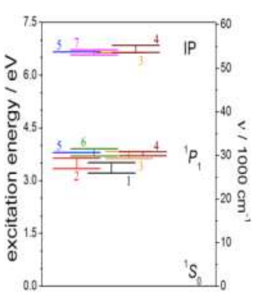
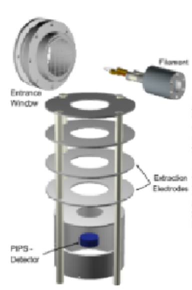
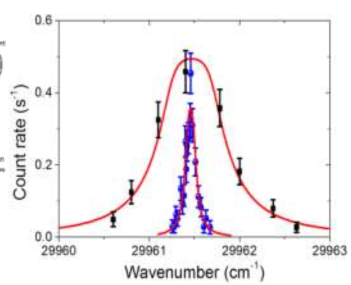
Nuclear properties of nobelium isotopes from laser spectroscopy

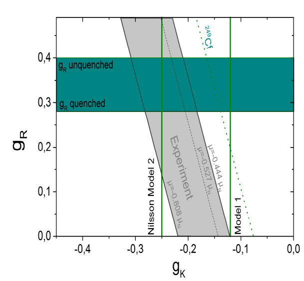
S. Raeder *for the RADRIS collaboration*

Helmholtz Institut Mainz







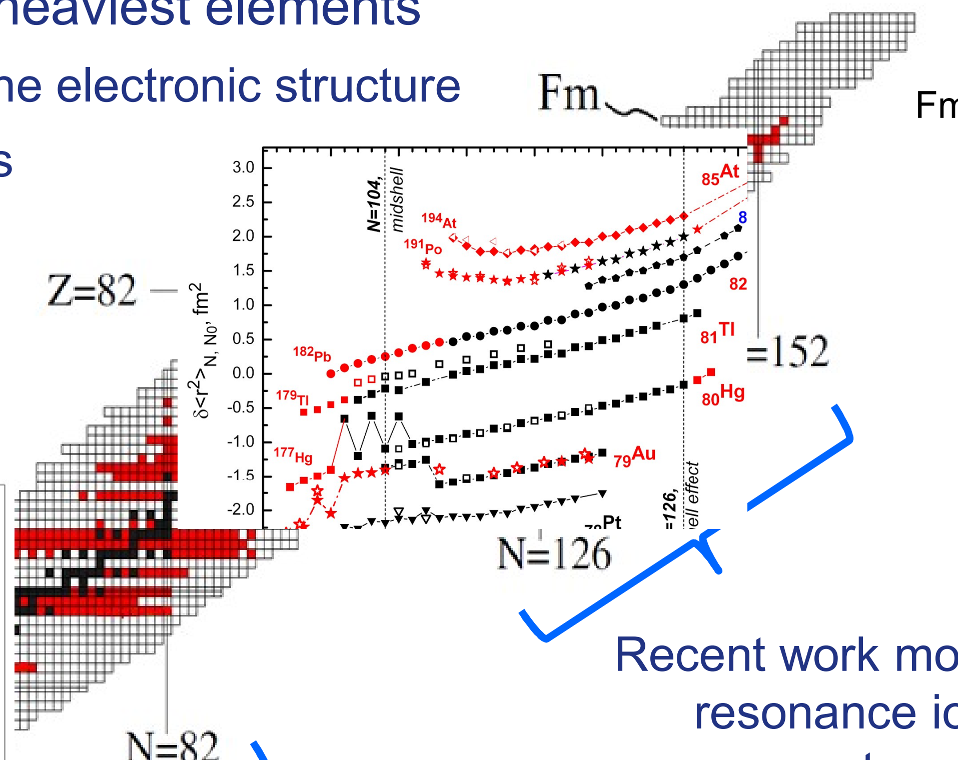


GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

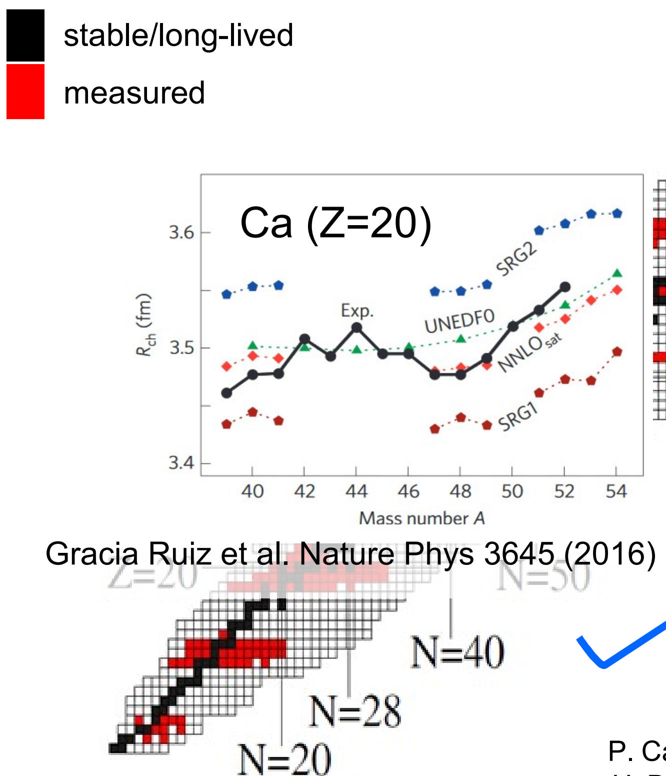
Landscape of Optical Spectroscopy

Optical spectroscopy on the heaviest elements

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



Recent work mostly by resonance ionization spectroscopy (RIS)



Gracia Ruiz et al. Nature Phys 3645 (2016)

Recent work mostly by collinear laser spectroscopy

P. Campbell et al., Prog. Part. Nucl. Phys. 86 (2016) 127-180
H. Backe et al., Nucl Phys. A 944, 492 (2015)

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Landscape of Optical Spectroscopy

Optical spectroscopy on the heaviest elements

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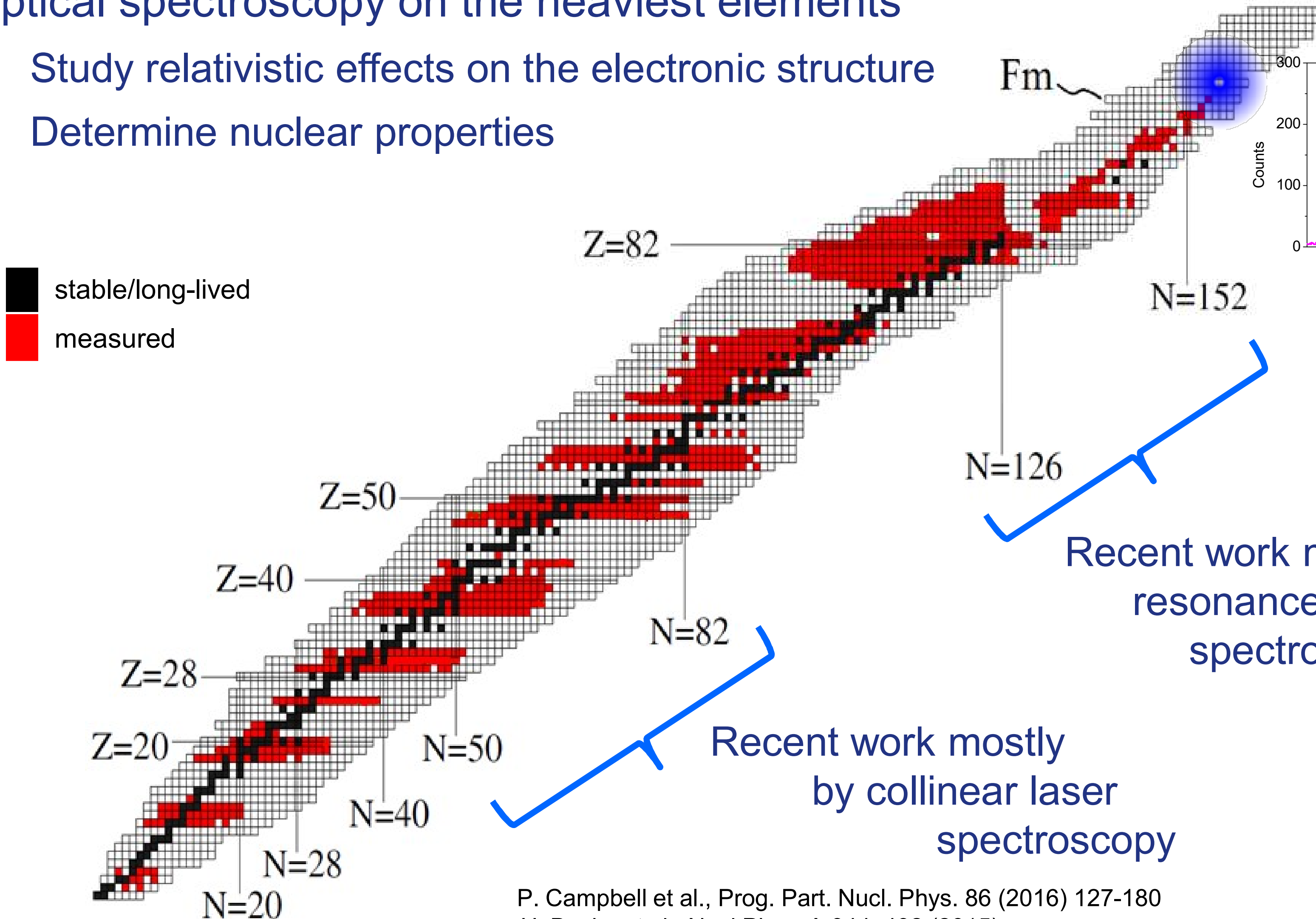

