“Novel Aspects in the study of Heavy and Super Heavy Elements“

Laser Spectroscopy

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- Ground state properties of isotopes in the heavy and super heavy element region: what do we know (apart from masses)?

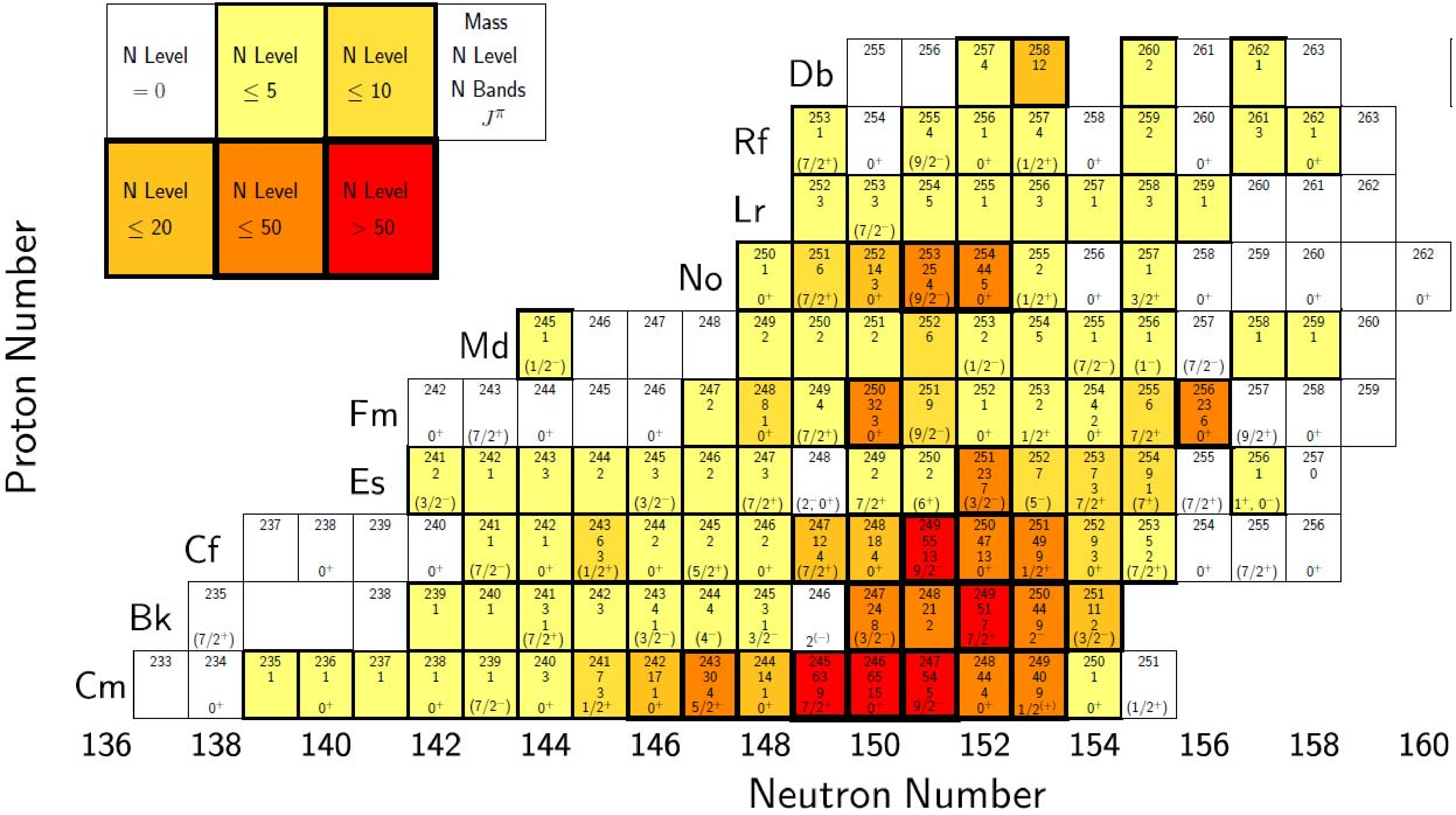
- What can be learned from laser spectroscopy?

- In-gas jet or in-gas cell laser ionization spectroscopy
“Heavy Element Laser IOnization Spectrocopy – HELIOS”

- Feasibility studies in other regions of the nuclear chart

- Conclusion and Outlook:

Excited Levels



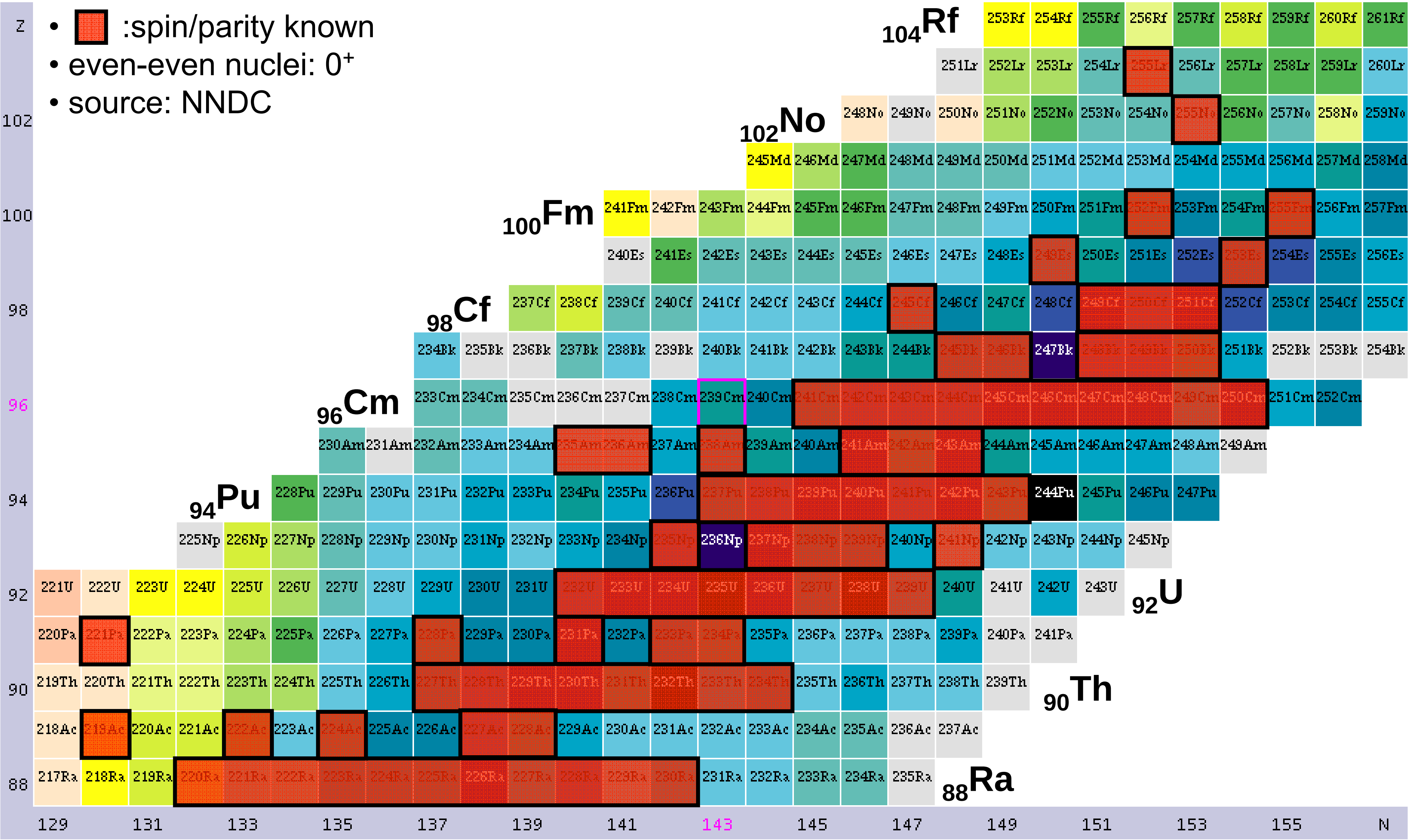
N Level = 0	N Level ≤ 5	N Level ≤ 10	Mass N Level N Bands J^π
N Level ≤ 20	N Level ≤ 50	N Level > 50	

Proton Number	136		138		140		142		144		146		148		150		152		154		156		158		160
Db															255	256	257 4	258 12		260 2	261	262 1	263		
Rf														253 1 $(7/2^+)$	254 0^+	255 4 $(9/2^-)$	256 1 0^+	257 4 $(1/2^+)$	258 0^+	259 2	260 0^+	261 3	262 1 0^+	263	
Lr														252 3	253 3 $(7/2^-)$	254 5	255 1	256 3	257 1	258 3	259 1	260	261	262	
No													250 1 0^+	251 6 $(7/2^+)$	252 14 3 0^+	253 25 4 $(9/2^-)$	254 44 5 0^+	255 2 $(1/2^+)$	256 0^+	257 1 $3/2^+$	258 0^+	259	260 0^+		262 0^+
Md									245 1 $(1/2^-)$	246	247	248	249 2	250 2	251 2	252 6	253 2 $(1/2^-)$	254 5	255 1 $(7/2^-)$	256 1 (1^-)	257 $(7/2^-)$	258 1	259 1	260	
Fm							242 0^+	243 $(7/2^+)$	244 0^+	245	246 0^+	247 2	248 8 1 0^+	249 4 $(7/2^+)$	250 32 3 0^+	251 9 $(9/2^-)$	252 1 0^+	253 2 $1/2^+$	254 4 2 0^+	255 6 $7/2^+$	256 23 6 0^+	257 $(9/2^+)$	258 0^+	259	
Es							241 2 $(3/2^-)$	242 1	243 3	244 2	245 3 $(3/2^-)$	246 2	247 3 $(7/2^+)$	248 $(2^-, 0^+)$	249 2 $7/2^+$	250 2 (6^+)	251 23 7 $(3/2^-)$	252 7 (5^-)	253 7 3 $7/2^+$	254 9 1 (7^+)	255 $(7/2^+)$	256 1 $(1^+, 0^-)$	257 0		
Cf				237	238 0^+	239	240 0^+	241 1 $(7/2^-)$	242 1 0^+	243 6 3 $(1/2^+)$	244 2 0^+	245 2 $(5/2^+)$	246 2 0^+	247 12 4 $(7/2^+)$	248 18 4 0^+	249 55 13 $9/2^-$	250 47 13 0^+	251 49 9 $1/2^+$	252 9 3 0^+	253 5 2 $(7/2^+)$	254 0^+	255 $(7/2^+)$	256 0^+		
Bk			235 $(7/2^+)$			238	239 1	240 1	241 3 1 $(7/2^+)$	242 3	243 4 1 $(3/2^-)$	244 4 (4^-)	245 3 1 $3/2^-$	246 $2^{(-)}$	247 24 8 $(3/2^-)$	248 21 2	249 51 7 $7/2^+$	250 44 9 2^-	251 11 2 $(3/2^-)$						
Cm		233	234 0^+	235 1	236 1 0^+	237 1	238 1 0^+	239 1 $(7/2^-)$	240 3 0^+	241 7 3 $1/2^+$	242 17 1 0^+	243 30 4 $5/2^+$	244 14 1 0^+	245 63 9 $7/2^+$	246 65 15 0^+	247 54 5 $9/2^-$	248 44 4 0^+	249 40 9 $1/2^{(+)}$	250 1 0^+	251 $(1/2^+)$					

