

# Content Lecture 3



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## Resonance Ionization Spectroscopy (RIS)

### Principle

RILIS : Application as a Highly Selective Laser Ion Source

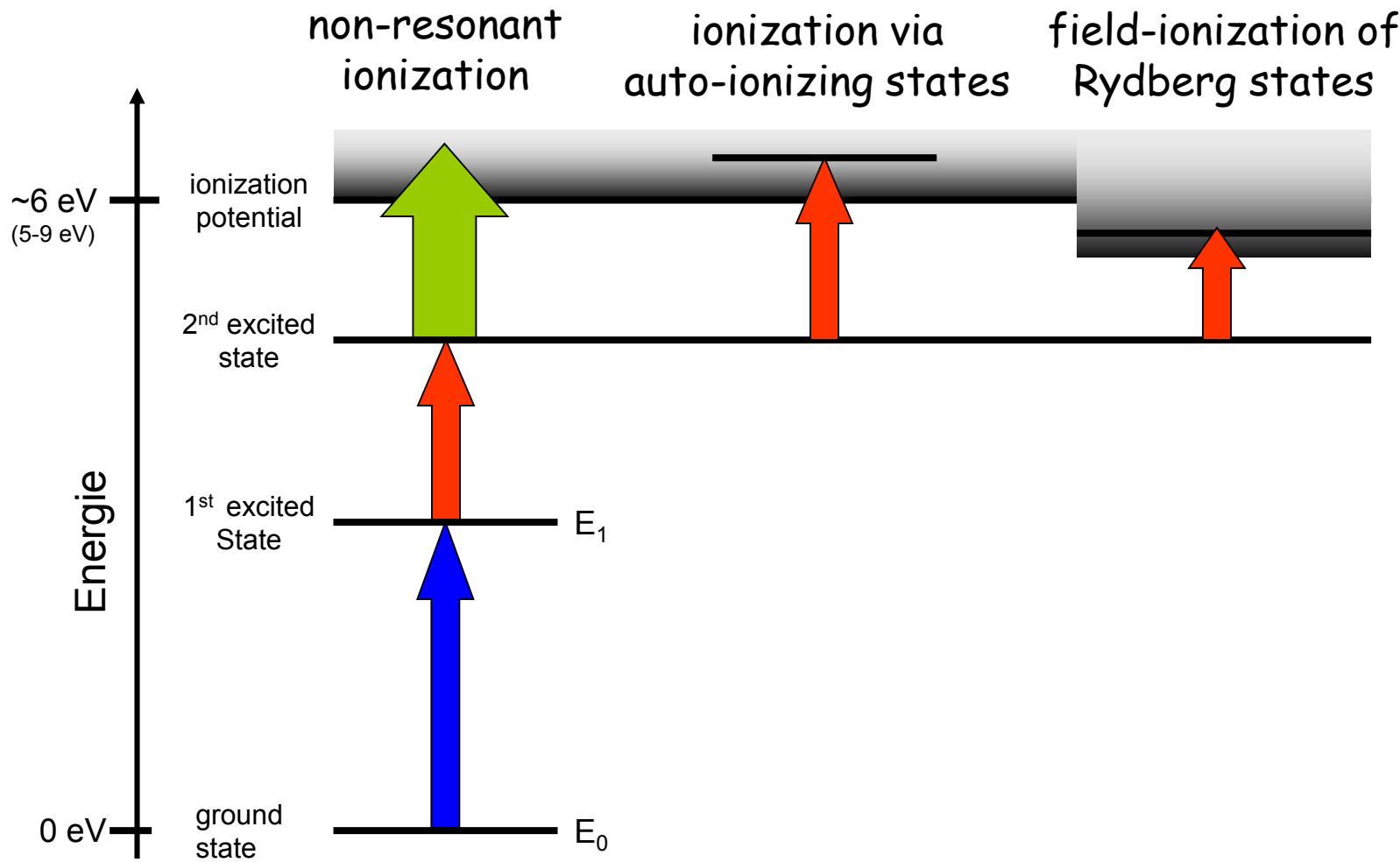
### In-Source Spectroscopy

### Collinear Resonance Ionization (CRIS)

### Gas-Cell Spectroscopy (here: Superheavy Spectroscopy)



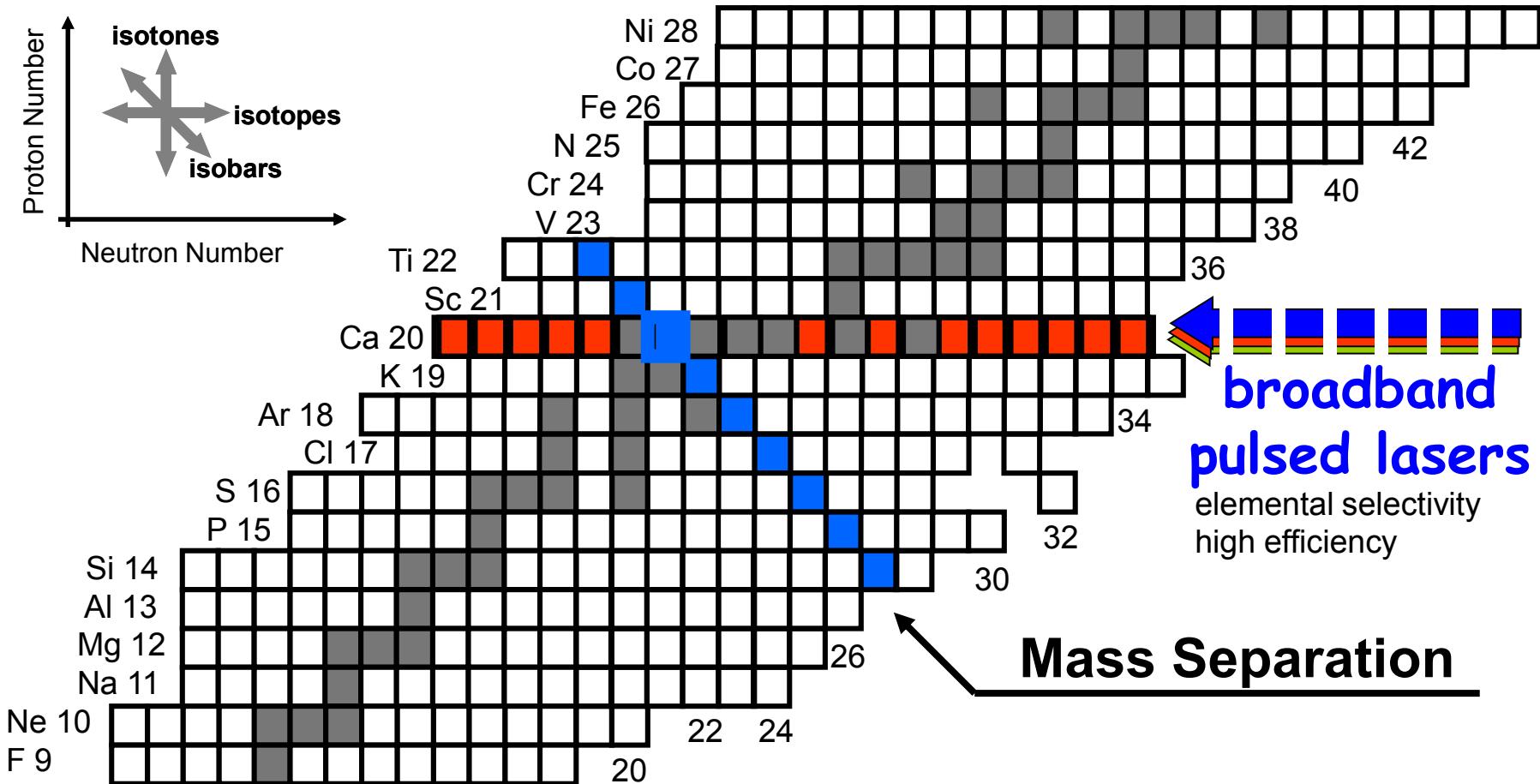
# Principle of Resonance Ionization



# Resonance Ionization for Selective Isotope Production



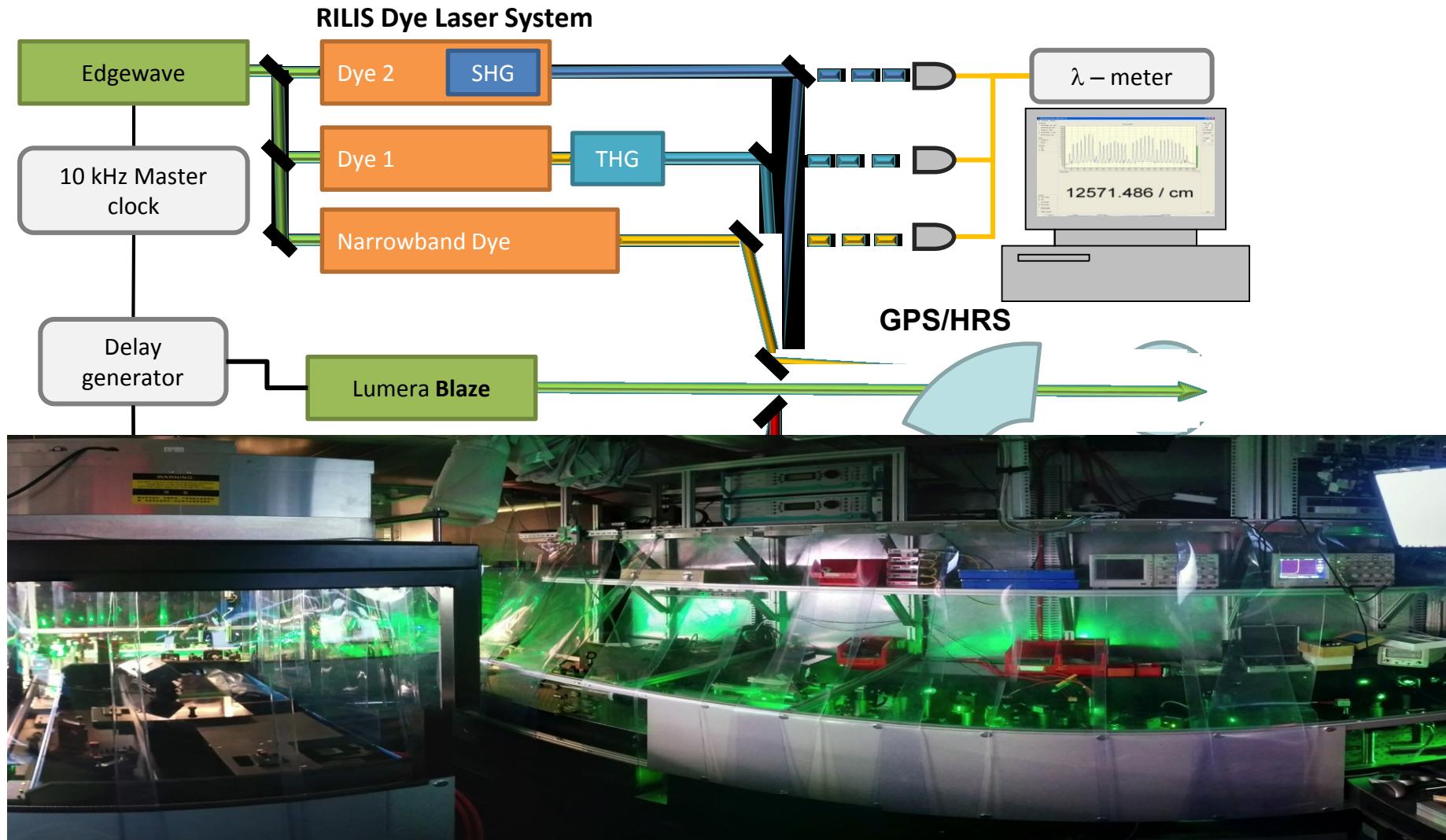
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# Setup of the ISOLDE RILIS



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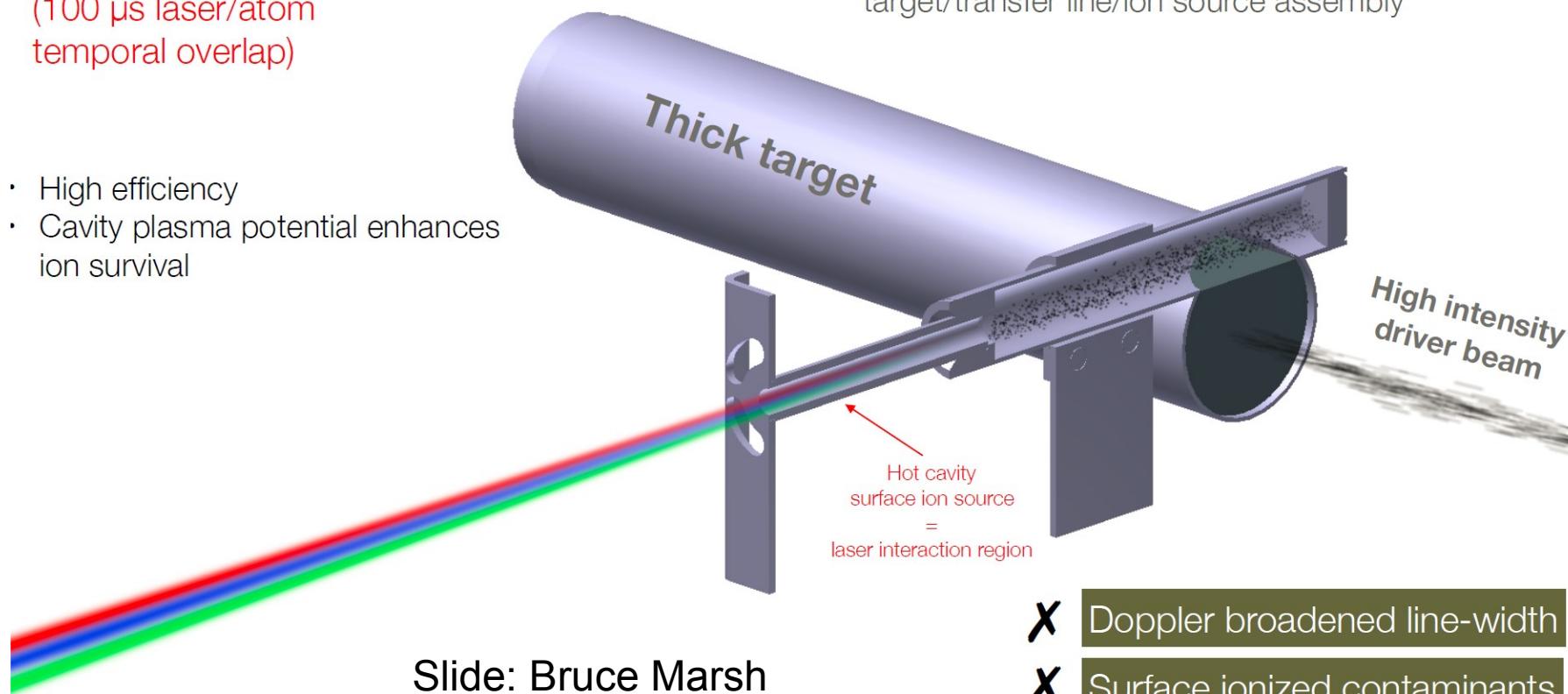


