Laser spectroscopy of Fermium-255 at the RISIKO mass separator facility

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PLATAN Conference 2024 in Jyväskylä
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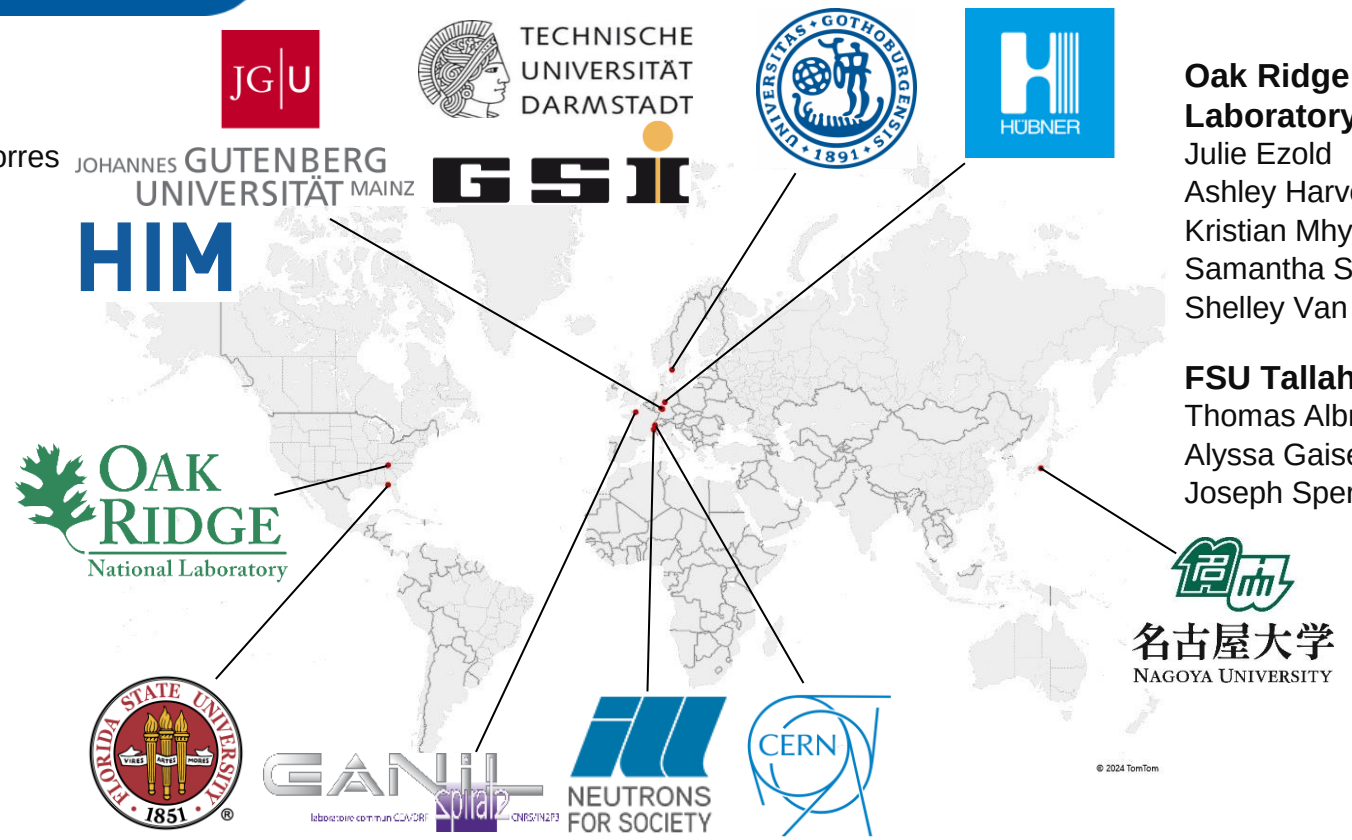

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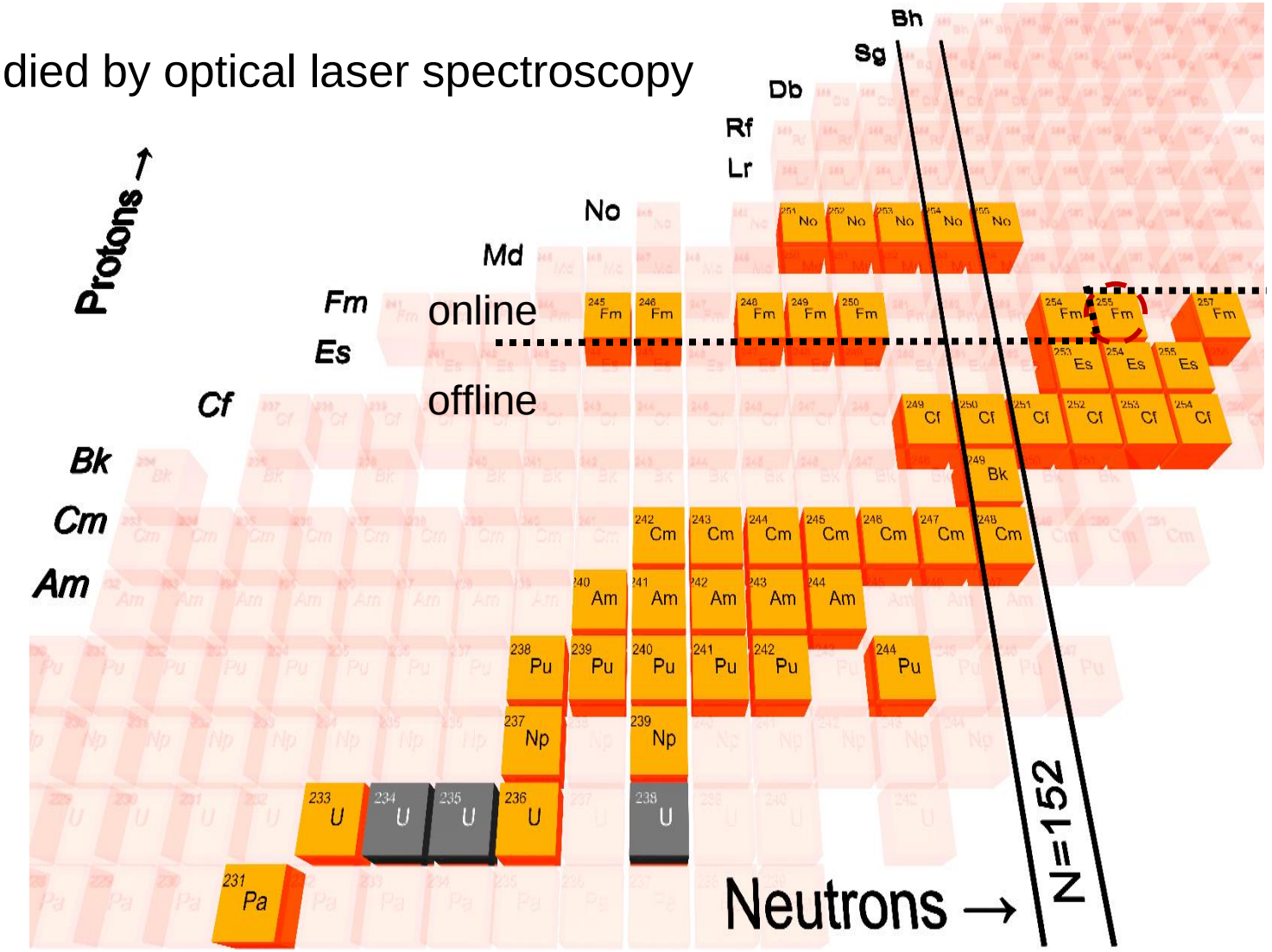
Laser spectroscopy investigations of actinides