Neutron Number

R.-D.Herzberg and P.T.Greenlees, Prog. Part. Nuc. Phys. 61, 674 (2008)

Spin/parity

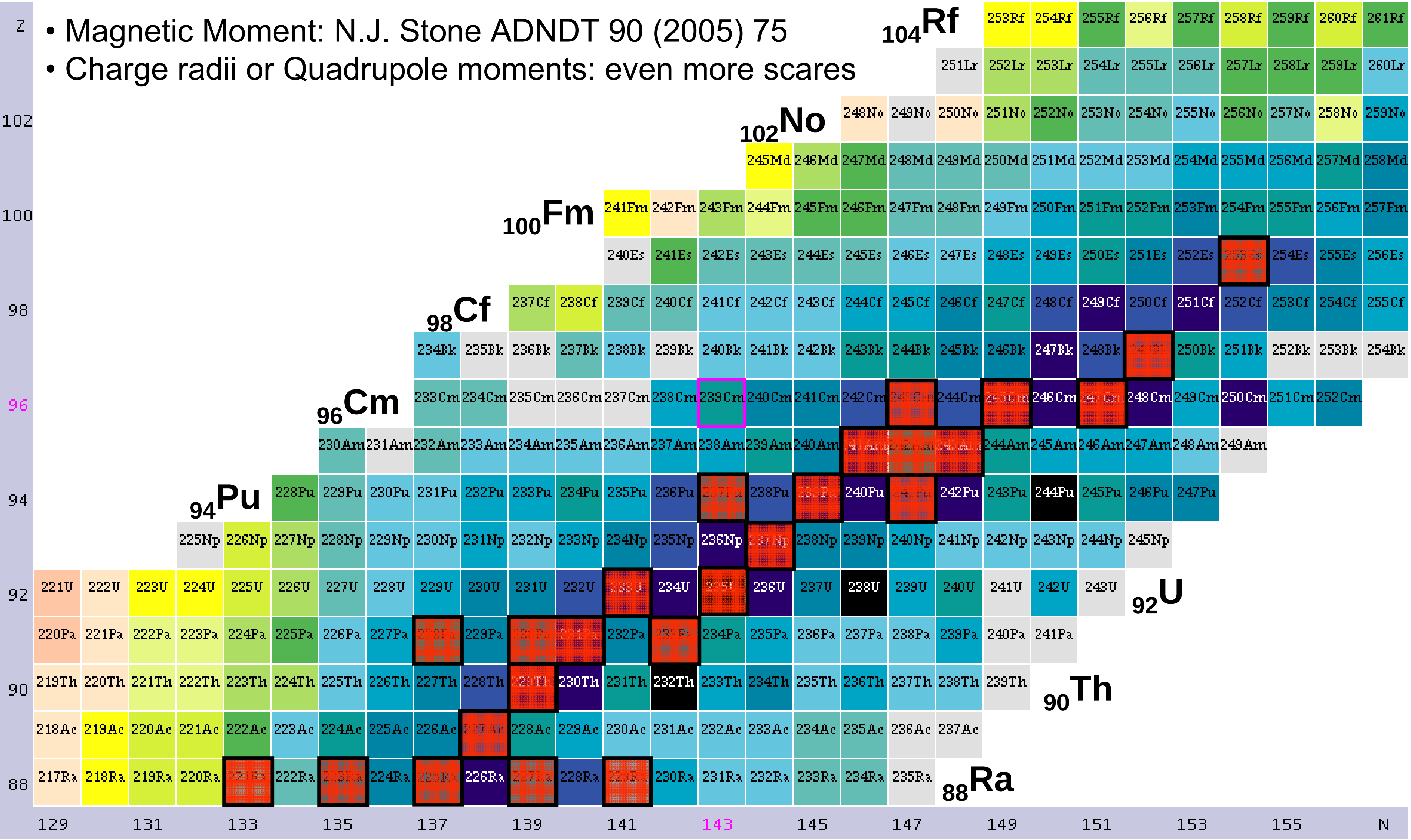


- 🟥 :spin/parity known
- even-even nuclei: 0^+
- source: NNDC

Z																			$_{104}$Rf		253Rf	254Rf	255Rf	256Rf	257Rf	258Rf	259Rf	260Rf	261Rf
																				251Lr	252Lr	253Lr	254Lr	255Lr	256Lr	257Lr	258Lr	259Lr	260Lr
102																$_{102}$No		248No	249No	250No	251No	252No	253No	254No	255No	256No	257No	258No	259No
																245Md	246Md	247Md	248Md	249Md	250Md	251Md	252Md	253Md	254Md	255Md	256Md	257Md	258Md
100											$_{100}$Fm		241Fm	242Fm	243Fm	244Fm	245Fm	246Fm	247Fm	248Fm	249Fm	250Fm	251Fm	252Fm	253Fm	254Fm	255Fm	256Fm	257Fm
													240Es	241Es	242Es	243Es	244Es	245Es	246Es	247Es	248Es	249Es	250Es	251Es	252Es	253Es	254Es	255Es	256Es
98									$_{98}$Cf		237Cf	238Cf	239Cf	240Cf	241Cf	242Cf	243Cf	244Cf	245Cf	246Cf	247Cf	248Cf	249Cf	250Cf	251Cf	252Cf	253Cf	254Cf	255Cf
									234Bk	235Bk	236Bk	237Bk	238Bk	239Bk	240Bk	241Bk	242Bk	243Bk	244Bk	245Bk	246Bk	247Bk	248Bk	249Bk	250Bk	251Bk	252Bk	253Bk	254Bk
96							$_{96}$Cm		233Cm	234Cm	235Cm	236Cm	237Cm	238Cm	239Cm	240Cm	241Cm	242Cm	243Cm	244Cm	245Cm	246Cm	247Cm	248Cm	249Cm	250Cm	251Cm	252Cm	