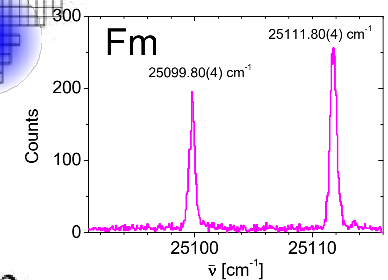

M. Sewtz,et al., PRL 90, (2003), 163002-1

Recent work mostly by resonance ionization spectroscopy (RIS)

Recent work mostly by collinear laser spectroscopy

P. Campbell et al., Prog. Part. Nucl. Phys. 86 (2016) 127-180
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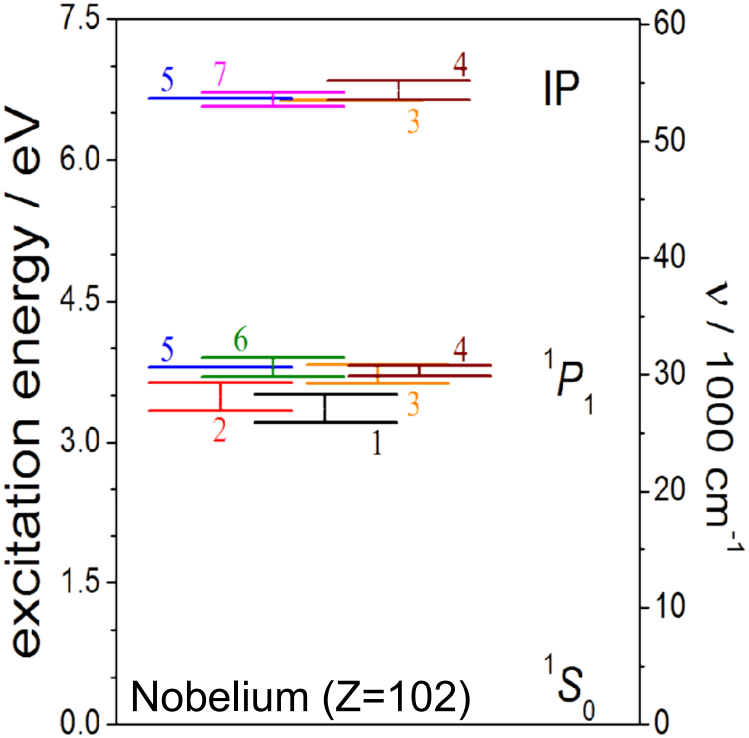
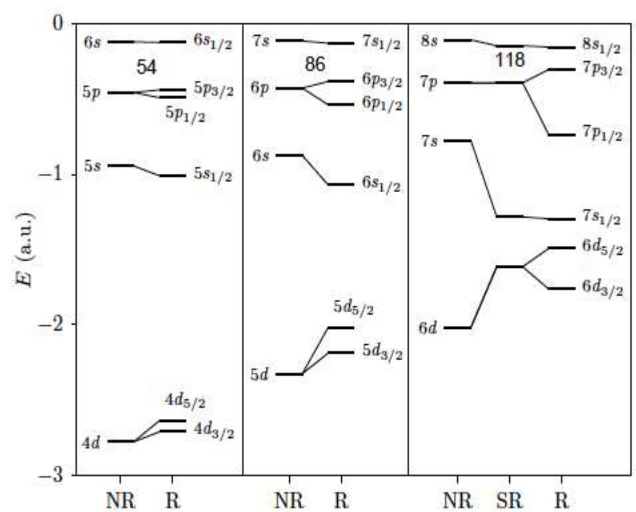
Motivation - Atomic Structure



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

- Zα → 1: large QED contribution & relativistic effects in the electronic structure



P. Jerabek et al., PRL **120,** 053001 *(2018)*

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

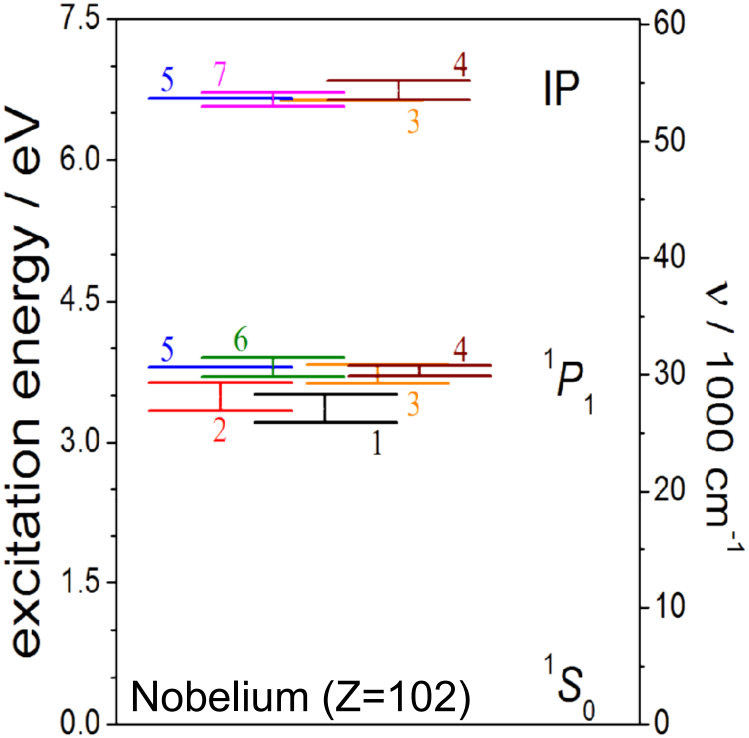
4 (RCC): V.A.Dzuba et al., Phys. Rev. A 90 (2014) 012504

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 - 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

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

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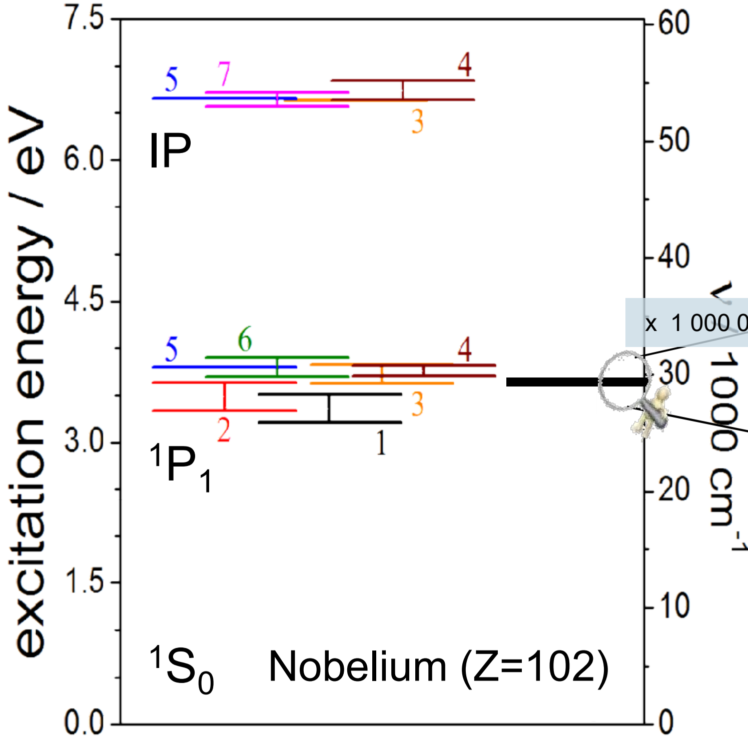
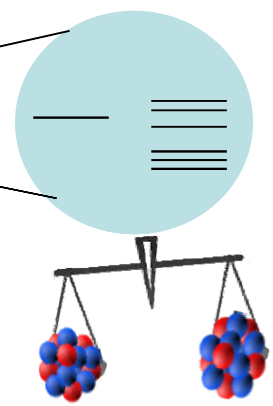
Motivation – Nuclear Properties



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

Nuclear ground state properties from



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

3 (IHFSCC): A.Borschevsky et al., Phys. Rev. A 75 (2007) 042514

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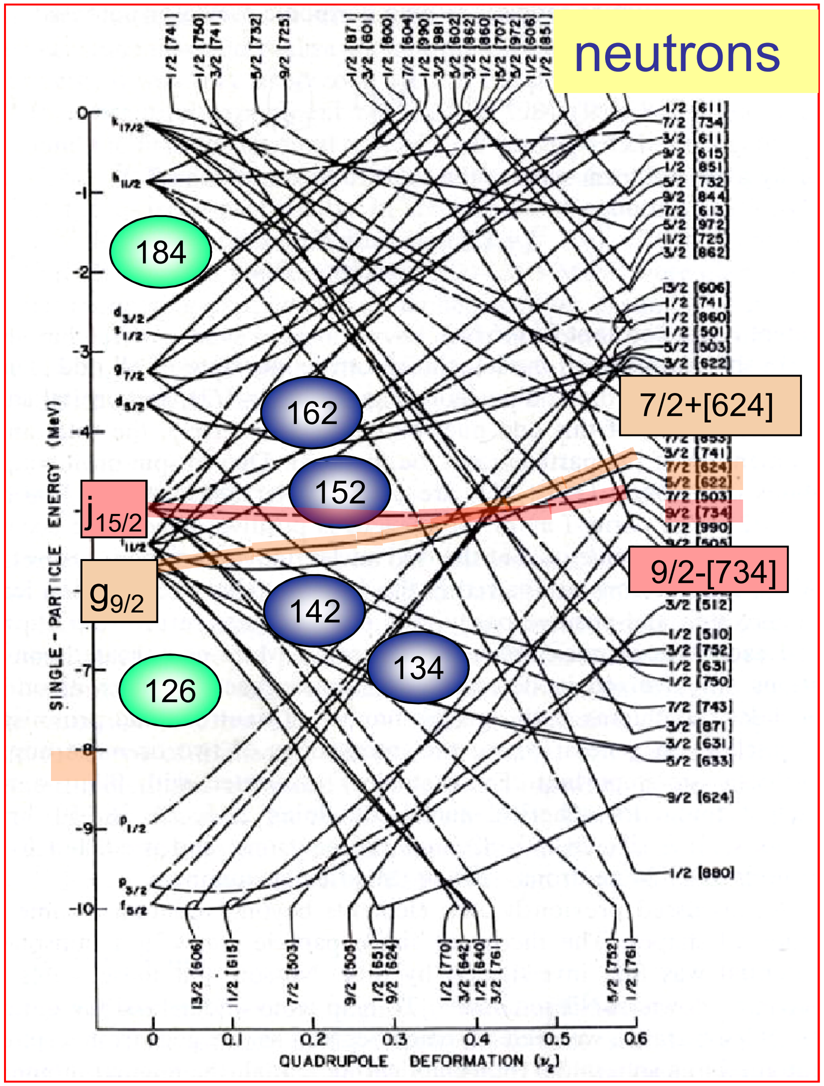
Nuclear Information from Laser Spectroscopy