Individual atomic and nuclear structure studied by optical laser spectroscopy

- Ionization scheme development
- Information about atomic and nuclear structure:
  - **Atom**: Level structure, IP
  - **Nucleus**: Ground state properties (spin, moments, size, shape)

Talks/ Posters:	
Tu, 14:00	- S. Raeder
Tu, 14:30	- S. Berndt
Tu, 17:30	- M. Gonzalez
Fr, 09:00	- R. Heinke
Fr, 10:10	- K. Wendt

Focus on Fm-255



Adapted from M. Laatiaoui

Resonance Ionization Mass Spectrometry (RIMS)

How to select Fm-255?

Resonant laser ionization

➢ Select Element

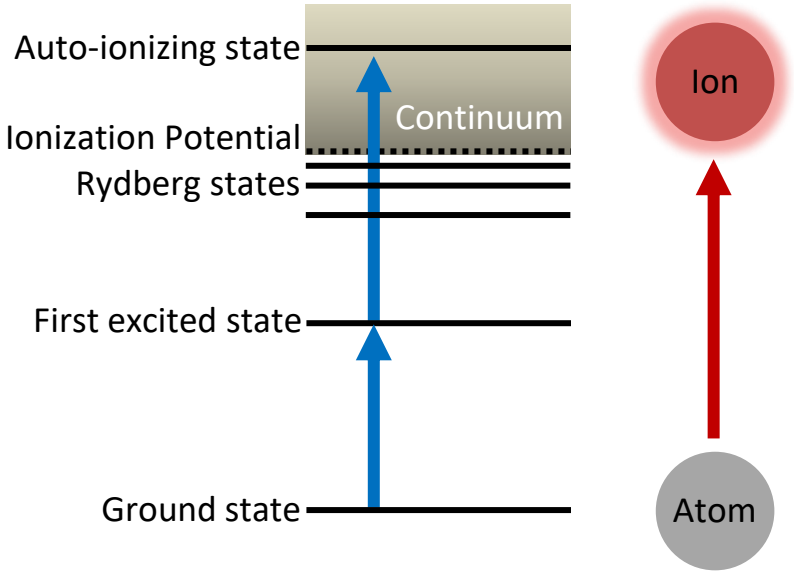
+

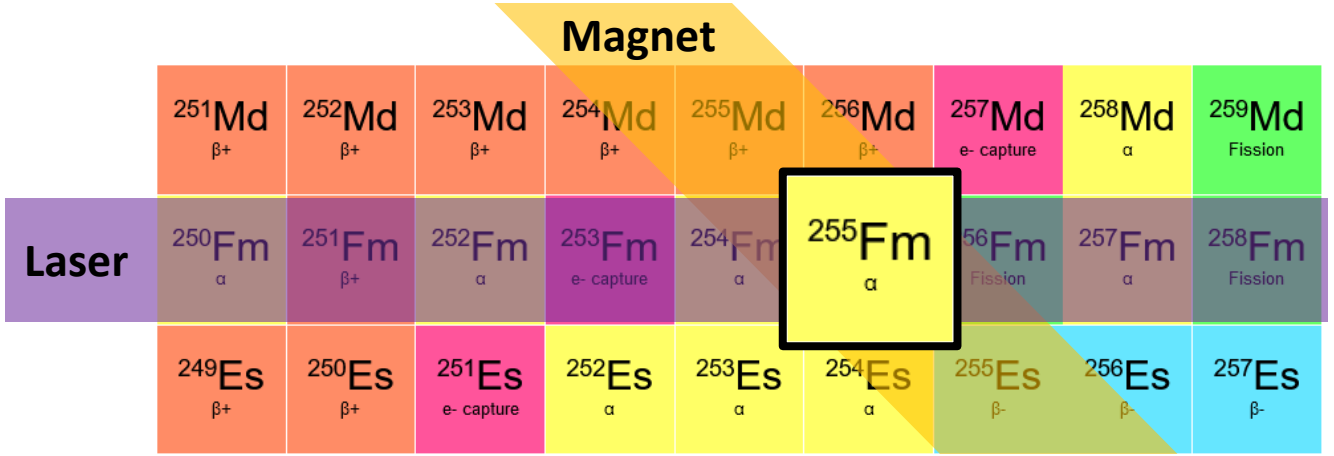
High transmission mass separation

➢ Select Isotope

=

Monoisotopic ion beams





Longest lifed Fm isotope: ^{257}Fm (~100 d)