## 36 RILIS ionized elements routinely available

### Laser requirements:

>10 kHz rep rate  
(100  $\mu$ s laser/atom  
temporal overlap)

- High efficiency
- Cavity plasma potential enhances ion survival



# RILIS Elements



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H																				He
Li	Be																			
Na	Mg																			
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr			
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe			
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn			
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo			
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu						
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr						

Feasible      Dye schemes tested      Ti:Sa schemes tested      Dye and Ti:Sa schemes tested

# RILIS statistics for 2015 on-line operation



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17 elements

23 RILIS runs

116 operating days

Ag, Al, Au, Ba, Be, Ca,  
Cd, Cu, Dy,  
Ga, Hg, In, Mg, Mn, Po, Tl,  
Zn

**2550 hours** (*not including setup time of >1000 person-hours*)

**> 75 %** of ISOLDE Physics

Statistics B. Marsh, K. Johnston



# Strength of the RIS technique



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## Sensitivity: Current record ~0.01 ions/s

Physics Letters B 719 (2013) 362–366

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Physics Letters B

[www.elsevier.com/locate/physletb](http://www.elsevier.com/locate/physletb)



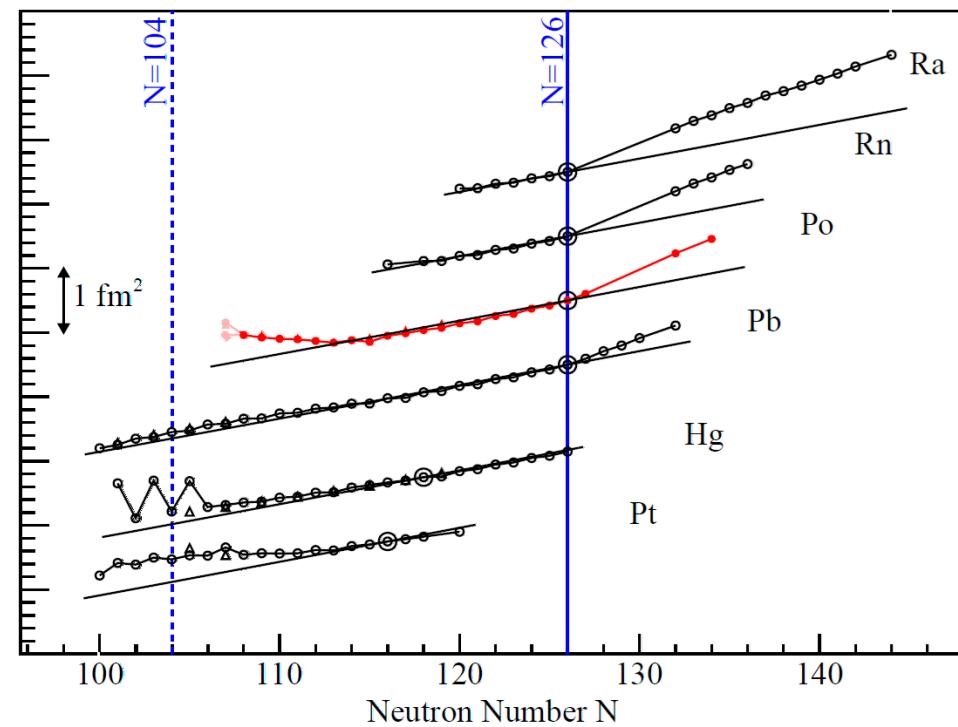
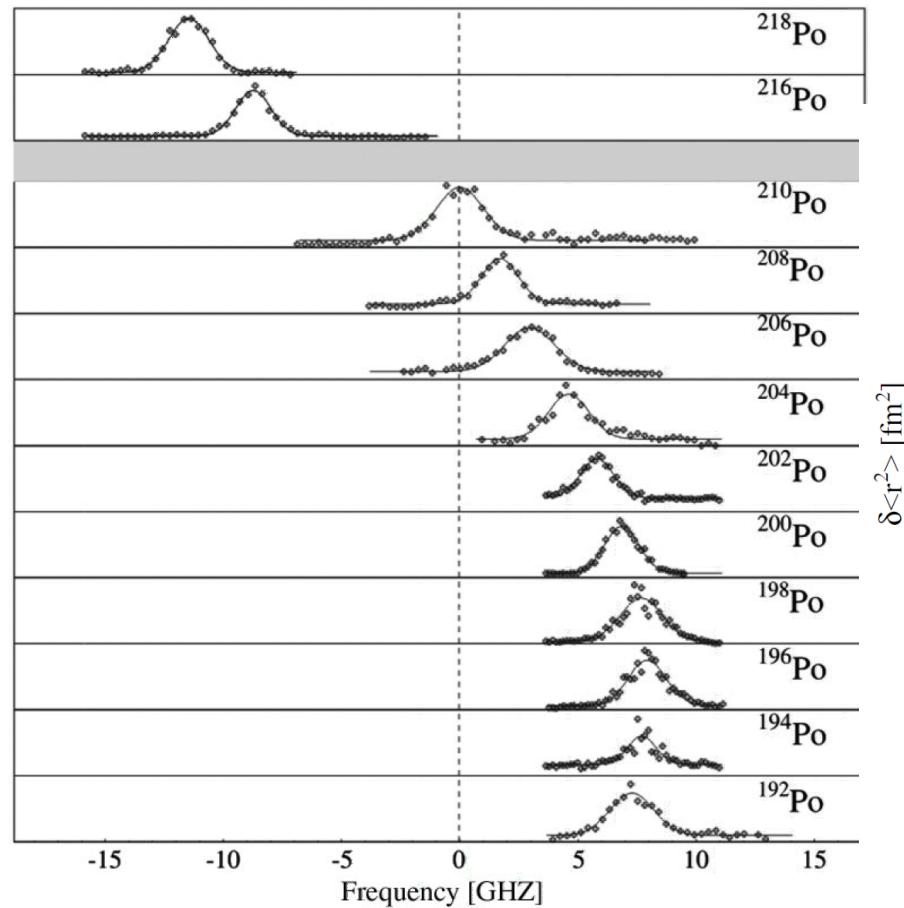
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Charge radii of odd- $A$   $^{191-211}\text{Po}$  isotopes

M.D. Seliverstov <sup>a,b,c,d,e,f,\*</sup>, T.E. Cocolios <sup>a,g</sup>, W. Dexters <sup>a</sup>, A.N. Andreyev <sup>a,d,e,f</sup>, S. Antalic <sup>h</sup>, A.E. Barzakh <sup>b</sup>, B. Bastin <sup>a,1</sup>, J. Büscher <sup>a</sup>, I.G. Darby <sup>a</sup>, D.V. Fedorov <sup>b</sup>, V.N. Fedoseyev <sup>g</sup>, K.T. Flanagan <sup>i,j</sup>, S. Franschoo <sup>k</sup>, S. Fritzsche <sup>l,m</sup>, G. Huber <sup>c</sup>, M. Huyse <sup>a</sup>, M. Keupers <sup>a</sup>, U. Köster <sup>n</sup>, Yu. Kudryavtsev <sup>a</sup>, B.A. Marsh <sup>g</sup>, P.L. Molkanov <sup>b</sup>, R.D. Page <sup>o</sup>, A.M. Sjödin <sup>g,p,1</sup>, I. Stefan <sup>k</sup>, J. Van de Walle <sup>a,g,2</sup>, P. Van Duppen <sup>a,g</sup>, M. Venhart <sup>a,q</sup>, S.G. Zemlyanov <sup>r</sup>

<http://dx.doi.org/10.1016/j.physletb.2013.01.043>

# In-Source Spectroscopy of Polonium



# Volume and deformation-induced $\delta\langle r^2 \rangle$

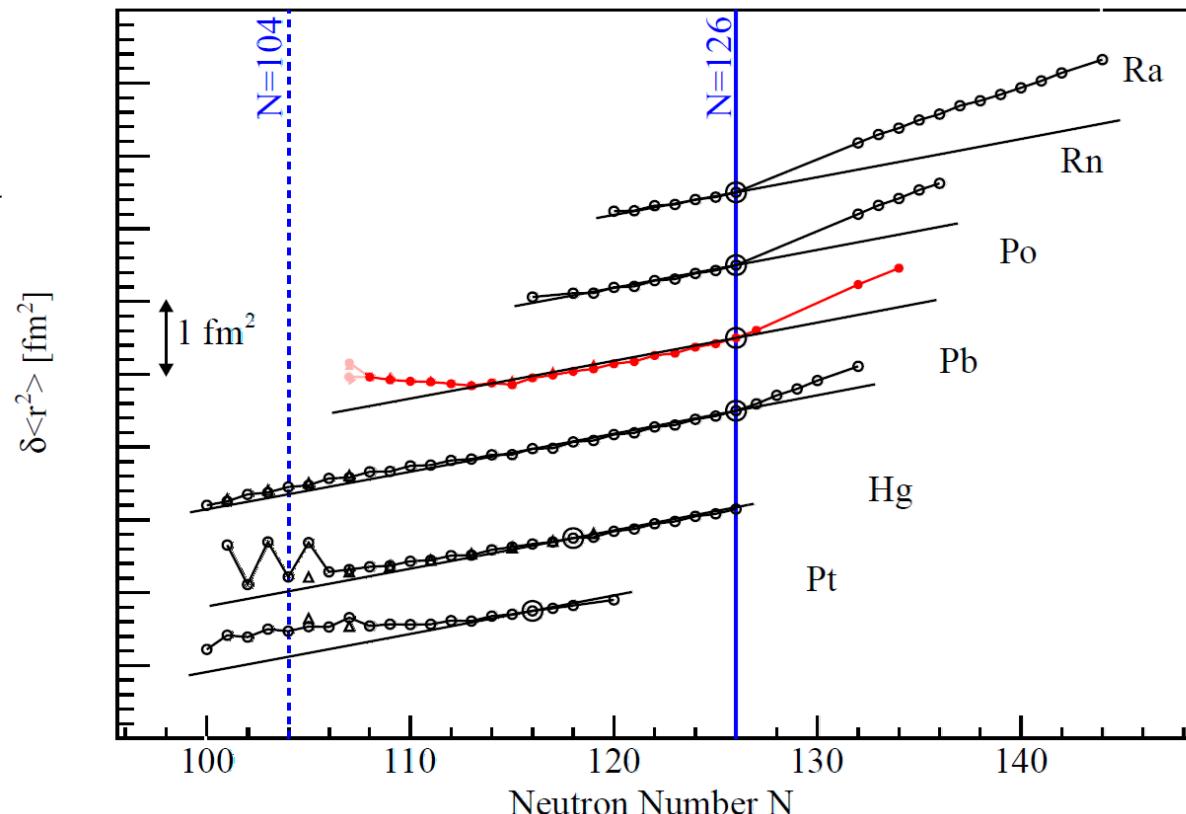


- Increasing Volume

$$\langle r^2 \rangle_{Sph} = \frac{3}{5} R_0^2 = \frac{3}{5} \sqrt[3]{A^2} r_0^2$$

$$\delta\langle r^2 \rangle_{Sph} = \langle r^2 \rangle_{Sph} \frac{2}{3} \frac{\delta A}{A} = \frac{2}{5} r_0^2 \frac{\delta A}{\sqrt{A}}$$

Homogenously charged sphere with sharp edge at  $r = R_0 = r_0 A^{1/3}$



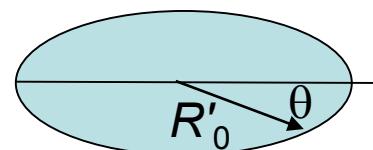
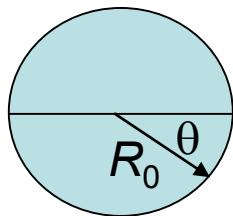
# Volume and deformation-induced $\delta\langle r^2 \rangle$



- Increasing Volume
- Deformation

$$\langle r^2 \rangle_{Sph} = \frac{3}{5} R_0^2 = \frac{3}{5} \sqrt[3]{A^2} r_0^2$$

$$\delta\langle r^2 \rangle_{Sph} = \langle r^2 \rangle_{Sph} \frac{2}{3} \frac{\delta A}{A} = \frac{2}{5} r_0^2 \frac{\delta A}{\sqrt{A}}$$

