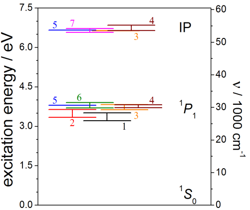
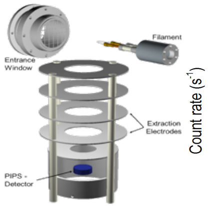
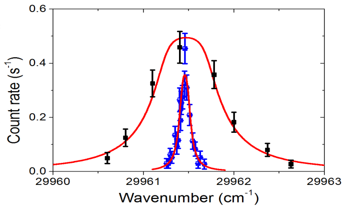
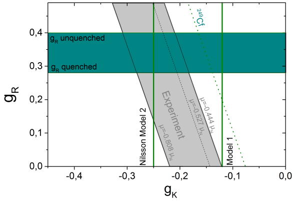
Laser spectroscopy on nobelium isotopes at SHIP

S. Raeder *for the RADRIS collaboration*
Helmholtz Institut Mainz









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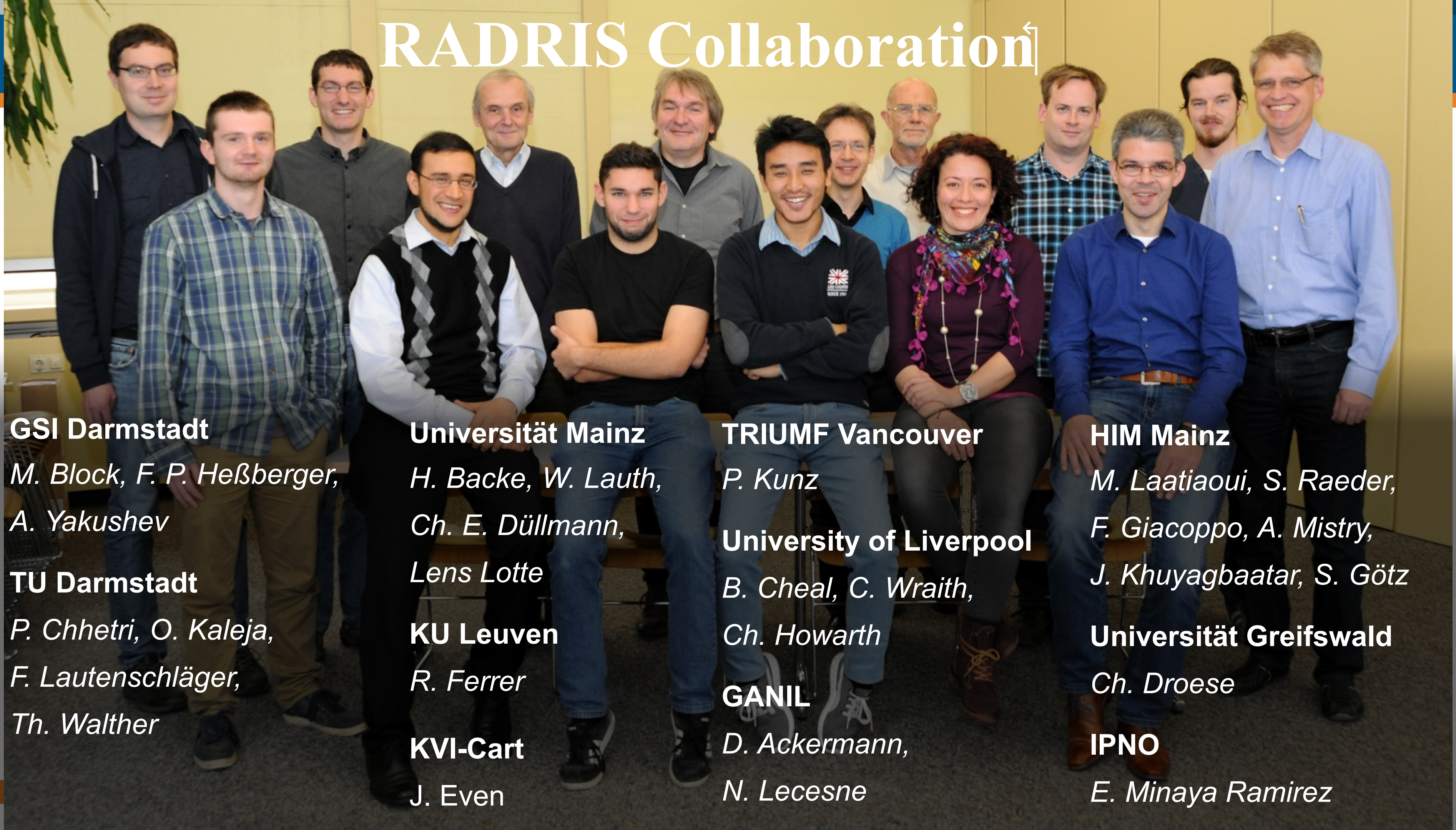
TRIUMF
UNIVERSITY OF LIVERPOOL
HELMHOLTZ ASSOCIATION
GSI

RADRIS Collaboration



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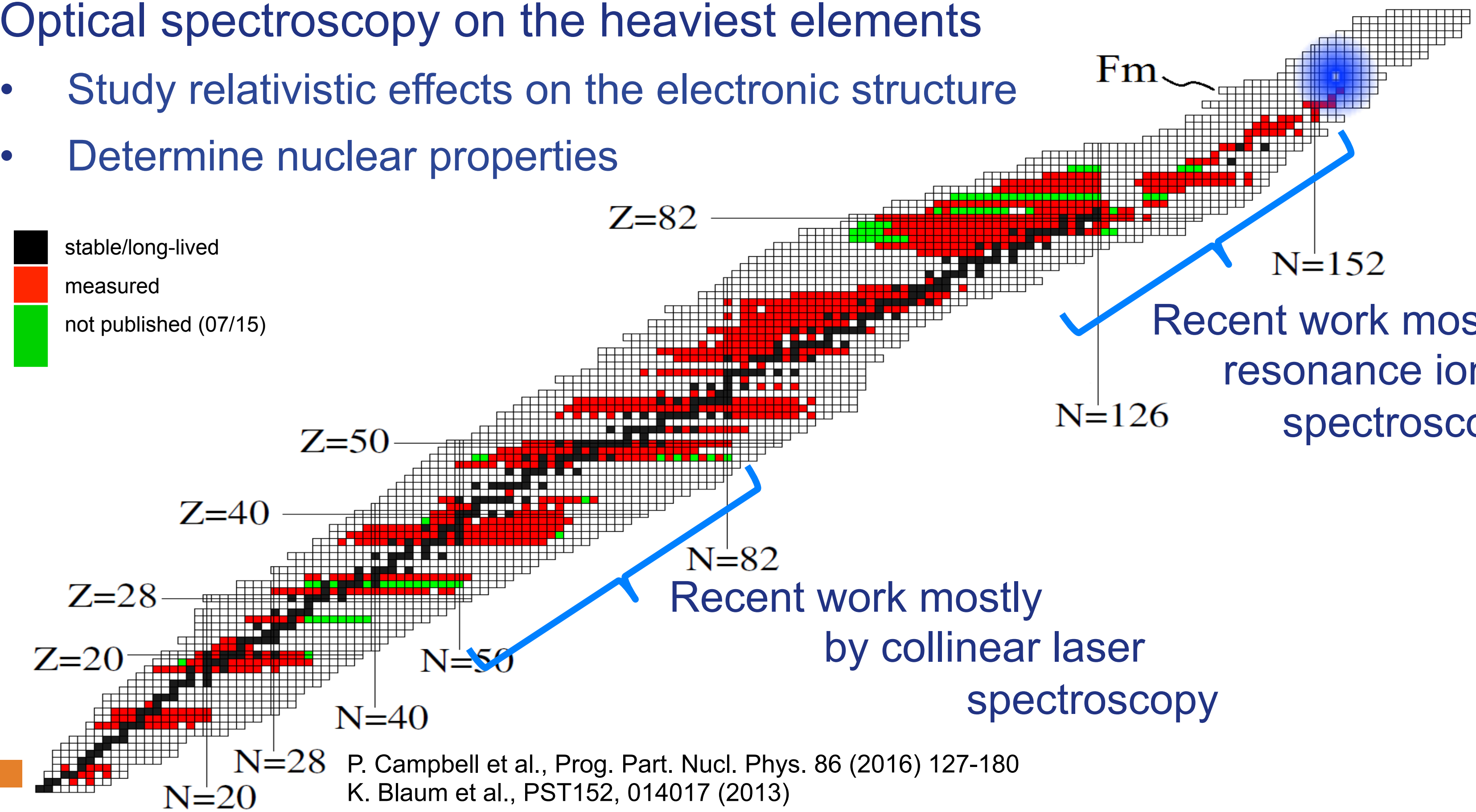
IPNO

