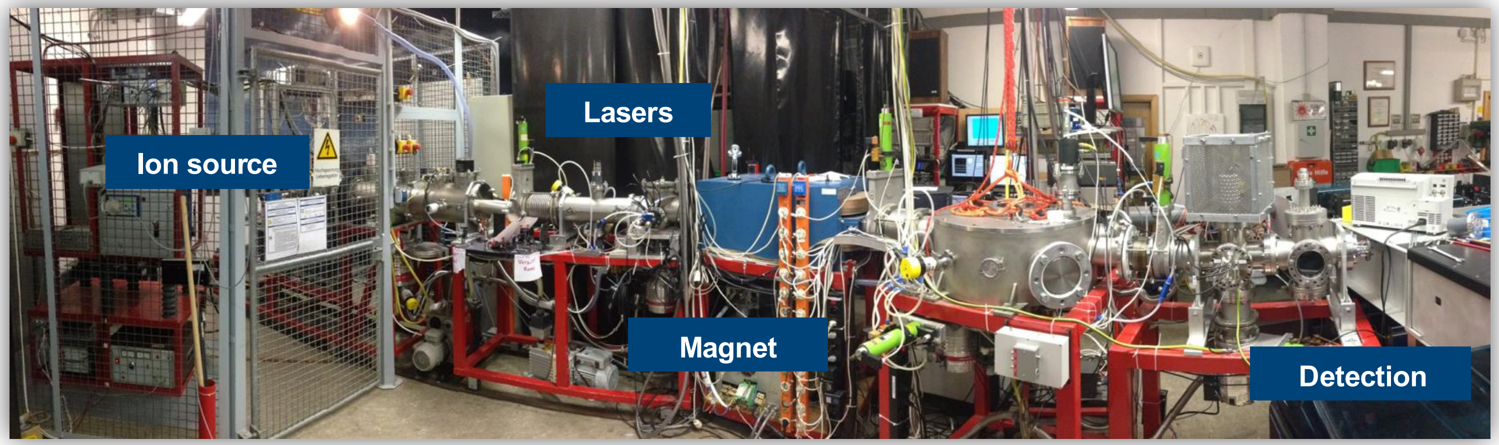
RISIKO Setup at Mainz University

RISIKO

Prof. K. Wendt





T. Kieck et al., NIM A 945, 162602 (2019).
V. Fedosseev et al., J. Phys. G Nucl. Part. Phys. 44, 084006 (2017).

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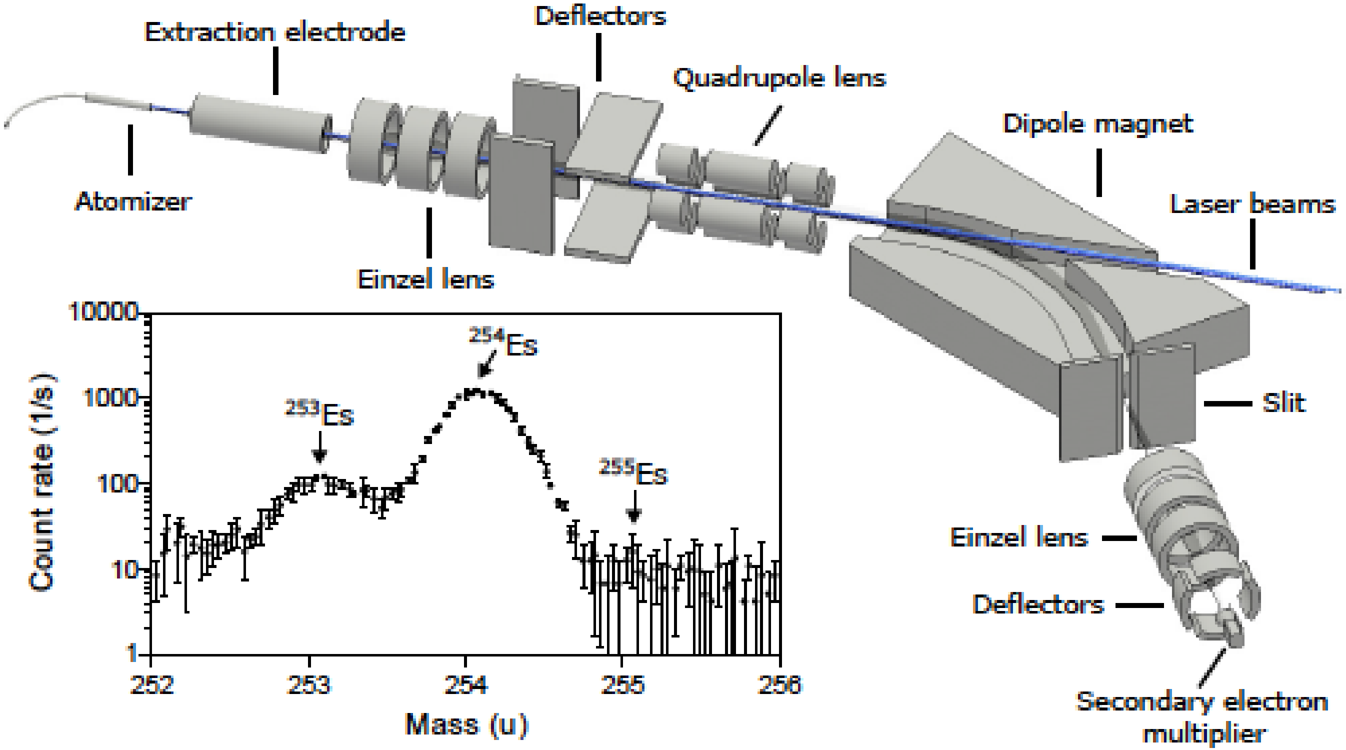
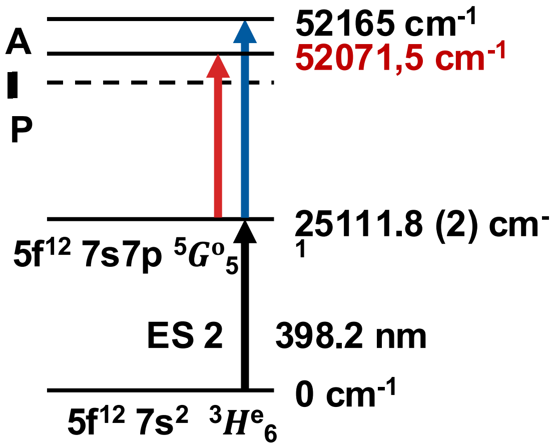
Hyperfine Spectroscopy of Es at RISIKO/Mainz

RISIKO separator