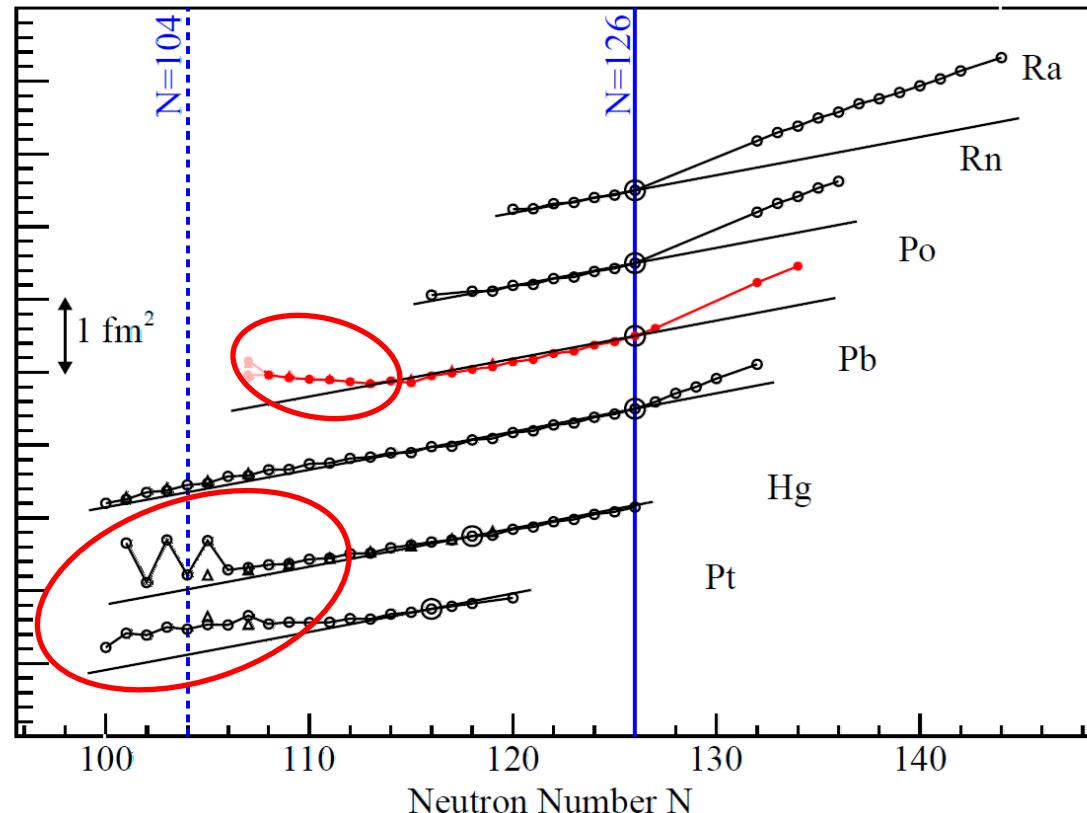


$$\rho_{Def}(\vec{r}') = \rho_{Sph}(r)(1 + \beta_2 Y_{20}(\theta))$$

$$\delta\langle r^2 \rangle_{Def} = \delta\langle r^2 \rangle_{Sph}^{AA'} + \boxed{\frac{5}{4\pi} \langle r^2 \rangle_{Sph} \delta\langle \beta_2^2 \rangle^{AA'}}$$

Deformation

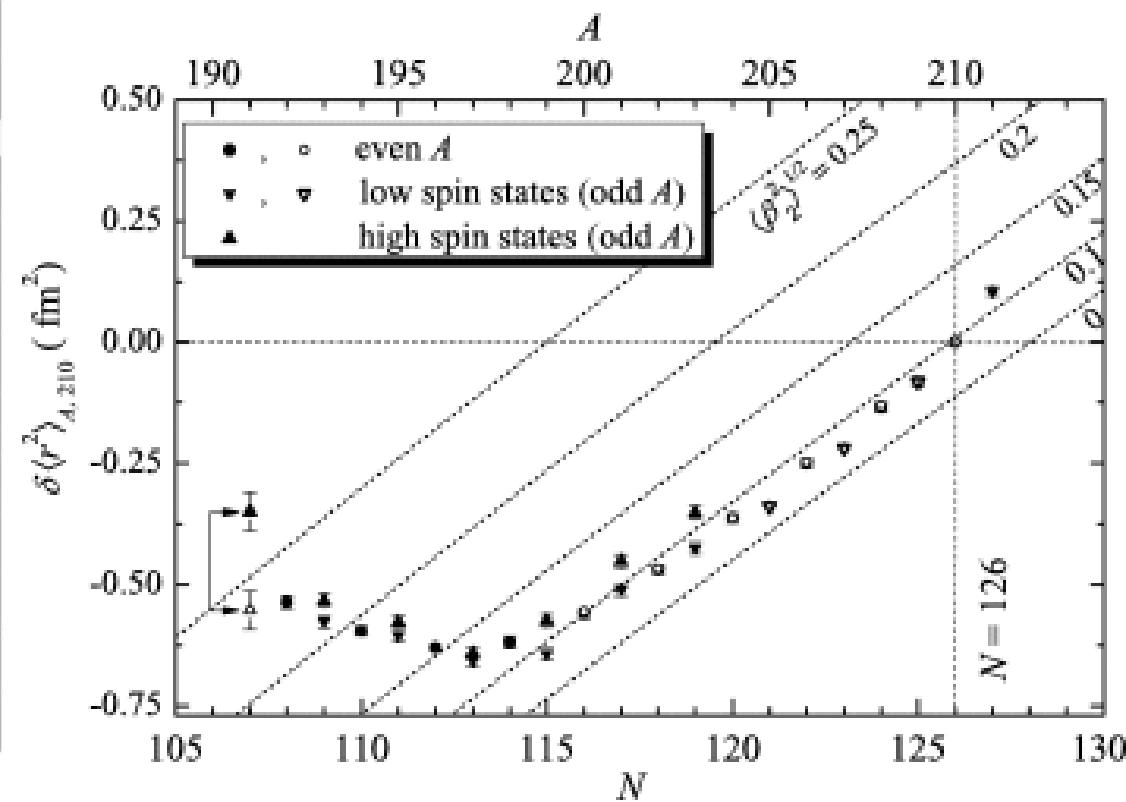
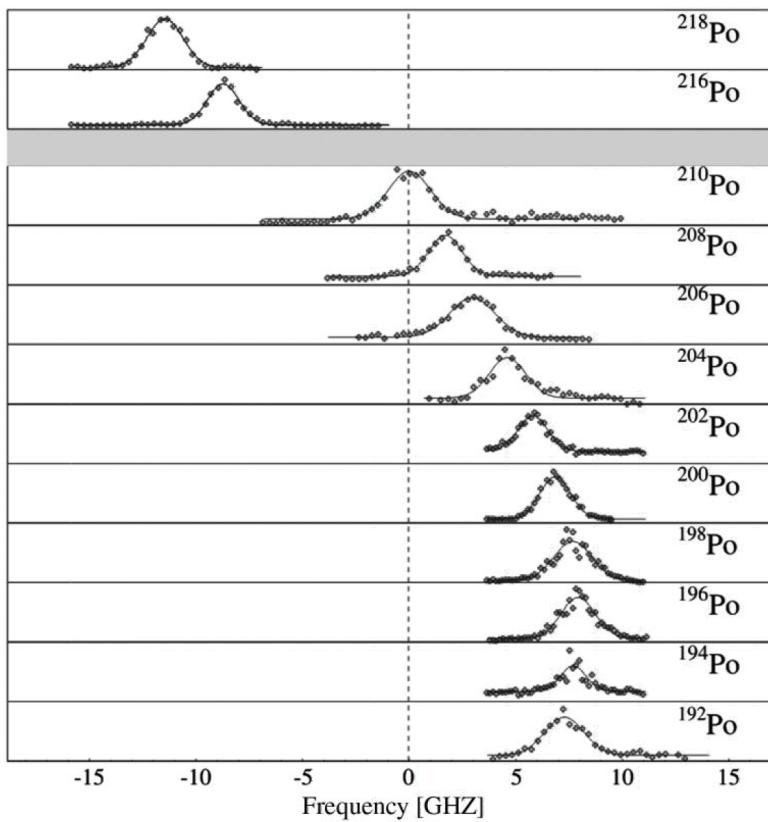
Homogenously charged sphere with sharp edge at  $r = R_0 = r_0 A^{1/3}$



# In-Source Spectroscopy of Polonium



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# 1977: Odd-Even Staggering in Hg



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## Nuclear Shape Staggering in Very Neutron-Deficient Hg Isotopes Detected by Laser Spectroscopy<sup>(a)</sup>

T. Kühl, P. Dabkiewicz, C. Duke,<sup>(b)</sup> H. Fischer, H.-J. Kluge, H. Kremmling, and E.-W. Otten  
Institut für Physik, Universität Mainz, Mainz, Germany  
(Received 1 April 1977)

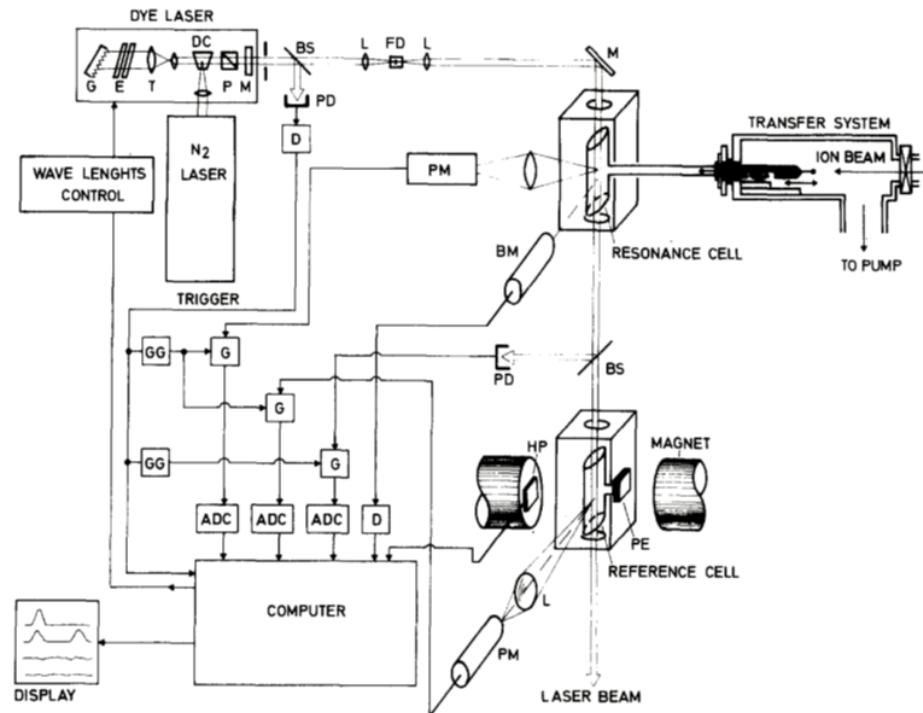
Volume 60A, number 4

PHYSICS LETTERS

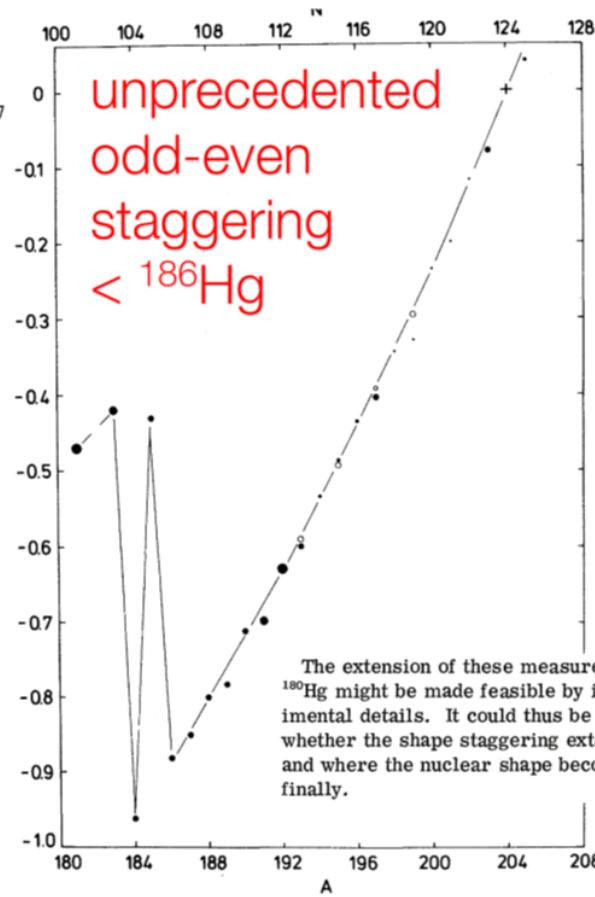
VOLUME 39, NUMBER 4

PHYSICAL REVIEW LETTERS

25 JULY 1977



7 March 1977

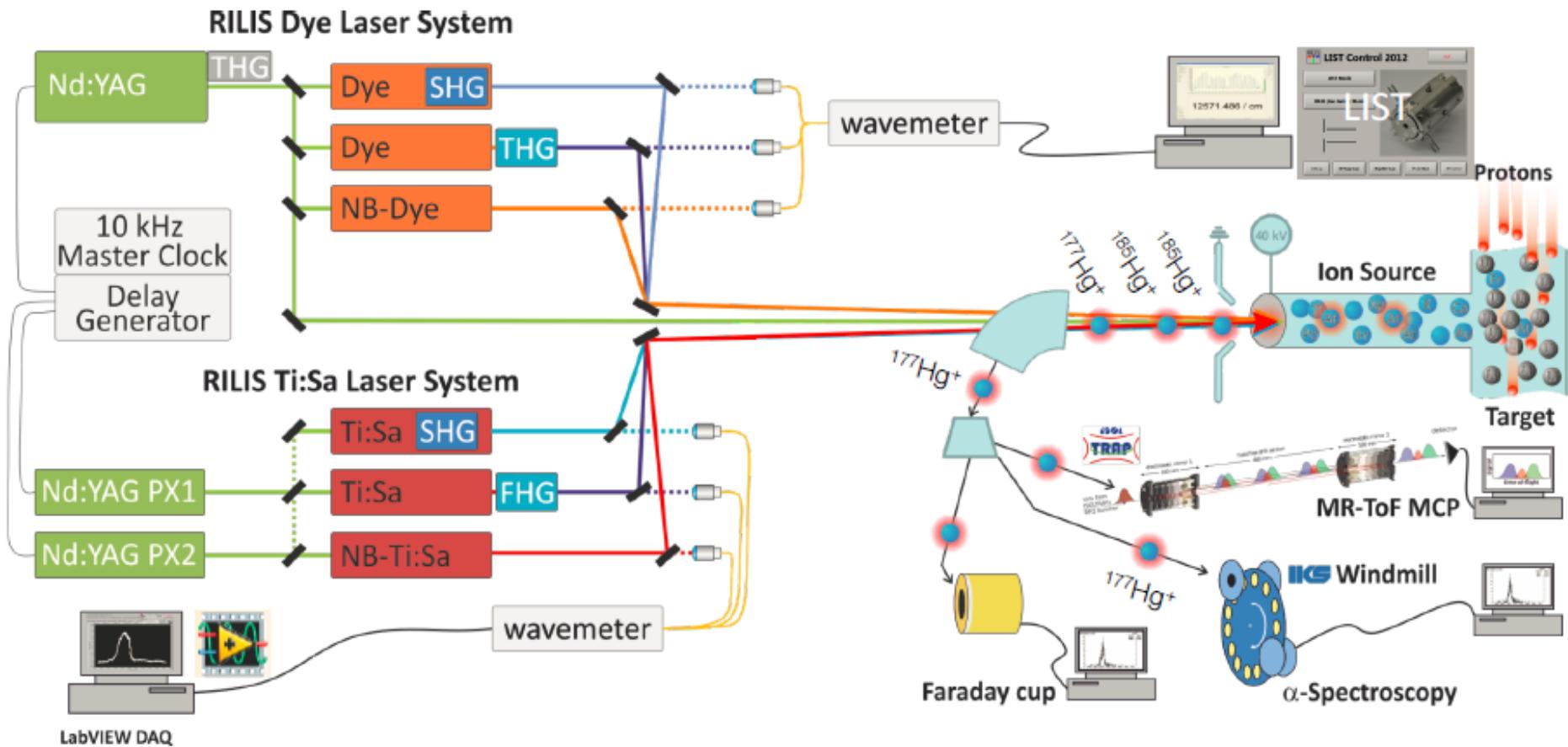


The extension of these measurements down to  $^{180}\text{Hg}$  might be made feasible by improving experimental details. It could thus be determined whether the shape staggering extends further, and where the nuclear shape becomes stabilized finally.