							230Am	231Am	232Am	233Am	234Am	235Am	236Am	237Am	238Am	239Am	240Am	241Am	242Am	243Am	244Am	245Am	246Am	247Am	248Am	249Am			
94				$_{94}$Pu		228Pu	229Pu	230Pu	231Pu	232Pu	233Pu	234Pu	235Pu	236Pu	237Pu	238Pu	239Pu	240Pu	241Pu	242Pu	243Pu	244Pu	245Pu	246Pu	247Pu				
				225Np	226Np	227Np	228Np	229Np	230Np	231Np	232Np	233Np	234Np	235Np	236Np	237Np	238Np	239Np	240Np	241Np	242Np	243Np	244Np	245Np					
92	221U	222U	223U	224U	225U	226U	227U	228U	229U	230U	231U	232U	233U	234U	235U	236U	237U	238U	239U	240U	241U	242U	243U		$_{92}$U				
	220Pa	221Pa	222Pa	223Pa	224Pa	225Pa	226Pa	227Pa	228Pa	229Pa	230Pa	231Pa	232Pa	233Pa	234Pa	235Pa	236Pa	237Pa	238Pa	239Pa	240Pa	241Pa							
90	219Th	220Th	221Th	222Th	223Th	224Th	225Th	226Th	227Th	228Th	229Th	230Th	231Th	232Th	233Th	234Th	235Th	236Th	237Th	238Th	239Th	$_{90}$Th							
	218Ac	219Ac	220Ac	221Ac	222Ac	223Ac	224Ac	225Ac	226Ac	227Ac	228Ac	229Ac	230Ac	231Ac	232Ac	233Ac	234Ac	235Ac	236Ac	237Ac									
88	217Ra	218Ra	219Ra	220Ra	221Ra	222Ra	223Ra	224Ra	225Ra	226Ra	227Ra	228Ra	229Ra	230Ra	231Ra	232Ra	233Ra	234Ra	235Ra	$_{88}$Ra									
	129		131		133		135		137		139		141		143		145		147		149		151		153		155		N

Magnetic Moment

- Magnetic Moment: N.J. Stone ADNDT 90 (2005) 75
- Charge radii or Quadrupole moments: even more scares