K. Wendt et al.



- Laser ionization In hot cavity
- mass-separated ion detection

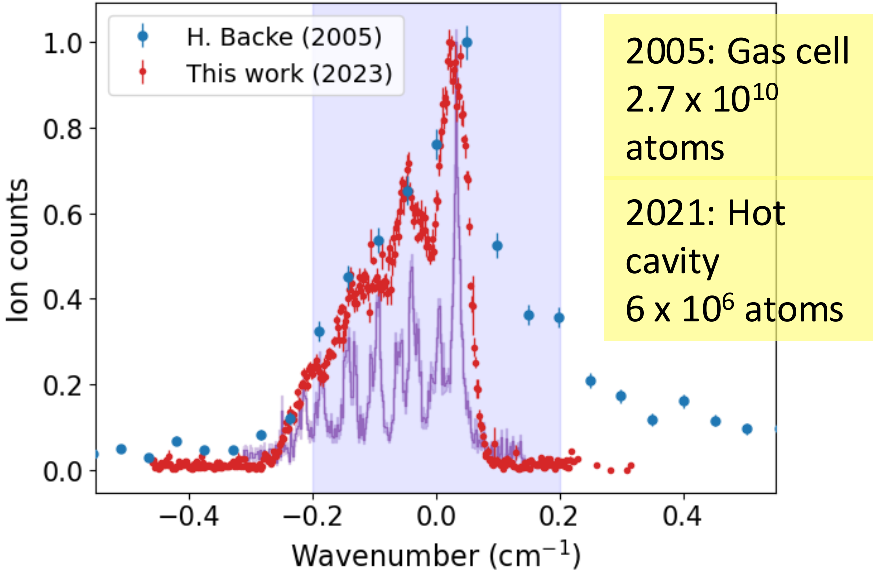
Laser Spectroscopy of Fm Isotopes



RISIKO mass separator in Mainz

- laser spectroscopy on Fm samples with only 10^7 atoms

- first studies of ^{255}Fm ($t_{1/2}$=20h) in gas cell by M. Sewtz, H. Backe et al. with variant of RADRIS method in 2003
- 8 atomic level in Fm identified



