Laser Spectroscopy of the Heaviest Elements at SHIP at GSI

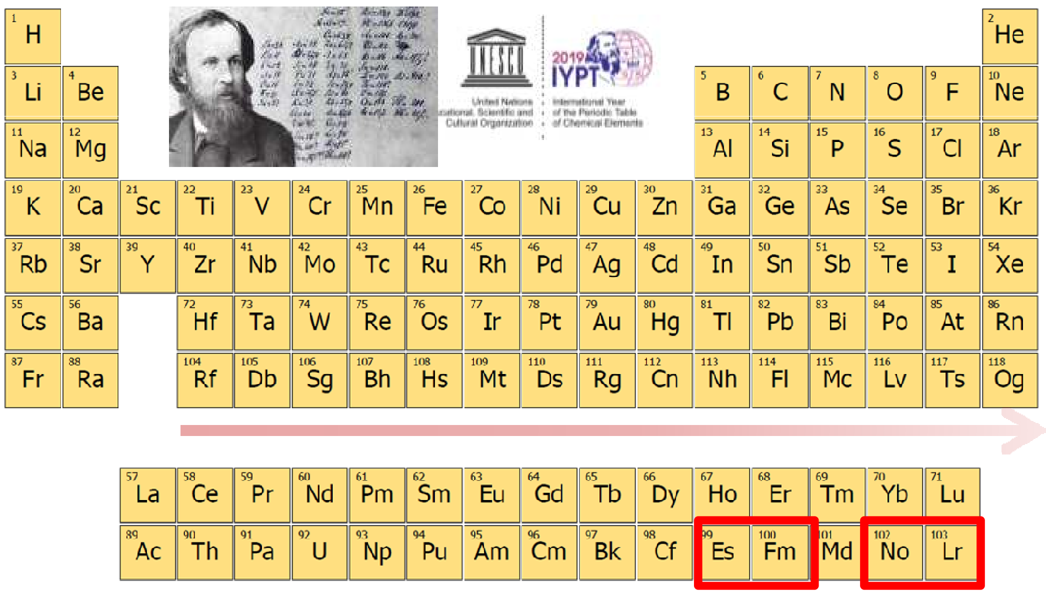
S. Raeder

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

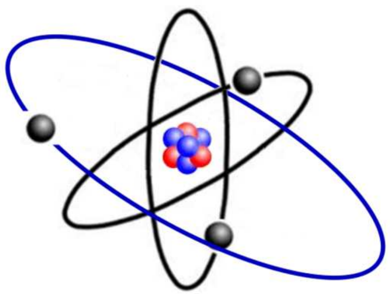
Properties of the Heaviest Elements

Laser spectroscopy for fundamental properties

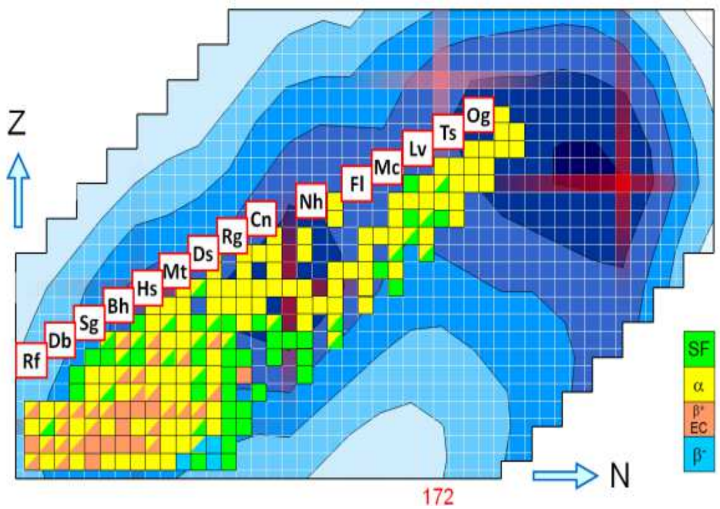
- Understanding of atomic structure & chemical behaviour
- Nuclear structure: what is their shape and size ?



Electron shell
atomic structure
chemical properties
→ defines the element



Nucleus
nuclear structure
stability of elements



Courtesy Ch. E. Düllmann

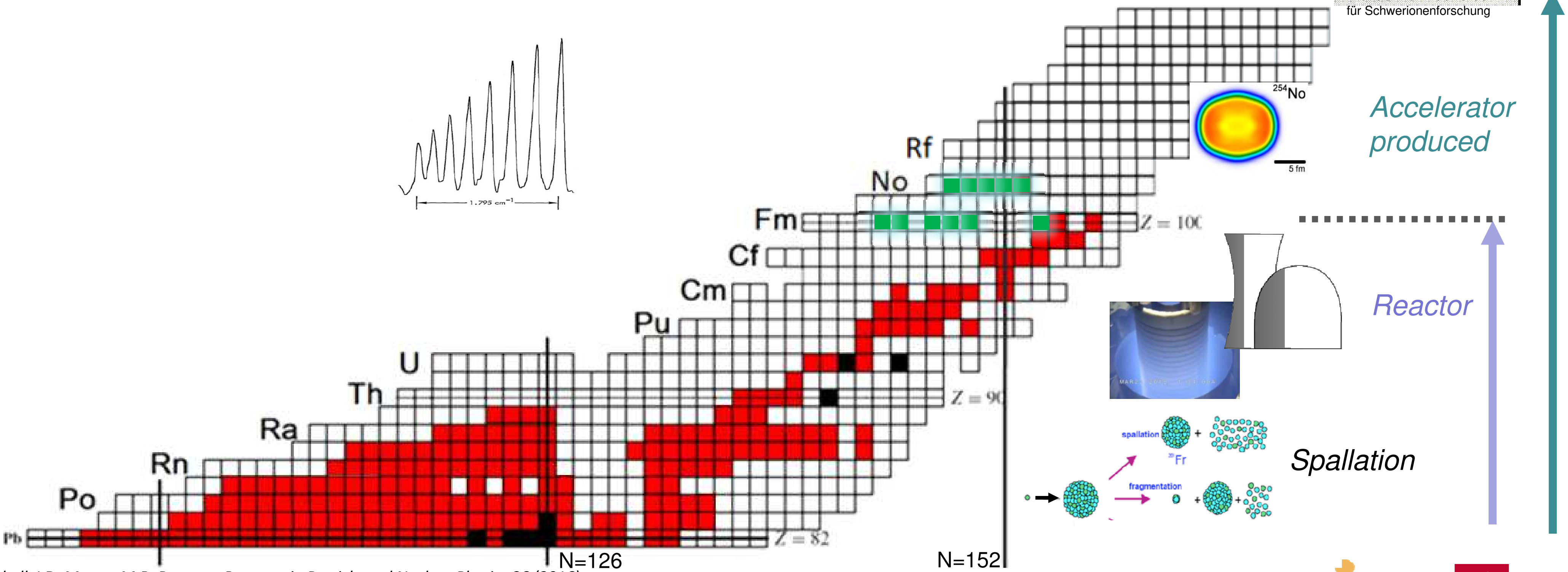
HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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



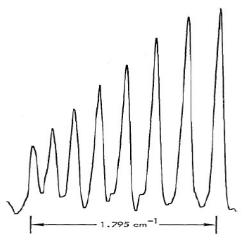
P. Campbell, I.D. Moore, M.R. Pearson, Progress in Particle and Nuclear Physics 86 (2016).
M. Block, M. Laatiaoui, S. Raeder, Progress in Particle and Nuclear Physics (2020).

HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Optical Investigation of Heavy Elements

Laser spectroscopy for fundamental properties

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



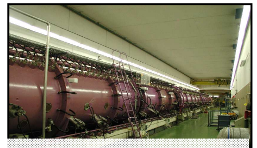
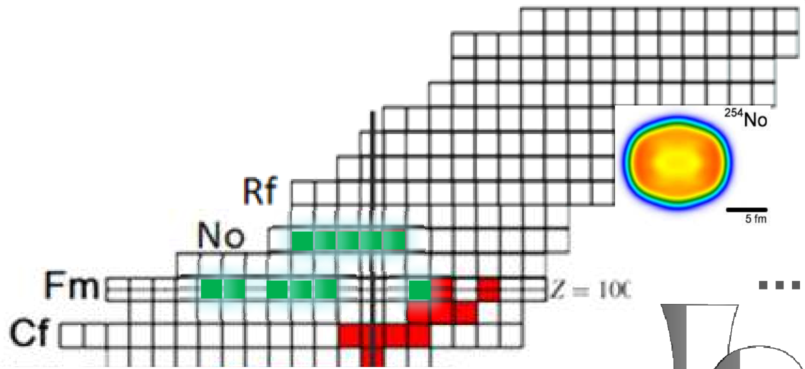
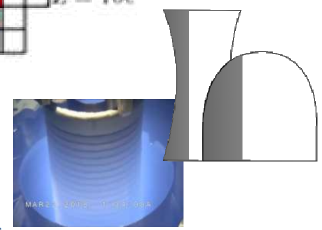


Bild: GSI Helmholtzzentrum für Schwerionenforschung

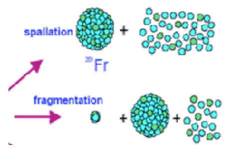


Accelerator produced

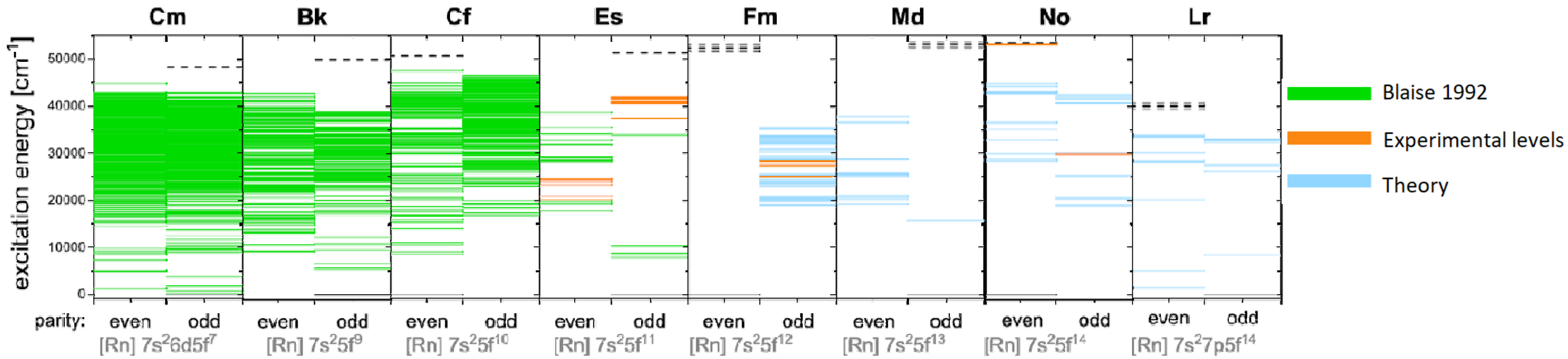
Reactor



Spallation



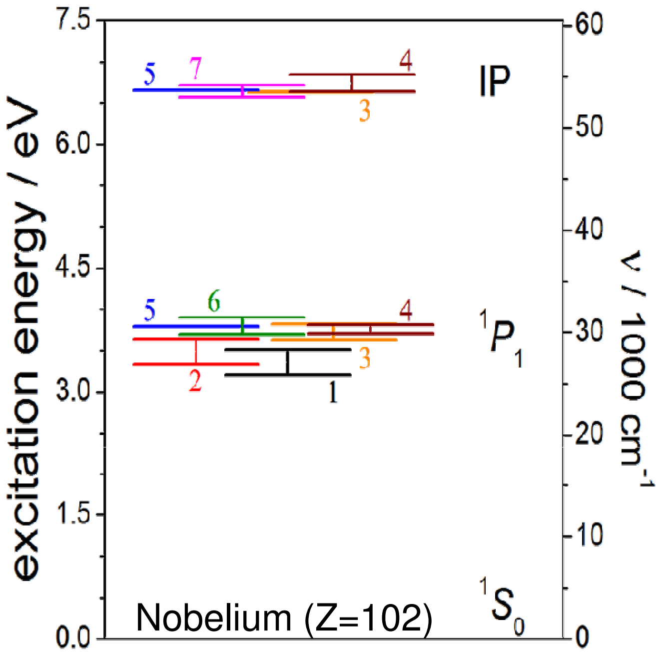
Atomic information for heavy elements is sparse !!



P. Campbell, I.D. Moore, M.R. Pearson, Progress in Particle and Nuclear Physics 86 (2016).
M. Block, M. Laatiaoui, S. Raeder, Progress in Particle and Nuclear Physics (2020).

HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Motivation - Atomic Structure



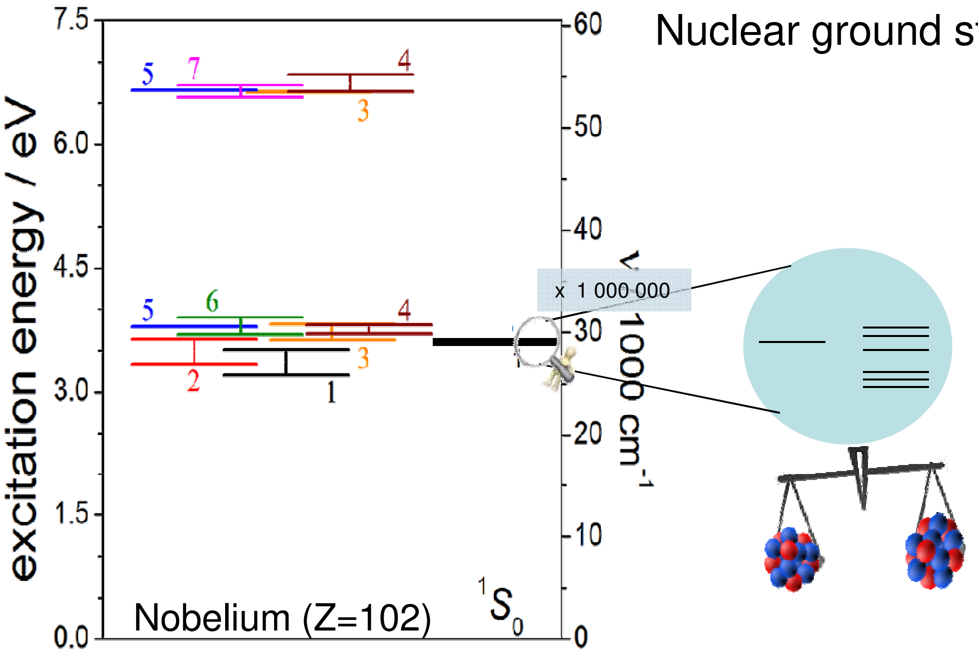
Atomic ground state: [Rn]$5f^{14}7s^2$ $^1S_0$