Production of heavy actinides for off-line studies

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

Fm 248 34.5 s α 7.87, 7.83 ε sf	Fm 249 2.6 m ε α 7.520 γ (~45...) e⁻	Fm 250 1.8 s / 30 m IT α?, sf? α 7.43 sf	Fm 251 5.30 h ε γ 881, 453... e⁻ α 6.834, 6.783...	Fm 252 25.39 h α 7.039, 6.998... γ (96, 42), e⁻ sf	Fm 253 3.0 d ε α 6.943, 6.673... γ 272, (145...)	Fm 254 3.240 h α 7.192, 7.150... γ (99, 43...), e⁻ sf σ ~76	Fm 255 20.07 h α 7.022, 6.963... sf γ 81, (58...), e⁻ σ 26, σf 3300	Fm 256 157.1 m sf α 6.915, 6.870 σ ~45	Fm 257 100.5 d α 6.520..., sf γ 241,179..., e⁻ σf 2950	Fm 258 370 µs sf
Es 247 4.55 m ε α 7.323, 7.275... α → g	Es 248 24 m ε α 6.879, 6.907... α → g βsf	Es 249 102.2 m ε α 6.776, 6.716 γ 380, 813, 375... α → g	Es 250 2.22 h / 8.6 h ε γ 989 1032 829... ε γ 829 303 349... e⁻	Es 251 33 h ε γ 178, (153...), e⁻ α 6.492, 6.462...	Es 252 471.7 d α 6.632, 6.562... γ (52...), e⁻, α → g ε γ 785, 139...	Es 253 20.47 d α 6.633, 6.591... γ (42, 3...), e⁻ sf σ 178 ÷ 5.8	Es 254 39.3 h / 275.7 d β⁻ 0.5... γ 64... α 6.5... σ ~1... σf 1826 ...129... ...749 σf 1800	Es 255 39.8 d β⁻ α 6.40... sf γ (33...) σ ~55	Es 256 7.6 h / 25.4 m β⁻ γ 862 231 173..., e⁻ βsf β⁻	Es 257 7.7 d sf β⁻ γ 26, 46, 49...
Cf 246 35.7 h α 6.750, 6.708... γ (42, 96...), e⁻, g sf	Cf 247 3.11 h ε γ 294 (448 418...), e⁻ α 6.296, 6.238	Cf 248 333.5 d α 6.258, 6.217... γ (43, 99), e⁻, g sf	Cf 249 351 a α 5.81...58... γ 388... g sf σ 497, σf 1642	Cf 250 13.08 a α 6... γ (... sf σ 2034, σf 112	Cf 251 898 a α 5... 6.0... γ 17... σ 2850, σf 4895	Cf 252 2.647 a α 6.1...76... γ (4... 155... σ 20.3, σf 32	Cf 253 17.81 d β⁻ 0.3... γ (46), α 5.980... σ 17, σf 1300	Cf 254 60.5 d sf α 5.833, 5.791 σ 4.5	Cf 255 85 m β⁻	Cf 256 12.3 m sf
Bk 245 4.95 d sf ε γ 253, 381... e⁻, g α 5.886 6.147..., α → g	Bk 246 1.80 d / ? ε γ 799 1081, 834 1124... e⁻	Bk 247 1380 a α 5.531, 5.710 5.688... γ 84, 265..., e⁻ g, sf?	Bk 248 23.7 h / >9 a β⁻ 0.9... γ 551... ε e⁻ α? β⁻? ε?	Bk 249 327.2 d β⁻ 0.1 α 5.414, 5.386... γ (327, 308...), sf σ 746, σf 2.5	Bk 250 3.217 h β⁻ 0.7, 1.8... γ 989, 1032 1029... σ ~350, σf 960	Bk 251 55.6 m β⁻ ~0.9, 1.1... γ 178, 130, 153... e⁻		Bk 253 ? >10 m β⁻ ?	
Cm 244 18.11 a sf α 5.805, 5.763... γ (43...), e⁻, g sf σ 15.3, σf 1.04	Cm 245 8423 a sf α 5.361, 5.304... γ 175, 133..., e⁻, g sf σ 369, σf 2018	Cm 246 4760 a α 5.386, 5.343... γ (45), e⁻, g sf σ 1.22, σf 0.14	Cm 247 1.56·10⁷ a α 4.870, 5.267... γ 402, 278..., g σ 57, σf 83	Cm 248 3.48·10⁵ a α 5.078, 5.035... γ, e⁻, g, sf σ 2.63, σf 0.37	Cm 249 64.15 m β - 0.9... γ 634, (560, 369...) e⁻ σ 1.6	Cm 250 ~8300 a sf α?, β⁻? σ ~80	Cm 251 16.8 m β⁻ 1.4... γ 543, 530, 390 438...			