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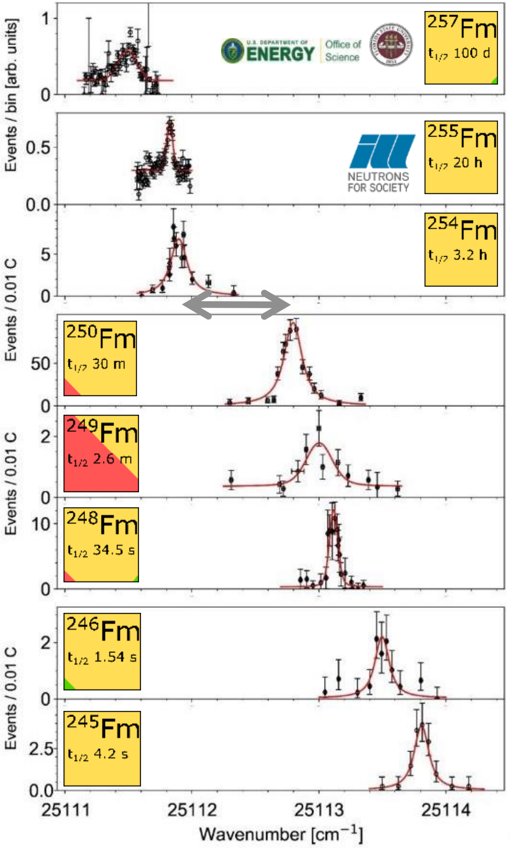
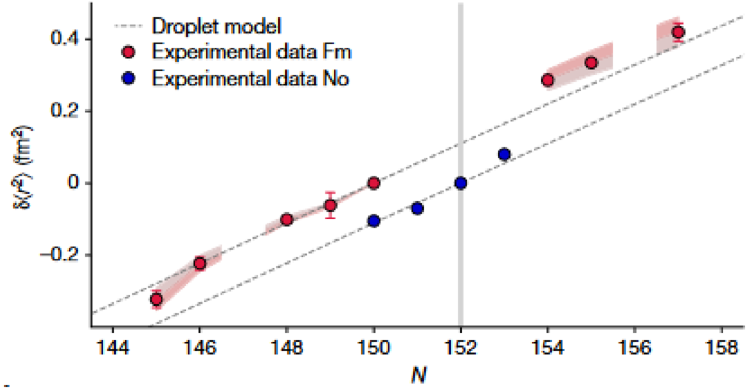
Laser Spectroscopy of Fm (Z=100) Isotopes



- isotope shifts in Fm isotope chain produced in different direct and indirect schemes
- determined change in nuclear charge radii from isotope shift with F factor from atomic theory



J. Warbinek et al., Nature 634, 1075 (2024) and PhD thesis University of Mai

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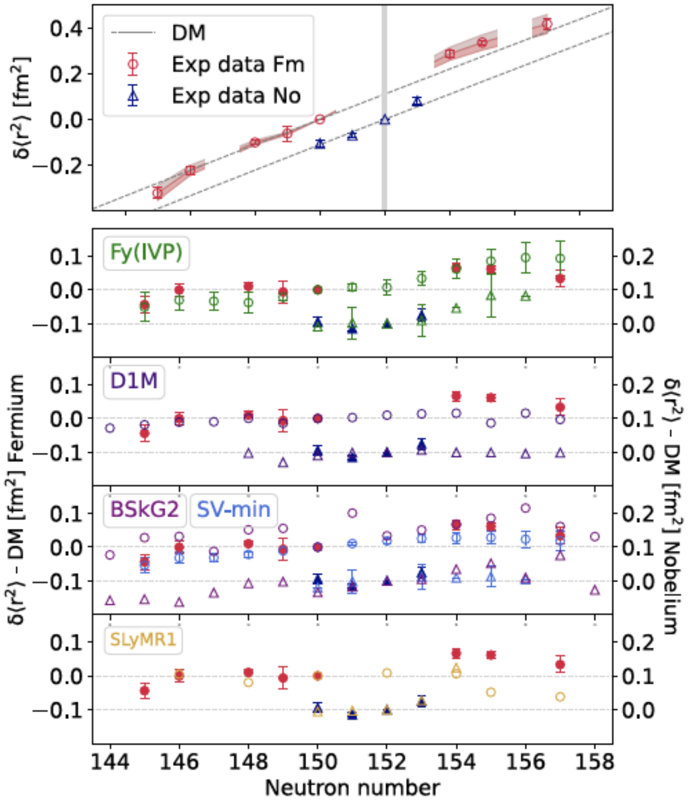
FAIR Phase-0 Research Program