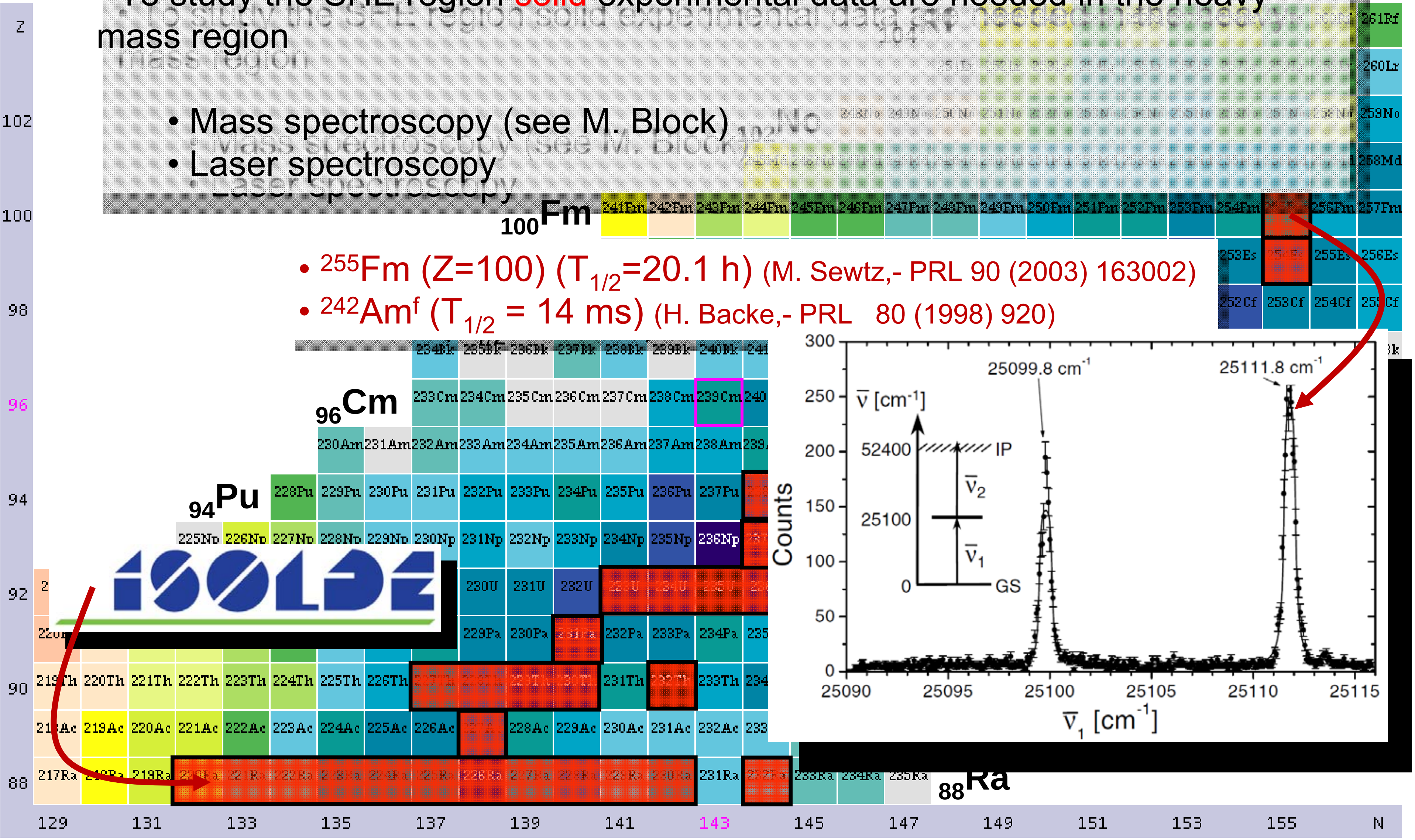
Z																					253Rf	254Rf	255Rf	256Rf	257Rf	258Rf	259Rf	260Rf	261Rf
																				251Lr	252Lr	253Lr	254Lr	255Lr	256Lr	257Lr	258Lr	259Lr	260Lr
102																		248No	249No	250No	251No	252No	253No	254No	255No	256No	257No	258No	259No
																245Md	246Md	247Md	248Md	249Md	250Md	251Md	252Md	253Md	254Md	255Md	256Md	257Md	258Md
100													241Fm	242Fm	243Fm	244Fm	245Fm	246Fm	247Fm	248Fm	249Fm	250Fm	251Fm	252Fm	253Fm	254Fm	255Fm	256Fm	257Fm
													240Es	241Es	242Es	243Es	244Es	245Es	246Es	247Es	248Es	249Es	250Es	251Es	252Es	253Es	254Es	255Es	256Es
98											237Cf	238Cf	239Cf	240Cf	241Cf	242Cf	243Cf	244Cf	245Cf	246Cf	247Cf	248Cf	249Cf	250Cf	251Cf	252Cf	253Cf	254Cf	255Cf
									234Bk	235Bk	236Bk	237Bk	238Bk	239Bk	240Bk	241Bk	242Bk	243Bk	244Bk	245Bk	246Bk	247Bk	248Bk	249Bk	250Bk	251Bk	252Bk	253Bk	254Bk
96									233Cm	234Cm	235Cm	236Cm	237Cm	238Cm	239Cm	240Cm	241Cm	242Cm	243Cm	244Cm	245Cm	246Cm	247Cm	248Cm	249Cm	250Cm	251Cm	252Cm	
							230Am	231Am	232Am	233Am	234Am	235Am	236Am	237Am	238Am	239Am	240Am	241Am	242Am	243Am	244Am	245Am	246Am	247Am	248Am	249Am			
94						228Pu	229Pu	230Pu	231Pu	232Pu	233Pu	234Pu	235Pu	236Pu	237Pu	238Pu	239Pu	240Pu	241Pu	242Pu	243Pu	244Pu	245Pu	246Pu	247Pu				
				225Np	226Np	227Np	228Np	229Np	230Np	231Np	232Np	233Np	234Np	235Np	236Np	237Np	238Np	239Np	240Np	241Np	242Np	243Np	244Np	245Np					
92	221U	222U	223U	224U	225U	226U	227U	228U	229U	230U	231U	232U	233U	234U	235U	236U	237U	238U	239U	240U	241U	242U	243U						
	220Pa	221Pa	222Pa	223Pa	224Pa	225Pa	226Pa	227Pa	228Pa	229Pa	230Pa	231Pa	232Pa	233Pa	234Pa	235Pa	236Pa	237Pa	238Pa	239Pa	240Pa	241Pa							
90	219Th	220Th	221Th	222Th	223Th	224Th	225Th	226Th	227Th	228Th	229Th	230Th	231Th	232Th	233Th	234Th	235Th	236Th	237Th	238Th	239Th								
	218Ac	219Ac	220Ac	221Ac	222Ac	223Ac	224Ac	225Ac	226Ac	227Ac	228Ac	229Ac	230Ac	231Ac	232Ac	233Ac	234Ac	235Ac	236Ac	237Ac									
88	217Ra	218Ra	219Ra	220Ra	221Ra	222Ra	223Ra	224Ra	225Ra	226Ra	227Ra	228Ra	229Ra	230Ra	231Ra	232Ra	233Ra	234Ra	235Ra										
	129		131		133		135		137		139		141		143		145		147		149		151		153		155		N