10^{14} atoms

10^{13} atoms

10^{12} atoms

10^{11} atoms

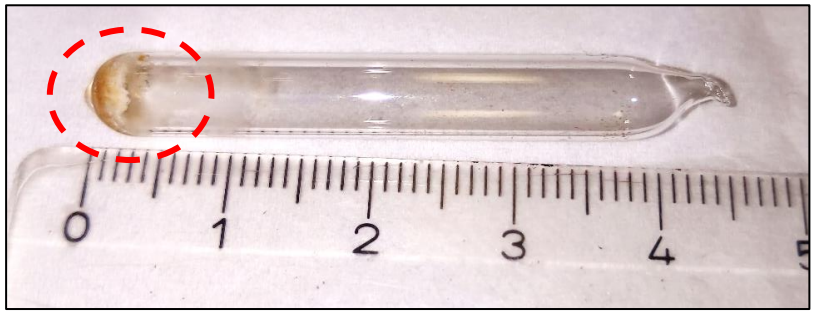
10^{10} atoms

10^{9} atoms

10^{8} atoms

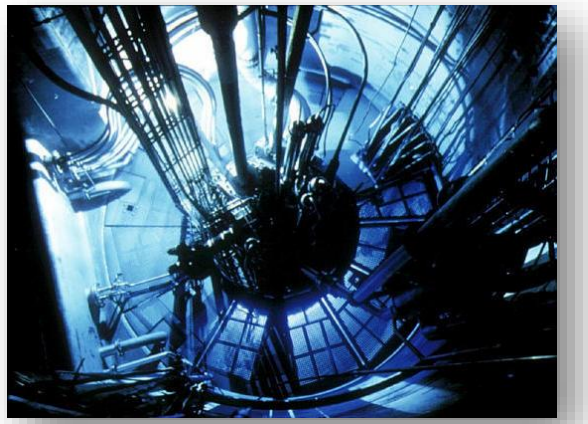
10^{7} atoms

10^{6} atoms



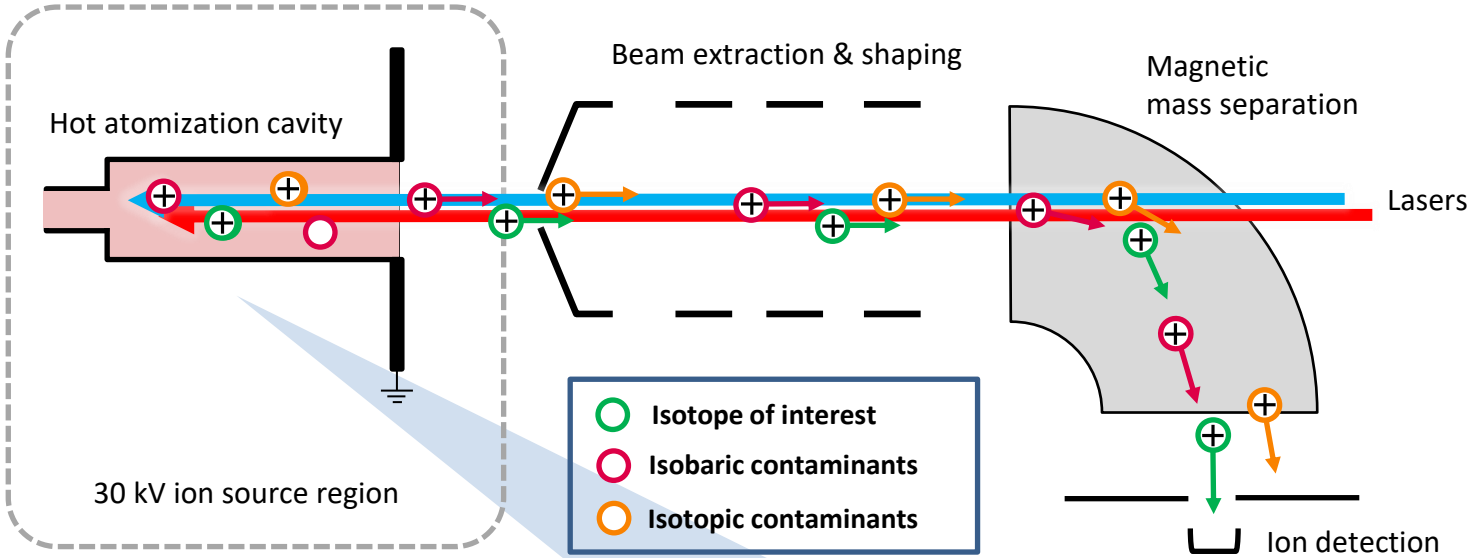
NEUTRONS FOR SOCIETY

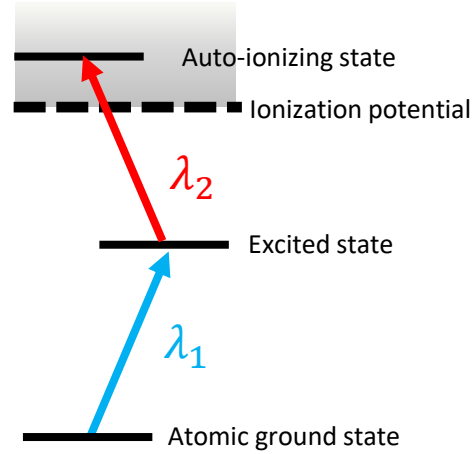
High Flux Reactor at ILL



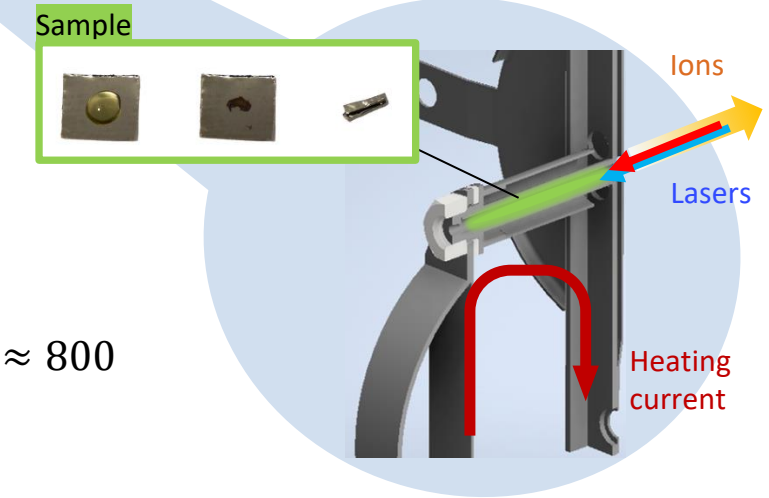
Slide from S. Berndt

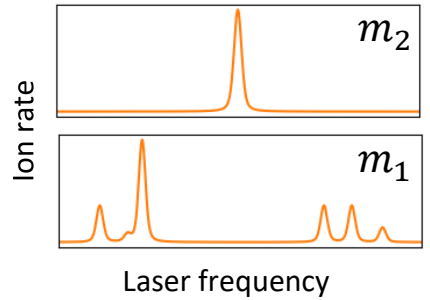
RISIKO setup at Mainz (no PI-LIST)