- 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

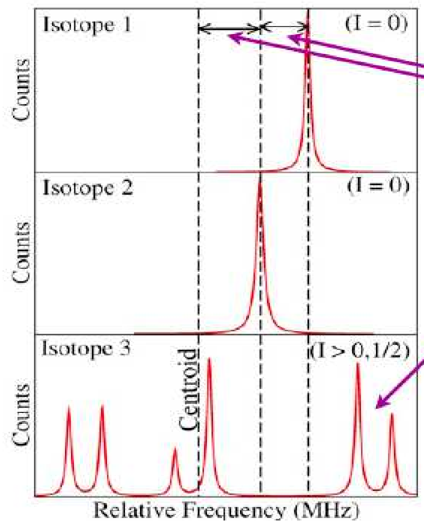
1, 2 (MCDF): S.Fritzsche, Eur. Phys. J. D 33 (2005) 15
3 (IHFSCC): A.Borschevsky et al., Phys. Rev. A 75 (2007) 042514
4 (RCC): V.A.Dzuba et al., Phys. Rev. A 90 (2014) 012504
5 (MCDF): Y.Liu et al., Phys. Rev. A 76 (2007) 062503
6 (MCDF): P.Indelicato et al., Eur. Phys. J. D 45 (2007) 155
7 (extrapolation): J.Sugar, J. Chem. Phys. 60 (1974) 4103

Motivation – 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

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

Model calculations

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

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

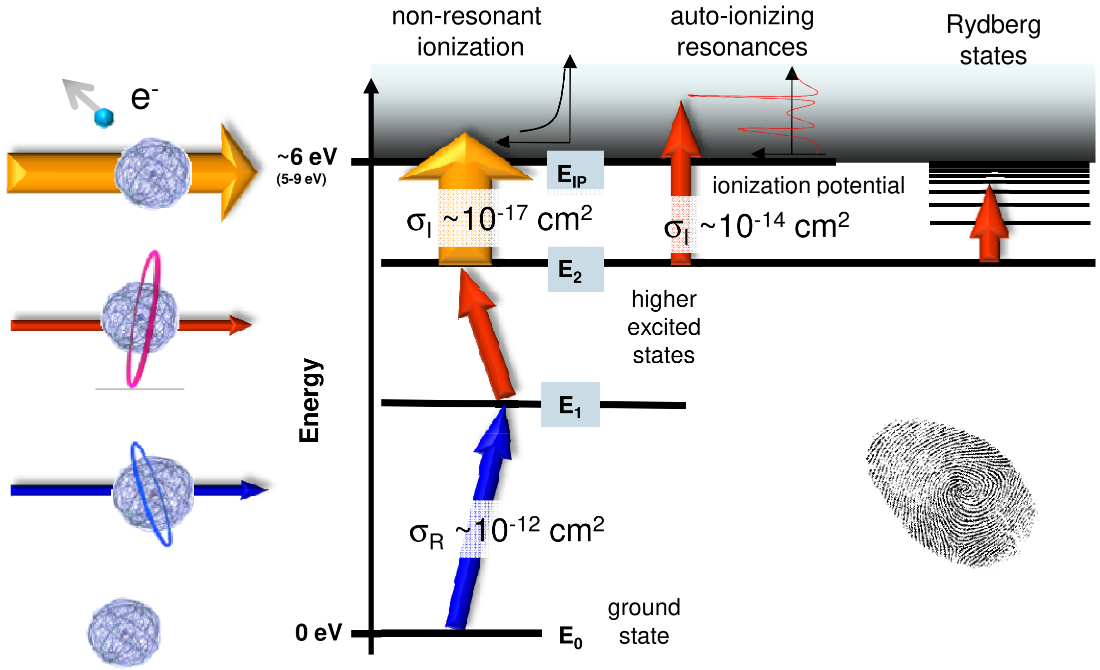
5 (MCDF): Y.Liu et al., Phys. Rev. A 76 (2007) 062503

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

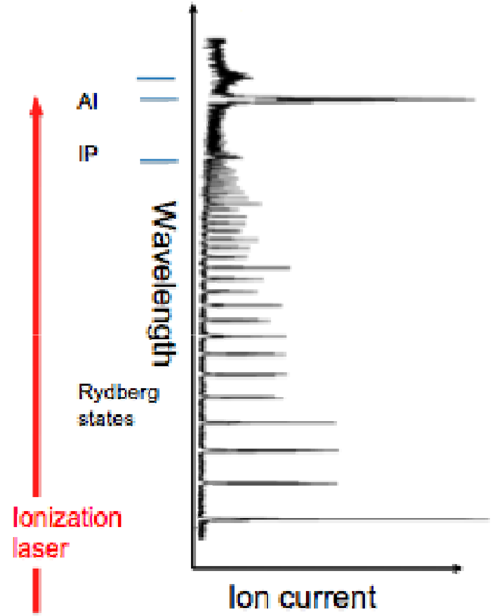
7 (extrapolation): J.Sugar, J. Chem. Phys. 60 (1974) 4103

HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Resonance Ionization Spectroscopy