E. Minaya Ramirez

Landscape of optical spectroscopy

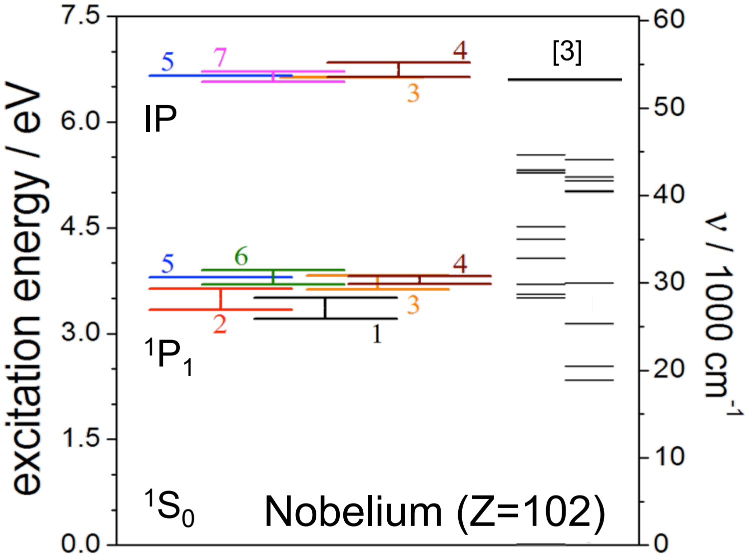
Optical spectroscopy on the heaviest elements

- Study relativistic effects on the electronic structure
- Determine nuclear properties



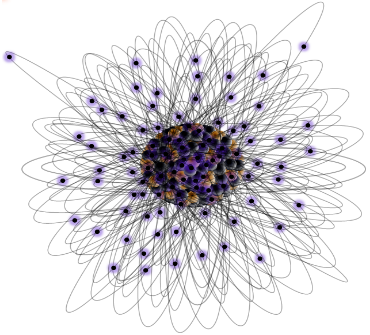
P. Campbell et al., Prog. Part. Nucl. Phys. 86 (2016) 127-180
K. Blaum et al., PST152, 014017 (2013)

Motivaton - Atomic Properties



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

- Zα → 1: relativistic effects in the electronic structure
- Strong electron correlations
- Benchmark predictive power of atomic theory
- Ionization potential IP



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

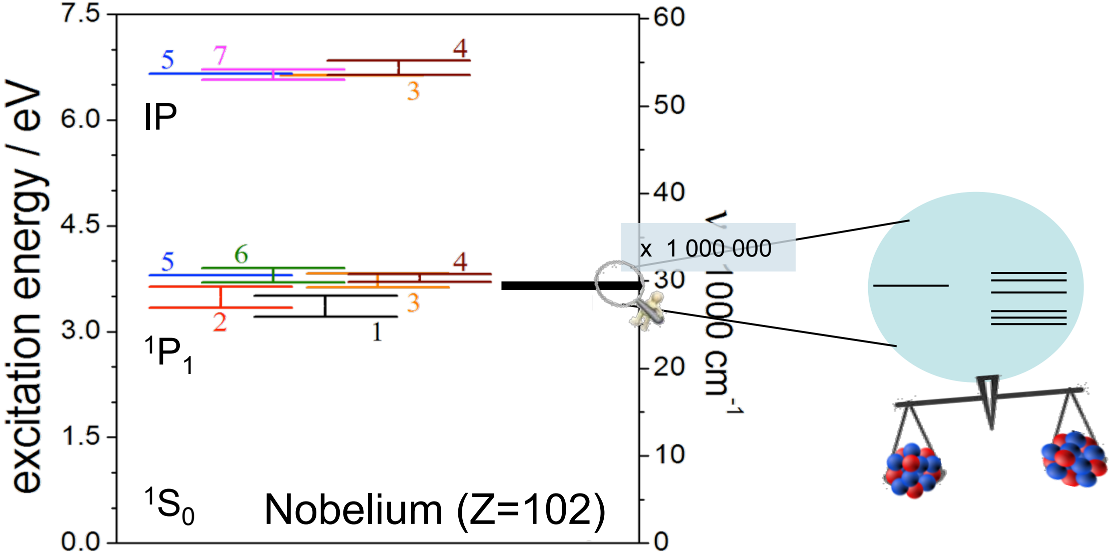
4 (RCC): V.A.Dzuba et al., Phys. Rev. A 90 (2014) 012504

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

Motivaton – Nuclear Properties



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

Hyperfine splitting (HFS)

μ, Q, I Ground state parameters

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

Isotope shift

Δr^2 Nuclear Shape, deformation

$$\delta\nu^{A'A} = F\lambda^{A'A} + (N+S)\left(\frac{A'-A}{A'A}\right)$$

Model calculations

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

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Velocity filter SHIP

Isotope of Interest:

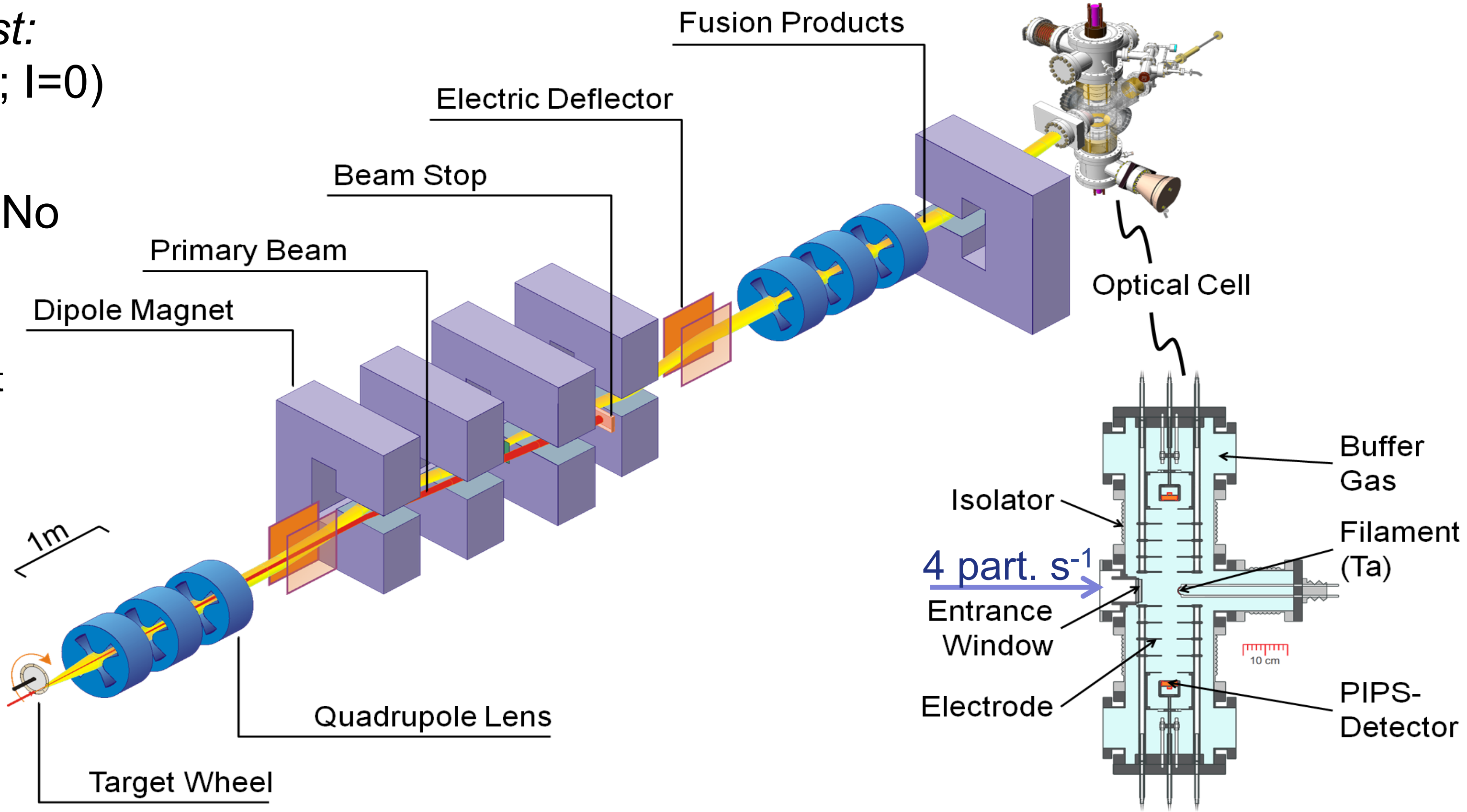
^{254}No ($T_{½}$ = 55 s; I=0)

^{208}Pb(^{48}Ca,2n)^{254}No

σ=1800 nb

→ ~17 s^{-1} pμA^{-1}

@Target



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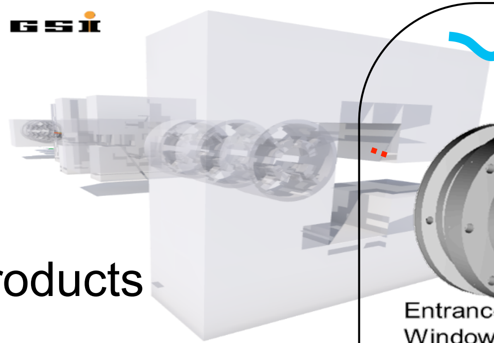
Radiation Detected Resonance Ionization Spectroscopy

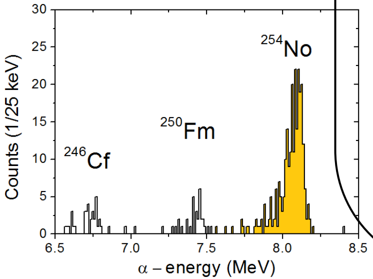


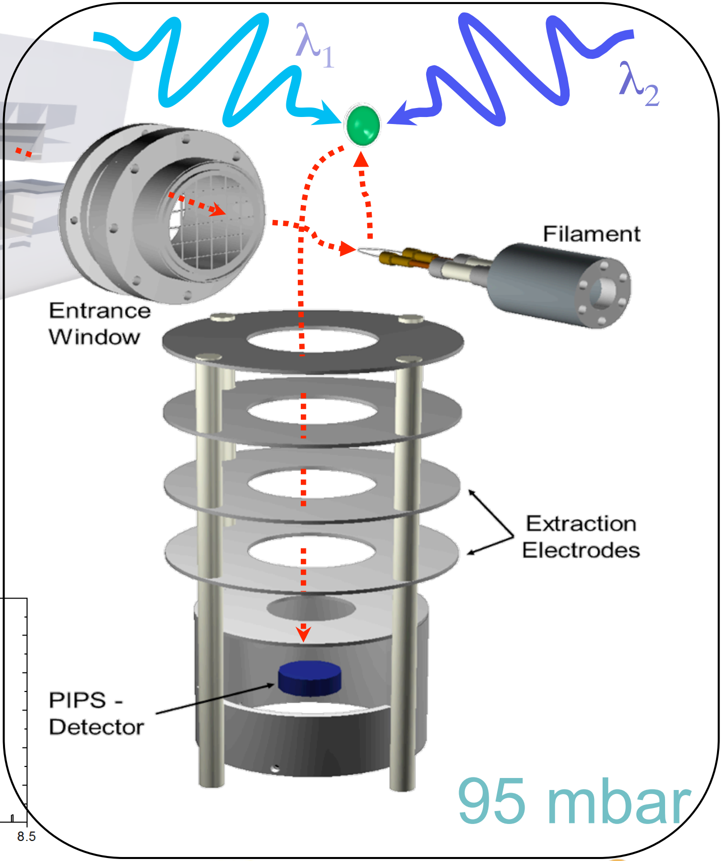
RADRIS Method:

- Thermalizing of incoming fusion products
- Collecting onto thin tantalum wire
- Evaporation and two-step photoionization process
- Transport to detector and detection of alpha decay

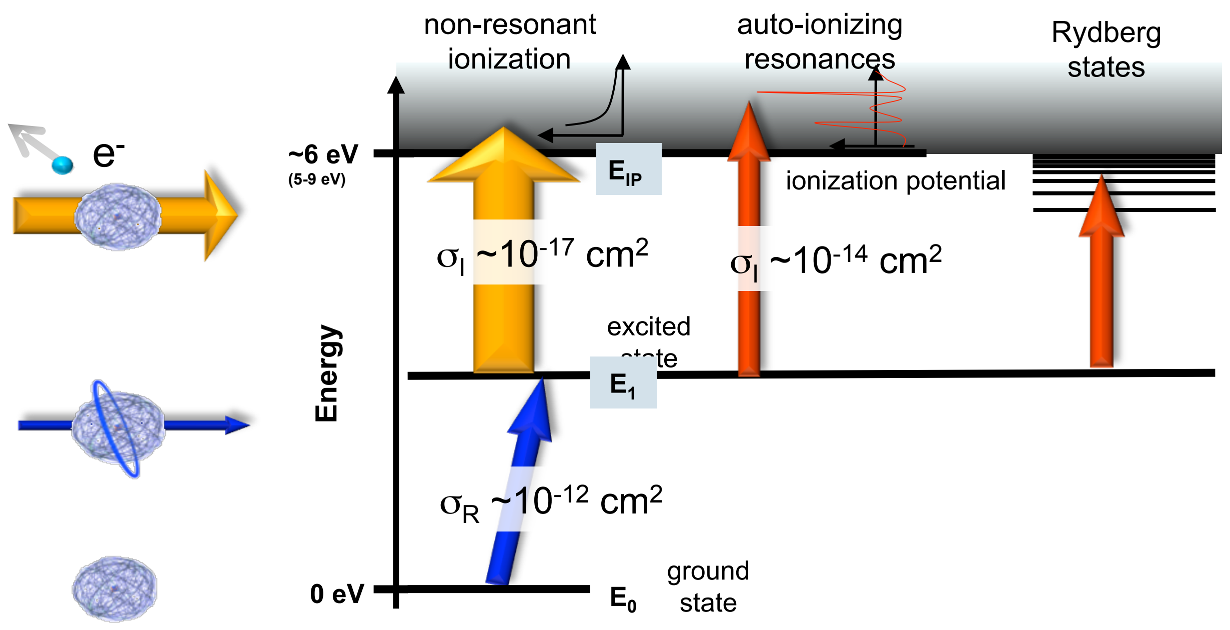
H. Backe et al., Nucl Phys. A ***944****, 492 (2015)*