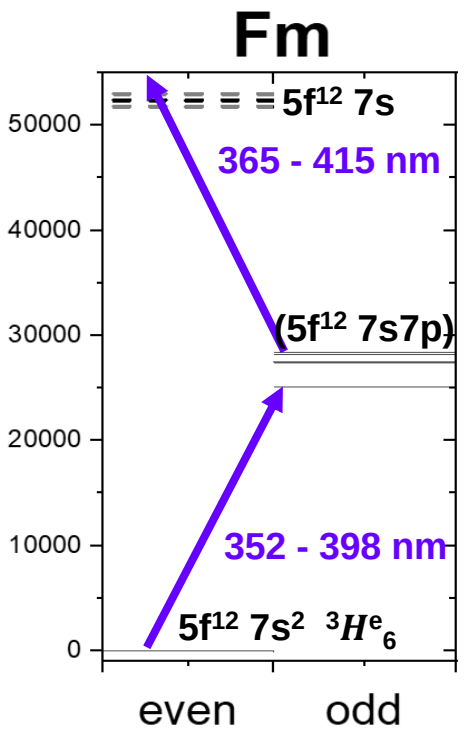
- Chemical sample preparation
- Sample evaporation in hot cavity
- Multi-step insource photoionization by pulsed lasers
- Mass separation in dipole magnet $\frac{m}{\Delta m} \approx 800$
- Single ion detection





RISIKO

Previously known levels of Fermium



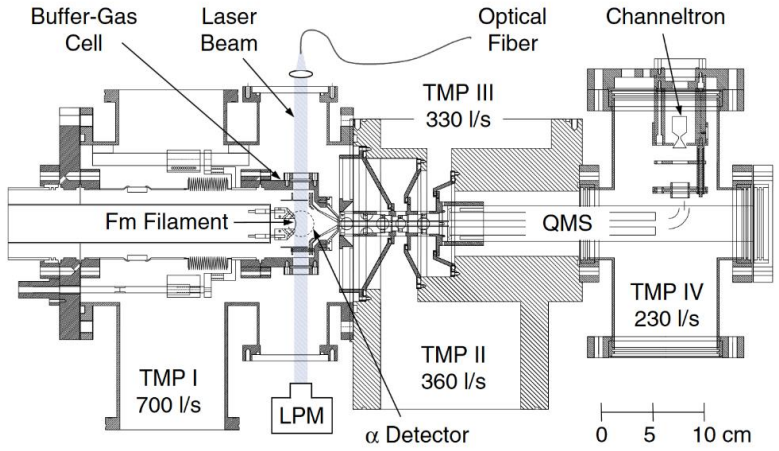
No.	Wavenumber [cm^{-1}]	Term
ES 7	28 391 (1.5)	$5f^{12}\ 7s^2\ {}^3I^o_7$
ES 6	28 377 (1.5)	
ES 5	28 185 (1.5)	
ES 4	27 466 (1.5)	$5f^{12}\ 7s^2\ {}^3H^o_6$
ES 3	27 389 (1.5)	$5f^{12}\ 7s^2\ {}^3G^o_5$
ES 2	25 111.8 (2)	$5f^{12}\ 7s^2\ {}^5G^o_5$
ES 1	25 099.8 (2)	$5f^{12}\ 7s^2\ {}^5I^o_6$
GS	0	$5f^{12}\ 7s^2\ {}^3H^e_6$

M. Sewtz et al., Phys. Rev. Lett. ***90****, 163002 (2003)*
H. Backe et al., Hyperfine Interact. ***162****, 3 (2006)*
S.O. Allehabi et al., JQSRT ***253****, 107137 (2020)*

Experimental setup from Sewtz and Backe:

In Gas Resonance Ionization Spectroscopy

IGRIS (10^{10} atoms)



Pre-determined ionization potential:

- 52400 (600) cm^{-1} [1, theo.]
- 52600 (1000) cm^{-1} [2, exp.]

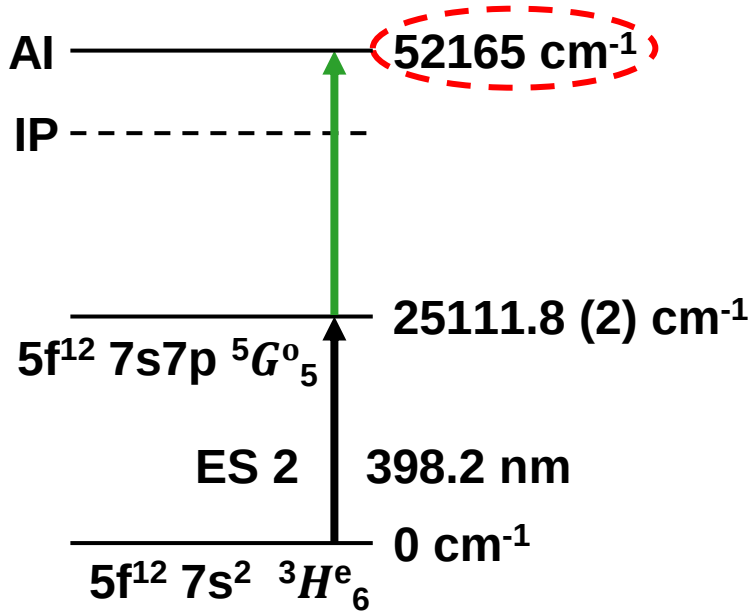
[1] J. Sugar et al., J. Chem. Phys. ***60****, 4103 (1974)*
[2] T. K. Sato et al., J. Am. Chem. Soc. ***140****, 14609 (2018)*

Scan of excited state (25 111.8 cm^{-1})

- Autoionizing state (AI) for ionization

  sensitive to total angular momentum

  F of hyperfine structure (HFS)

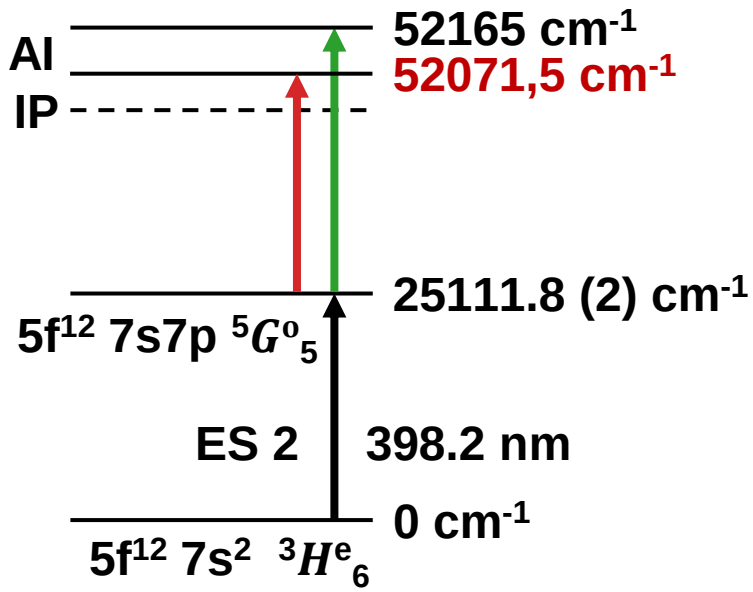


Scan of excited state (25 111.8 cm^{-1})