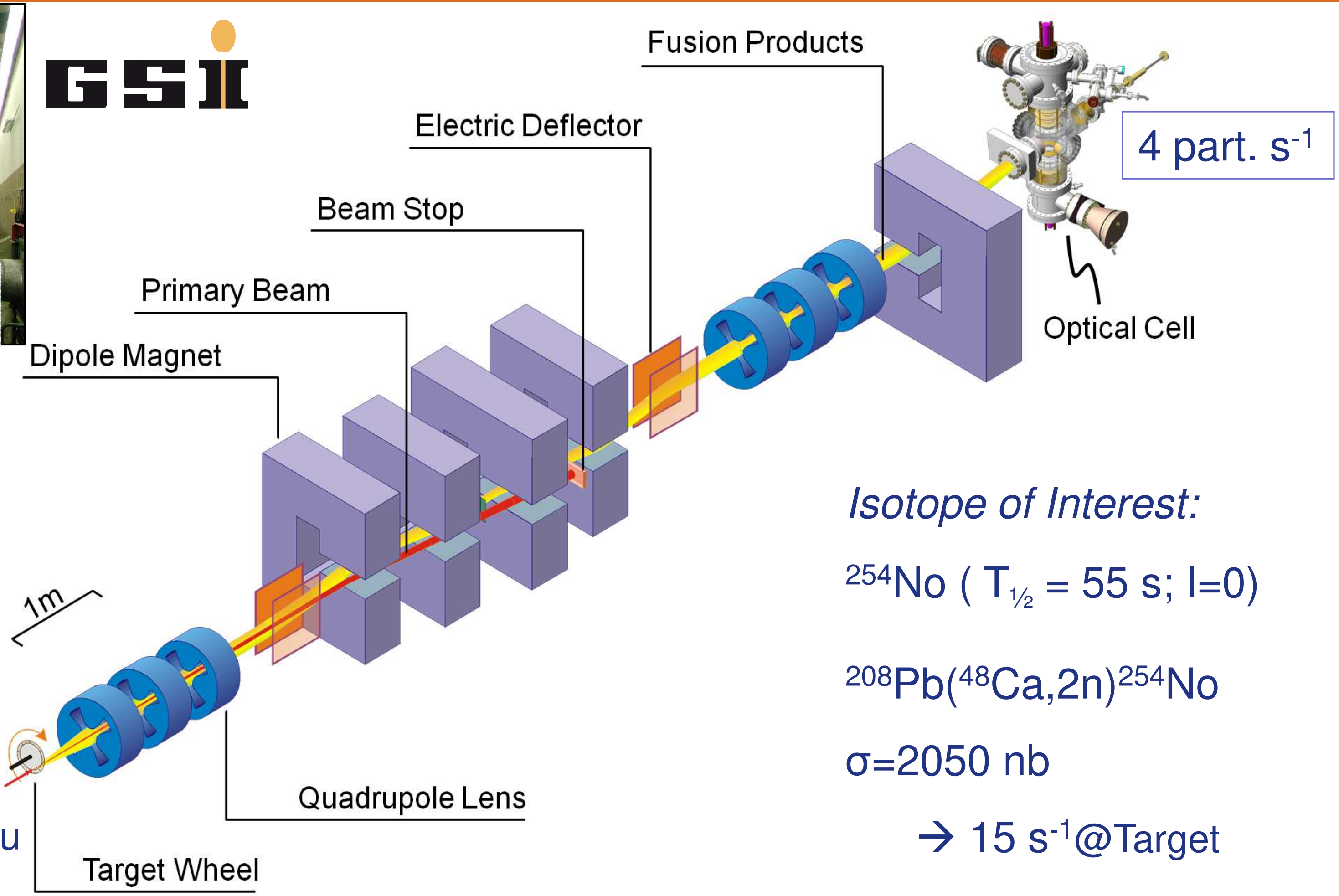


Atomic properties



- Resonant laser excitation – selective & efficient
- Efficient excitation schemes generally exist for every element
- Atomic spectra incomplete – non-resonant ionization unavoidable

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

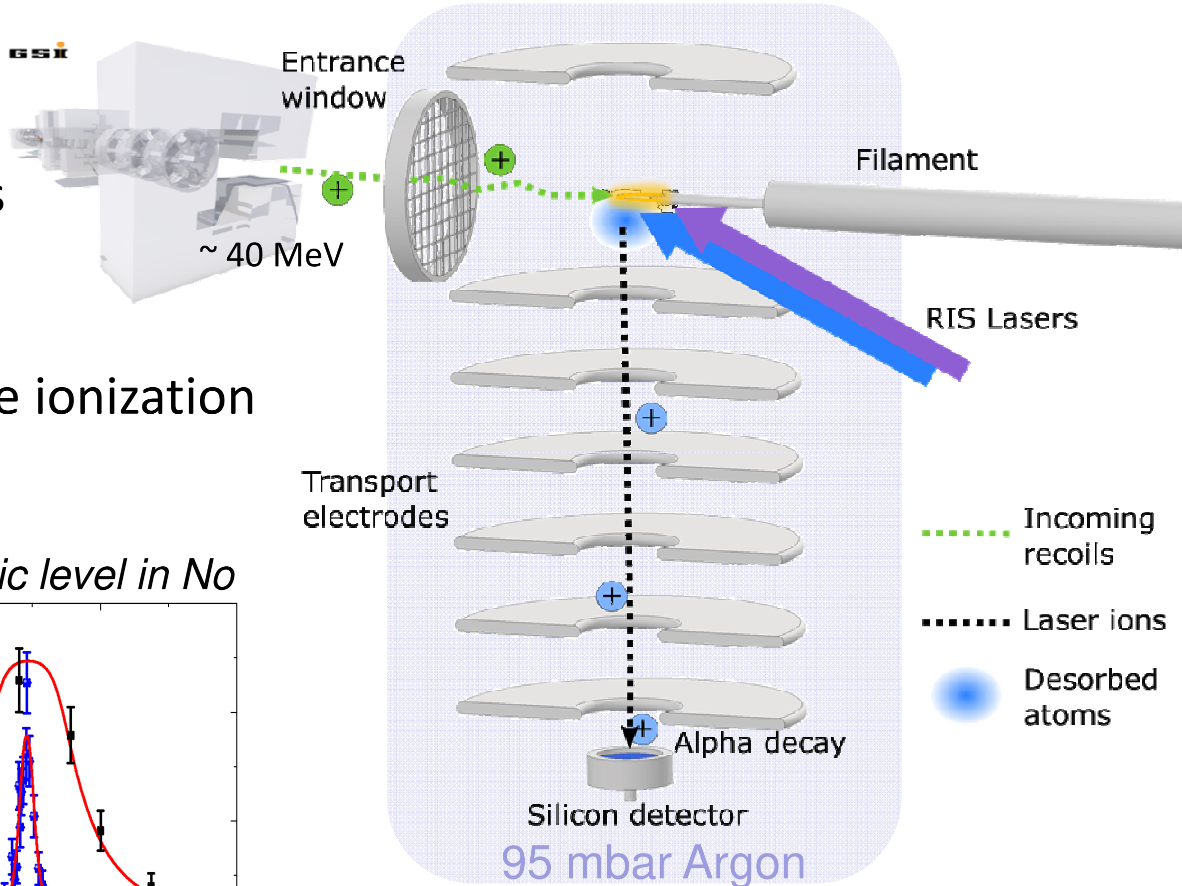
σ=2050 nb

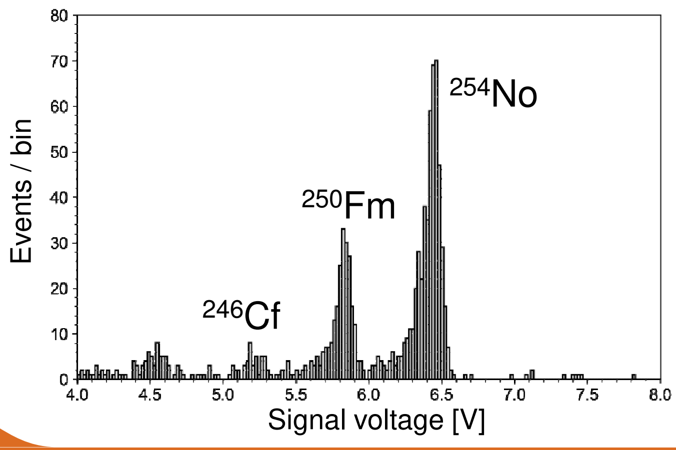
→ 15 s^{-1}@Target

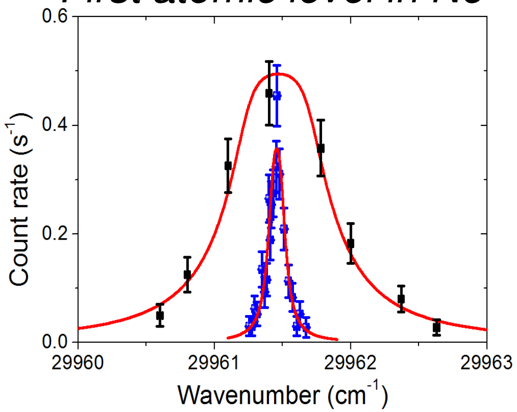
Radiation Detected Resonance Ionization Spectroscopy

RADRIS Method:

- Thermalizing of incoming fusion products
- Collection & neutralization on filament
- Evaporation and two-step laser resonance ionization
- Selective, efficient detection via α-decay







H. Backe et al., Eur. Phys. J. D 45, 99 (2007).
F. Lautenschläger et al., NIMB 383, 115 (2016).
M. Laatiaoui et al., Nature 538, 495–498 (2016).
J. Warbinek et al., Atoms 10, 41 (2022).