Optical Spectroscopy

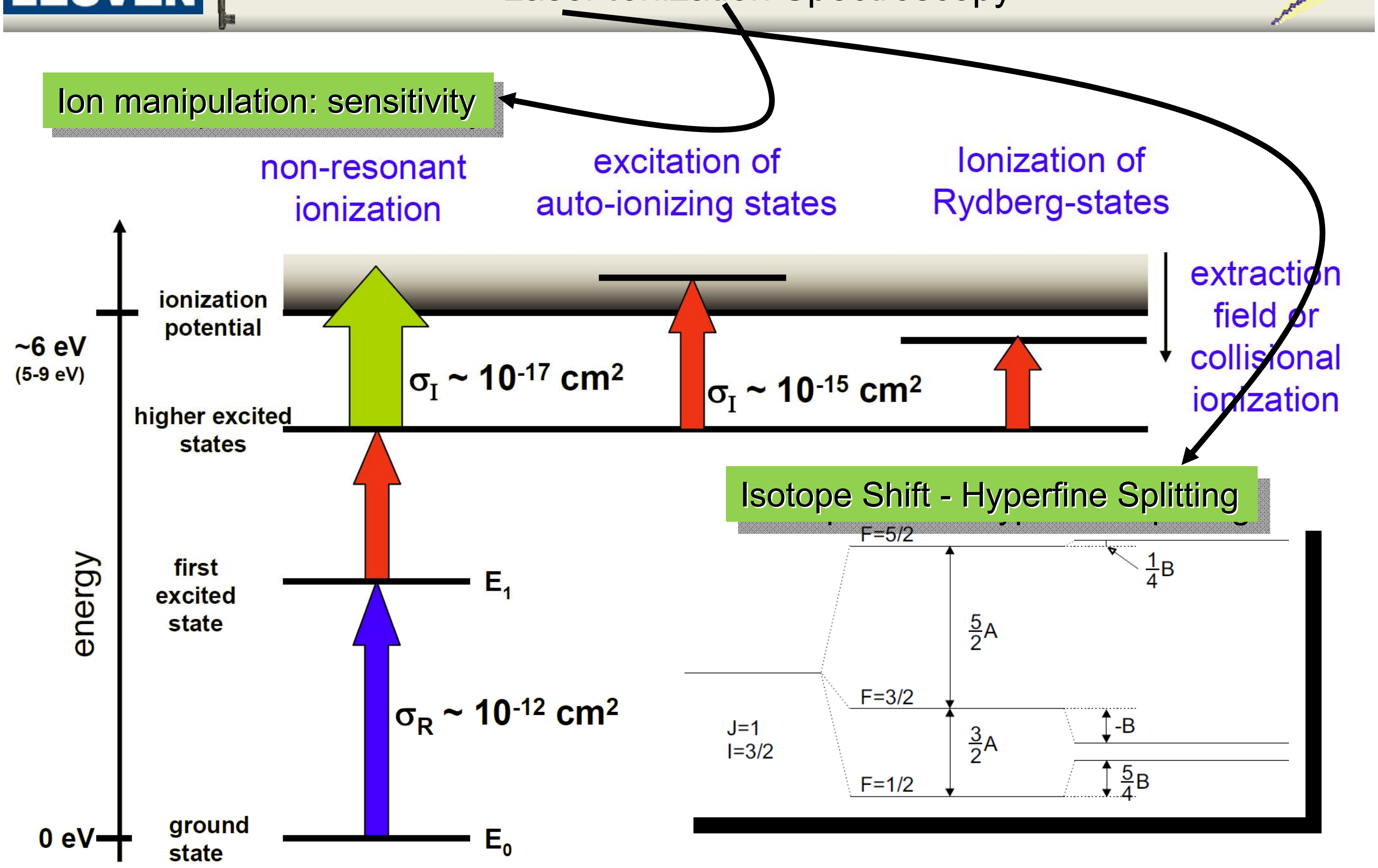
- To study the SHE region solid experimental data are needed in the heavy-mass region
  - Mass spectroscopy (see M. Block)
  - Laser spectroscopy