F. Lautenschläger et al., NIMB ***383****, 115 (2016)*





Resonance Ionization Spectroscopy



Non-resonant ionization is 2-3 order of magnitude less efficient

BUT does not depend on knowledge on the atomic structure

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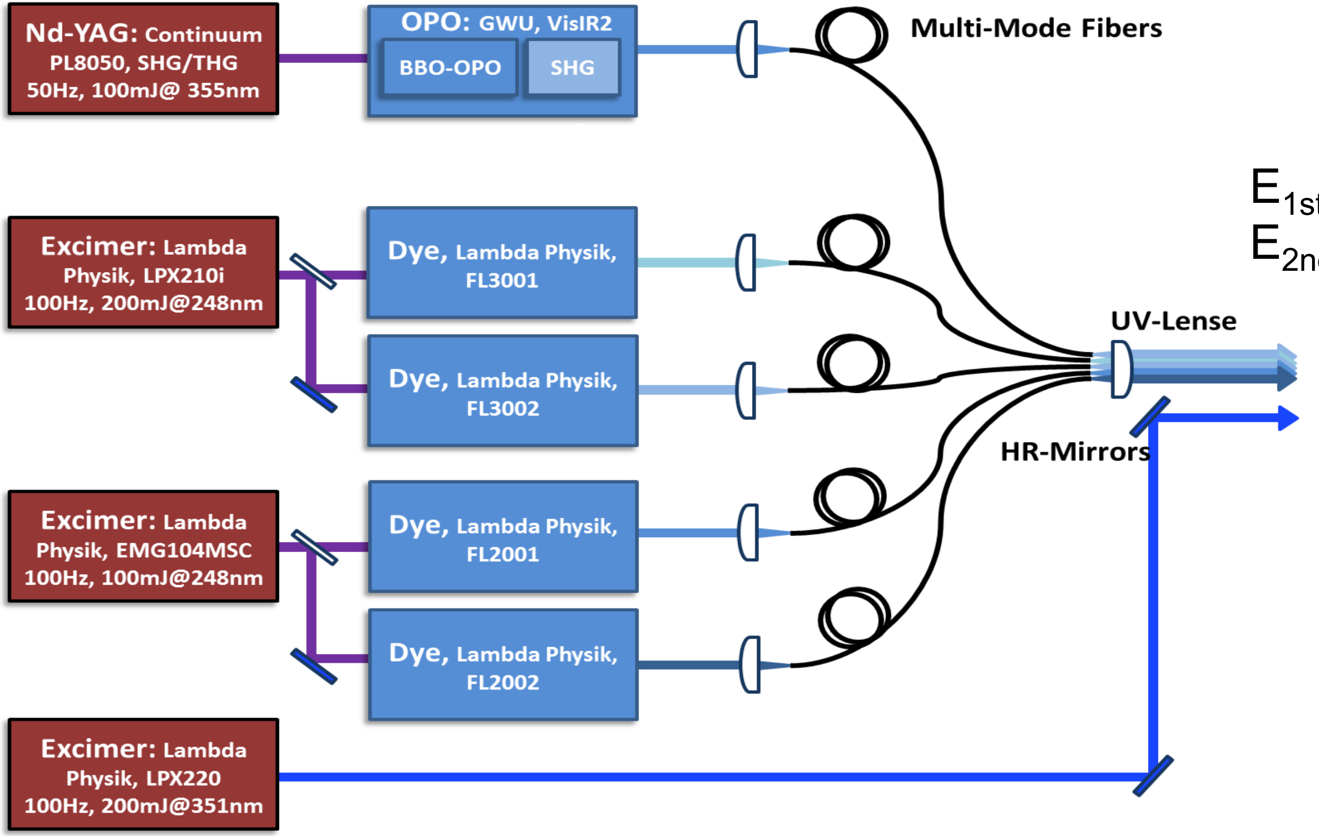
Laser system



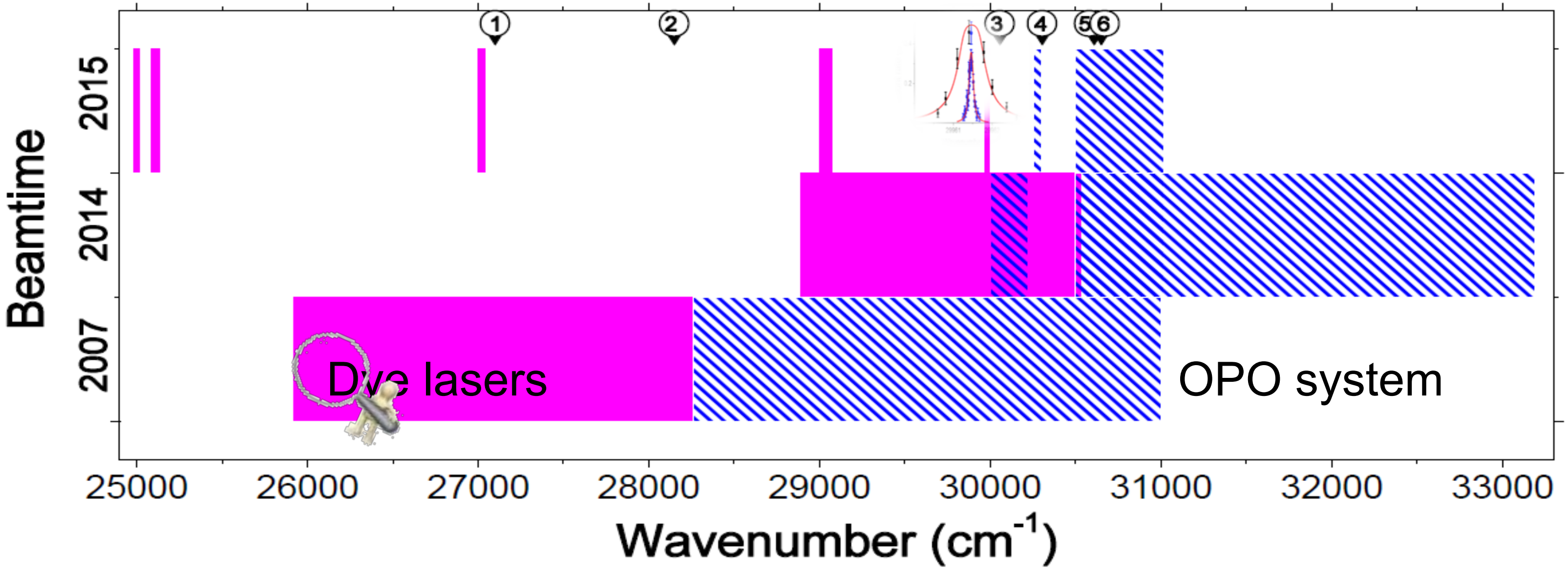
$E_{1st\ Step}$/pulse > 150 μJ
$E_{2nd\ Step}$/pulse > 30000 μJ