# In-Source Spectroscopy of Mercury Isotopes



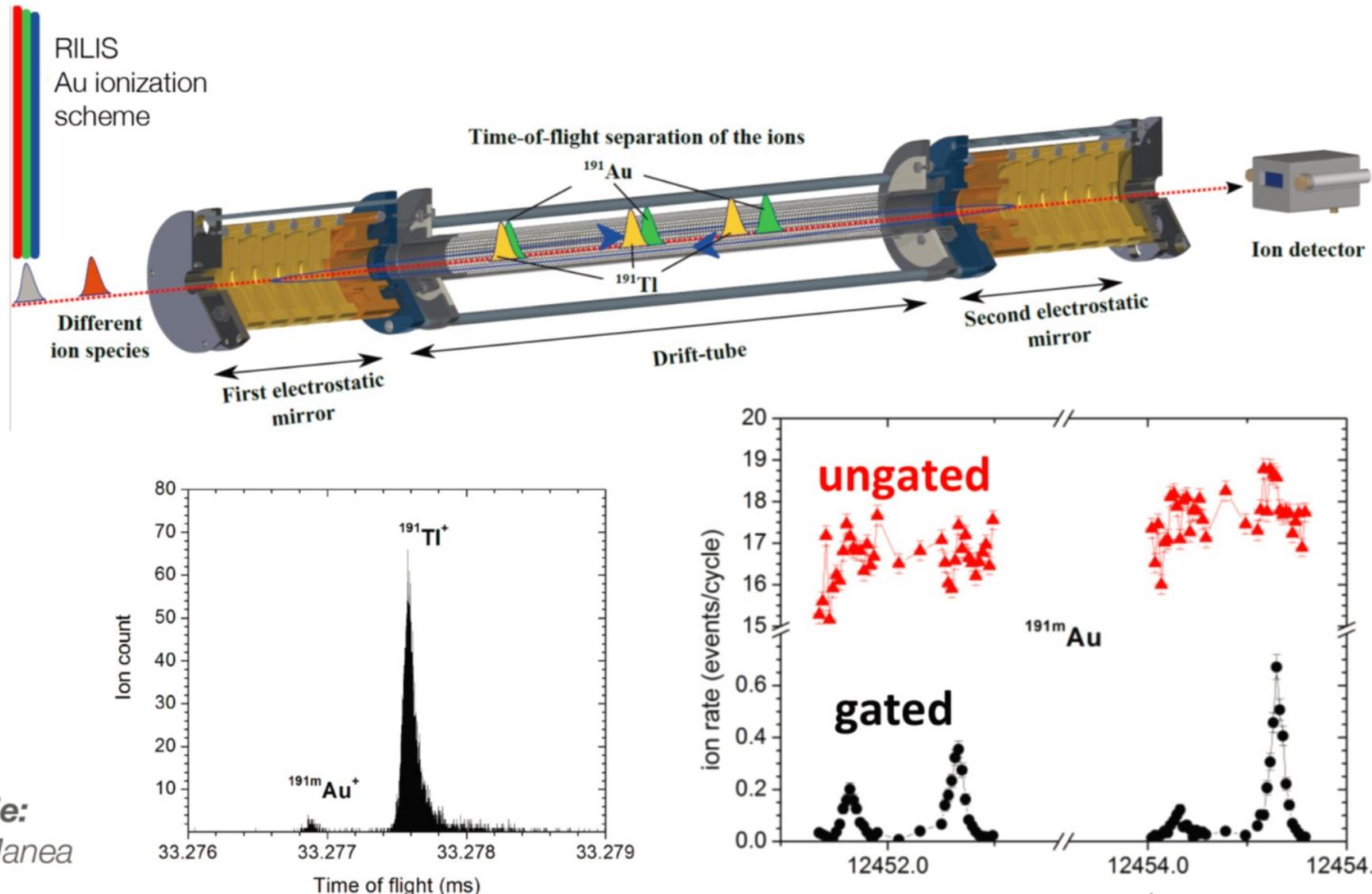
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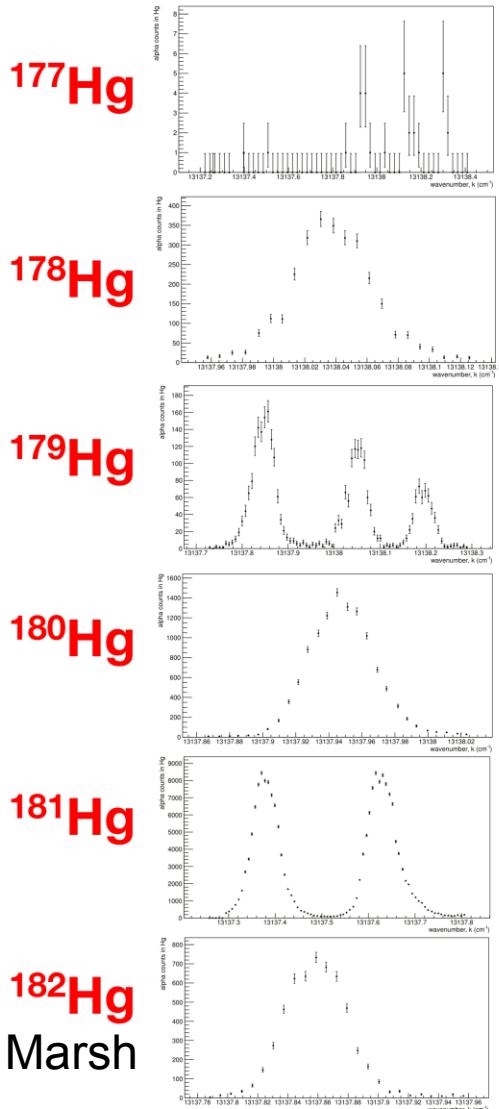
# In-Source Spectroscopy: Increasing Selectivity & MR-TOF



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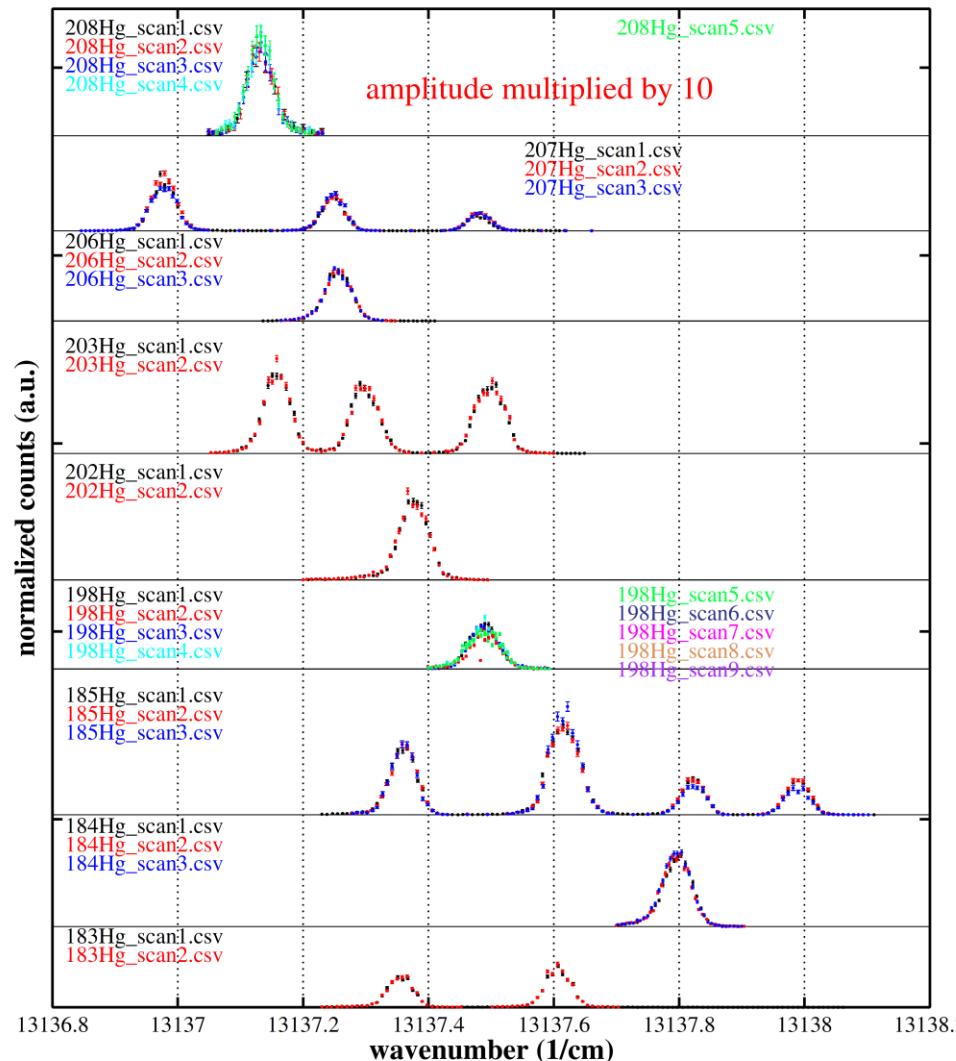


# Resonance Spectra of Mercury Isotopes



**177Hg**  
**178Hg**  
**179Hg**  
**180Hg**  
**181Hg**  
**182Hg**

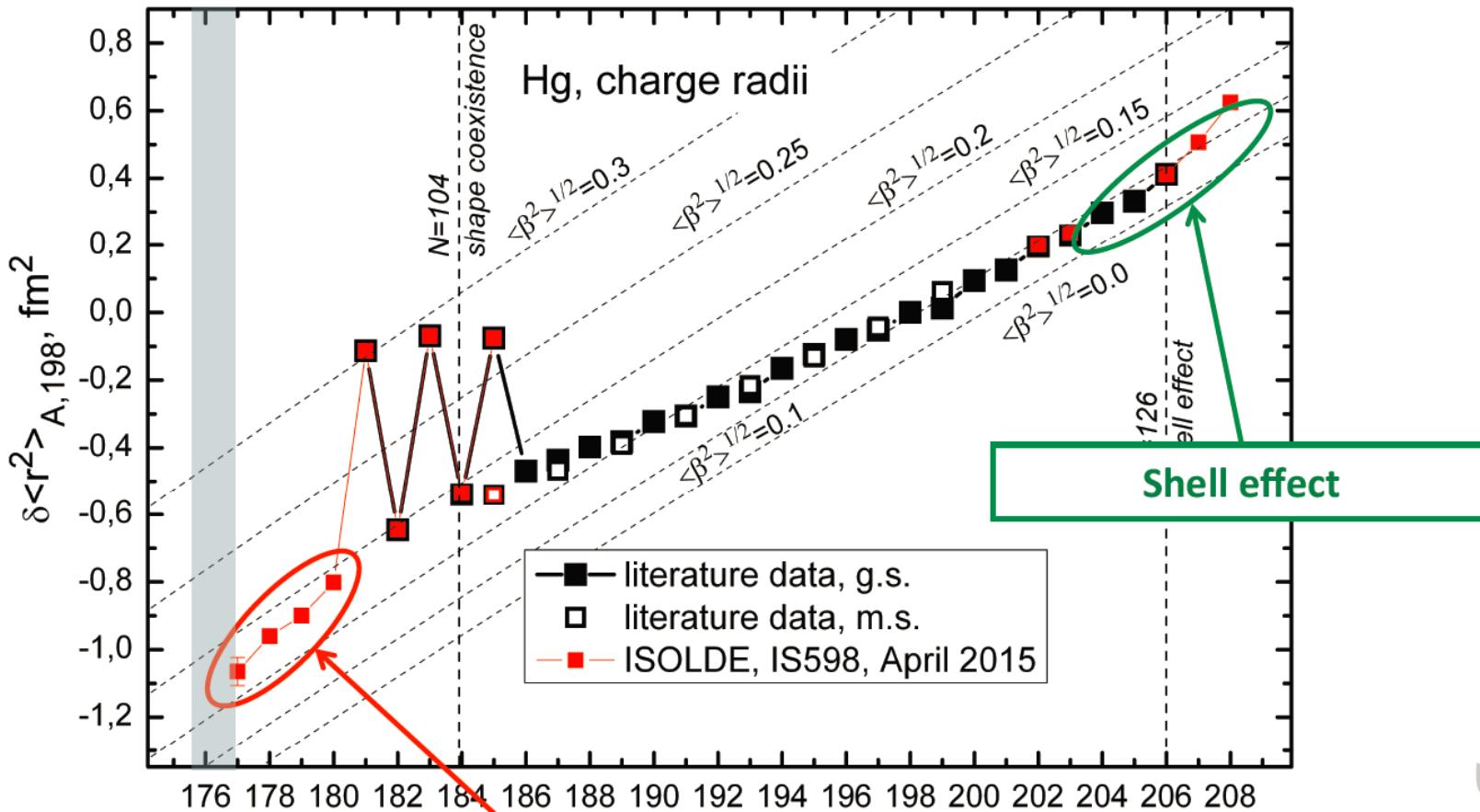
normalized counts (a.u.)