Results – Comparison with Theoretical Calculations



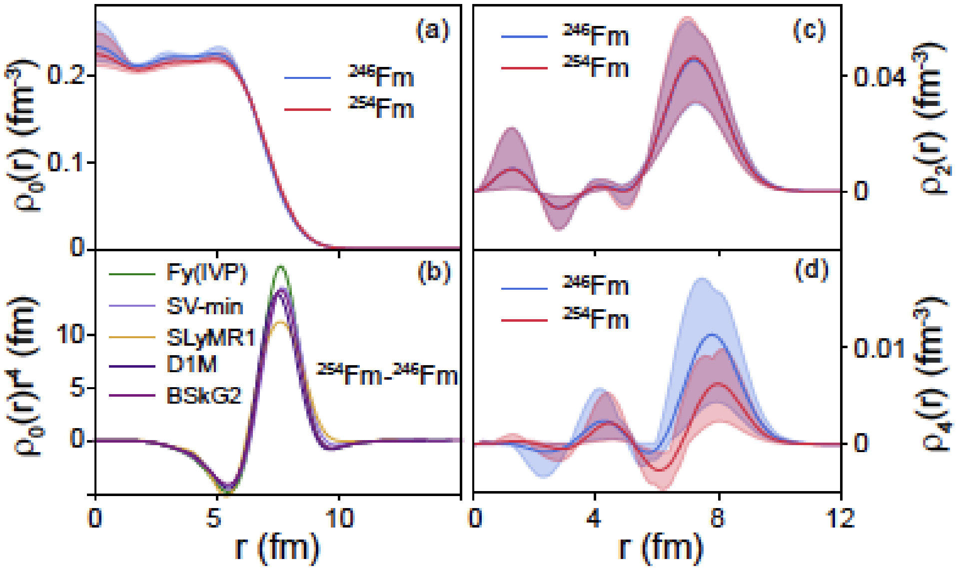
calculations of charge radii using different nuclear energy density functionals by:

W. Nazarewicz, P. G. Reinhard, S. Goriely, S. Hilaire, S. Peru, M. Bender, B. Bally

- different nuclear models agree well with each other and with laser spectroscopy data
- charge radii show no significant signature of nuclear single-particle structure

J. Warbinek et al., Nature 634, 1075 (2024)

Theoretical calculations



B. Bally, M. Bender, S. Goriely, S. Hilaire, W. Nazarewicz, S. Peru, P.G. Reinhard, W. Ryssens

- different nuclear models agree well with each other and with experimental data
- charge radii show no significant signature of single-particle structure