$\delta\nu_{OPO}$ ~ 90 GHz
$\delta\nu_{Dye}$ ~ 6 GHz

M.Laatiaoui et al., Hyperfine Interact. **227** (2014) 69

Level search in ^{254}No

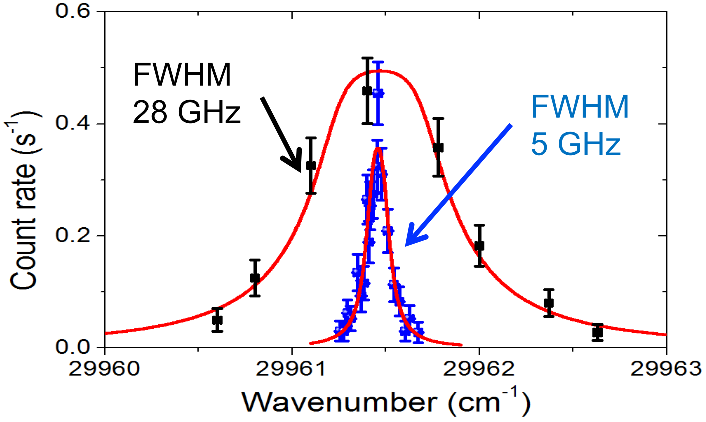
Year	2007	2014
Scan range (cm^{-1})	25920 – 31001	28887 – 33191
Net scan time (h)	39	67

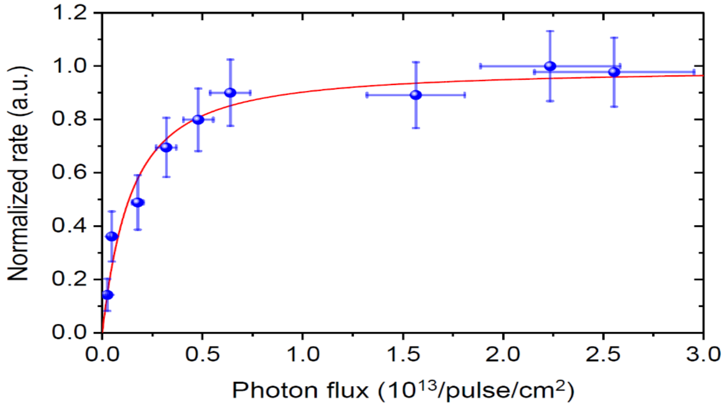


1: MCDF (2005), 2: MCDF (2005), 3: IHFSCC (2007), 4: RCC (2014), 5: MCDF (2007), 6: MCDF (2007)

The ground-state transition

Observed strong atomic ground state transition





Saturation of signal already at energies on the order of a few µJ/pulse

	ν_1 (cm^{-1})	A_{ki} (s^{-1}) x 10^8
Experiment [1]	29,961.457(7)$_{stat}$	4.2 (2.6)$_{stat}$
IHFSCC [2]	30,100(800)	5.0
MCDF [3]	30,650(800)	2.7

Agrees with predicted $^1S_0 \rightarrow {}^1P_1$ transition

[1] M. Laatiaoui et al., Nature (in press) *[2] A. Borschevsky et al., Phys. Rev. A **75** (2007) 042514*
*[3] P. Indelicato et al., Eur. Phys. J. D **45**, (2007) 155*

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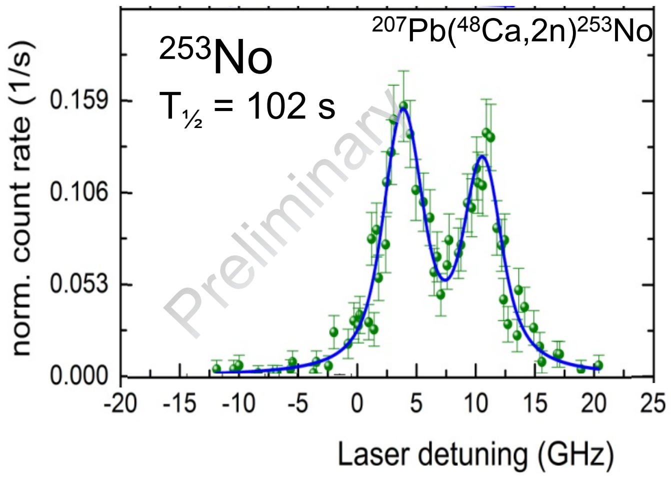
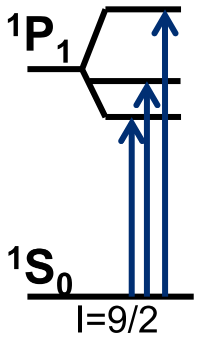
Hyperfine structure studies in ^{253}No





- 2 peaks resolved (3 peaks expected)
- Assuming a prolate shape & best fit to the data:

  ➔ I=7/2 nuclear spin can be excluded

  ➔ A = 734(46) MHz; B = 2815(686) MHz

$$A = \mu \frac{B_e(0)}{IJ}$$

$$B = eQ_s \left\langle \frac{\delta^2 V}{\delta z^2} \right\rangle_{z=0}$$

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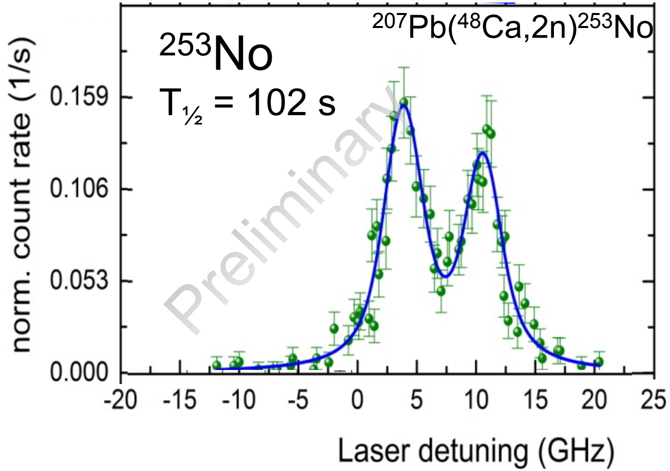
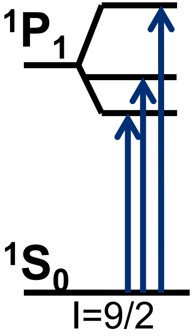
Hyperfine structure studies in ^{253}No





- 2 peaks resolved (3 peaks expected)
- Assuming a prolate shape & best fit to the data:
  - ➔ I=7/2 nuclear spin can be excluded
  - ➔ A = 734(46) MHz; B = 2815(686) MHz
- Feedback from atomic theory for nuclear moments