13136.8    13137    13137.2    13137.4    13137.6    13137.8    13138    13138.2

wavenumber (1/cm)

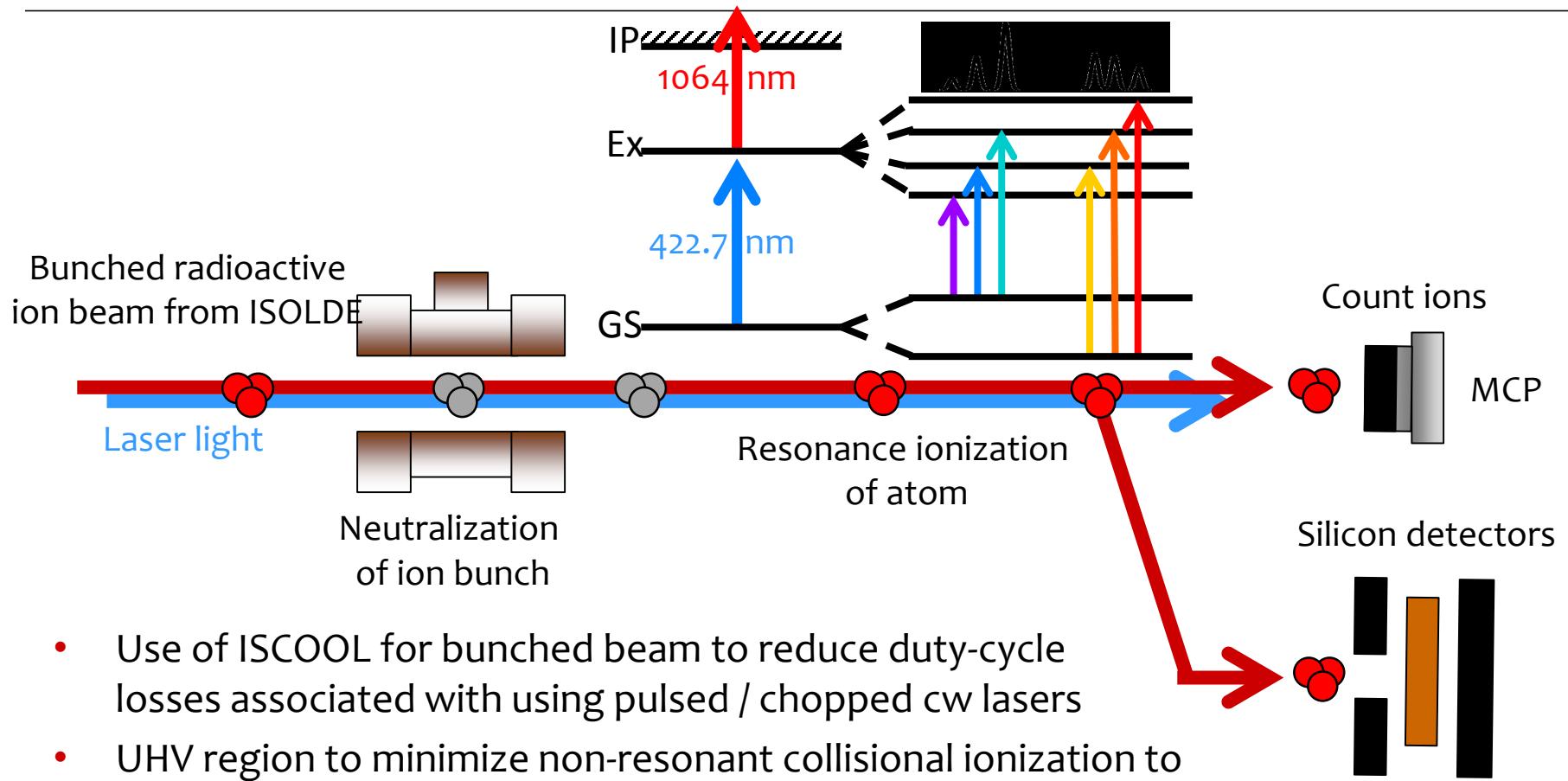
# Charge Radii of Mercury Isotopes



# Combining Collinear Spectroscopy and Resonance Ionization: CRIS



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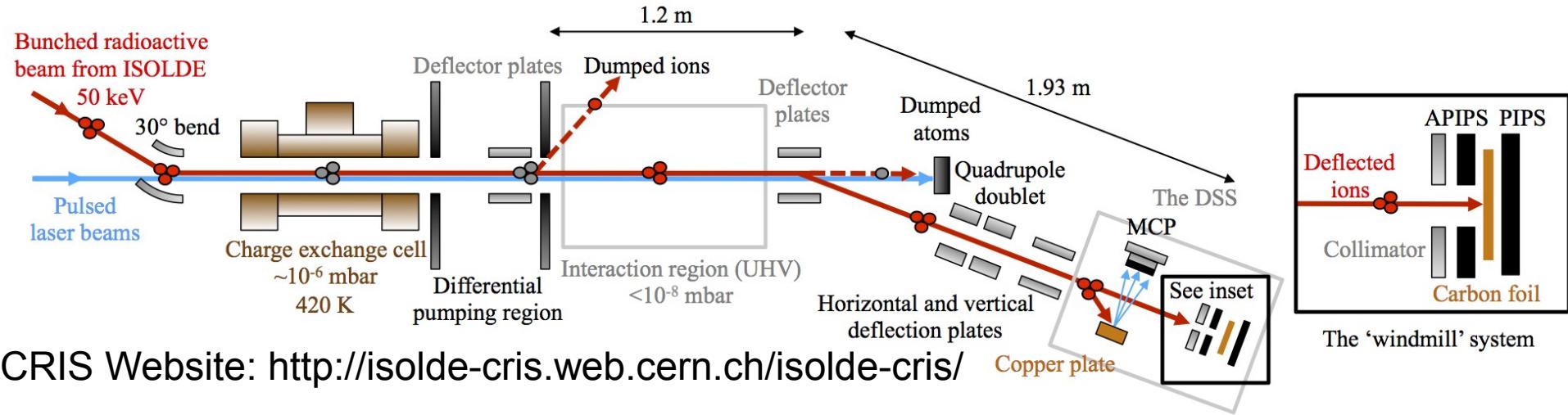


- Use of ISCOOL for bunched beam to reduce duty-cycle losses associated with using pulsed / chopped cw lasers
- UHV region to minimize non-resonant collisional ionization to minimize background
- Collinear geometry reduces thermal Doppler broadening to below natural linewidth of the hyperfine transition (GHz to MHz)

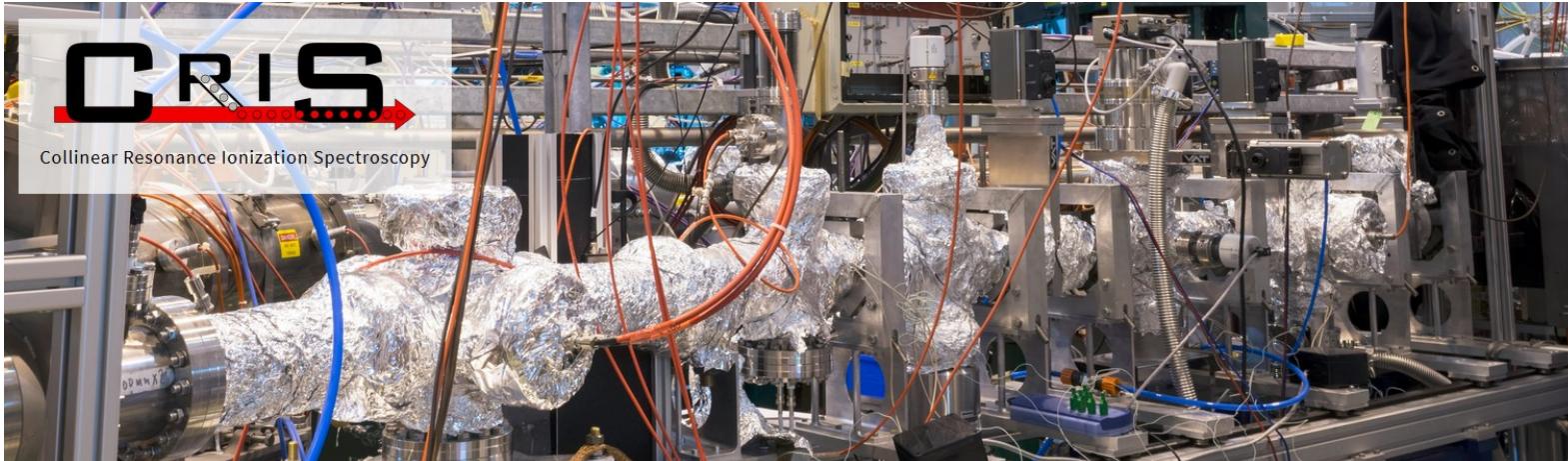
# The CRIS Technique



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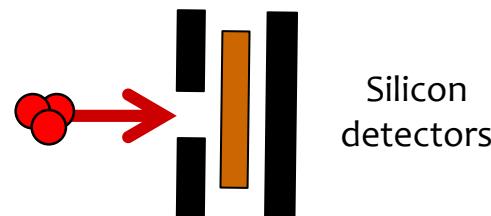
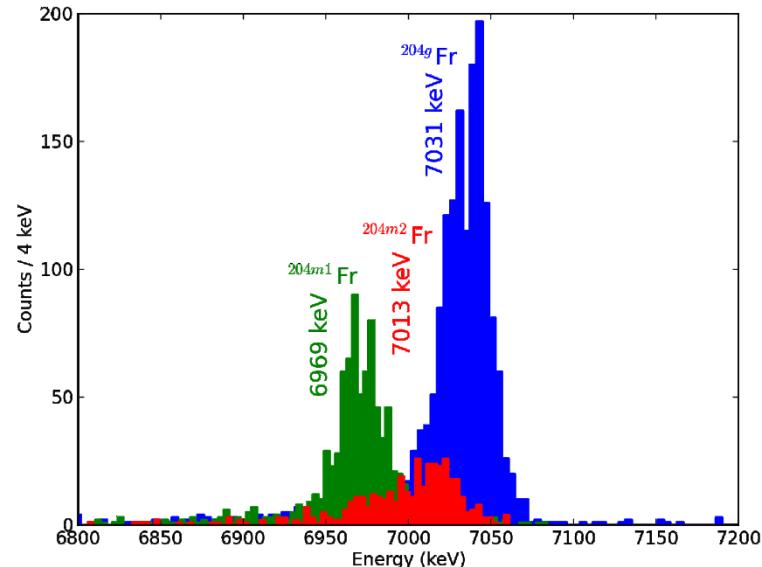
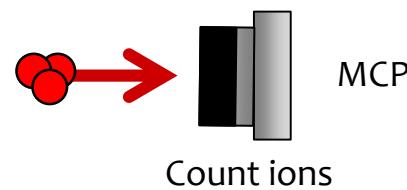
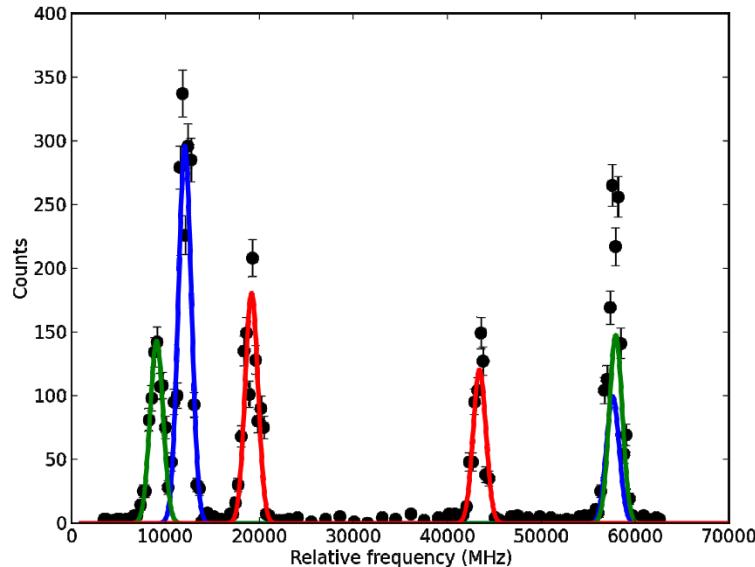
CRIS Website: <http://isolde-cris.web.cern.ch/isolde-cris/>



# Ion Detection - Gaining Additional Information

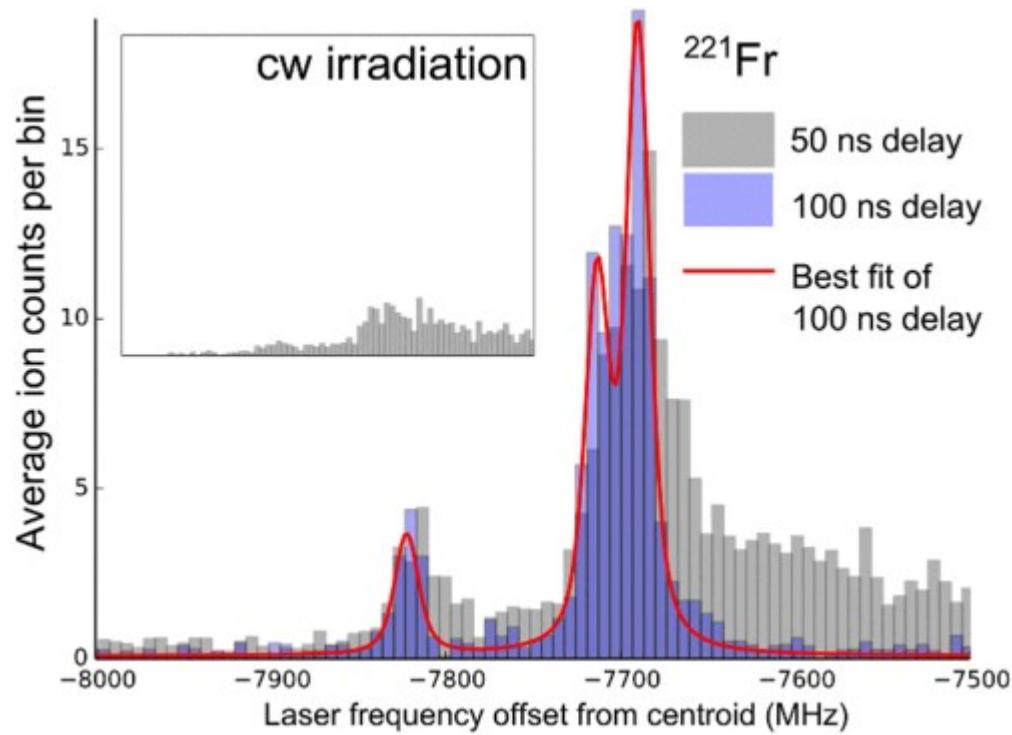


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- Sensitivity of technique comes from:
  - Detection of resonant ions
  - Efficient laser ionization
  - Almost background free detection
- Implantation of the resonant ions in a carbon foil allows their radioactive decay to be measured
- Provides additional information on the isotope (or isomer) under investigation