Orbital energy changes with deformation – Nilsson model



Hyperfine structure:

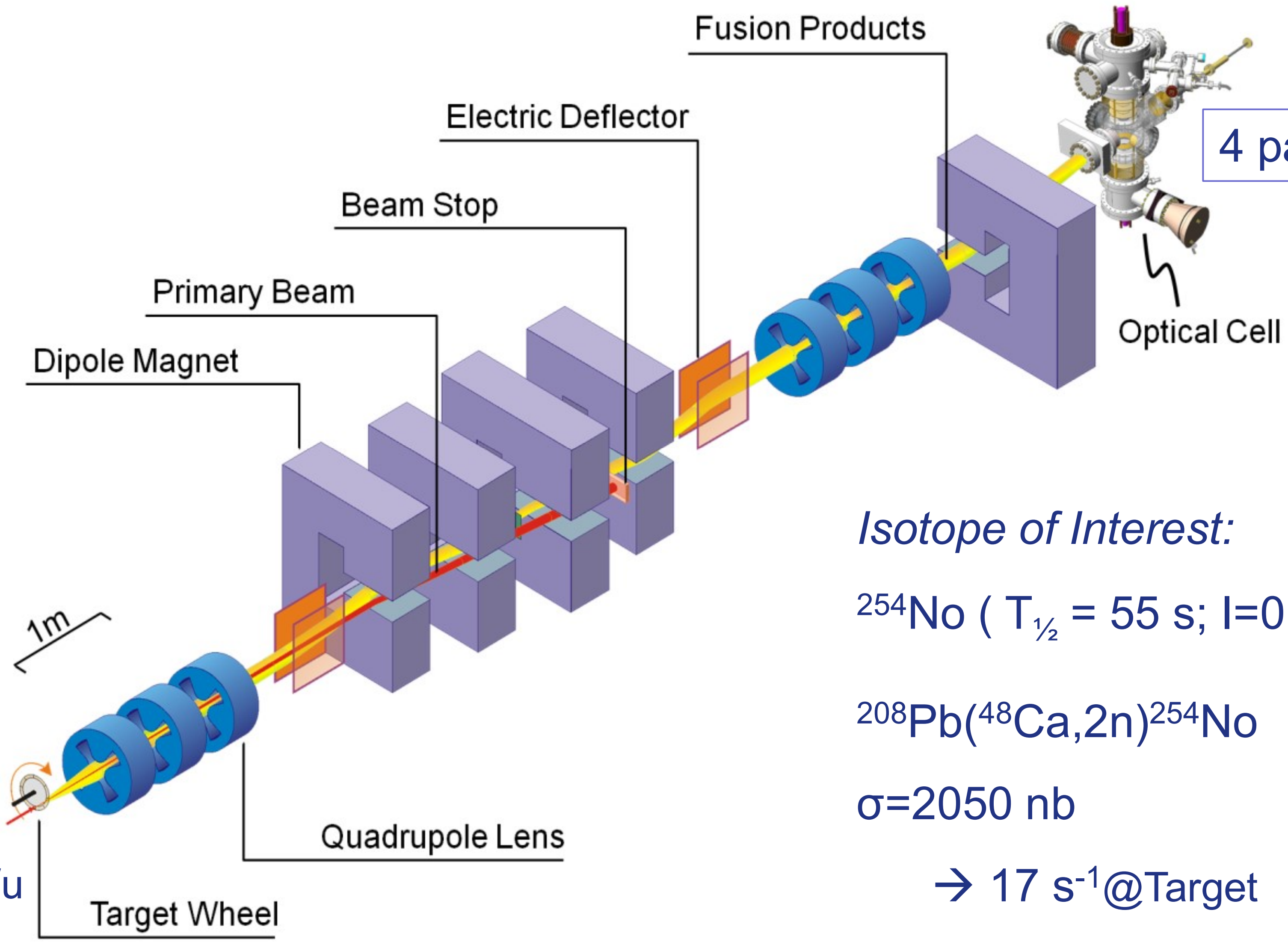
- Deformation (Q, β_2) from HFS
- Magnetic moments $\mu = g \cdot I$

Provides g-factors of unpaired nucleon characteristic for the wavefuctions

Charge radii:

- Change in deformation

Production: Velocity Filter SHIP



4 part. s^{-1}

^{48}Ca
4.55 MeV/u

Isotope of Interest:

^{254}No ($T_{½}$ = 55 s; I=0)

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

σ=2050 nb

→ 17 s^{-1}@Target

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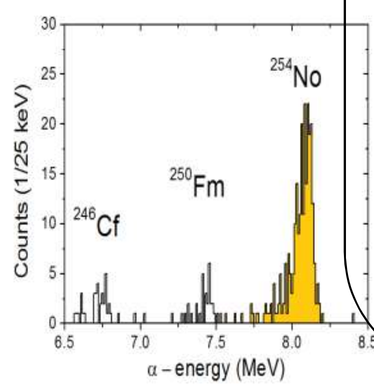
RADRIS Method:

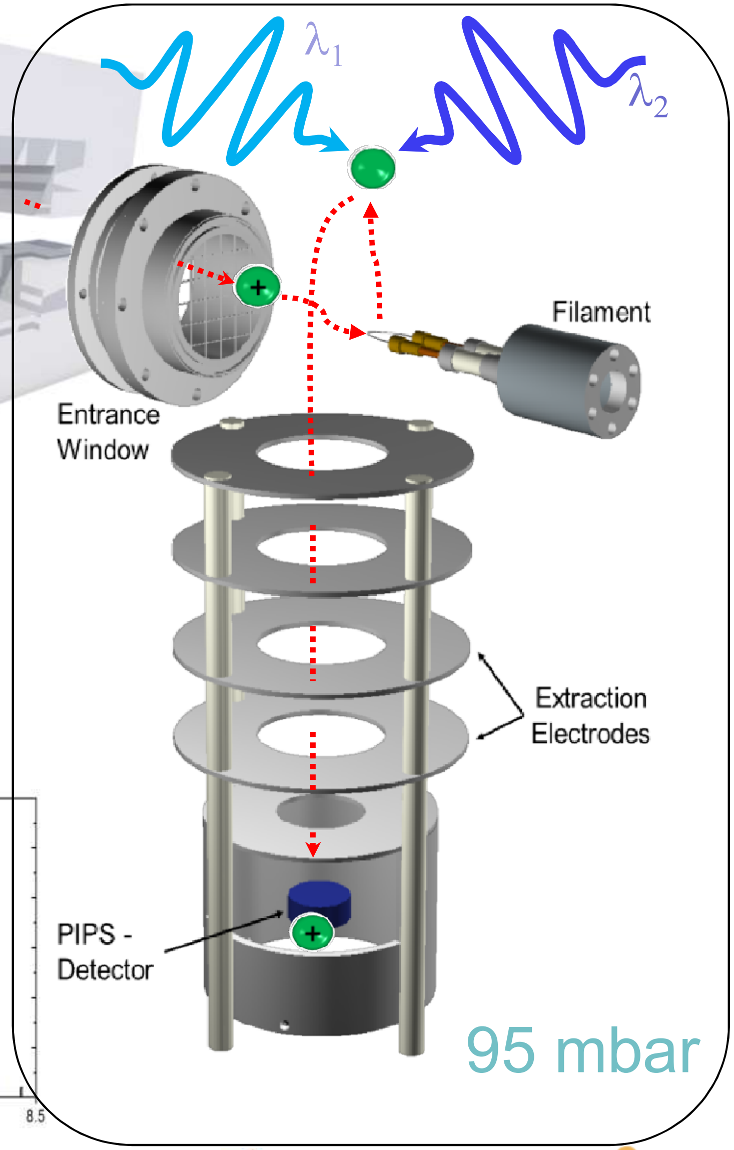
- Thermalizing of incoming fusion products