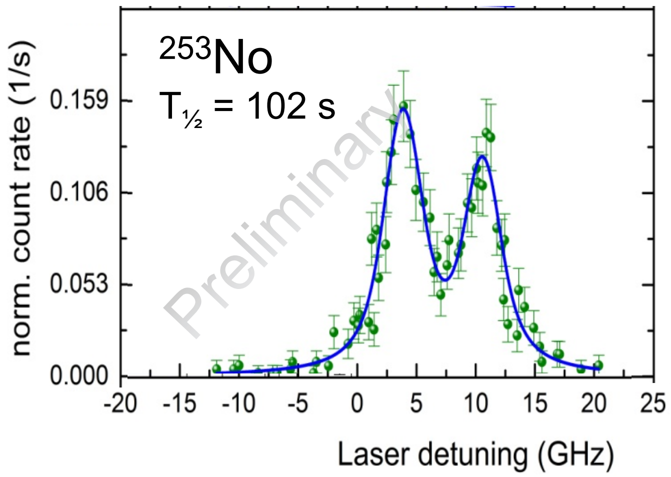
$$A = \mu \frac{B_e(0)}{IJ}$$

$$B = eQ_s \left\langle \frac{\delta^2 V}{\delta z^2} \right\rangle_{z=0}$$

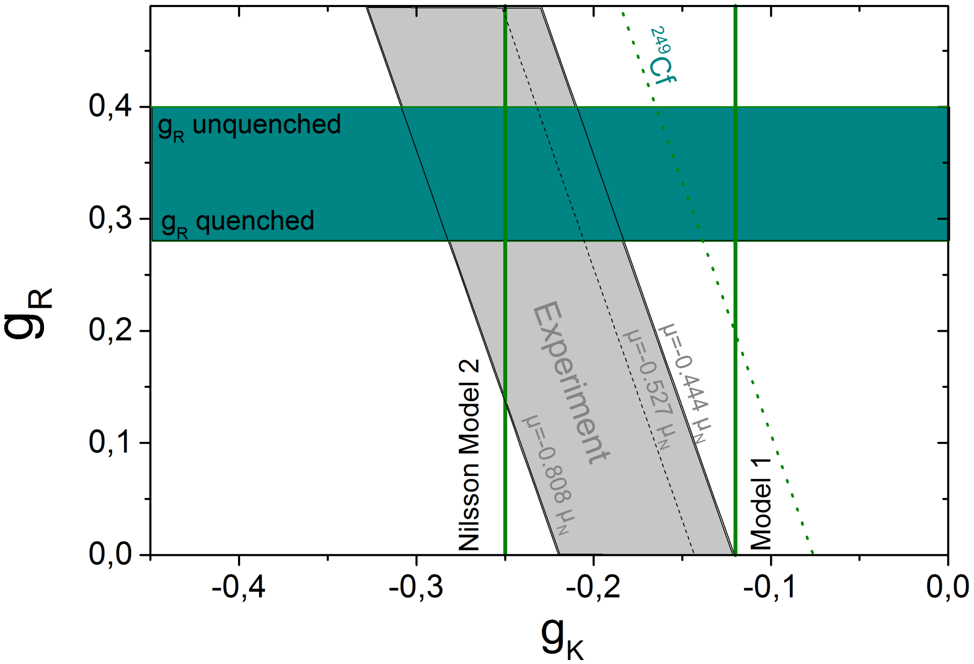
	Ref.	μ (μ_N)	Q_s (b)
Laser spec. (this work)	RCC [1]	-0.444 ±0.028*	5.79 ±1.42*
	RCC [2]	-0.527 ±0.034*	
	MCDF [3]	-0.808±0.051*	6.34 ±1.56*
Nucl. structure	[4]	-0.593	7.145

[1] V.A. Dzuba et al. (RCC), [2] A. Borschevsky et al. (RCC), [3] R. Beerwerth & S. Fritzsche (MCDF),
*[4] R.D. Herzberg et al., Eur. Phys. J. A **42**, 333-337 (2009), *: Error from the fit*

Hyperfine structure studies in ^{253}No



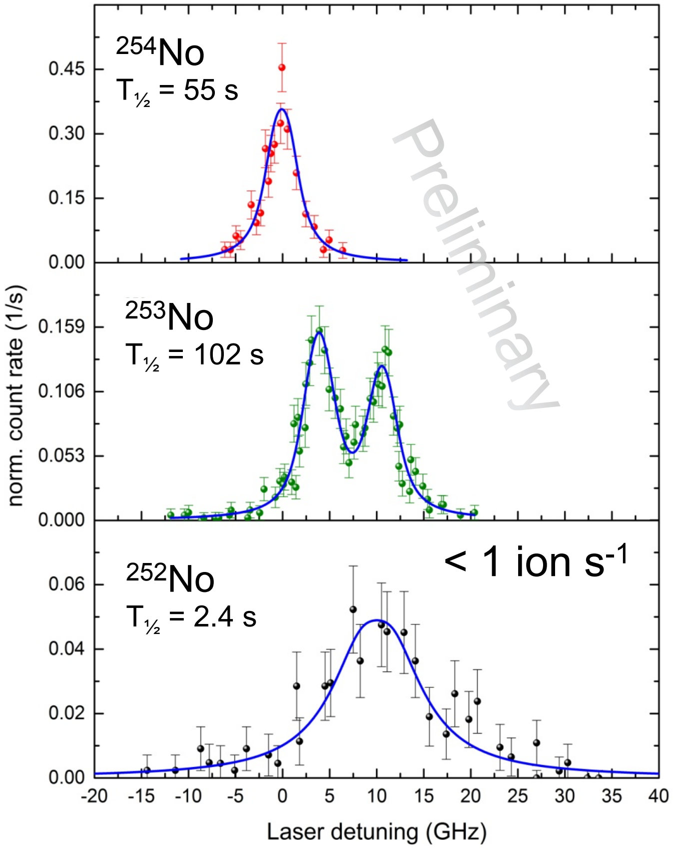
$$\mu = g_R I + (g_K - g_R)\frac{K^2}{I+1}$$



→ Nuclear model independent confirmation of expected nuclear properties

*[1] V.A. Dzuba et al. (RCC), [2] A. Borschevsky et al. (RCC), [3] R. Beerwerth & S. Fritzsche (MCDF), [4] R.D. Herzberg et al., Eur. Phys. J. A **42**, 333-337 (2009), [5] P. Reiter et al. PRL 95, 032501 (2005)*

Isotope shift of $^{252-254}$No



Input from atomic theory

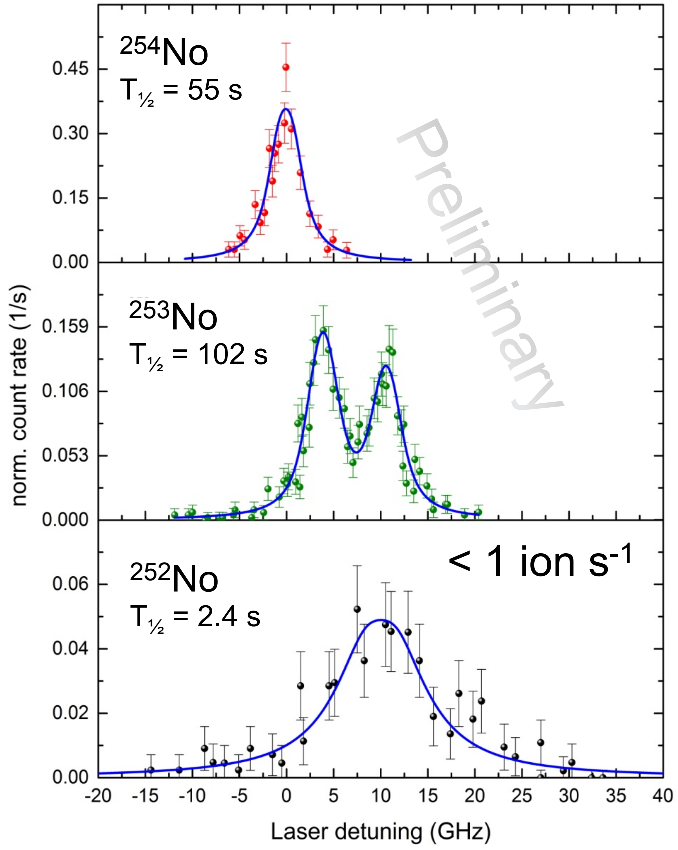
- Mass-shift constant: 1066 GHz u
- Field-shift parameter: -113.2 GHz/fm^2

(R. Beerwerth & S. Fritzsche (MCDF))

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

Isotope	N	$\delta\langle r^2\rangle$ (fm^2)
^{254}No	152	0
^{253}No	151	$-0.057\ (1)_{stat}$
^{252}No	150	$-0.089\ (4)_{stat}$