• To study the SHE region solid experimental data are needed in the heavy-mass region
• Mass spectroscopy (see M. Block)
• Laser spectroscopy

- ^{255}Fm (Z=100) ($T_{1/2}$=20.1 h) (M. Sewtz,- PRL 90 (2003) 163002)
- ^{242}Am^{f} ($T_{1/2}$ = 14 ms) (H. Backe,- PRL 80 (1998) 920)



Laser Ionization Spectroscopy



Ion manipulation: sensitivity

non-resonant ionization

excitation of auto-ionizing states

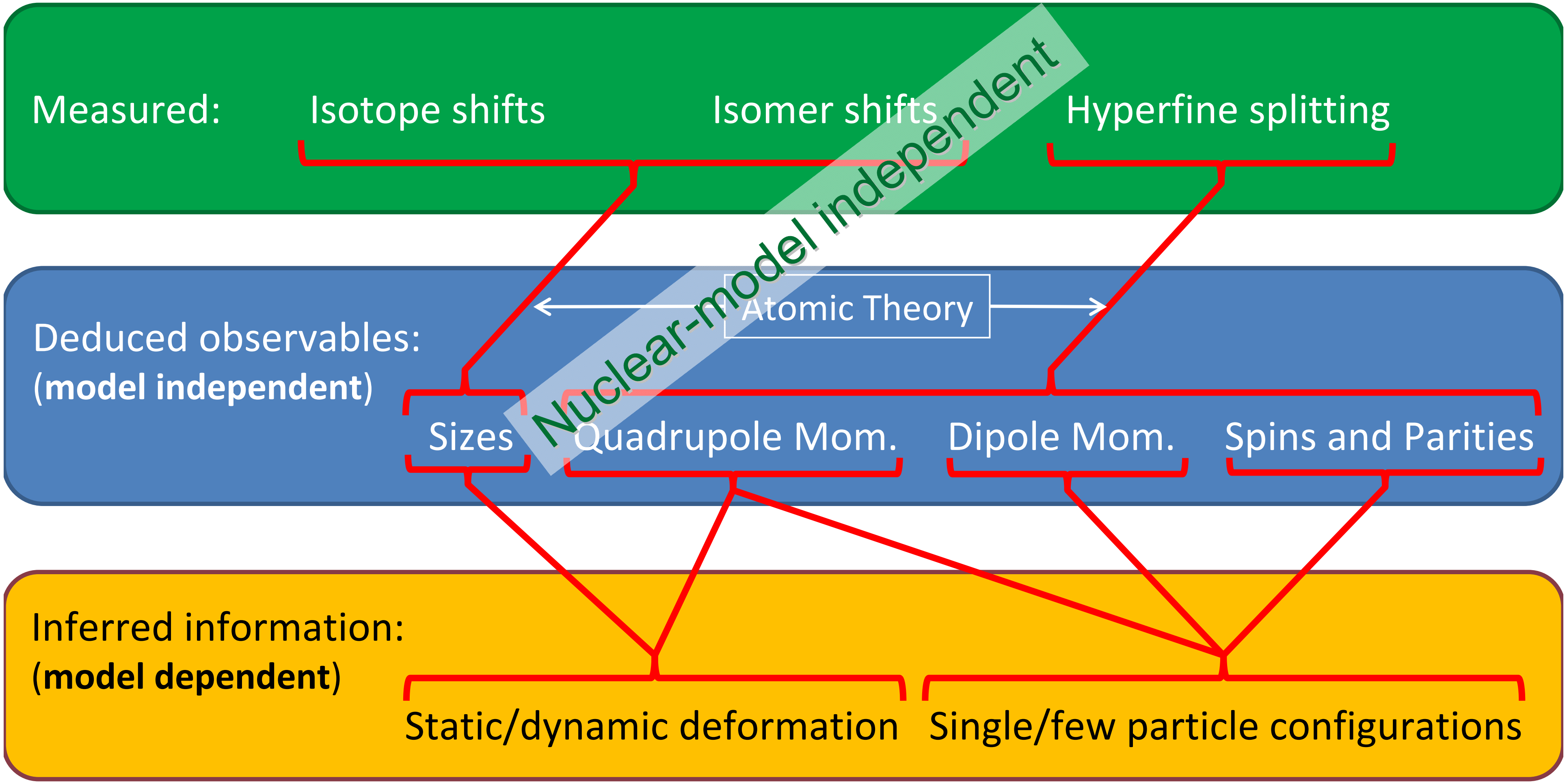
Ionization of Rydberg-states

extraction field or collisional ionization

Isotope Shift - Hyperfine Splitting

courtesy I. Moore

Laser Spectroscopy



Measured: Isotope shifts Isomer shifts Hyperfine splitting

Nuclear-model independent

Atomic Theory

Deduced observables:
(**model independent**)