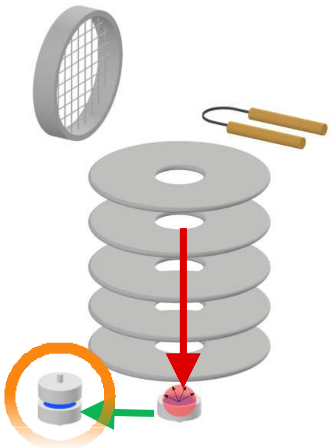
[1] M. Laatiaoui et al., Nature 538 (2016) 7626

HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

RADRIS advancements

Detector upgrade

- Direct detector collection
- Movable detector



Efficiency gain by factor > 2

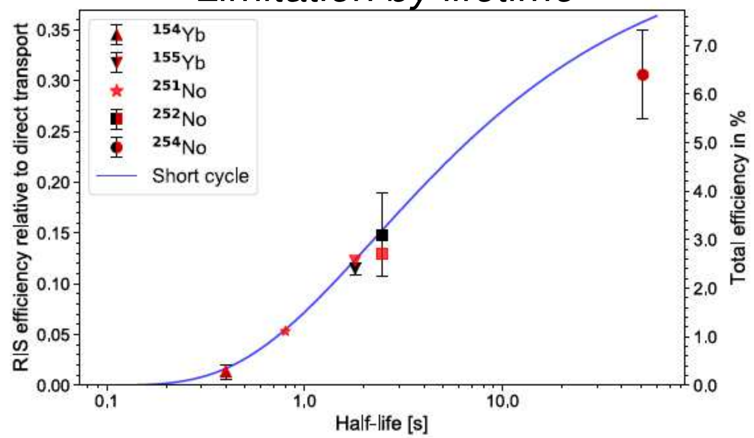
Total efficiency:

15% for $^{254}No^{a\dagger\ddagger*}$

(signal rate of 0.6 s^{-1})

[a] half-life dependend
[†] depends on kinematis
[‡] includes usage of 2nd detector
[*] Element dependent

Limitation by lifetime



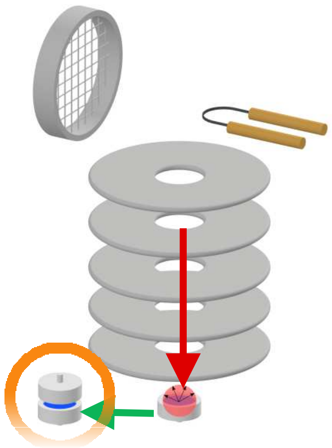
J. Warbinek et al., Atoms 10.2 (2022): 41.

HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

RADRIS advancements

Detector upgrade

- Direct detector collection
- Movable detector



Efficiency gain by factor > 2

Total efficiency:

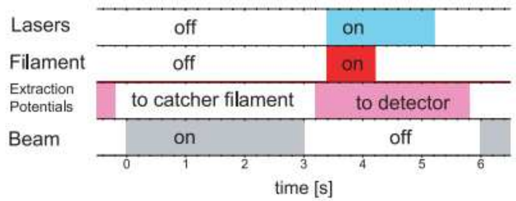
15% for $^{254}No^{a\dagger\ddagger*}$

(signal rate of 0.6 s^{-1})

[a] half-life dependend
[†] depends on kinematis
[‡] includes usage of 2nd detector
[*] Element dependent