- Autoionizing state (AI) for ionization

  sensitive to total angular momentum

  F of hyperfine structure (HFS)
- New AI found and used

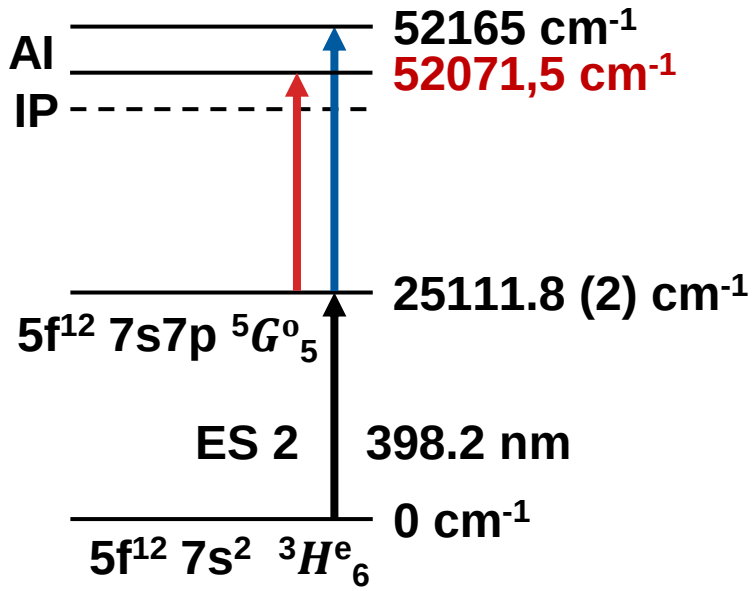


Comparison to H. Backe (25 111.8 cm^{-1})

- Autoionizing state (AI) for ionization

  sensitive to total angular momentum

  F of hyperfine structure (HFS)
- New AI found and used
- HFS for verification of structure

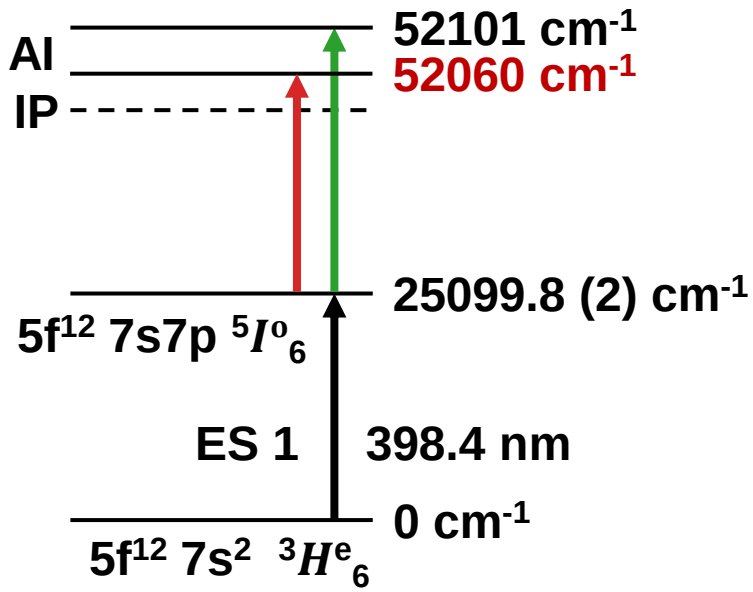


Scan of excited state (25 099.8 cm^{-1})

- Autoionizing state (AI) for ionization

  sensitive to total angular momentum

  F of hyperfine structure (HFS)
- New AI found and used

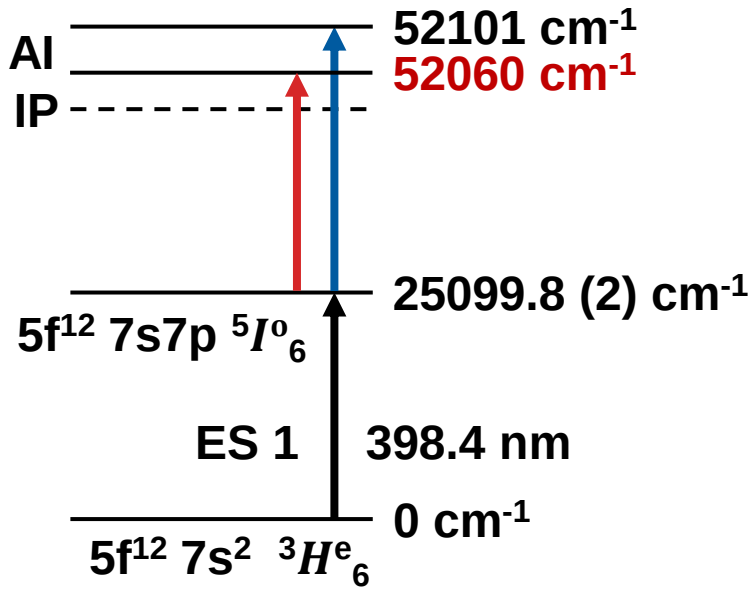


Comparison to H. Backe (25 099.8 cm^{-1})