- Collecting onto thin tantalum wire

- Evaporation and two-step photoionization process

- Transport to detector and detection of alpha decay

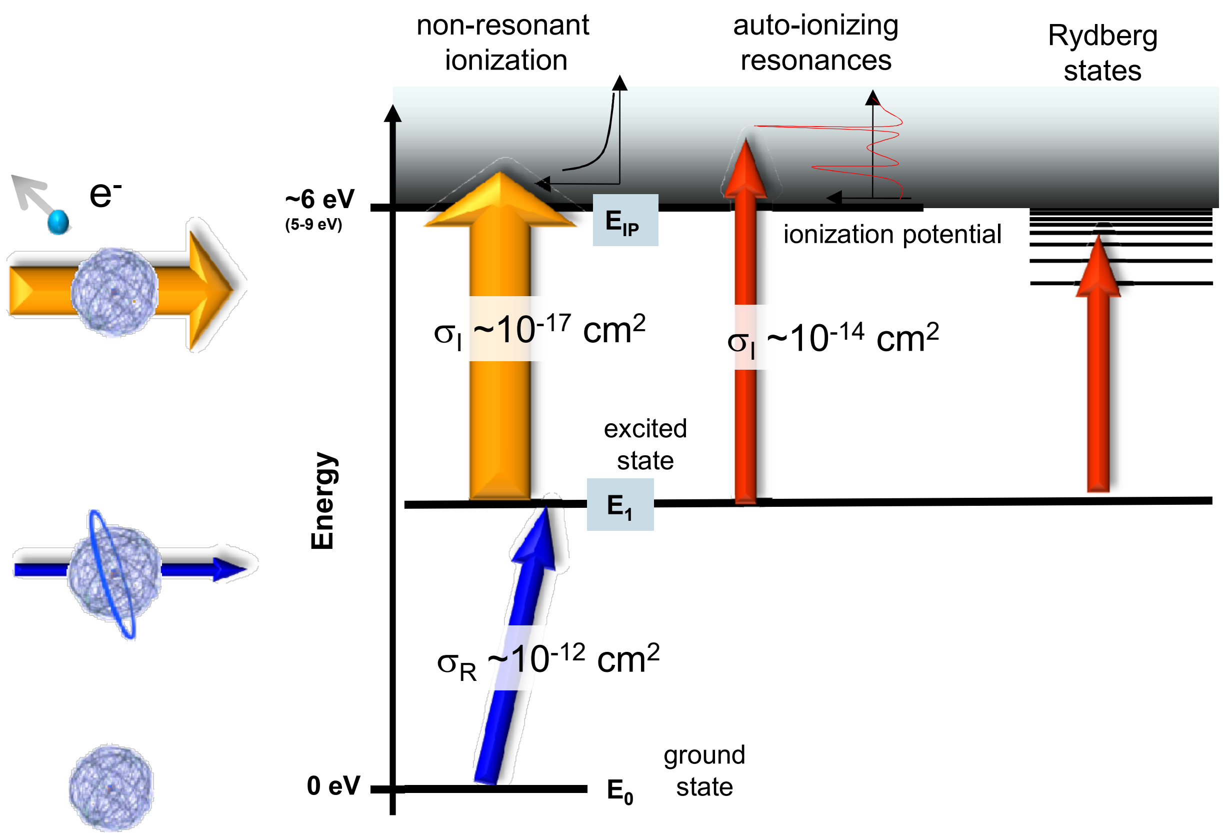




*H. Backe et al., Nucl Phys. A **944**, 492 (2015)*

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

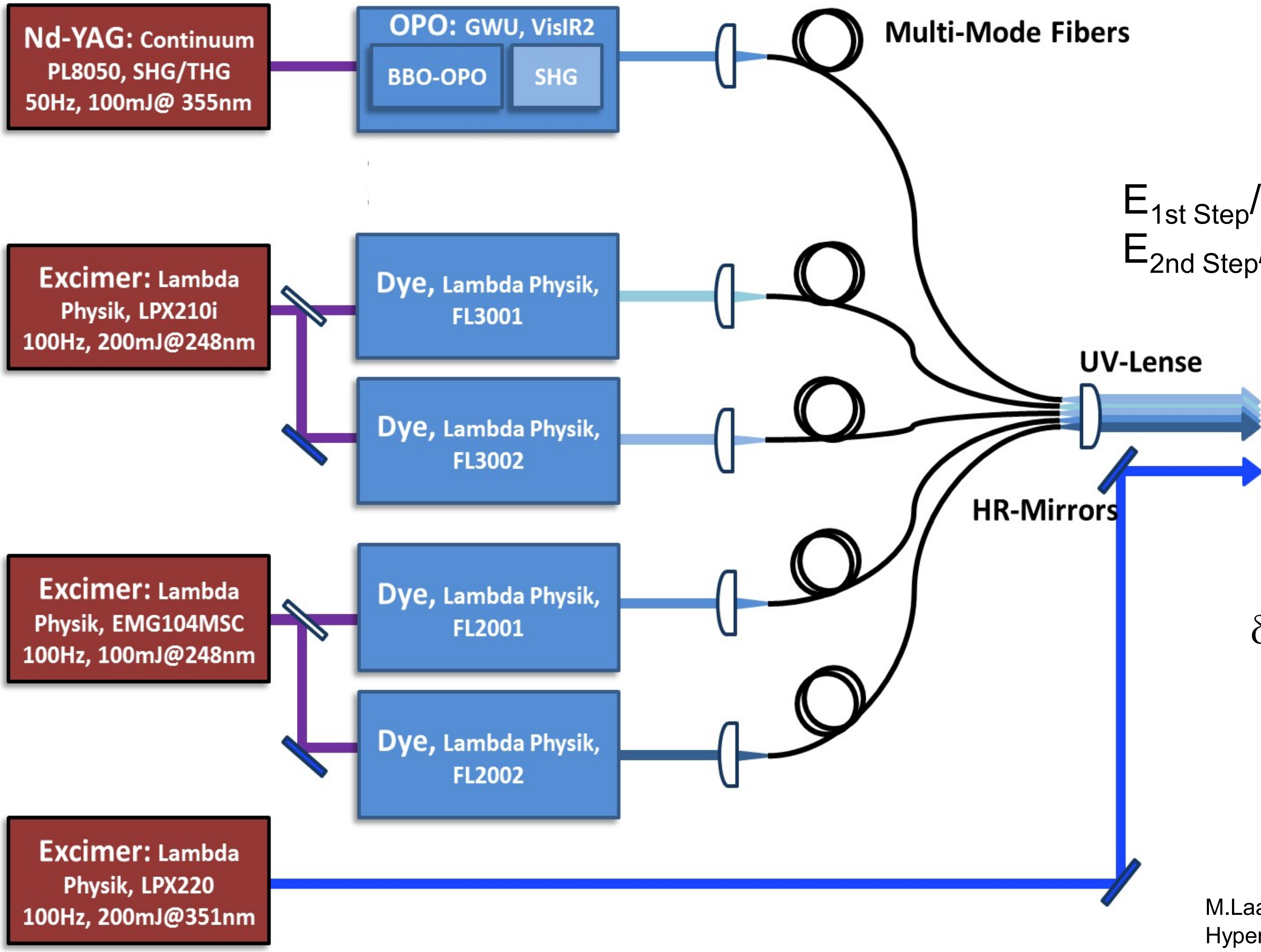
Resonance Ionization Spectroscopy



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

BUT does not depend on knowledge on the atomic structure

Laser System



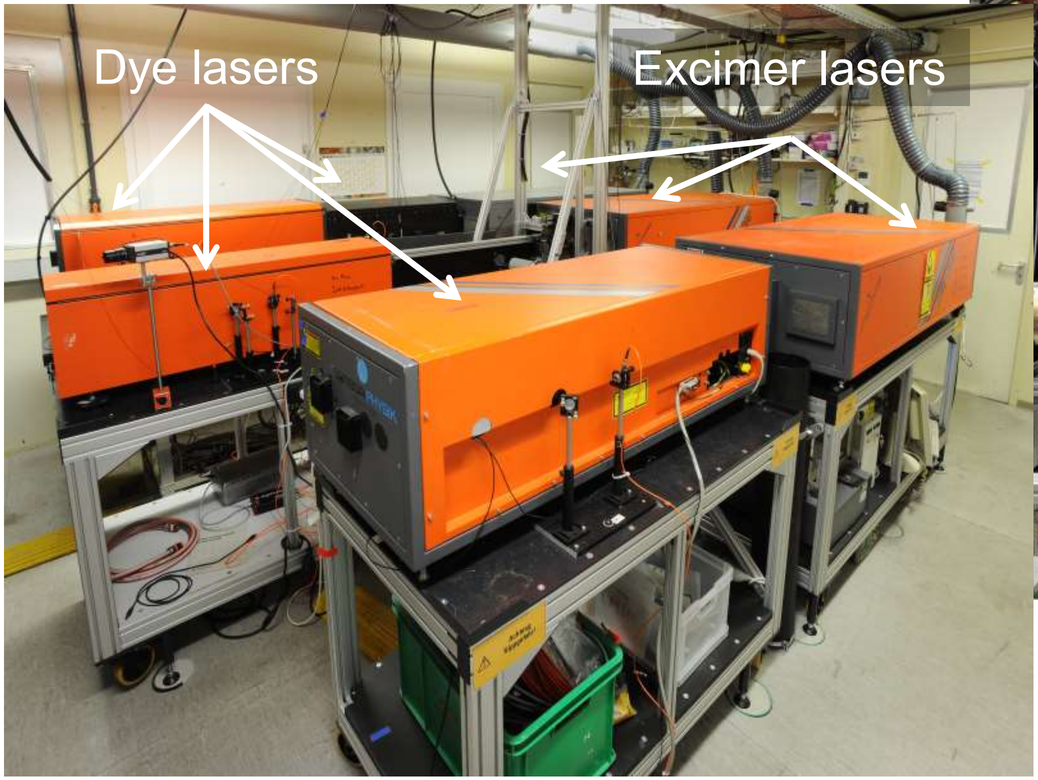
$E_{1st\ Step}$/pulse > 150 µJ
$E_{2nd\ Step}$/pulse > 30000 µJ