J. Warbinek et al., Nature 634, 1075 (2024)

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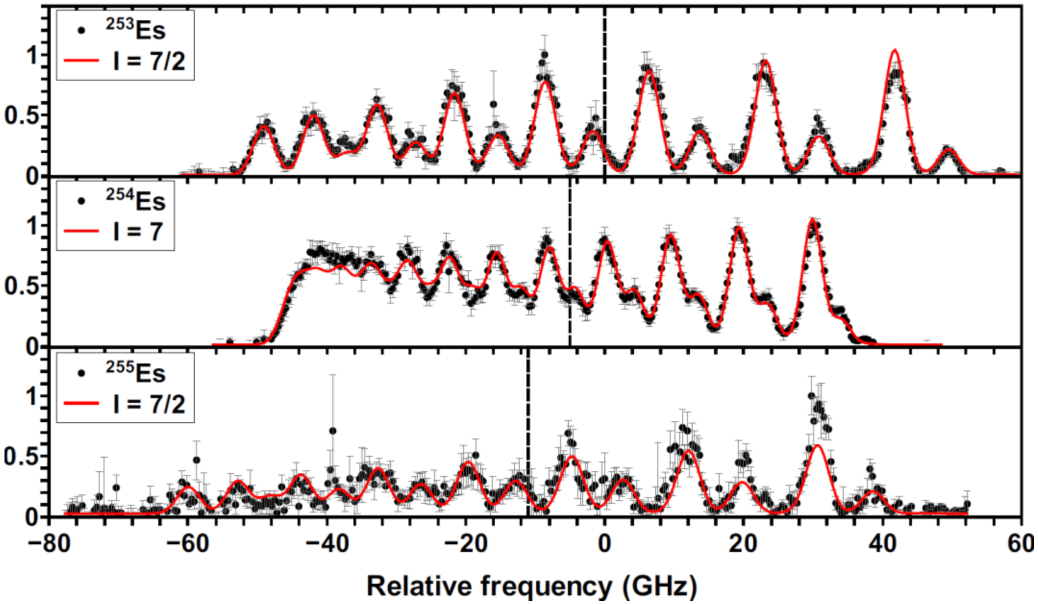
Hyperfine Spectroscopy of Es at RISIKO/Mainz

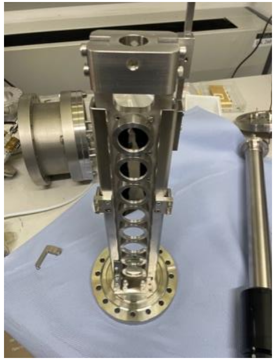


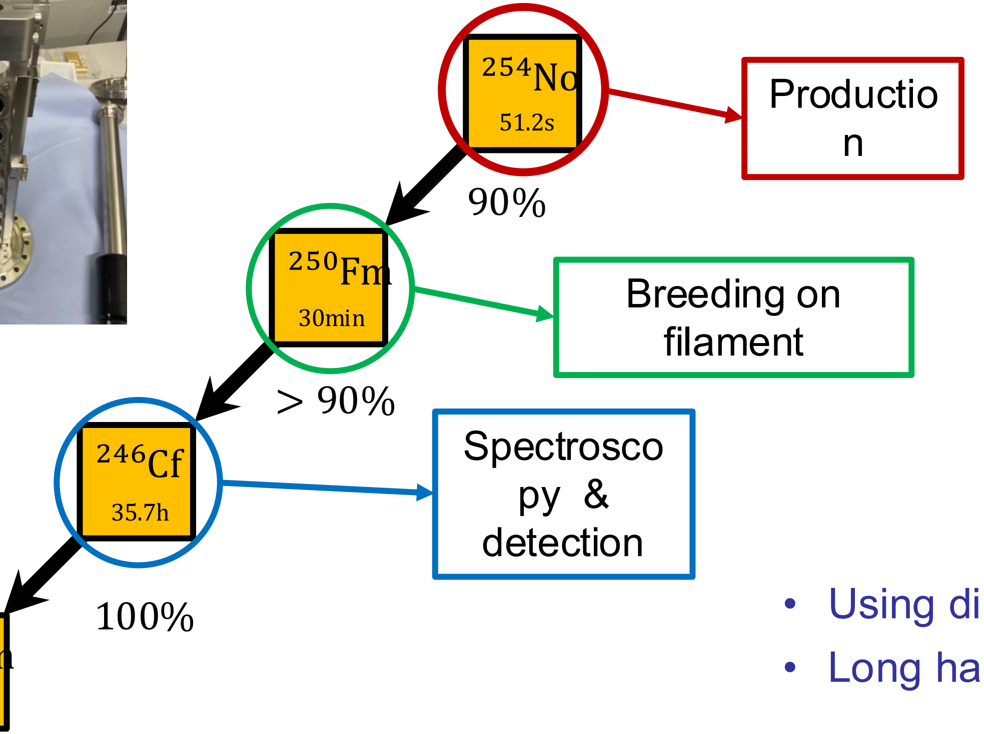
- Hyperfine measurements with picogram to femtogram samples
- complex hyperfine structure investigated for several transitions in $^{253\text{-}255}$Es
- spins and electromagnetic moments can be obtained from hyperfine parameters

The isotopes used in this research were supplied by the U.S. Department of Energy, Office of Science, by the Isotope Program in the Office of Nuclear Physics. The ^{253,254,255}Es and ^{255,257}Fm were provided to Florida State University and the University of Mainz via the Isotope Development and Production for Research and Applications Program through the Radiochemical Engineering and Development Center at Oak Ridge National Laboratory.