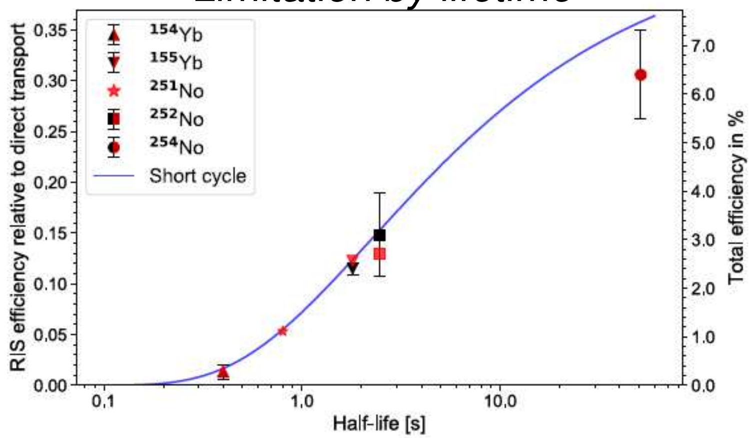
Improving RADRIS cycle

- Cylce limits efficiency
- Faster potential switching
- Limited by drift times

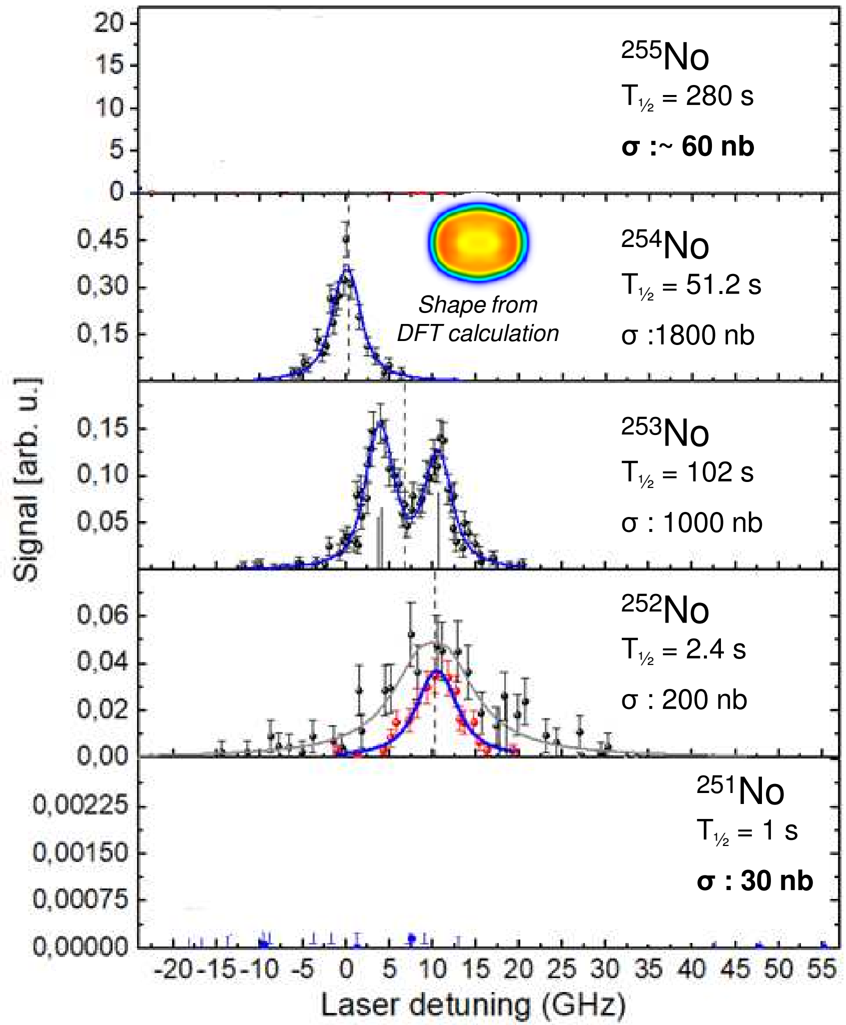


- Old cycle: 3 s break
- New cycle: 1-1.5 s break

Limitation by lifetime



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



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

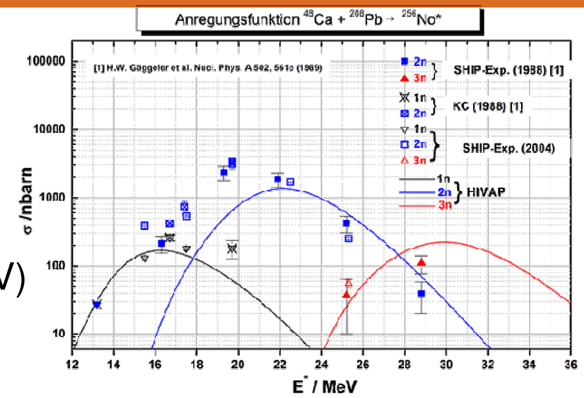
<u>2019:</u>

^{255}No 3.5 m

^{255}No indirect production via ^{255}Lr

α-energy (8.12 MeV) similar to ^{254}No (8.10 MeV)

Similar direct production rate



<u>2015:</u>

^{252}No 2.5 s	^{253}No 1.6 m	^{254}No 51.2 s

$^{252-254}$No with different targets $^{206-208}$Pb

<u>2022:</u>

^{251}No

^{251}No 0.8 s

short lifetime & low production rate complicate the measurements

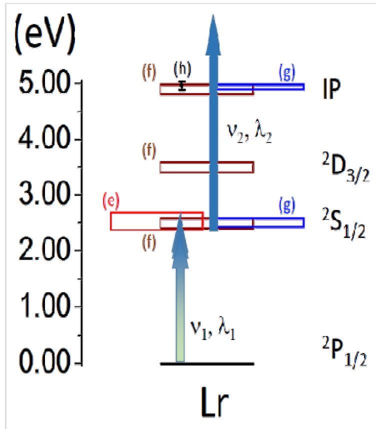
→ Only possible with improved RADRIS setup

Laser Spectroscopy of Lawrencium

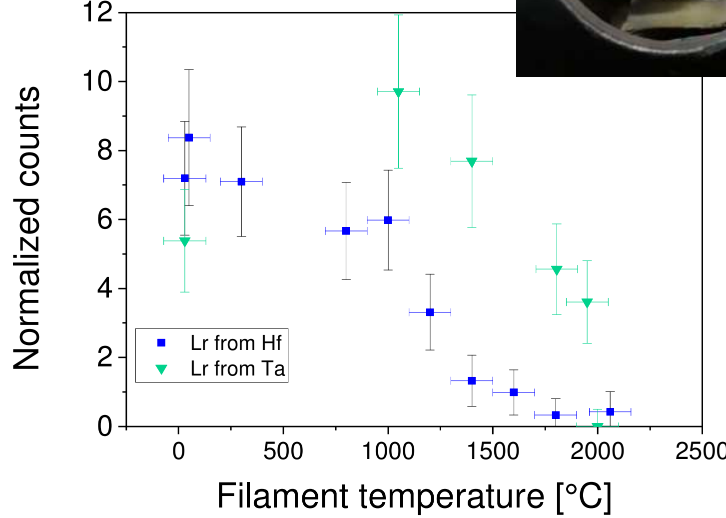
Next step: going heavier – Lawrencium (Lr, *Z*=103)

^{255}Lr
$t_{1/2}$ 31.1s

- Cross section known - production rate of 0.3 ions/s
- Search for 2 different states (predictions from theory)
  - 20,500 cm^{-1} ($^2S_{1/2}$)
  - 28,500 cm^{-1} ($^2D_{3/2}$)



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



Filament desorption: studied on-line

→ Hf is a suitable filament material

Level Search in Lawrencium (Z=103)

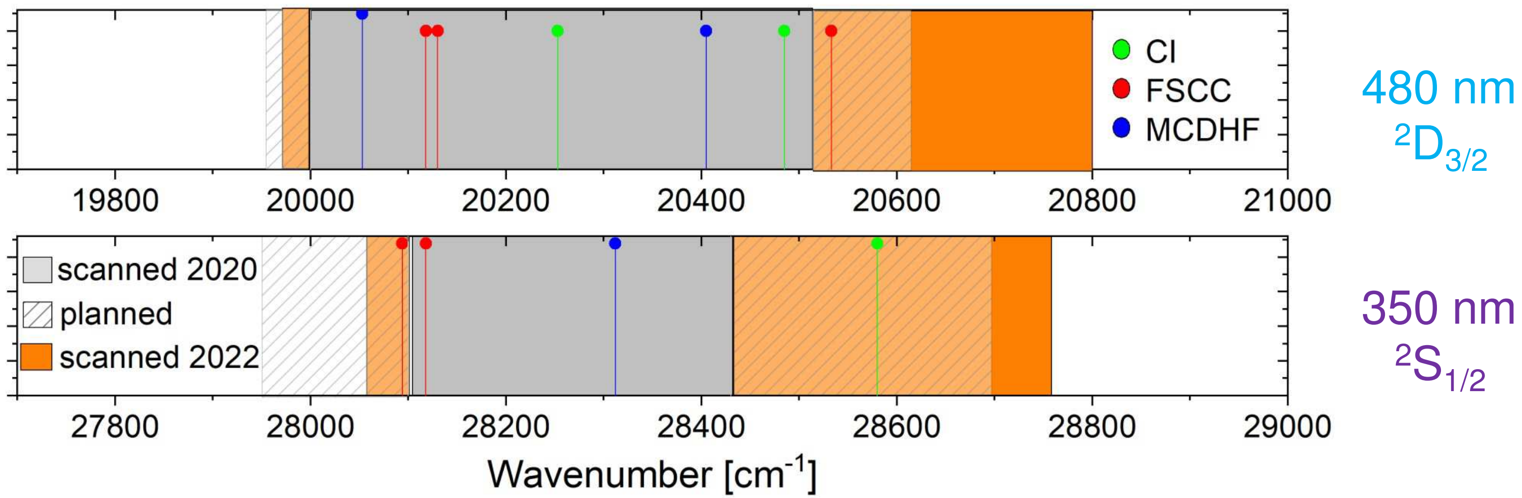
Preparation: Filament optimization & increased sensitivity with RADRIS upgrade