# Reaching High-Rsolution



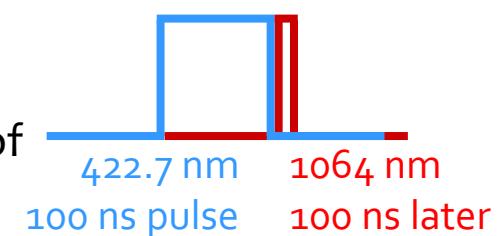
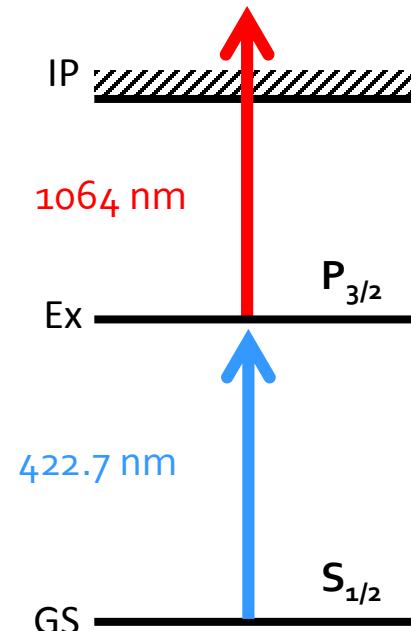
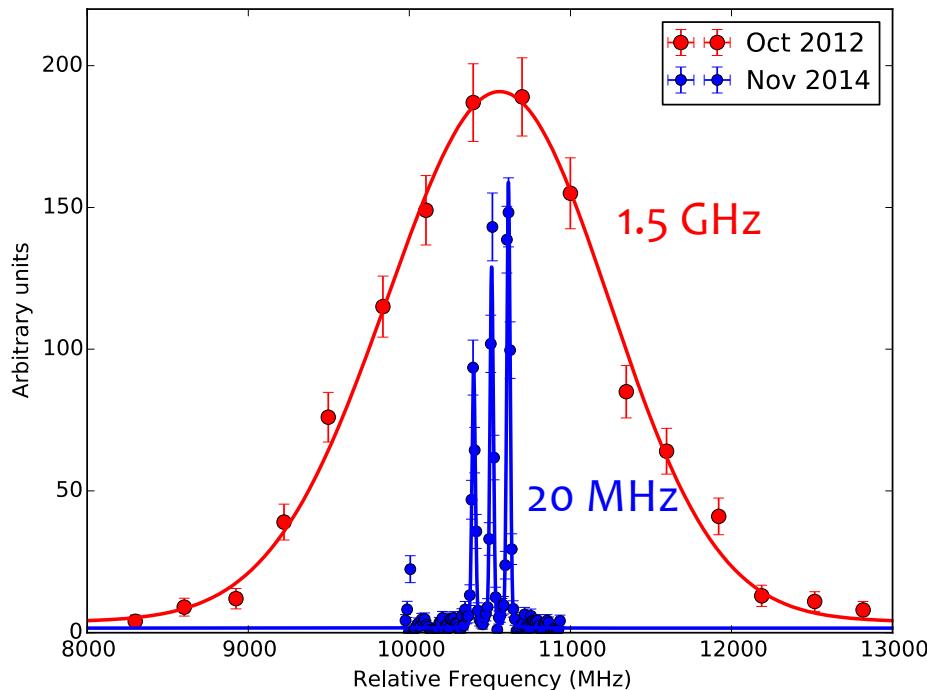
R. P. de Groote et al., PRL 115, 132501 (2015)

<https://doi.org/10.1103/PhysRevLett.115.132501>

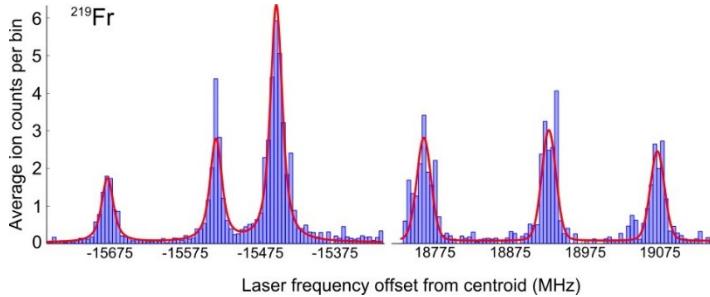
# High-Resolution CRIS



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- The 422 nm CW laser light from the Matisse Ti:Sa laser was chopped into pulses of 100 ns
- The 1064 nm ionization step was delayed by 100 ns after start of the 422 nm excitation step
  - Linewidths down to 20 MHz were achieved
  - Upper-state splitting could now be resolved
    - Extraction of quadrupole moments

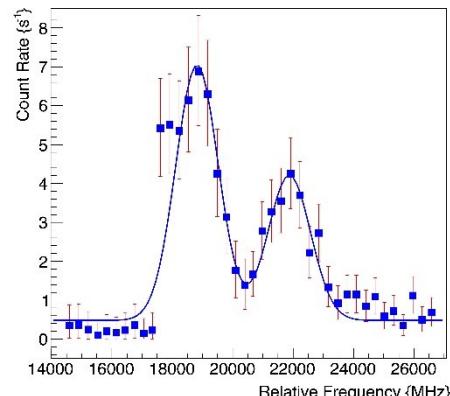
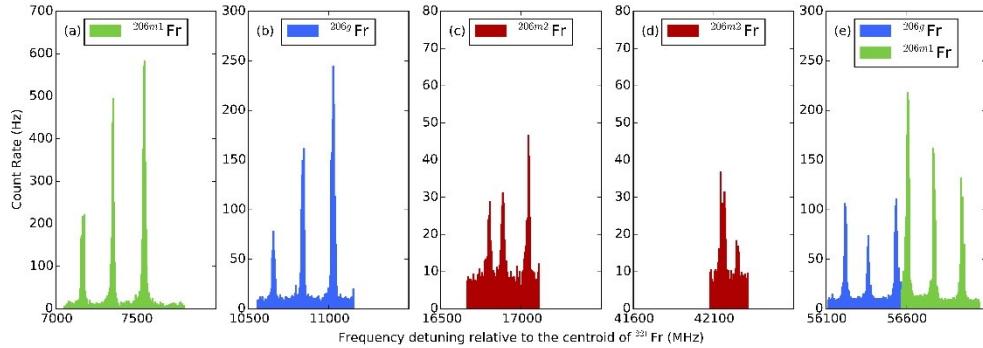


Quadrupole moment of  $^{219}\text{Fr}$  extracted  
 $Q_s = -1.21(2) \text{ eb}$   
 Linewidth of  $20(1) \text{ MHz}$

R.P. de Groot et al., Phys. Rev. Lett. **115** 132501 (2015)

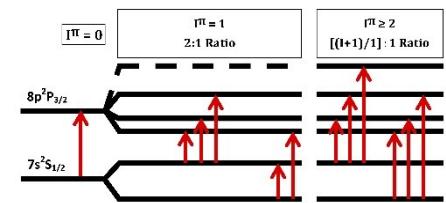
- Hyperfine parameters of  $3^+$ ,  $7^+$  and  $10^-$  states of  $^{206}\text{Fr}$  measured
- Laser-assisted nuclear decay spectroscopy performed on each state
- Branching ratios of  $^{206}\text{Fr}$  and  $^{202}\text{At}$

K.M. Lynch et al., Phys. Rev. C, Submitted (2015)



Hyperfine structure of  $^{214}\text{Fr}$   
 Shortest-lived isotope ( $t_{1/2} = 5 \text{ ms}$ )  
 measured with laser spectroscopy on-line  
 Possible due to 200 Hz repetition rate pulsed laser

G.J. Farooq-Smith et al., In preparation (2016)



# Laser Spectroscopy of the Heaviest Elements



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Slides provided by *Mustapha Laatiaoui* (now KU Leuven)

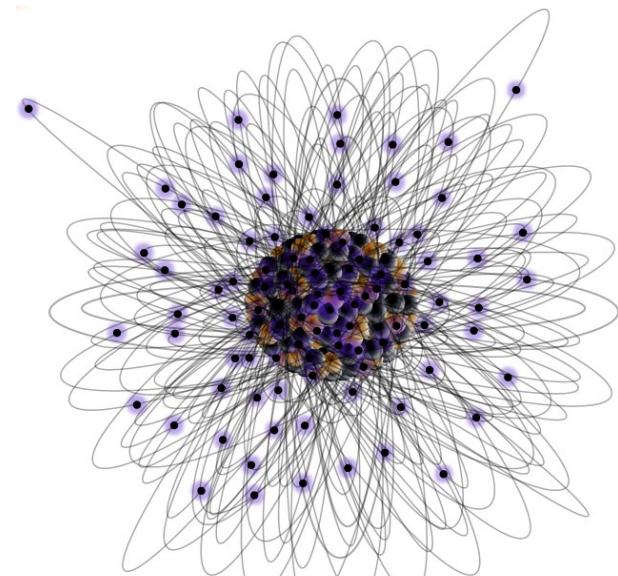
# Motivation



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- Atomic Physics:

➔ Study relativistic effects and how they influence the electronic structure



Nobelium  
Atom

# Motivation



## - Atomic Physics:

- Study relativistic effects and how they influence the electronic structure
- Provide a benchmark for atomic theories

## - Nuclear Physics (via hyperfine structure studies):

$$\Delta E_{HFS} = f(A, B, I, J)$$

- Study nuclear spin coupling
- Extraction of nuclear moments

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

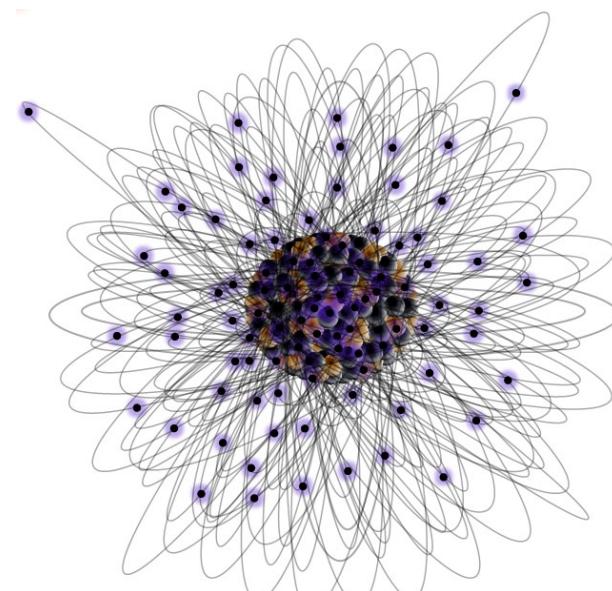
## - Nuclear Physics (via isotope shift measurements):

- Extraction of changes in the mean square charge radii

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

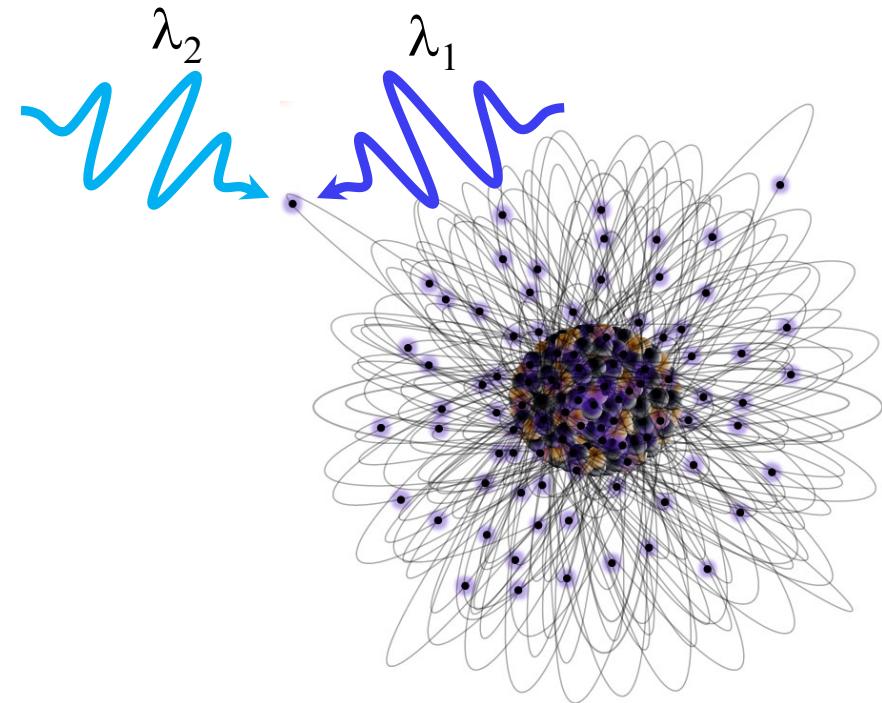
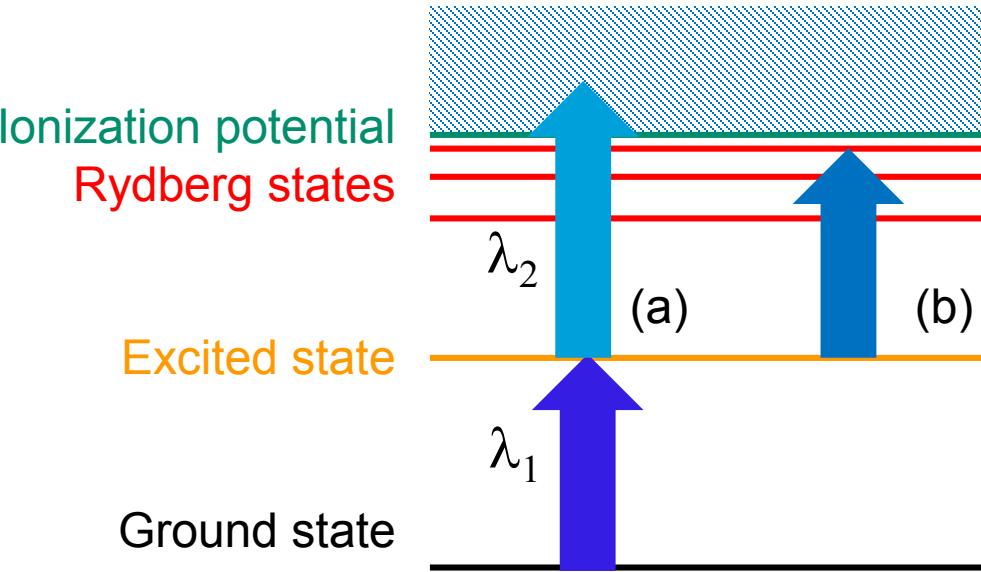
Slide:

M. Laatiaoui



Nobelium  
Atom

# 2-Step Resonance Ionization



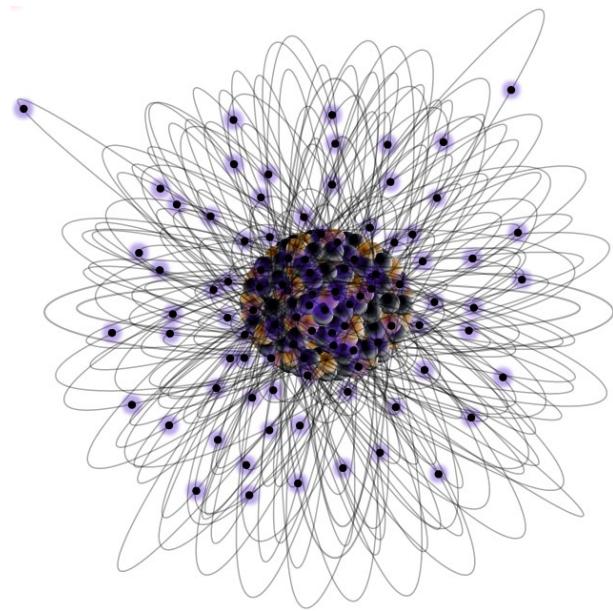
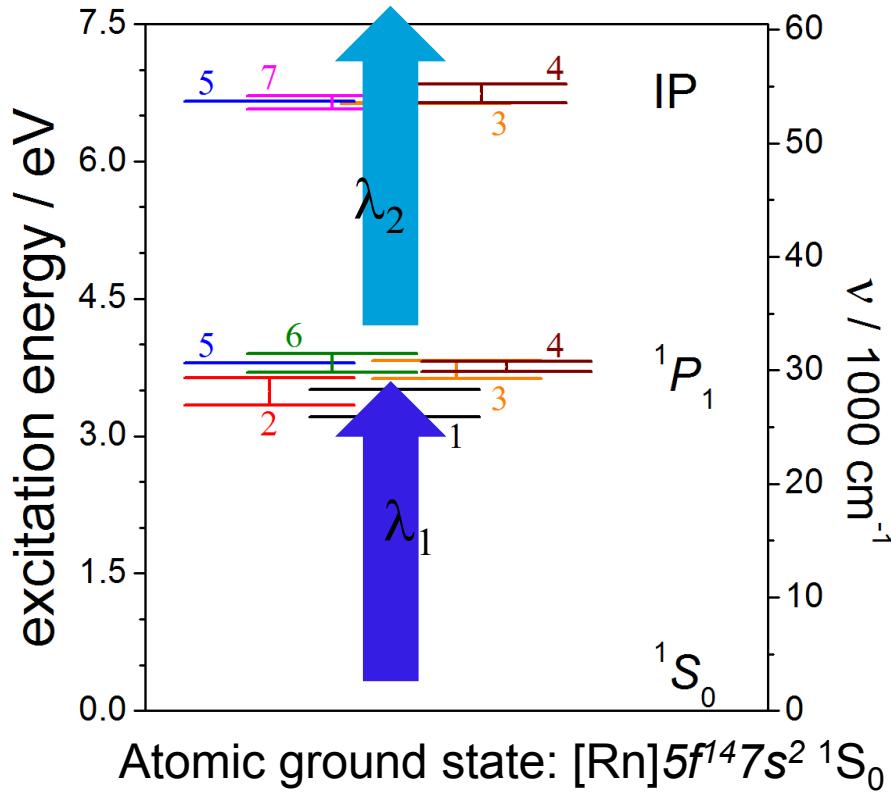
- Scenario (a) about 2 orders of magnitude less efficient compared with (b)

Nobelium  
Atom

# Predicted ground-state transition in nobelium



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Nobelium  
Atom

## 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

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

M. Laatiaoui

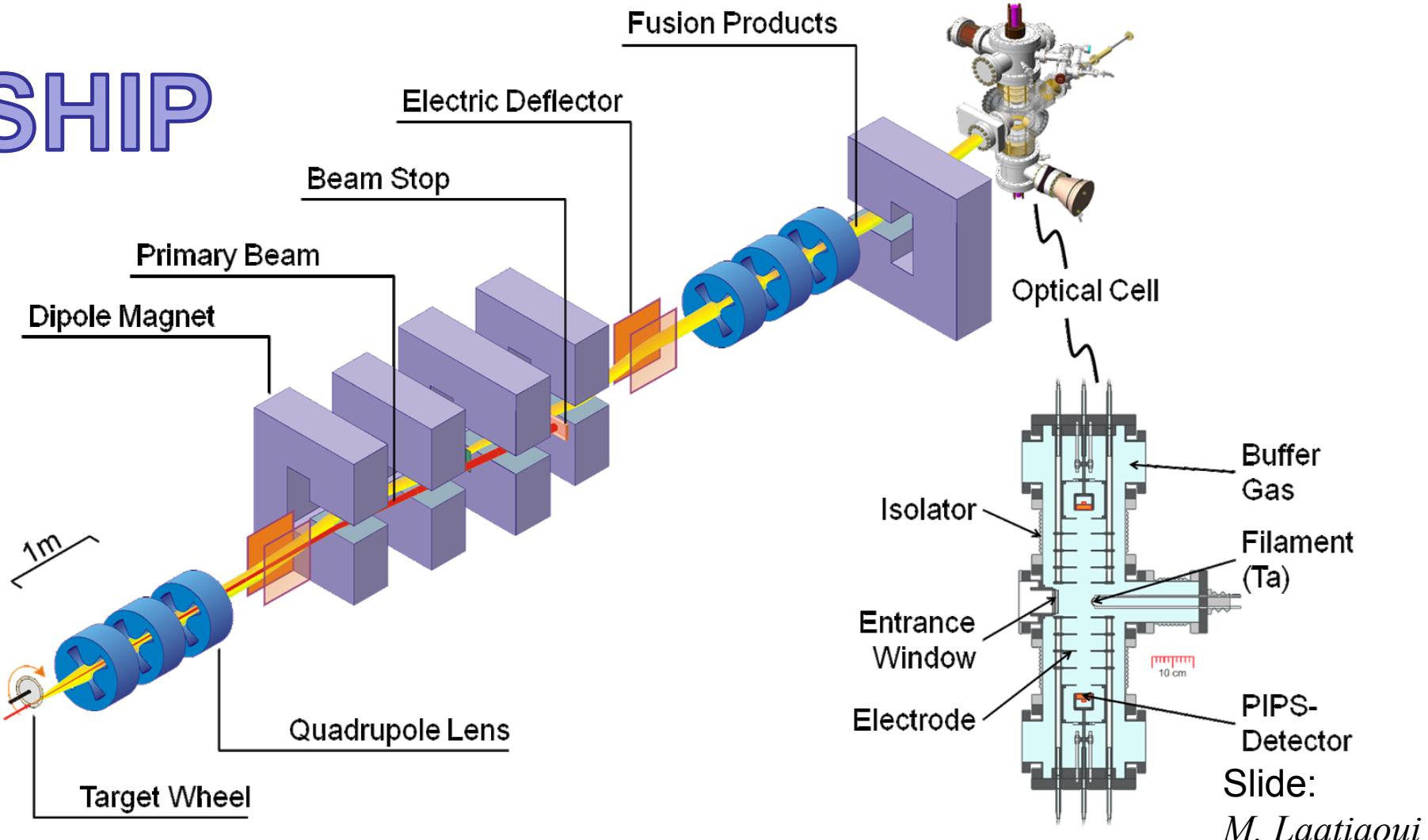
# Nobelium & Lawrencium isotopes



Isotope	I <sup>P</sup>	T <sub>1/2</sub> (s)	Nuclear reaction	Max. production on target (1/s)	Alpha energy (MeV)
<sup>251</sup> No	0	0.8	<sup>206</sup> Pb( <sup>48</sup> Ca,3n) <sup>251</sup> No	0.2	8.61
<sup>252</sup> No	0	2.4	<sup>206</sup> Pb( <sup>48</sup> Ca,2n) <sup>252</sup> No	4	8.42
<sup>253</sup> No	(9/2 <sup>-</sup> )	102	<sup>207</sup> Pb( <sup>48</sup> Ca,2n) <sup>253</sup> No	11	8.01
<sup>254</sup> No	<b>0</b>	<b>51</b>	<b><sup>208</sup>Pb(<sup>48</sup>Ca,2n)<sup>254</sup>No</b>	<b>17</b>	<b>8.10</b>
<sup>255</sup> No	(1/2 <sup>+</sup> )	186	<sup>208</sup> Pb( <sup>48</sup> Ca,1n) <sup>255</sup> No	2	8.12
<sup>255</sup> No	(1/2 <sup>+</sup> )	186	<sup>209</sup> Bi( <sup>48</sup> Ca,2n) <sup>255</sup> Lr → EC	1	8.12
<sup>255</sup> Lr	(1/2 <sup>-</sup> )	<b>31.1</b>	<b><sup>209</sup>Bi(<sup>48</sup>Ca,2n)<sup>255</sup>Lr</b>	<b>3.4</b>	<b>8.37</b>

# Setup

# SHIP



# Radiation Detected Resonance Ionization Spectroscopy (RADRIS)

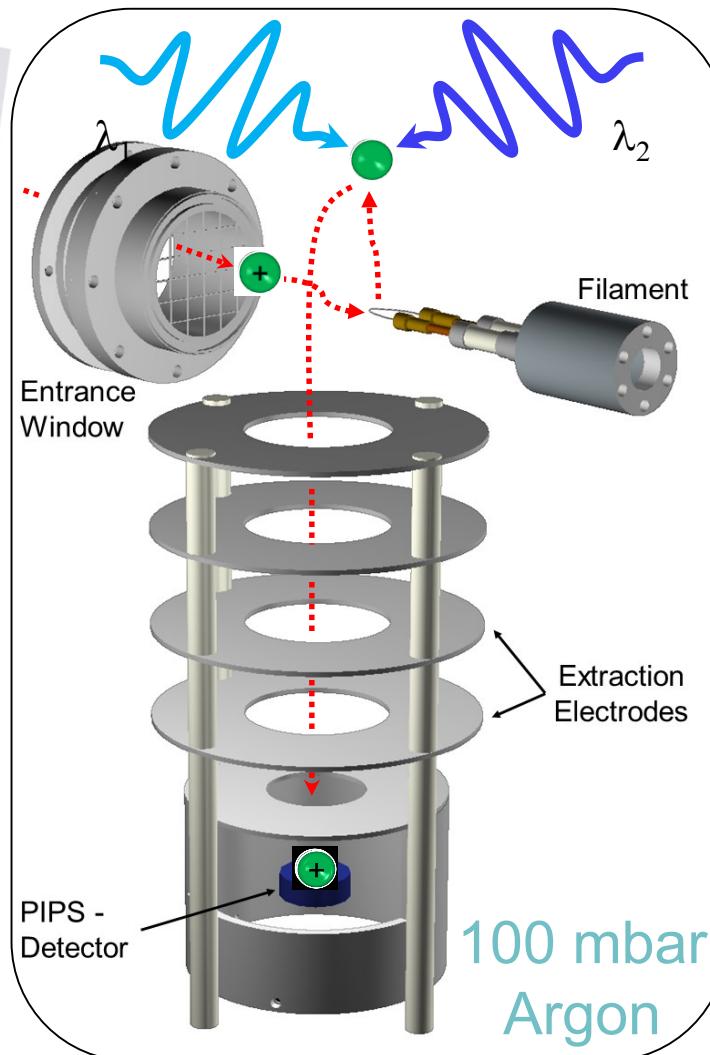


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gsi



# SHIP



## Beam on:

- 1- Stopping of fusion products
- 2- Accumulation on filament

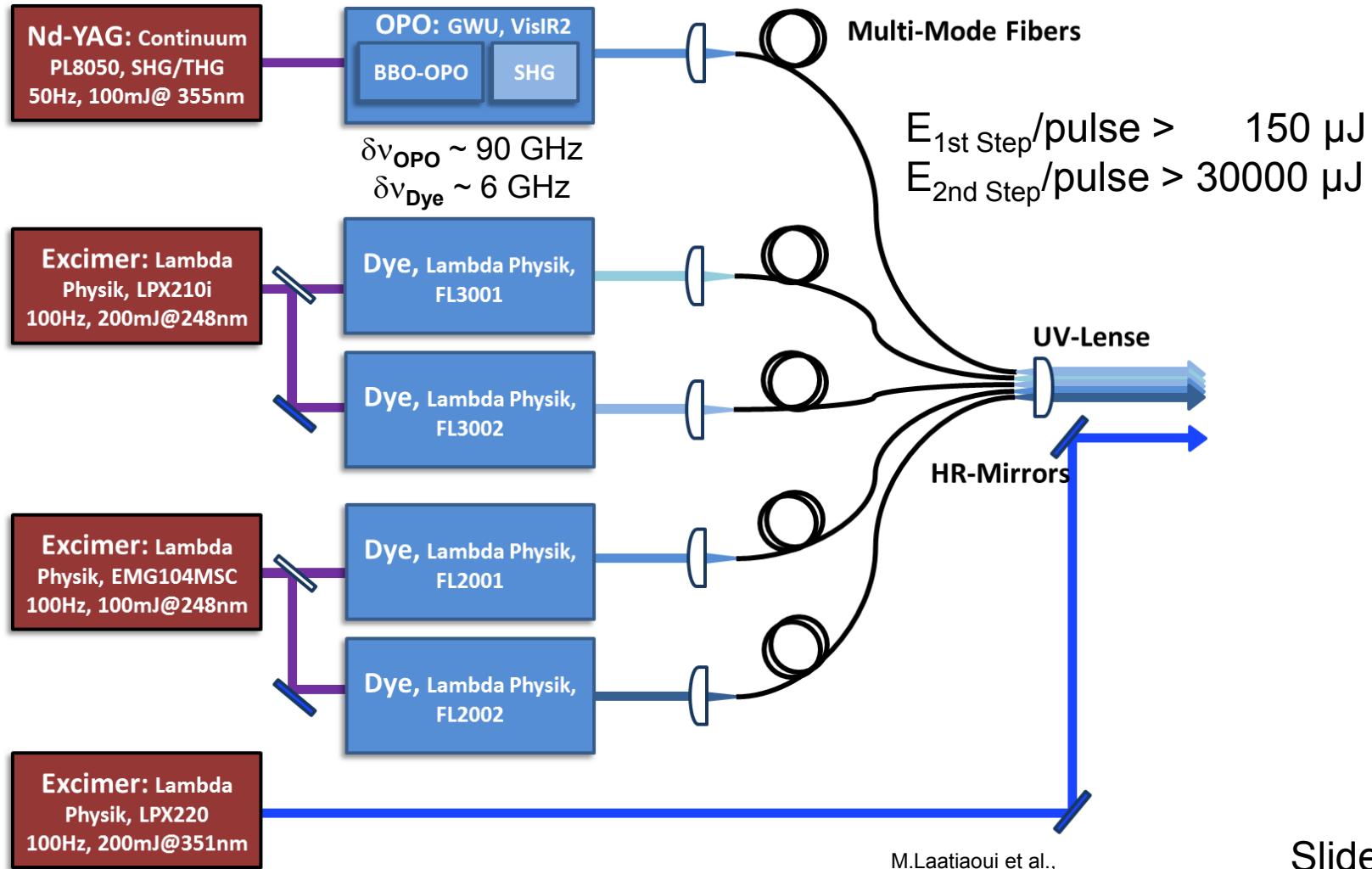
## Beam off:

- 3- Evaporation
- 4- Two-step resonance ionization
- 5- Accumulation on detector

## Cycle independent:

- 6- Radioactive decay detection

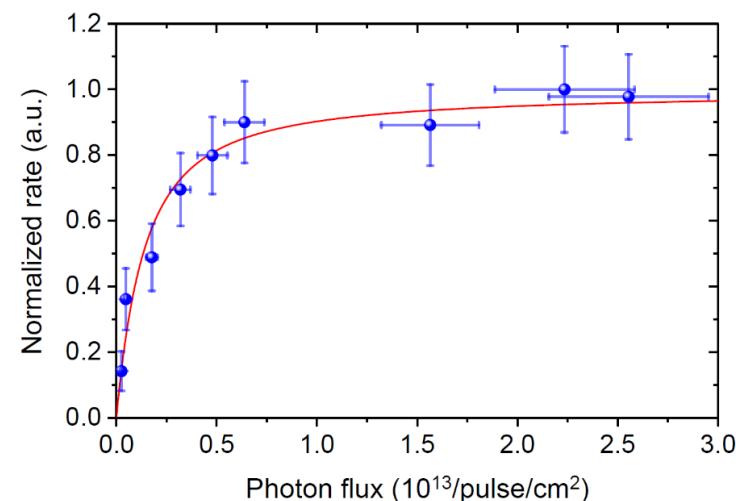
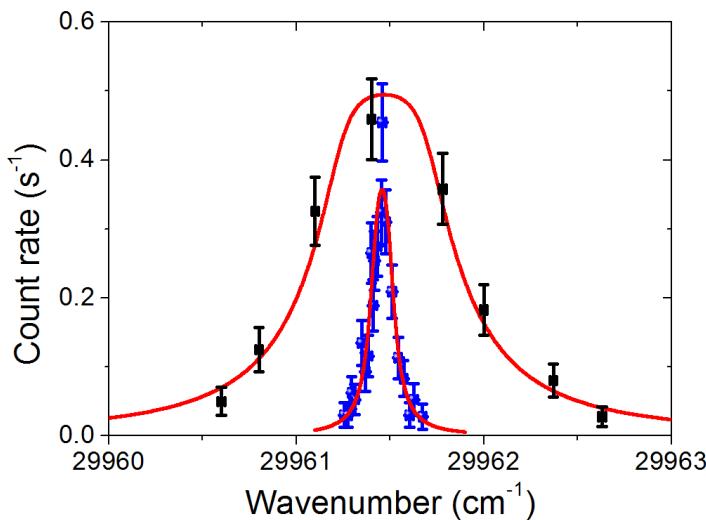
# Laser Systems



# The Ground-State Transition



- Strong atomic transition from  $^1S_0$  ground state to  $^1P_1$  excited state observed.
- Saturation of signal already at energies on the order of a few  $\mu\text{J}/\text{pulse}$



	$\nu_1 (\text{cm}^{-1})$	$A_{ki} (\text{s}^{-1}) \times 10^8$
Experiment [1]	$29,961.457(7)_{\text{stat}}$	$4.2 (2.6)_{\text{stat}}$
IHFSCC [2]	$30,100(800)$	5.0
MCDF [3]	$30,650(800)$	2.7

[1] M. Laatiaoui et al., *Nature* 538 (2016) 495

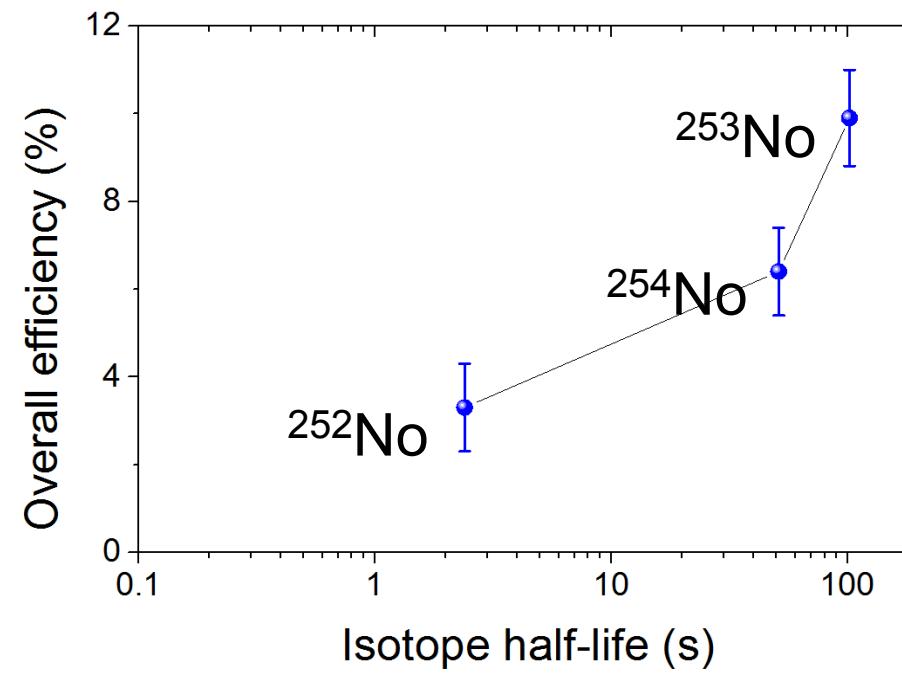
[2] A. Borschevsky et al., *Phys. Rev. A* 75 (2007) 042514

[3] P. Indelicato et al., *Eur. Phys. J. D* 45, (2007) 155

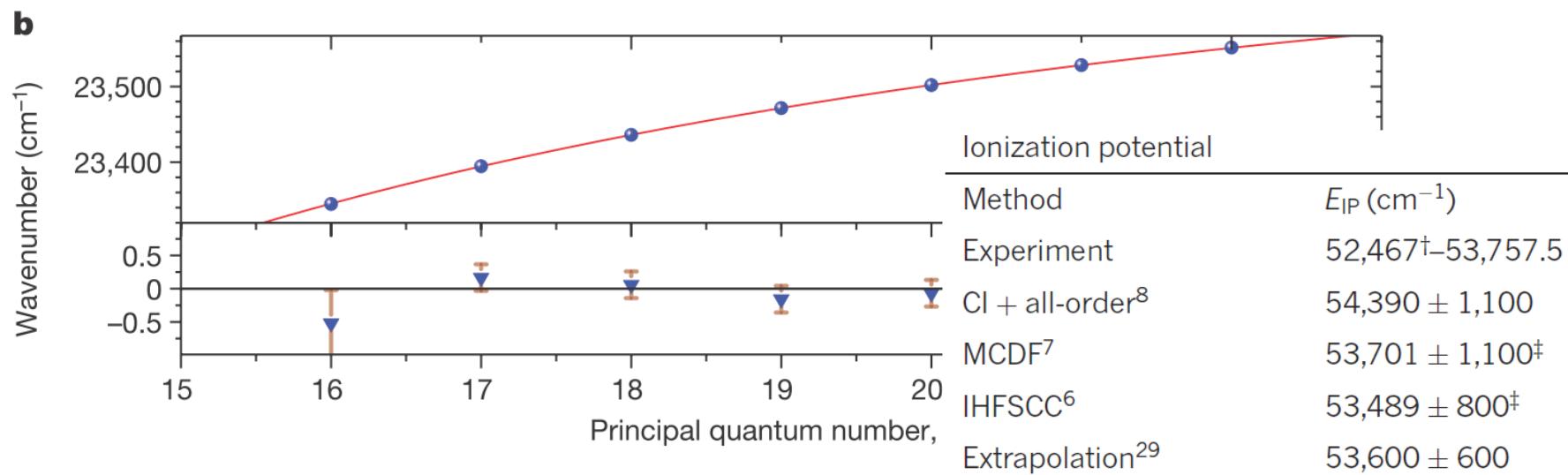
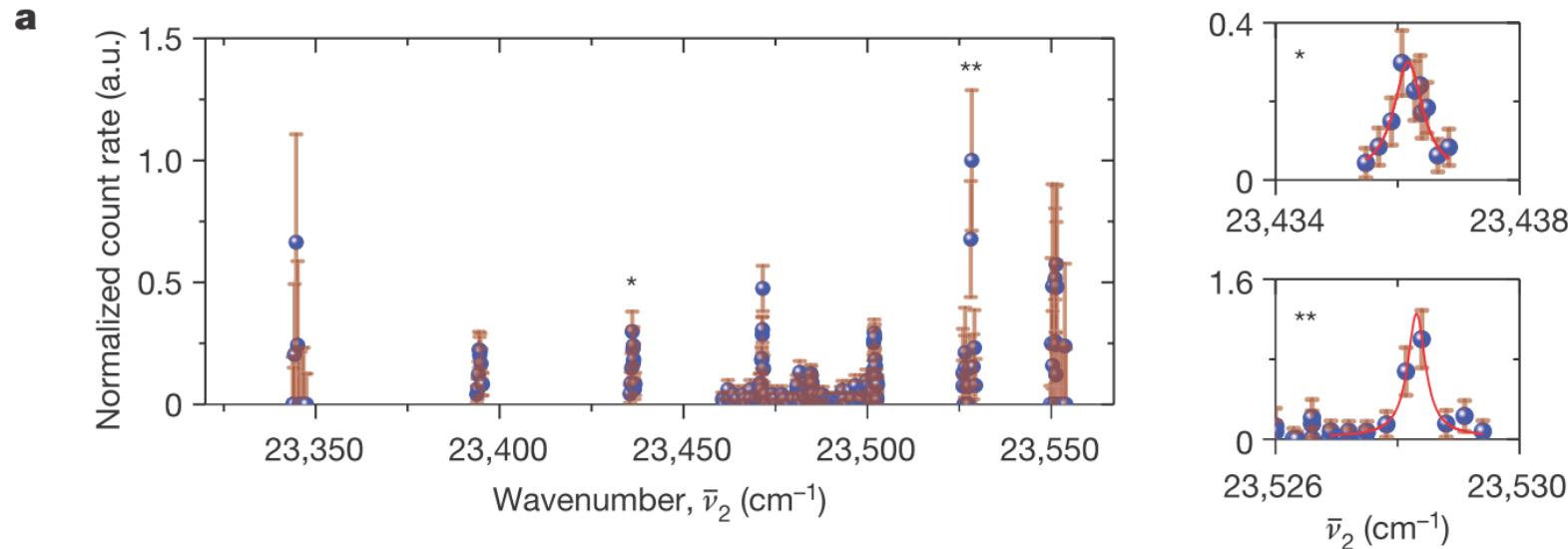
# RADRIS Efficiency:



- Hyperfine spectroscopy on  $^{253}\text{No}$
- Laser spectroscopy on  $^{252}\text{No}$  ( $\sigma = 500 \text{ nb}$ ,  $T_{1/2} = 2.4\text{s}$ ):
  - Less than 1 atom/s delivered to the cell
  - Overall efficiency:  $3.3 \pm 1.0 \%$
  - RADRIS applicability:  $T_{1/2}$ -range  $\sim 0.1 - 200 \text{ s}$



# Ionization Potential of No



# Outlook



TECHNISCHE  
UNIVERSITÄT  
DARMSTADT

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## Operating Collinear Laser Spectroscopy Setups :

- @ ISOLDE (COLLAPS & CRIS)
- @ Jyväskylä
- @ TRIUMF
- @ MSU (BECOLA)

## Under Development:

- Collinear Laser Spectroscopy @ ANL:  ${}^8\text{B}$  and CARIBU
- Absolute Nuclear Charge Radii from He-like and Li-like systems
- Collinear Laser Spectroscopy and polarized Nuclei @ ALTO
- Collinear Laser Spectroscopy @ RIKEN
- Collinear Laser Spectroscopy @ FAIR

## Resonance Ionization

- Gas-Jet Spectroscopy (Leuven, GSI)
- RILIS & In-Source Spectroscopy @ ISOLDE
- TRILIS @ TRIUMF
- Upcoming: GISELE @ GANIL, PALIS @ RIKEN, HELIOS @ GANIL

# Remember



- Resonance Ionization Spectroscopy (RIS) is an extremely sensitive tool to study short-lived isotopes
- RIS can be applied in hot cavities, gas cells, gas jets and on a fast atomic beam in collinear geometry
- Laser Ion Sources like the RILIS provide high efficiencies and clean beams
- Resolution and selectivity can be chosen by the linewidth of the lasers
- Nuclear deformation has a strong impact on the isotope shift
- The development of more and more sensitive and accurate techniques is still continuing and new techniques will become available in the future ...