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

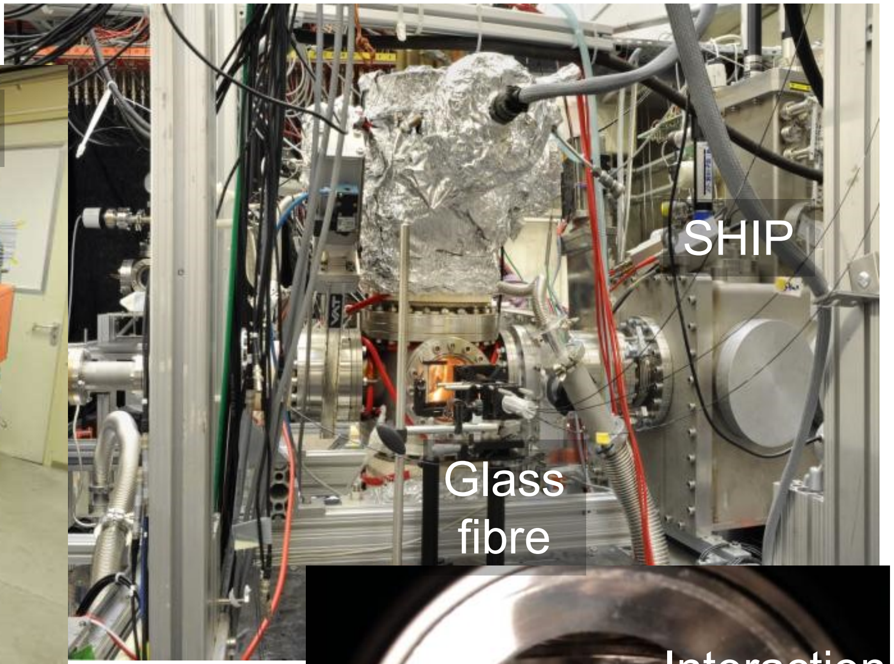
M.Laatiaoui et al.,
Hyperfine Interact. **227** (2014) 69

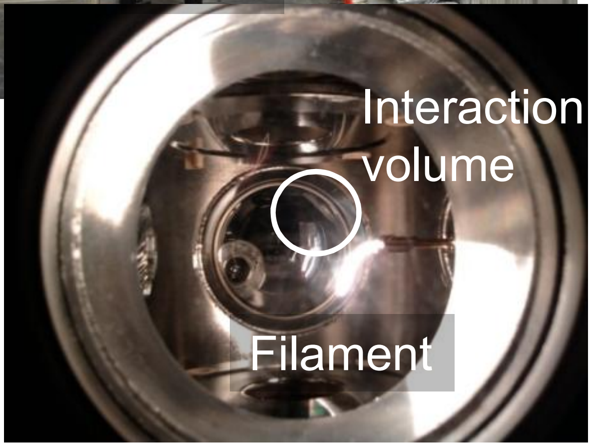
Laser System & Gas Cell Set-up

Laser system



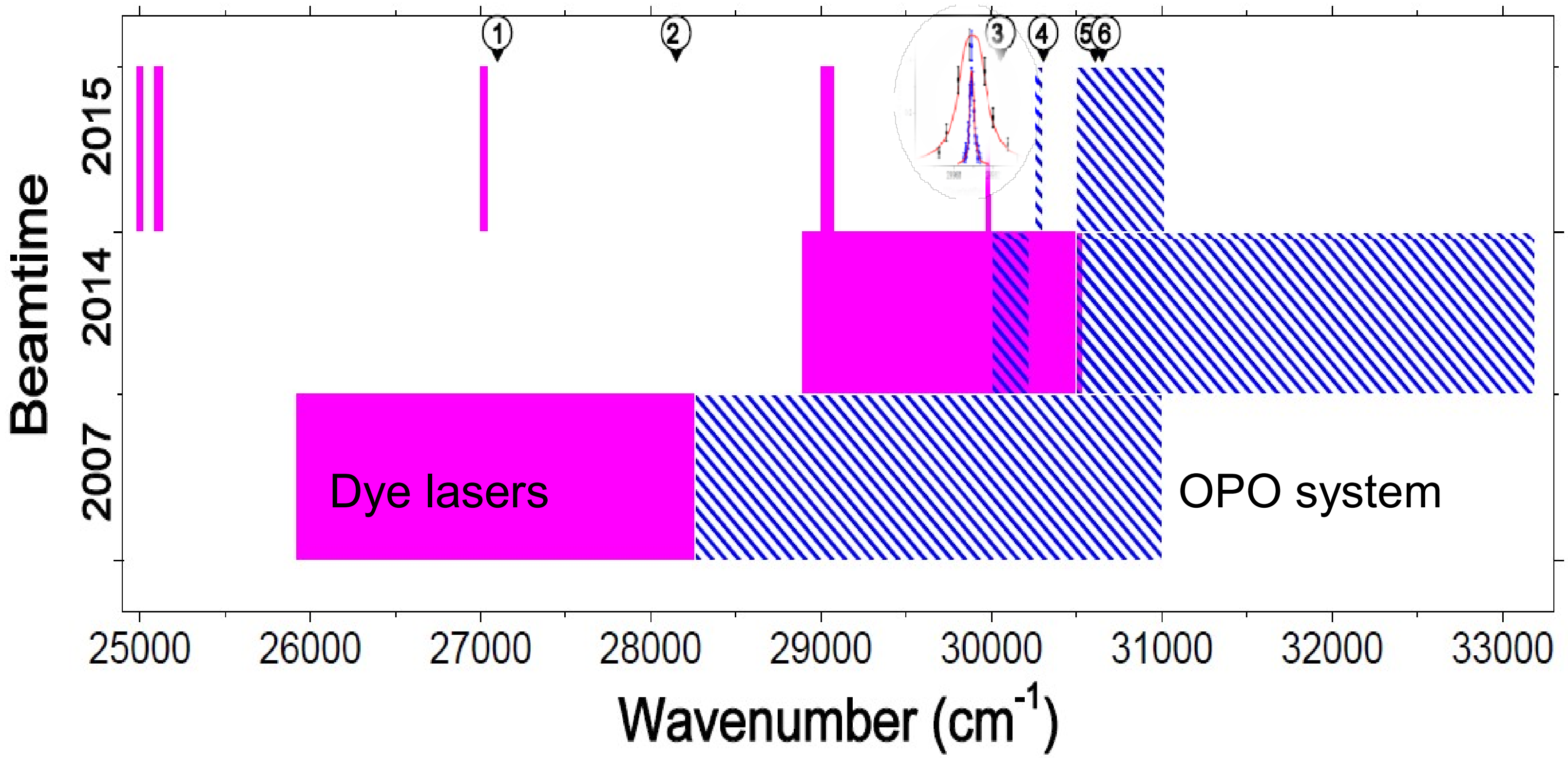
Gas cell





Level Search in ^{254}No

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

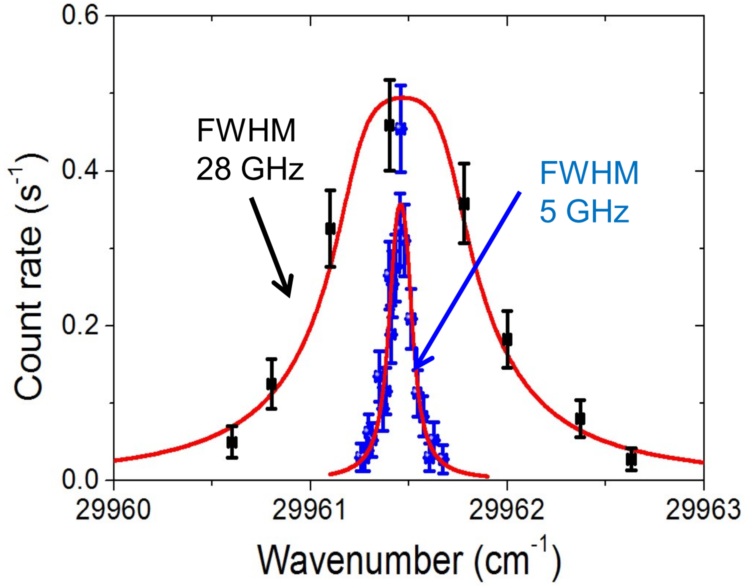


1: MCDF (2005), 2: MCDF (2005), 3: IHFSCC (2007), 4: RCC (2014), 5: MCDF (2007), 6: MCDF (2007)

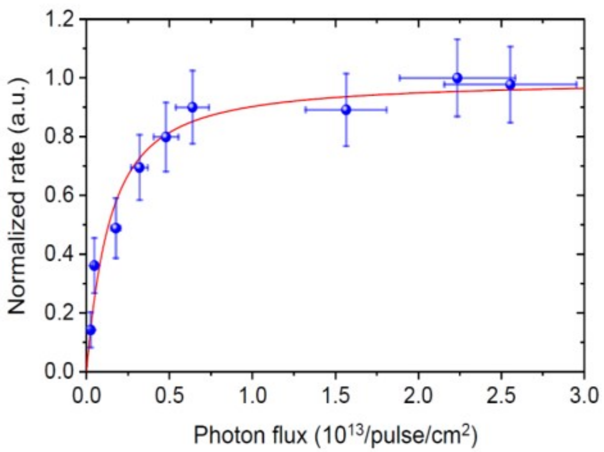
The Ground-State Transition

Observed strong atomic ground state transition

- Resolution 5 GHz
- Saturates at low photon fluxes
- A total efficiency of 6.4(10)% for ^{254}No
- < 30 000 atoms needed for experiment