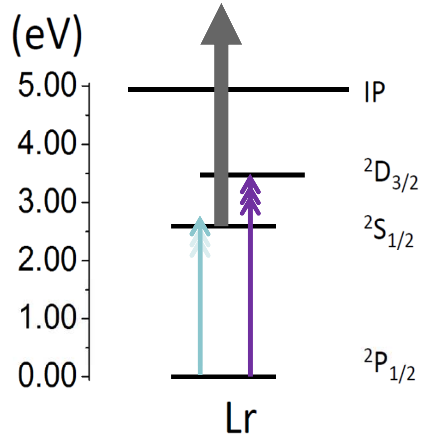
^{255}Lr
$t_{1/2}$ 31.1s

Extensive level search campaigns during beamtimes in 2020 and 2022

→ Exclusion for > 600 cm^{-1} in each region with high confidence

Uncertainty of atomic predictions > 300 cm^{-1}





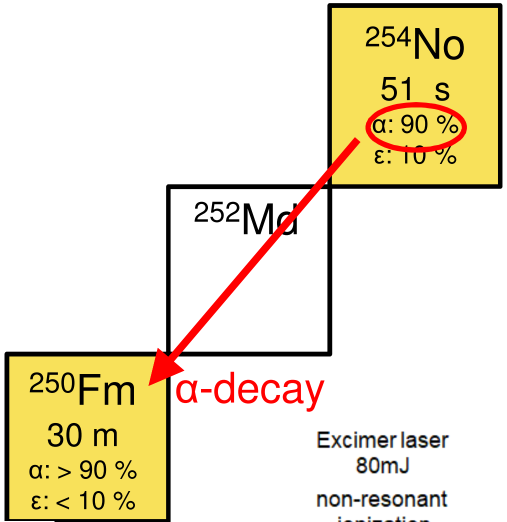
Kahl, E. V., et al. *arXiv preprint arXiv:2103.11287* (2021).
A. Borschevsky et al., Eur. Phys. J. D 45, 115 (2007).
V.A. Dzuba et al., Phys. Rev. A 90, 012504 (2014).
S. Fritzsche et al., Eur. Phys. J. D 45, (2007) 107-113.

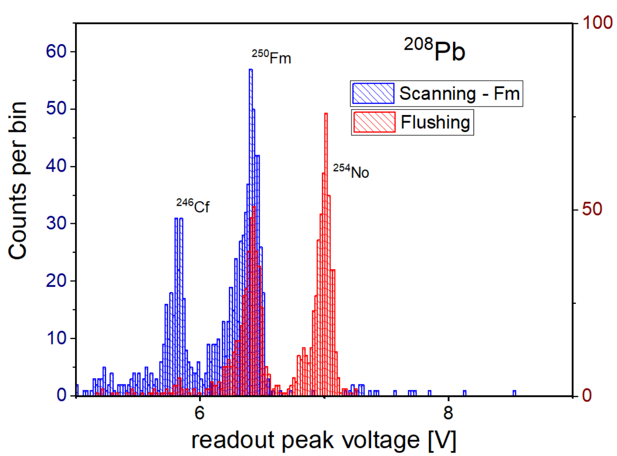
HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

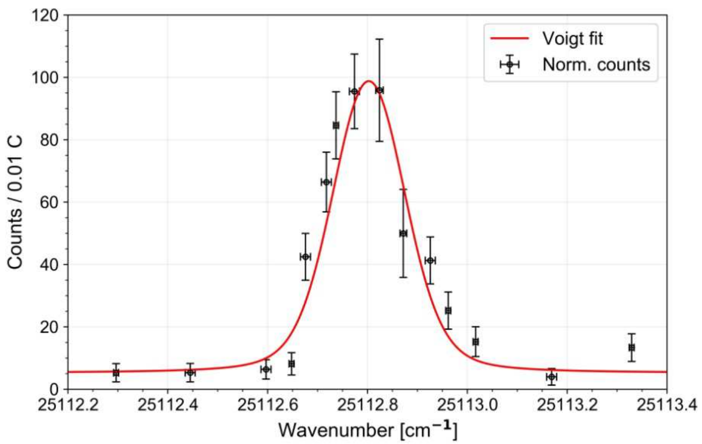
On-line Laser Spectroscopy of Fm Isotopes

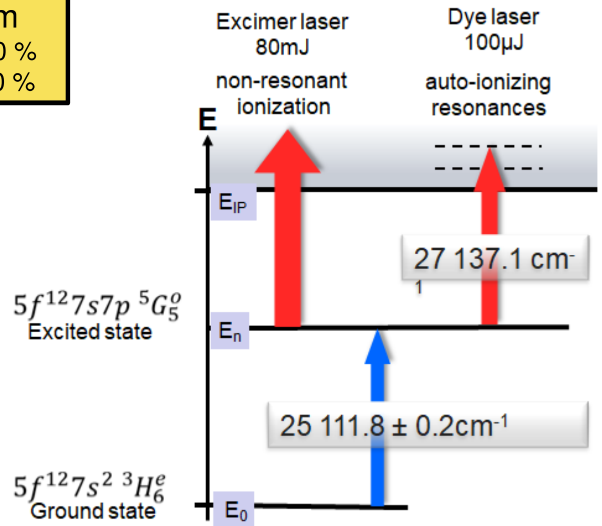
Fm (Z=100) - A new element for RADRIS

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









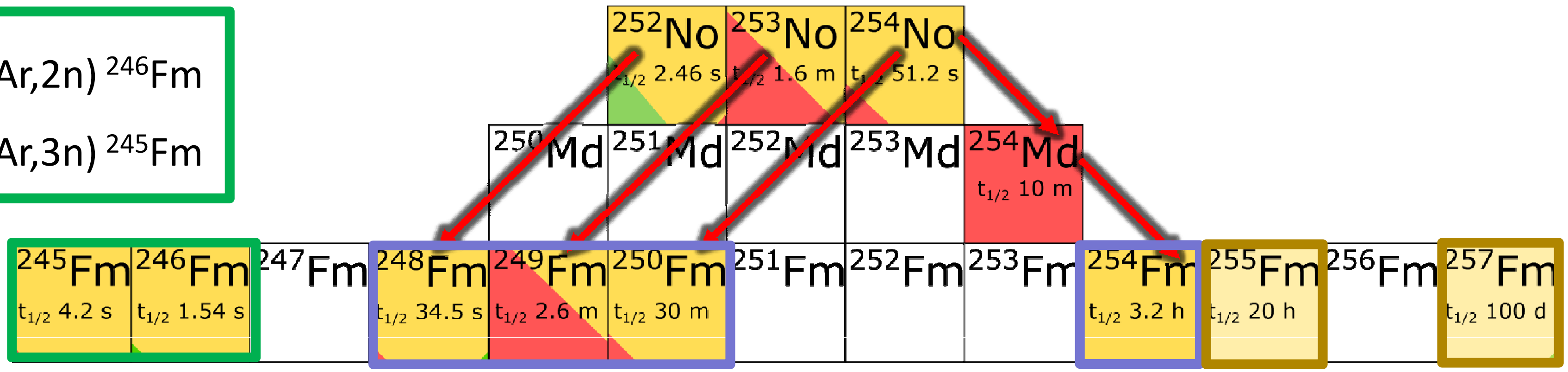
[Sew03] M. Sewtz, et al., *Phys. Rev. Lett.* 90.16 (2003): 163002.