Isotope shift of $^{252-254}No$



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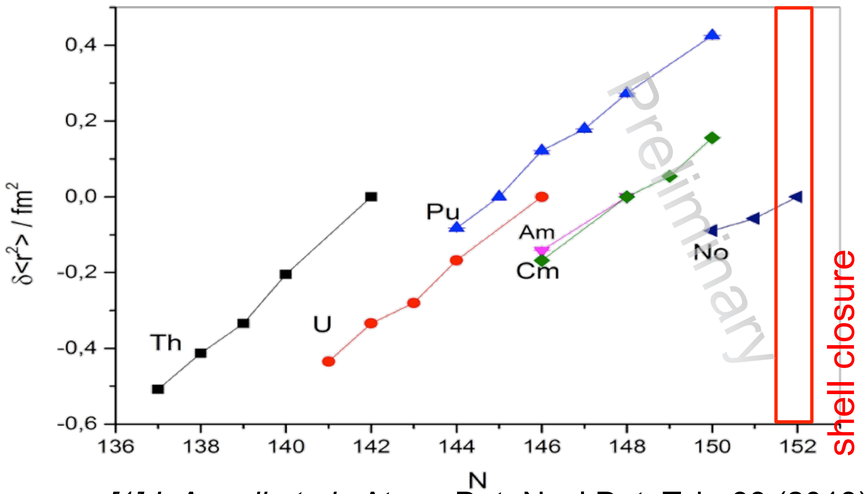


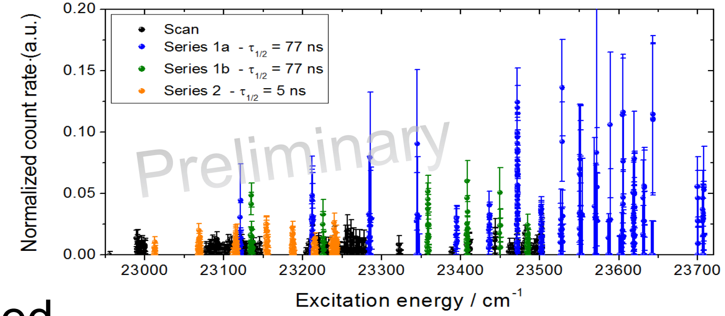
[1] I. Angeli et al., Atom. Dat. Nucl.Dat. Tab. 99 (2013) 69–95

Conclusions

- First laser spectroscopy on a transfermium element
- Strong $^{1}S_{0} \rightarrow {}^{1}P_{1}$ ground-state transition in the nobelium (Z=102) atom observed
- Access to nuclear structure from HFS in ^{253}No & IS for $^{252-254}$No

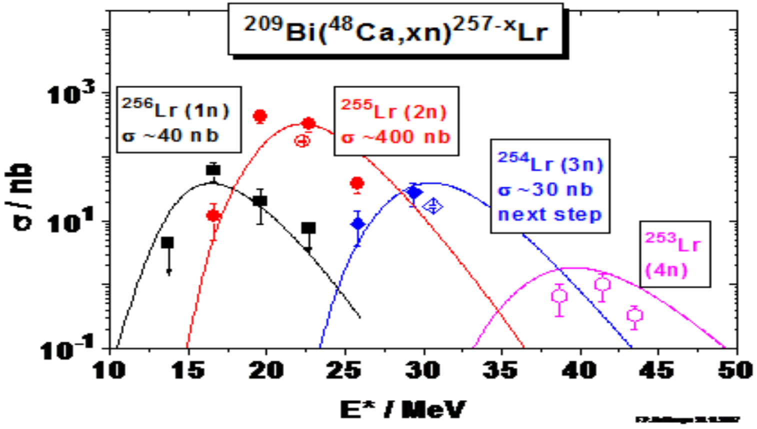
Conclusions

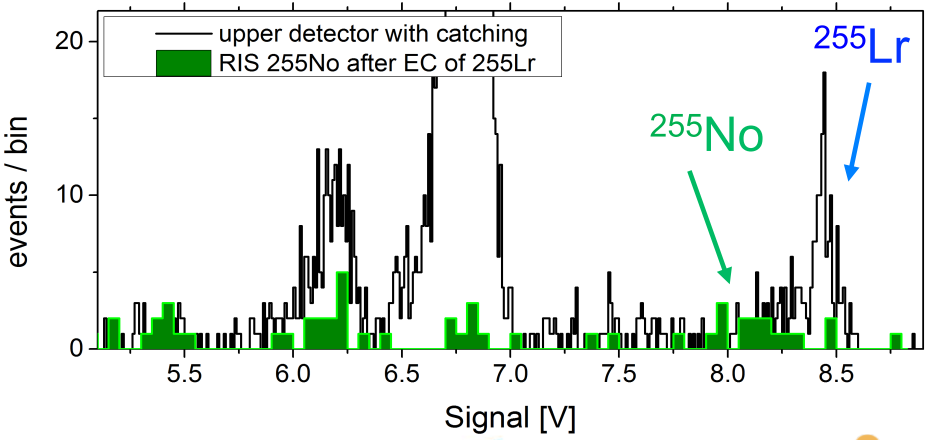
- First laser spectroscopy on a transfermium element
- Strong $^{1}S_{0} \rightarrow {}^{1}P_{1}$ ground-state transition in the nobelium (Z=102) atom observed
- Access to nuclear structure from HFS in ^{253}No & IS for $^{252\text{-}254}$No
- Overall efficiency up to 10%
- Different Rydberg series were observed
- Accurate value for the first IP of nobelium extracted



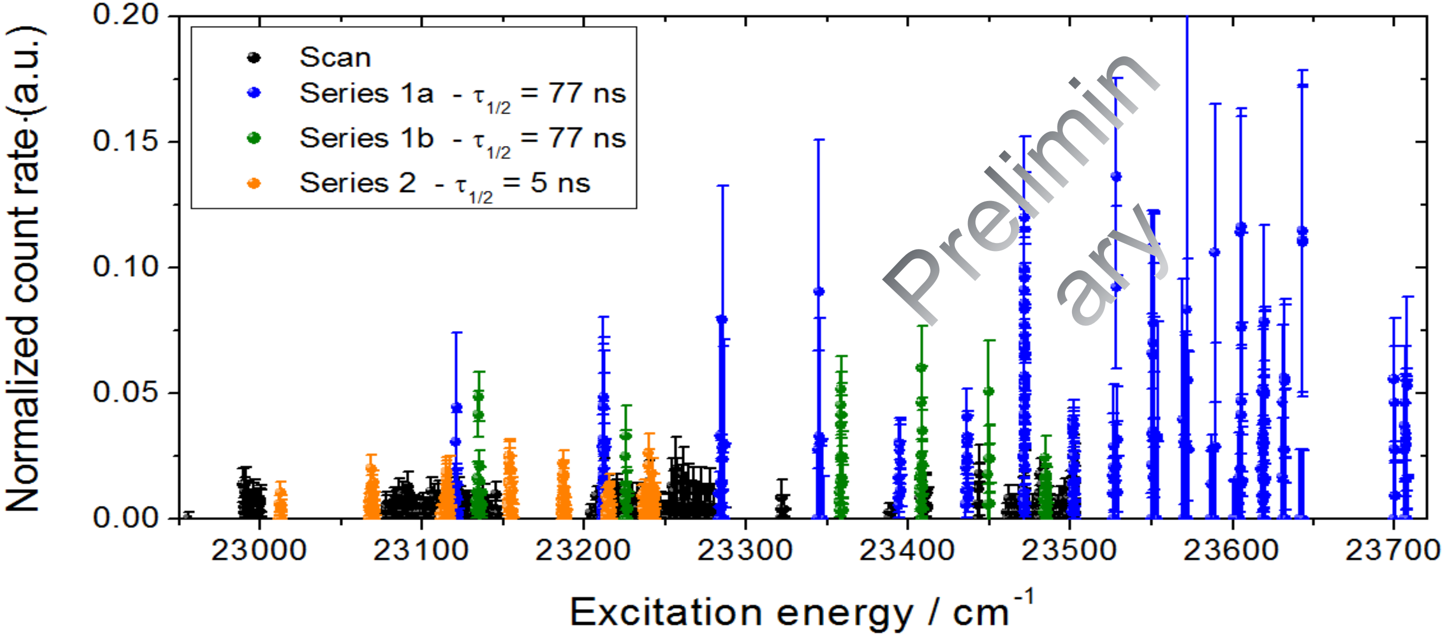
Outlook

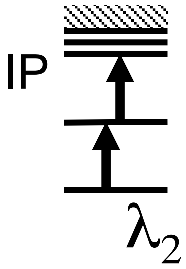
- Access the element lawrencium (Z=103) – started in 2016
    - Studying desorption and surface ionization mechanisms ...
    - First level search initiated (no resonances found so far)
- Resonance ionization of ^{255}No (produced via EC from ^{255}Lr)