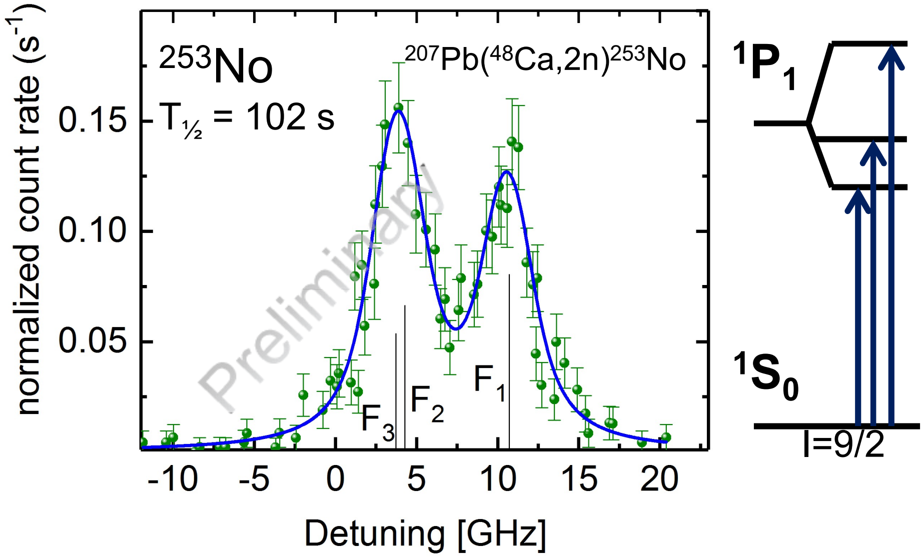
	ν_1 (cm^{-1})	A_{ki} (s^{-1}) x 10^8
Experiment [1]	$29{,}961.457(7)_{stat}$	$4.2\ (2.6)_{stat}$
IHFSCC [2]	30,100(800)	5.0
MCDF [3]	30,650(800)	2.7



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

[1] M. Laatiaoui et al., Nature 538 (2016) 7626 *[2] A. Borschevsky et al., Phys. Rev. A **75** (2007) 042514*
*[3] P. Indelicato et al., Eur. Phys. J. D **45**, (2007) 155*

Hyperfine Structure Studies in ^{253}No



Hyperfine structure partly resolved

- 2 peaks observed
  → 3 peaks expected

Energy splitting

$$\Delta E_{HFS} = A \cdot \frac{C}{2} + B \cdot \frac{3/4\,C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

$$C = F(F+1) - I(I-1) - J(J-1)$$

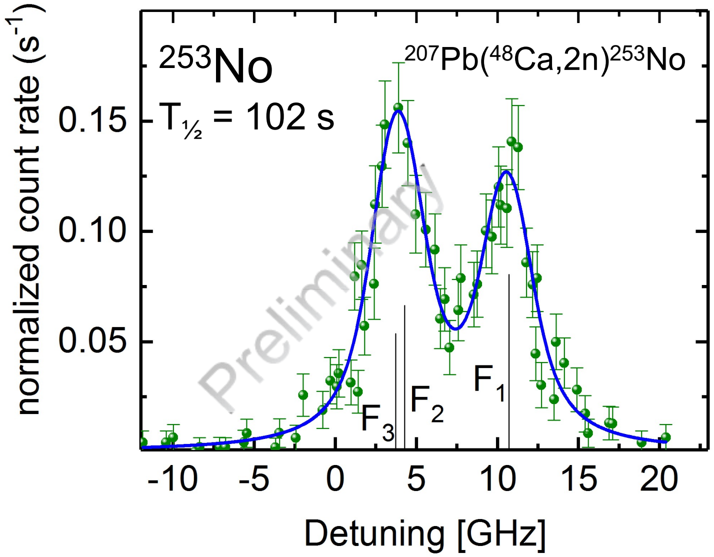
atomic
nuclear
properties

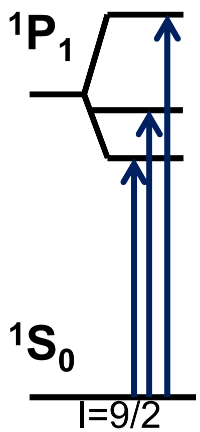
$$A = \mu \frac{B_e(0)}{IJ}$$

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

[1] V.A. Dzuba et al. (CI), [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





Hyperfine structure partly resolved

- 2 peaks observed
  → 3 peaks expected

Feedback from atomic theory for nuclear moments

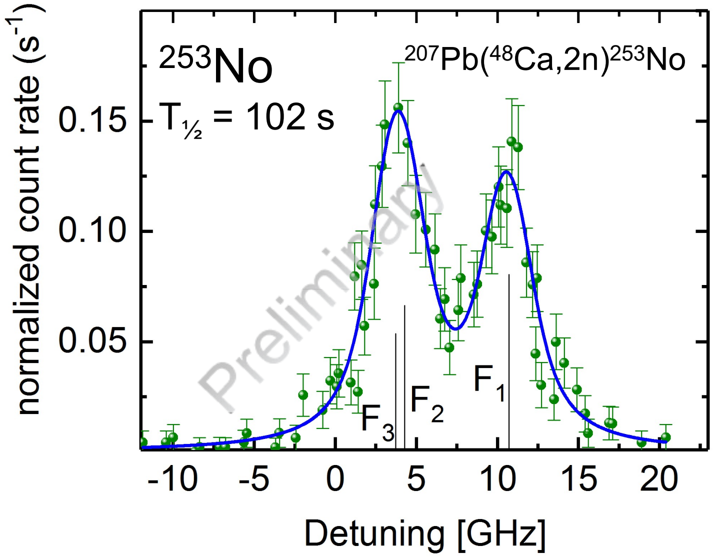
$$A = \mu \frac{B_e(0)}{IJ}$$

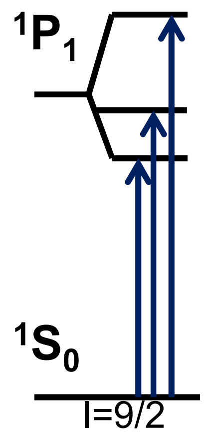
$$B = eQ_s \left\langle \frac{\delta^2 V}{\delta z^2} \right\rangle_{z=0}$$

	Ref.	A/μ_N (GHZ)	B/eb (GHZ)
Theory	CI [1]	-6.3(0.9)	0.486 (70)
	RCC [2]		0.465(70)
	MCDF [3]	-4.1(1.8)	0.444(75)

*[1] V.A. Dzuba et al. (CI), [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 Parameters of ^{253}No





Hyperfine structure partly resolved

- 2 peaks observed
  → 3 peaks expected

Determination of nuclear properties of ^{253}No

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

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

	μ (μ_N)	Q_s (eb)
Laser spec. (this work)	-0.527(33)[75]	5.9(14)[8]
	↑ -0.593 (calculated value)	↑ 7.145 eb from ^{254}No

[1] R.D. Herzberg et al., Eur. Phys. J. A ***42****, 333-337 (2009)*

[2] S. Raeder et al.,120(23), 232503, PRL (2018)

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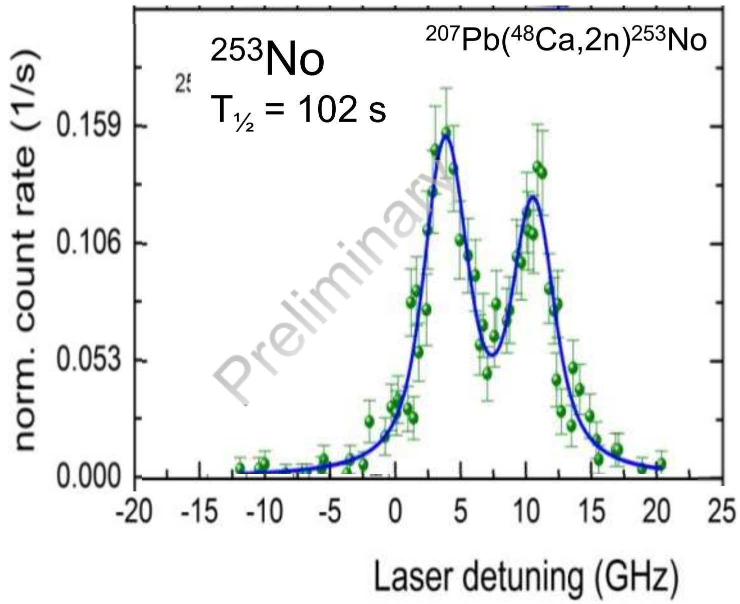
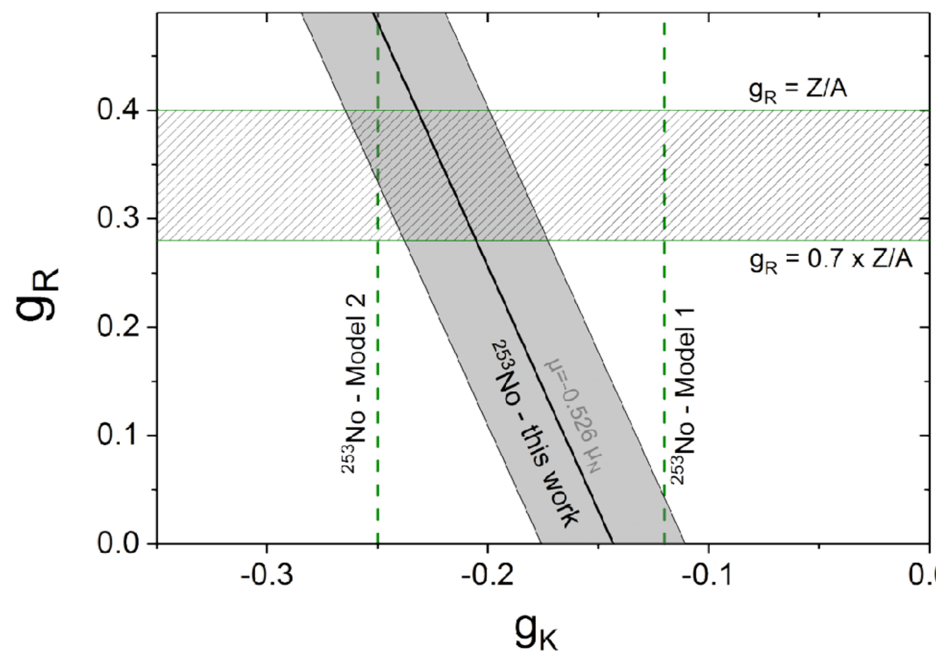
Hyperfine Structure Studies in ^{253}No