S. Raeder, S. Nothhelfer, K. Wendt, Ch. Düllmann,
T. Albrecht-Schönzart, MB et al.

Laser Spectroscopy of Californium Isotopes



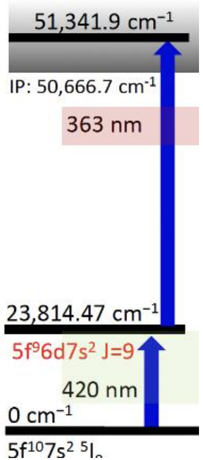


Isotope	Reaction
^{240}Cf	^{195}Pt(^{48}Ca, 3n)
^{241}Cf	^{196}Pt(^{48}Ca, 3n)
^{242}Cf	^{196}Pt(^{48}Ca, 2n)
^{244}Cf	^{198}Pt(^{48}Ca, 2n)
^{246}Cf	^{208}Pb(^{48}Ca, 2n) 90% α, >90% α

- Using direct and indirect production schemes
- Long half-life of ^{246}Cf needs tailored detector

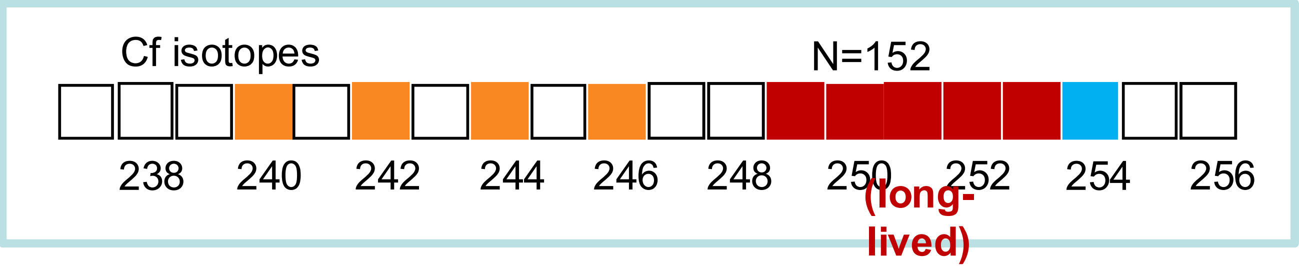
K. van Beek (PhD thesis), S. Raeder et al.

Laser Spectroscopy of Californium Isotopes



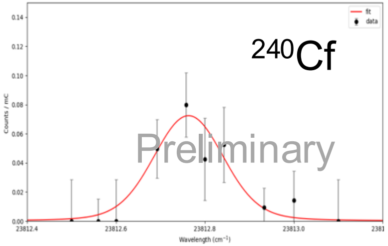
Goal: investigate the evolution of size and shape in the heavy elements

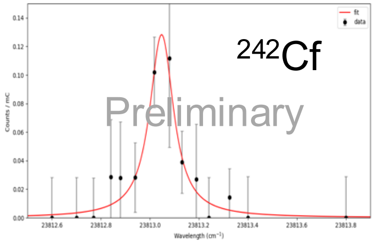
- extend systematic studies of radii and nuclear moments in Cf, Fm, and No isotopic chains around $N = 152$
- compare to state-of-the-art theoretical models

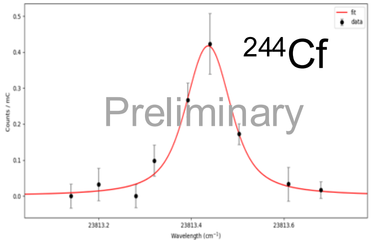


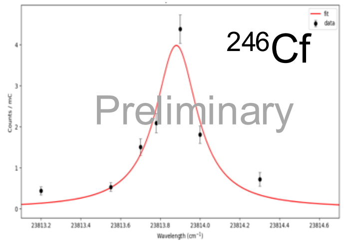
Nuclear structure

Nuclear Astrophysics (Kilonova)









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