Rydberg series

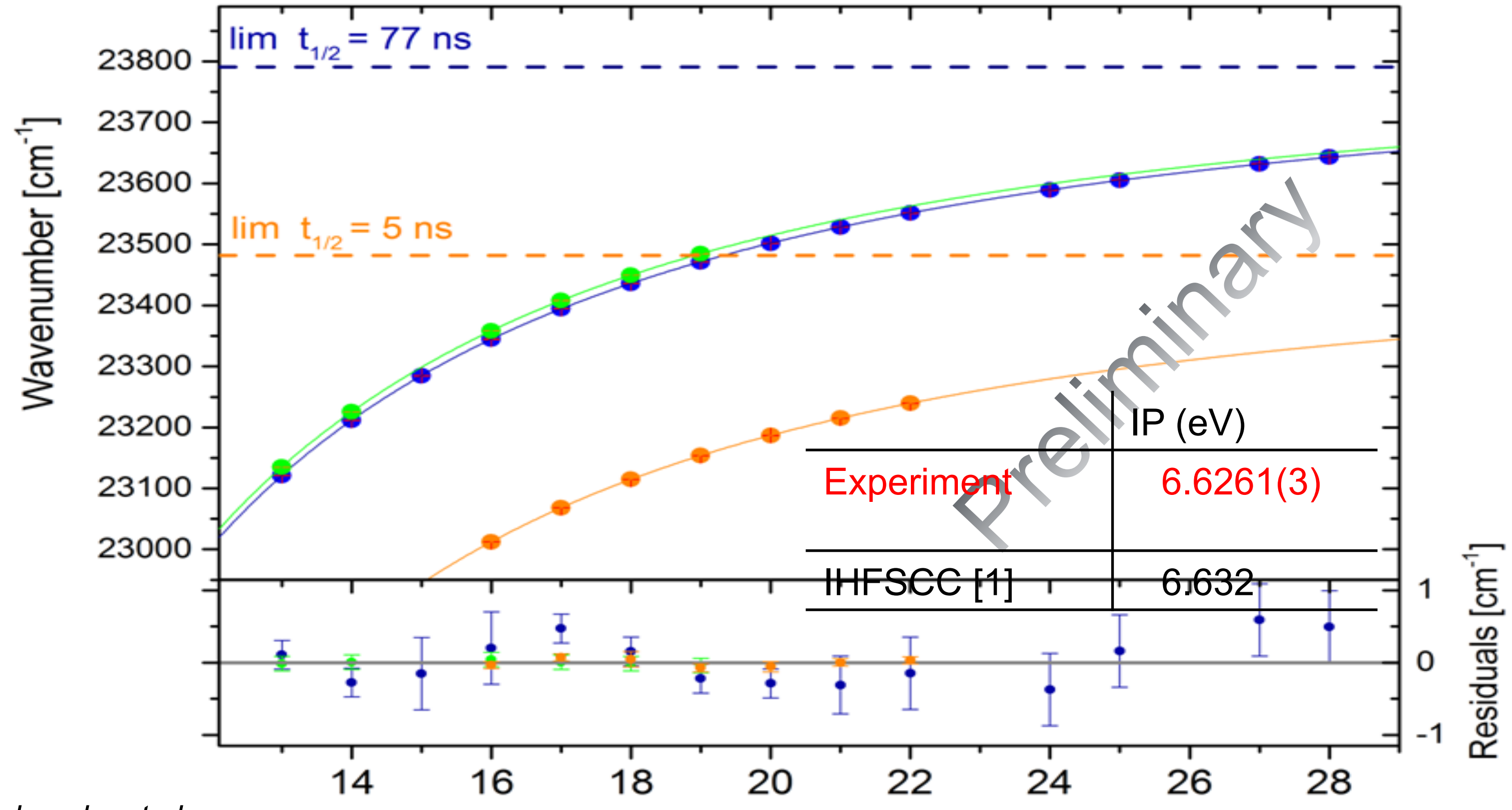




- Series fitted with Rydberg-Ritz formula:

$$E_n = E_{\mathrm{IP}} - \frac{R_\mu}{[n - \delta(n)]^2}.$$

Ionization limits & Ionization potential



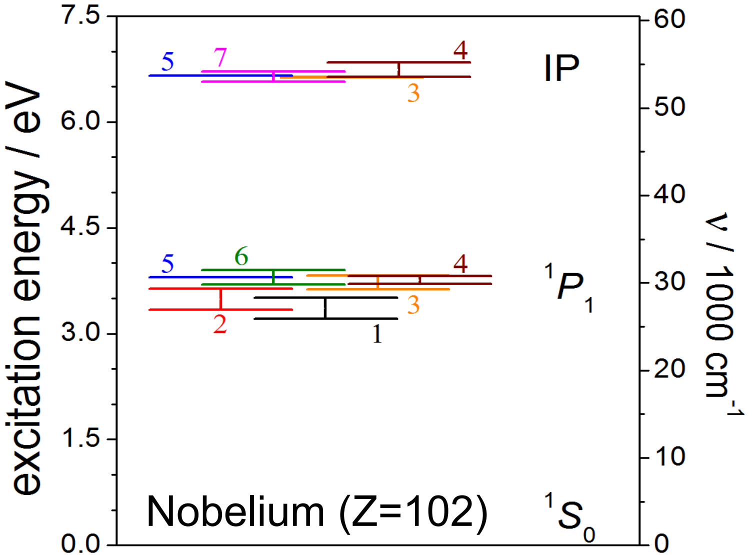
	IP (eV)
Experiment	6.6261(3)
IHFSCC [1]	6.632

[1] A. Borschevsky et al.,

Nobelium isotopes

Isotope	I^P	$T_{1/2}$ (s)	Nuclear reaction	Production rate @ 1μA_P (1/s)	α- energy (MeV)
^{252}No	0	2.4	^{206}Pb(^{48}Ca,2n)^{252}No	4	8.42
^{253}No	(9/2$^-$)	102	^{207}Pb(^{48}Ca,2n)^{253}No	11	8.01
^{254}No	0	51	^{208}Pb(^{48}Ca,2n)^{254}No	17	8.10
^{255}No	(1/2$^+$)	186	^{208}Pb(^{48}Ca,1n)^{255}No	2	8.12

Motivaton - Atomic Properties



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- Zα → 1: relativistic effects in the electronic structure
- Benchmark predictive power of atomic theory
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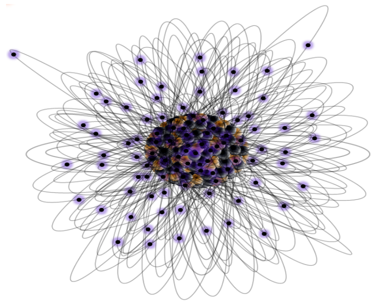

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