Single particle g-factor

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

Model1: P.Reiter et al., Phys. Rev. Lett. 95, 032501 (2005).
*Model 2: R.D. Herzberg et al., Eur. Phys. J. A **42**, 333-337 (2009)*

→ Nuclear model independent confirmation of expected nuclear properties

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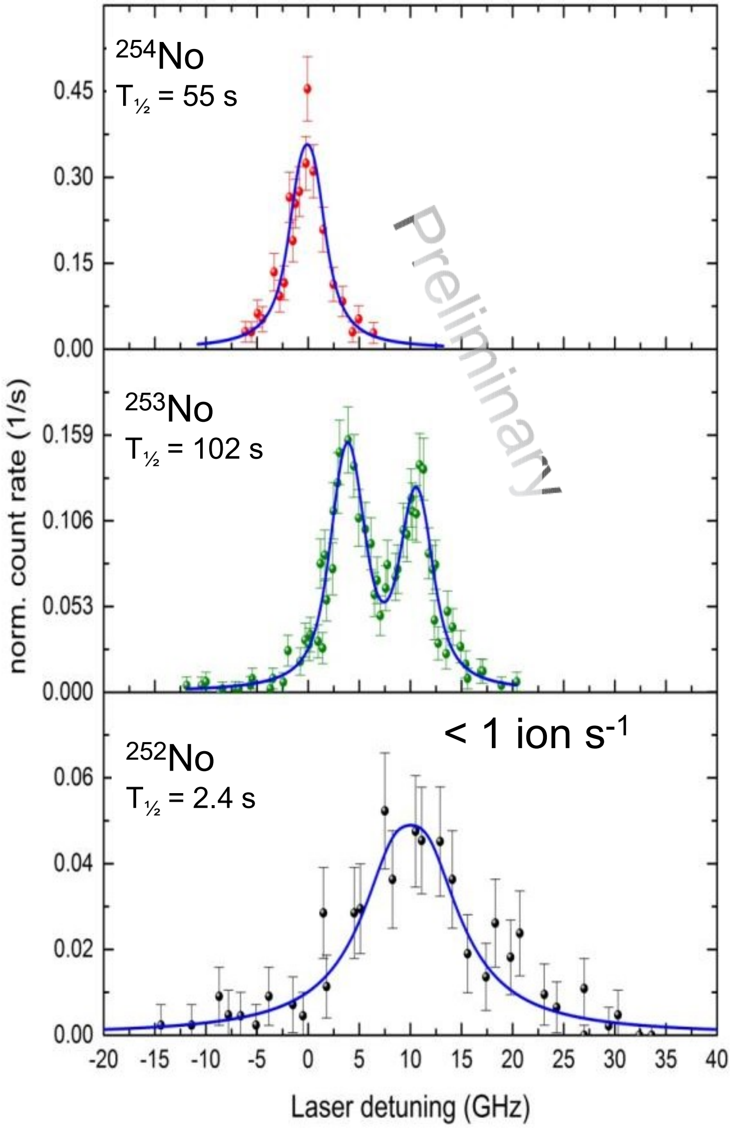
Isotope Shift of $^{252-254}$No



- Isotope shift for $^{252-254}$No measured
- Input from atomic theory
  - Mass-shift constant: 1044 GHz u
  - Field-shift parameter: -95.8(70) GHz/fm

(R. Beerwerth & S. Fritzsche (MCDF), V. Dzuba, M. Safranove (CI))

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

Isotope	N	δν (GHZ)	δ<r²> (fm²)
^{254}No	152	0	0
^{253}No	151	6.72(18)	-0.070 (2)[5]
^{252}No	150	10.08(69)	-0.105(7)[7]

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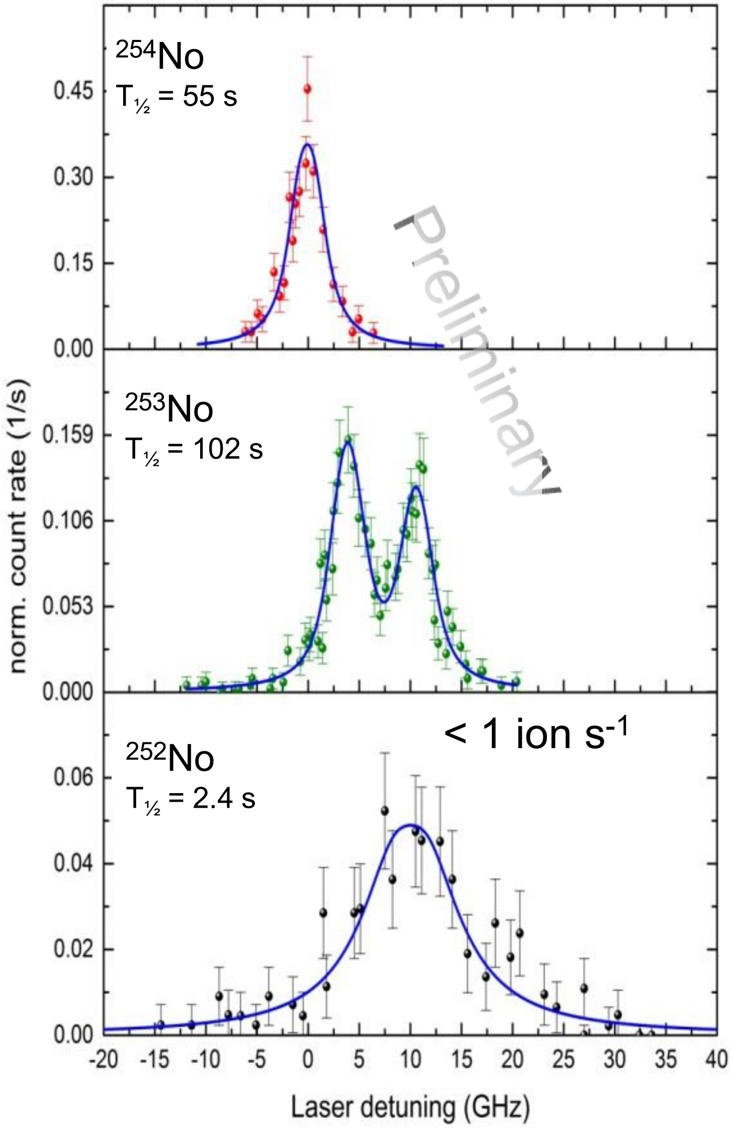
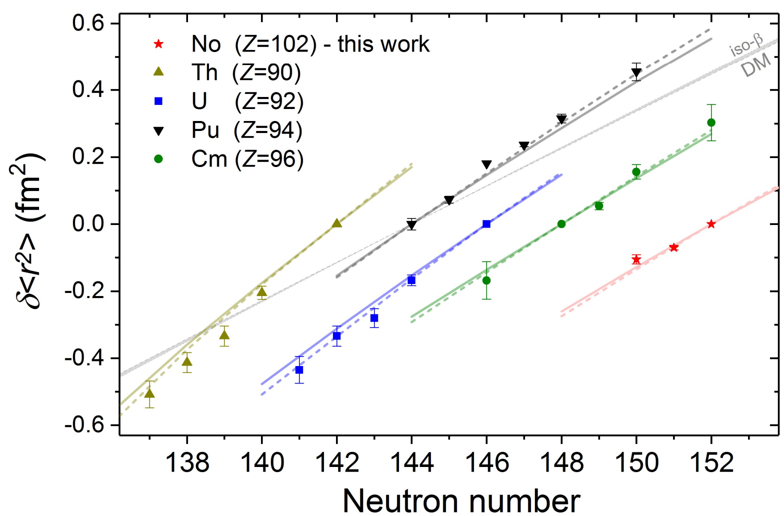
Isotope Shift of $^{252-254}$No



- Isotope shift for $^{252-254}$No measured
- Change in charge radii: Input from atomic theory
  - Mass-shift constant: 1044 GHz u
  - Field-shift parameter: -95.8(7.0) GHz/fm

(R. Beerwerth & S. Fritzsche (MCDF), V. Dzuba, M. Safranove (CI))



Agrees well with nuclear DFT calculations

(B. Schuetrumpf, W. Nazarewicz)

[1] S. Raeder et al.,120(23), 232503, PRL (2018)