Production of Fm Isotopes

Direct production using Ar beam

$^{208}Pb(^{40}Ar,2n)\,^{246}Fm$

$^{208}Pb(^{40}Ar,3n)\,^{245}Fm$



- Nobelium mother collected on filament
- Wait for decay

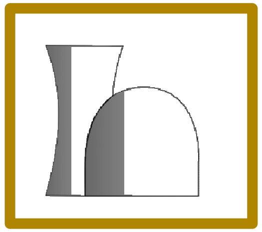
⟶ Desorption of daughter nuclides

$$^{208}Pb(^{48}Ca,2n)^{254}No \xrightarrow{\alpha} {}^{250}Fm$$

$$^{207}Pb(^{48}Ca,2n)^{253}No \xrightarrow{\alpha} {}^{249}Fm$$

$$^{206}Pb(^{48}Ca,2n)^{252}No \xrightarrow{\alpha} {}^{248}Fm$$

$$^{208}Pb(^{48}Ca,2n)^{254}No \xrightarrow{ec/\beta^+} {}^{254}Md \xrightarrow{ec/\beta^+} {}^{254}Fm$$



HIM HELMHOLTZ Helmholtz-Institut Mainz
GSI RESEARCH FOR GRAND CHALLENGES
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Isotope shifts of Fm isotopes

^{245}Fm $t_{1/2}$ 4.2 s

^{246}Fm $t_{1/2}$ 1.54 s

Cross sections as low as 13 nb or 4 particles/min

^{248}Fm $t_{1/2}$ 34.5 s

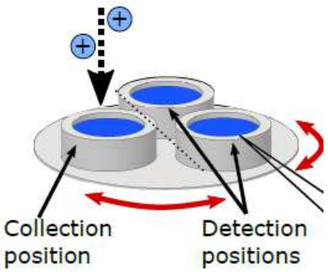
^{249}Fm $t_{1/2}$ 2.6 m

^{250}Fm $t_{1/2}$ 30 m

HFS in even-odd isotope: too small for gas cell
but yields constraints on *A, B* parameters

^{254}Fm $t_{1/2}$ 3.2 h

Customized, rotatable detector for ^{254}Fm ($t_{1/2}$ = 3 h)



NEUTRONS FOR SOCIETY

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

U.S. DEPARTMENT OF ENERGY | Office of Science

^{257}Fm $t_{1/2}$ 100 d

Offline measurements in hot cavity
HFS not resolved

FAIR Phase 0 Research Program

HIM HELMHOLTZ Helmholtz-Institut Mainz

GSI RESEARCH FOR GRAND CHALLENGES

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Change in Mean-Square Charge Radii

Preliminary

Courtesy S. Raeder

- Isotope shift → Change in the nuclear mean-square charge radii

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

Experiment Theory

New: Fm

- Atomic parameters from theory:

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

- Comparison to DFT calculations (even-even isotopes, B. Schütrumpf et al.)

  S. Raeder et al., Phys. Rev. Lett. 120, 232503 (2016).

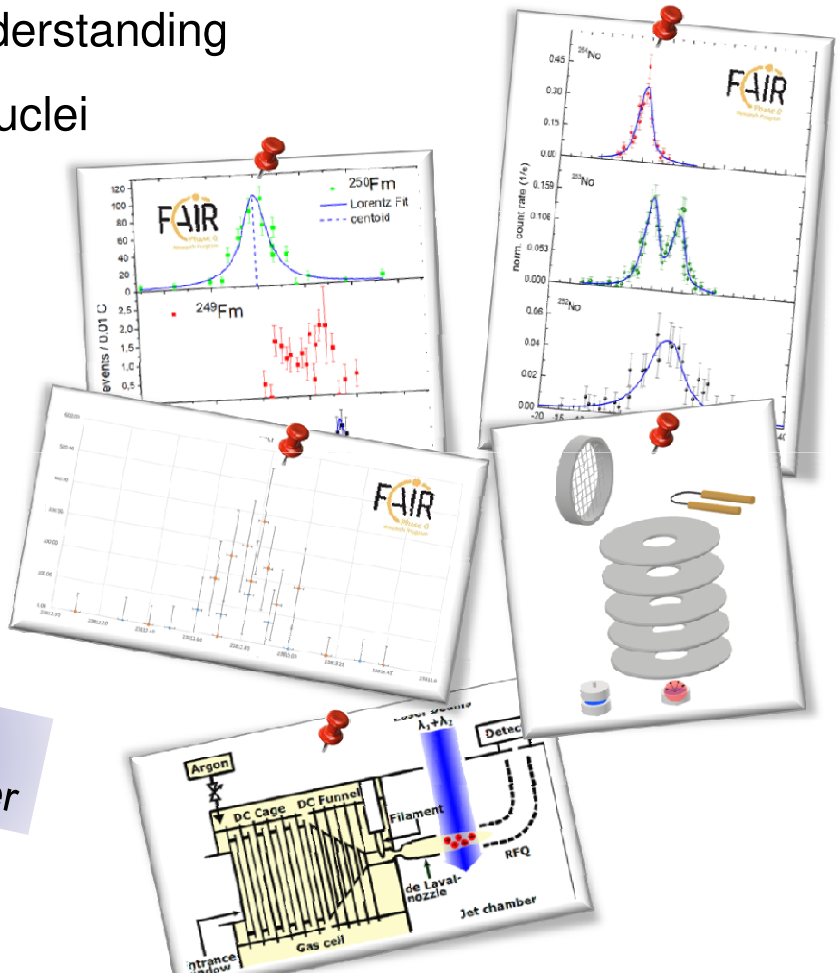
- Additional calculations (MREDF, HFB, [Fayans]) performed in collaboration with B. Bally, M. Bender, S. Goriely, S. Hilaire, W. Nazarewicz, S. Peru, P.G. Reinhard

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 ($^{251-255}$No)
  - ✓ First on-line measurements of Fm isotopes
  - ✓ first laser spectroscopy on on-line produced Cf isotopes
  - ➢ Level search in Lr going on
- JETRIS: laser spectroscopy with improved resolution
  - ✓ First gas jet laser spectroscopy of ^{254}No

Talk
M. Stemmler



Competitive laser spectroscopy program will continue

- ❖ RADRIS & gas jet beamtime running
- ❖ Gas jet: development for improved resolution

Collaboration

GSI Darmstadt

B. Andelic, M. Block, F. Giacoppo, F.P. Heßberger, O. Kaleja, A. Mistry, S. Raeder, J. Warbinek, A.Yakushev, M. Guiterrez-Torres

KU Leuven

A. Claessens, R. Ferrer, S. Kraemer, J. Romans, P. Chhetri, P. Van Duppen, S. Sels, F. Ivandikov, A. De Roubin

Universität Mainz

M. Laatiaoui, W. Lauth, E. Romero Romero, E. Kim, Ch. E. Düllmann, J. Auler, M. Stemmler, M. Kaja, K. Wendt

TU Darmstadt

Th. Walther

HIM Mainz

J. Auler, J. Lantis, St. Nothhelfer, D. Münzberg, E. Rickert, T. Kieck

GANIL

P. Chauveau, N. Lecesne H. Savajols, V. Manea

Jyväskylä

A. Raggio, I. Moore

TRIUMF Vancouver

P. Kunz, T. Mürbock

University of Liverpool

B. Cheal, Ch. Devlin

CEA Saclay

E. Rey-Herme, B. Sulignano, M. Vandebrouck,

This Marie Sklodowska-Curie Action (MSCA) Innovative Training Network (ITN) receives funding from the European Union H2020 Framework Programme under grant agreement no. 861198. LISA will run from November 2019 to October 2023.

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.