- Autoionizing state (AI) for ionization

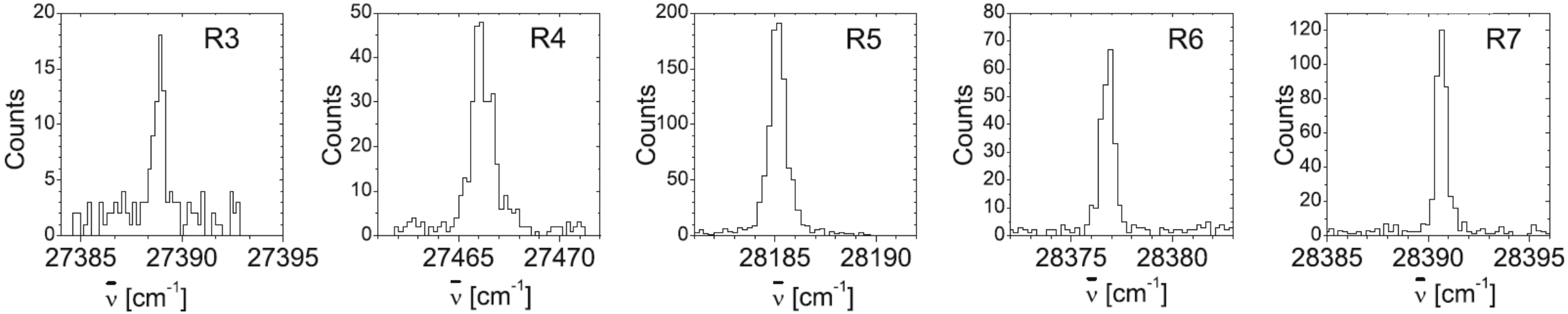
  sensitive to total angular momentum

  F of hyperfine structure (HFS)
- New AI found and used
- HFS for verification of structure



Further excited states from H. Backe

Resonance R3 and R4 not verified

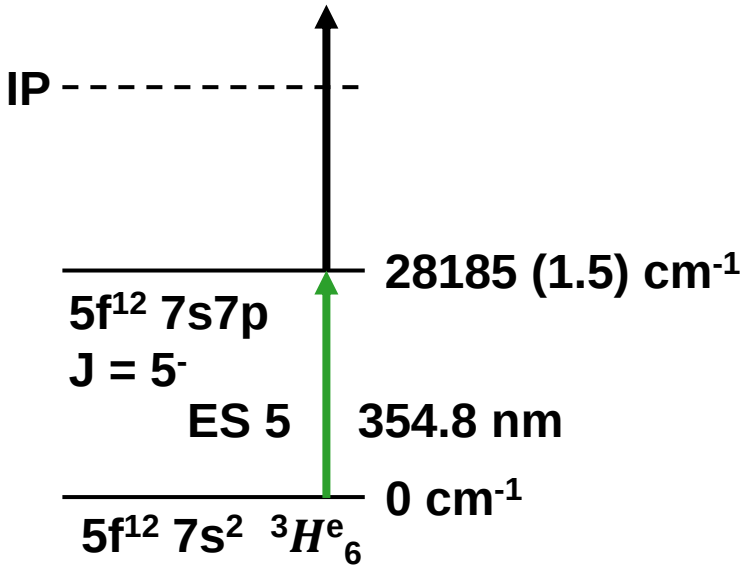


Continue on with resonances R5, R6 and R7

H. Backe et al., Hyperfine Interact. ***162****, 3 (2006)*

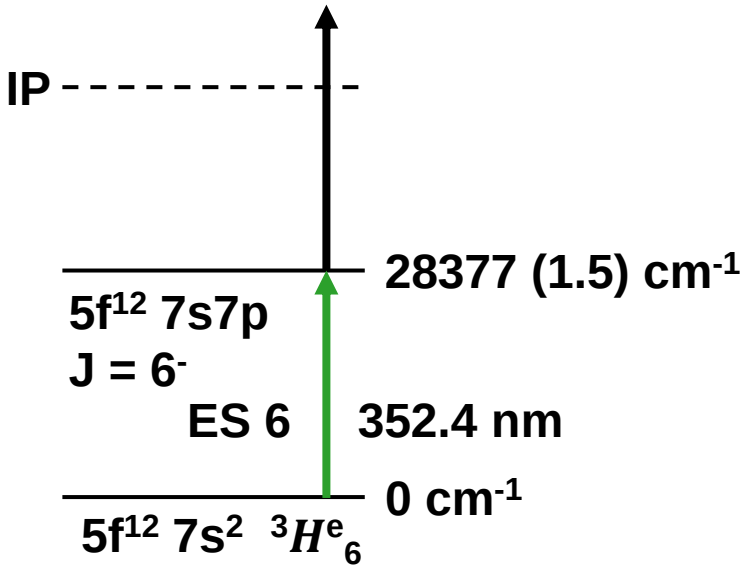
Scan of excited state (28 185 cm^{-1})

- Deviation to H. Backe:



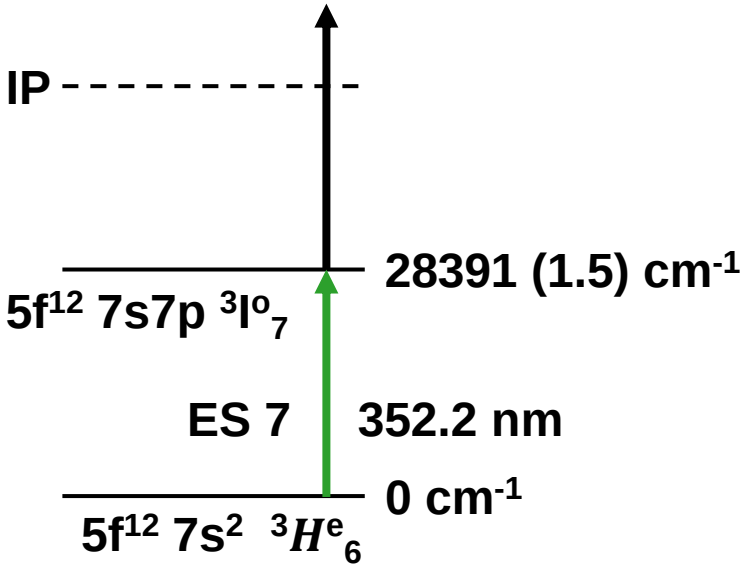
Scan of excited state (28 377 cm^{-1})

- Deviation to H. Backe:



Scan of excited state (28 391 cm^{-1})

- Deviation to H. Backe:



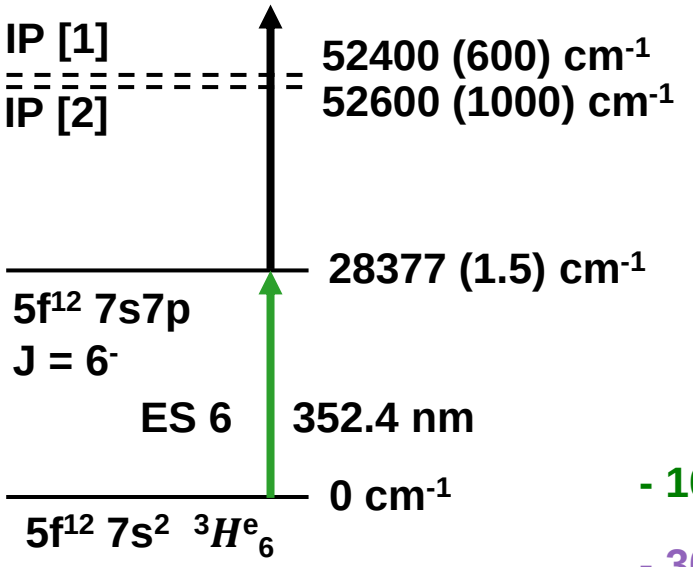
Half-life measurements

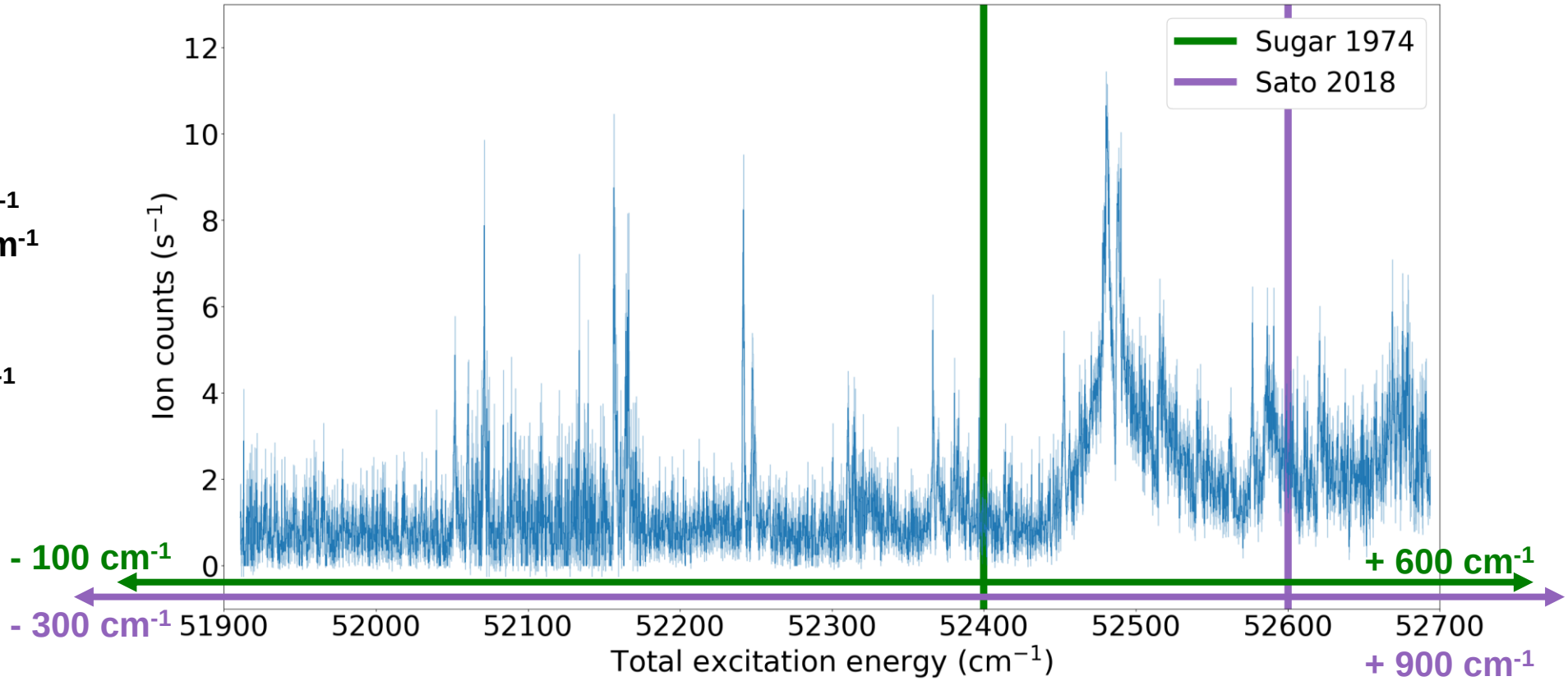
- Half-life determined for excited states 25 099.8 cm^{-1} and 25 111.8 cm^{-1}
  - In 2021 (10^7 atoms) and 2023 (10^9 atoms)
  - By controlled temporal shift of ionization laser
- Full agreement between data
- Half-life of excited states 28 187 cm-1, 28 377 cm-1 and 28 391 cm-1 not determinable

  Half-life shorter than laser pulse ($t_{1/2} < 50$ ns)

Scan of ionization laser in search of Rydberg states

- Scanned 800 cm^{-1} in search for Rydberg states
- Known IP values for fermium





[1] J. Sugar et al., J. Chem. Phys. **60**, 4103 (1974)
[2] T. K. Sato et al., J. Am. Chem. Soc. **140**, 14609 (2018)

Rydberg analysis - Lu Fano plot

Rydberg-Ritz formular:

$$E_n \approx IP - \frac{R_\mu}{(n - \delta(n))^2}$$

Configuration still unclear

[1] J. Sugar et al., J. Chem. Phys. **60**, 4103 (1974)
[2] T. K. Sato et al., J. Am. Chem. Soc. **140**, 14609 (2018)

Conclusion

- Performed laser spectroscopy with sample sizes of 1 pg (10^9 atoms) ^{255}Fm
- Transitions ES 1, ES 2, ES 5, ES 6 and ES 7 confirmed
- Half-lifes for ES 1 and ES 2 determind;

  upper limit set for ES 5, ES 6 and ES 7
- Rydberg series observed in ES 5 and ES 6
- HFS parameter for ES 1 and ES 2 determined

  (for Discussion: Poster M. Gonzales)

Thank you for your attention

RISIKO setup at Mainz