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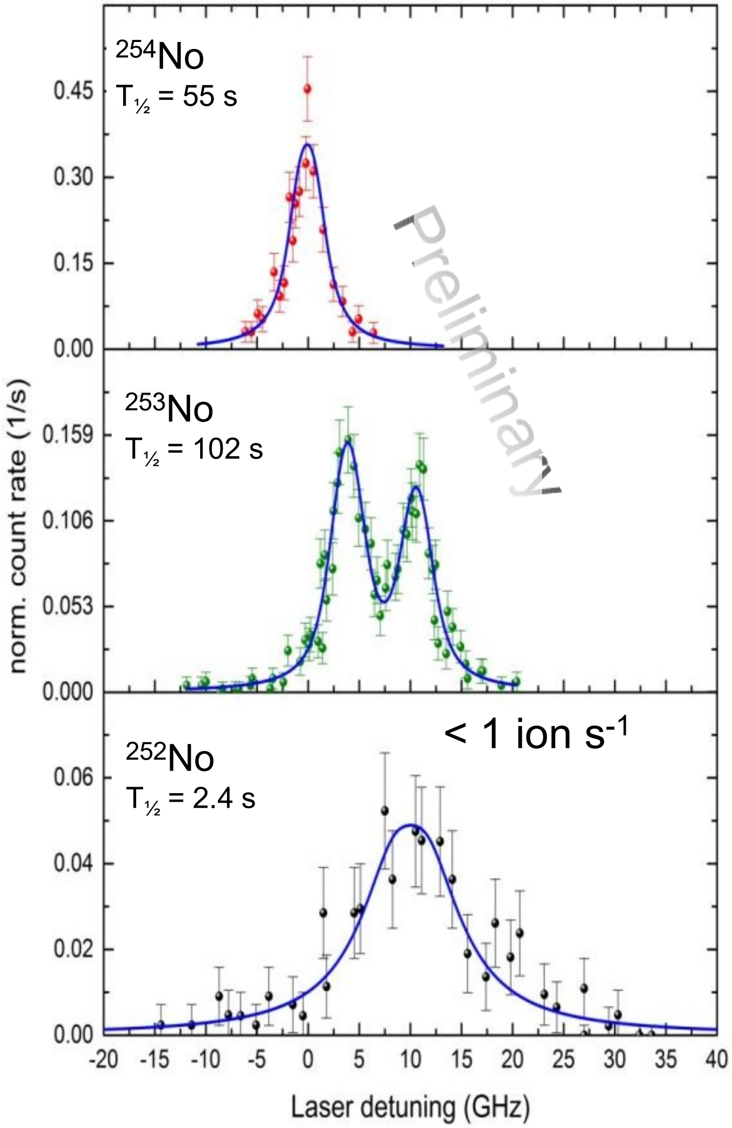
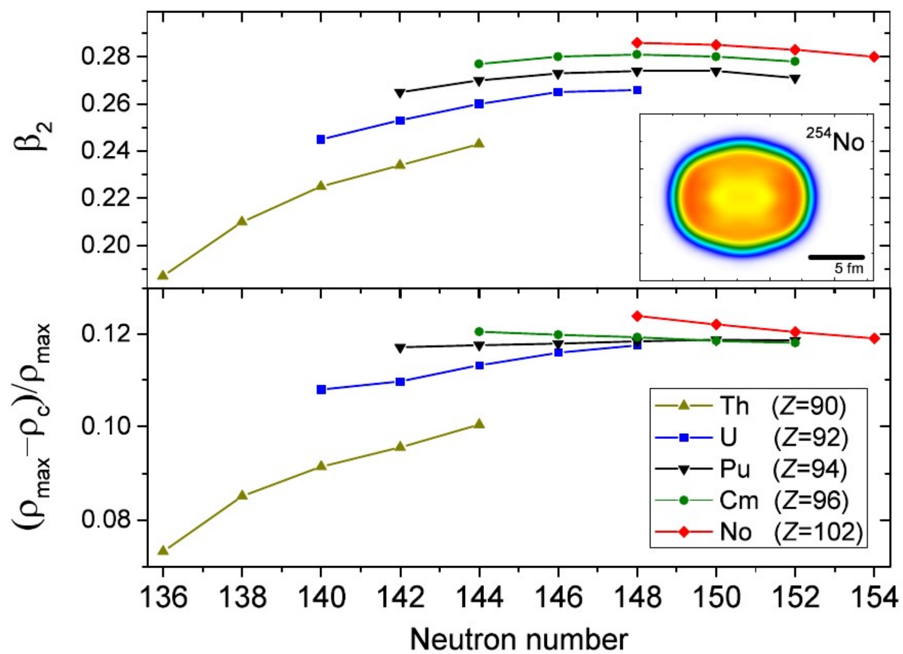
Isotope Shift of $^{252-254}No$



Deformation from DFT calculations



(B. Schuetrumpf, W. Nazarewicz)

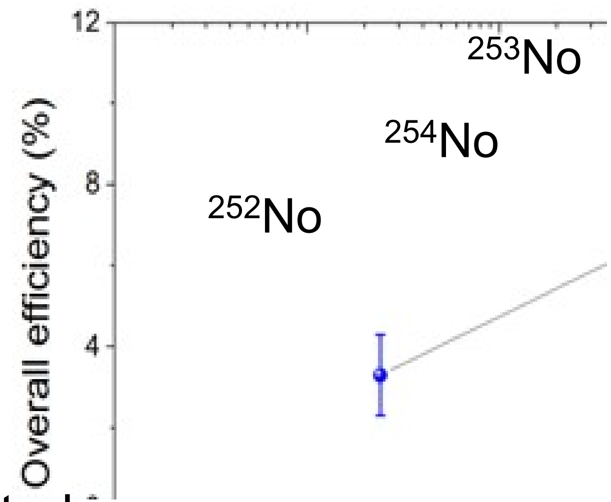
Central depression of nuclei

→ contributing to charge radius

[1] S. Raeder et al.,120(23), 232503, PRL (2018)

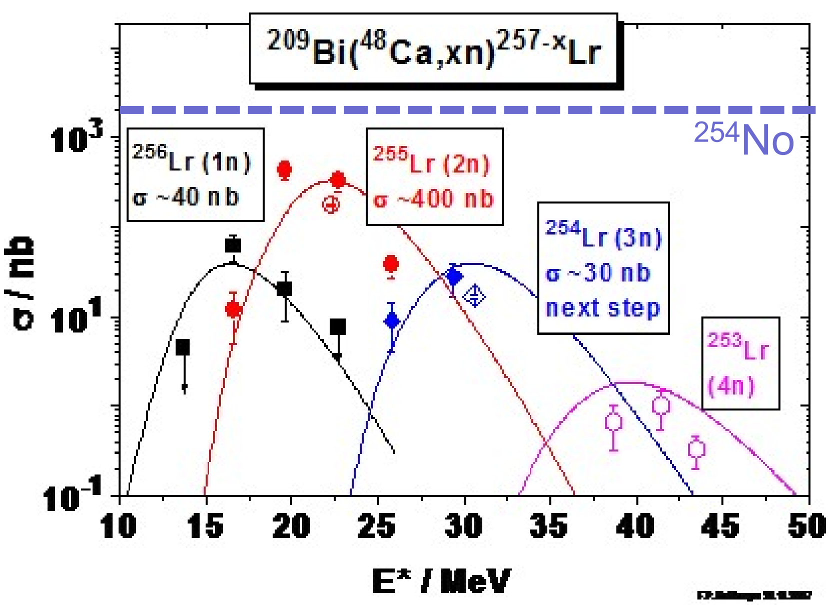
Summary of No Laser Spectrosocpy

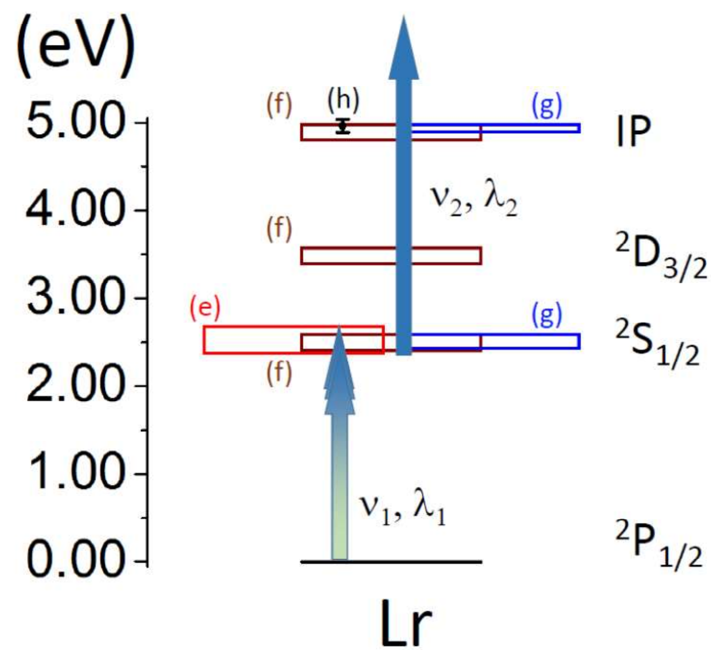
- First laser spectroscopy on a transfermium element
- Strong $^1S_0 \rightarrow {}^1P_1$ GS transition in the nobelium (Z=102) atom observed
- Identification of 32 atomic levels in nobelium
- Overall efficiency up to 8% (^{253}No)
- Accurate value for the first IP of nobelium extracted
- Access to nuclear structure from IS for $^{252-254}$No & HFS in ^{253}No



Next Steps for RADRIS at GSI

- Resonance ionization of other nobelium isotopes
  - ^{251}No – cross section of only 30 nb (~ 3 ions / minute produced)
  - ^{255}No – produced via EC from ^{255}Lr to avoid contamination from ^{254}No
- Extending laser spectroscopy to the element lawrencium (Z=103)





RADRIS Collaboration

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