Sizes Quadrupole Mom. Dipole Mom. Spins and Parities

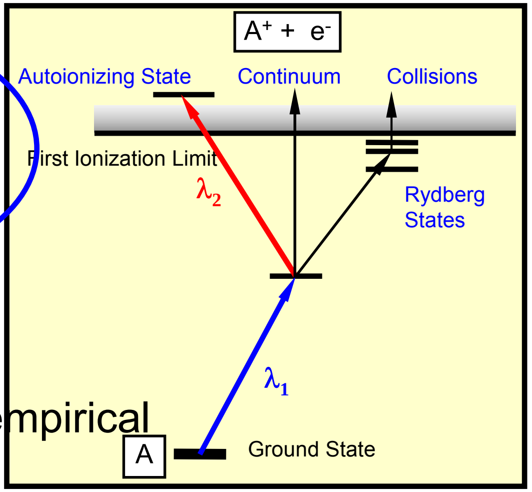
Inferred information:
(**model dependent**)

Static/dynamic deformation Single/few particle configurations

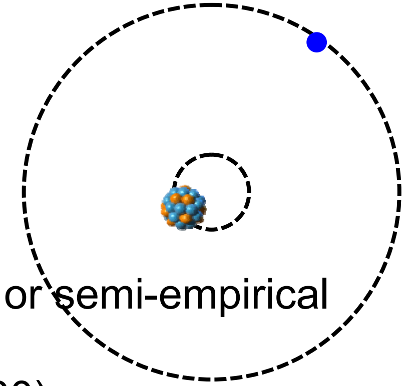
Otten E.W., Treatise on Heavy Ion Science vol 8 (1989) 517
Billowes J and Campbell P, J. Phys. G21 (1995) 707
Kluge H-J., Nörtershäuser, W. Spectrochim. Acta B 58 (2003) 1031
Kluge H-J., Hyperfine Interact. 196 (2010) 295
Cheal B.and Flanagan K., J. Phys. G. 37 (2010) 113101

Isotope Shift (monopole shift)

$$\delta\nu_i^{A,A'} = \nu_i^{A'} - \nu_i^{A} = F_i\,\delta\langle r^2\rangle^{A,A'} + M_i\,\frac{m'_A - m_A}{m'_A m_A}$$



- Mass shift:
  - $\propto \frac{1}{A^2}$ (for A>>1, reduces for increasing A): theory or semi-empirical
  - normal (change in reduced atomic mass) and specific (correlated electron momenta in the nuclear motion) shift
  - ~GHz (light elements, Z=10) to ~10 MHz (heavy elements, Z=80)



- Field shift:
  - **F_i** $\propto \Delta|\Psi(0)|^2$ (change of electron density at the nucleus): theory or semi-empirical
  - ~10 MHz (light elements, Z=10) to ~10 GHz (heavy elements, Z=80)

- Nuclear charge distribution:

$$\boxed{\delta\langle r^2\rangle^{A,A'}}$$

Hyperfine Structure

- Electromagnetic moments of nuclei with I≠0 influence the atomic electron levels and causes additional splittings: hyperfine structure

- Nuclei with spin (I>1/2) have a magnetic moment, shell electrons with total angular momentum J≠0 create a magnetic field:

interaction energy

$$W_D = -\mu \cdot B$$

- The spectroscopic quadrupole moment of nuclei with I≥1 interact with the electrical field gradient of the shell electrons with J≥1:

$$W_Q = eQ_s\left(\partial^2 V/\partial z^2\right)$$

- Atomic levels will split and shift (combination of nuclear and atomic spins):

$$\vec{F} = \vec{I} + \vec{J} \quad \left(\left|I - J\right| \le F \le I + J\right)$$

Total Nuclear Atomic

KATHOLIEKE UNIVERSITEIT LEUVEN

Hyperfine Structure

- Atomic levels will split and shift:

$$\vec{F} = \vec{I} + \vec{J} \quad \left(\left| I - J \right| \le F \le I + J \right)$$

$$W_F = \frac{1}{2} AC + B \frac{\frac{3}{4} C(C+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

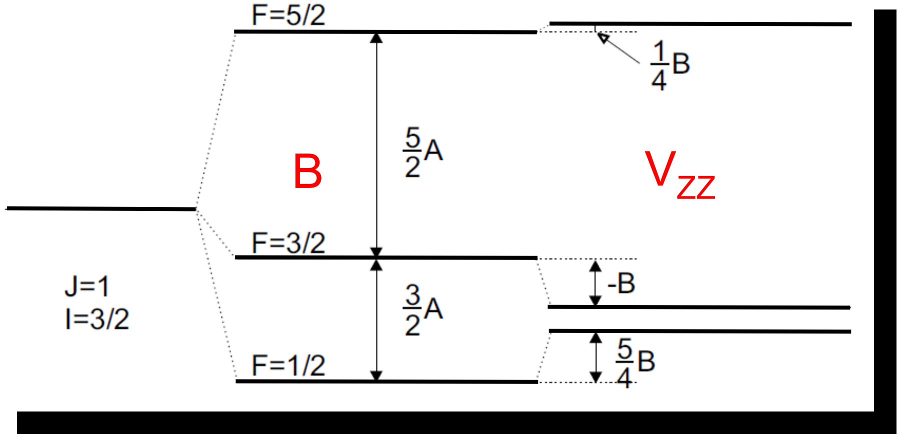
$$C = F(F+1) - I(I+1) - J(J+1).$$

$$A = \boxed{\mu_I} B_e(0) / \boxed{(IJ}\,)$$

$$B = e\boxed{Q_s} V_{ZZ}(0)$$

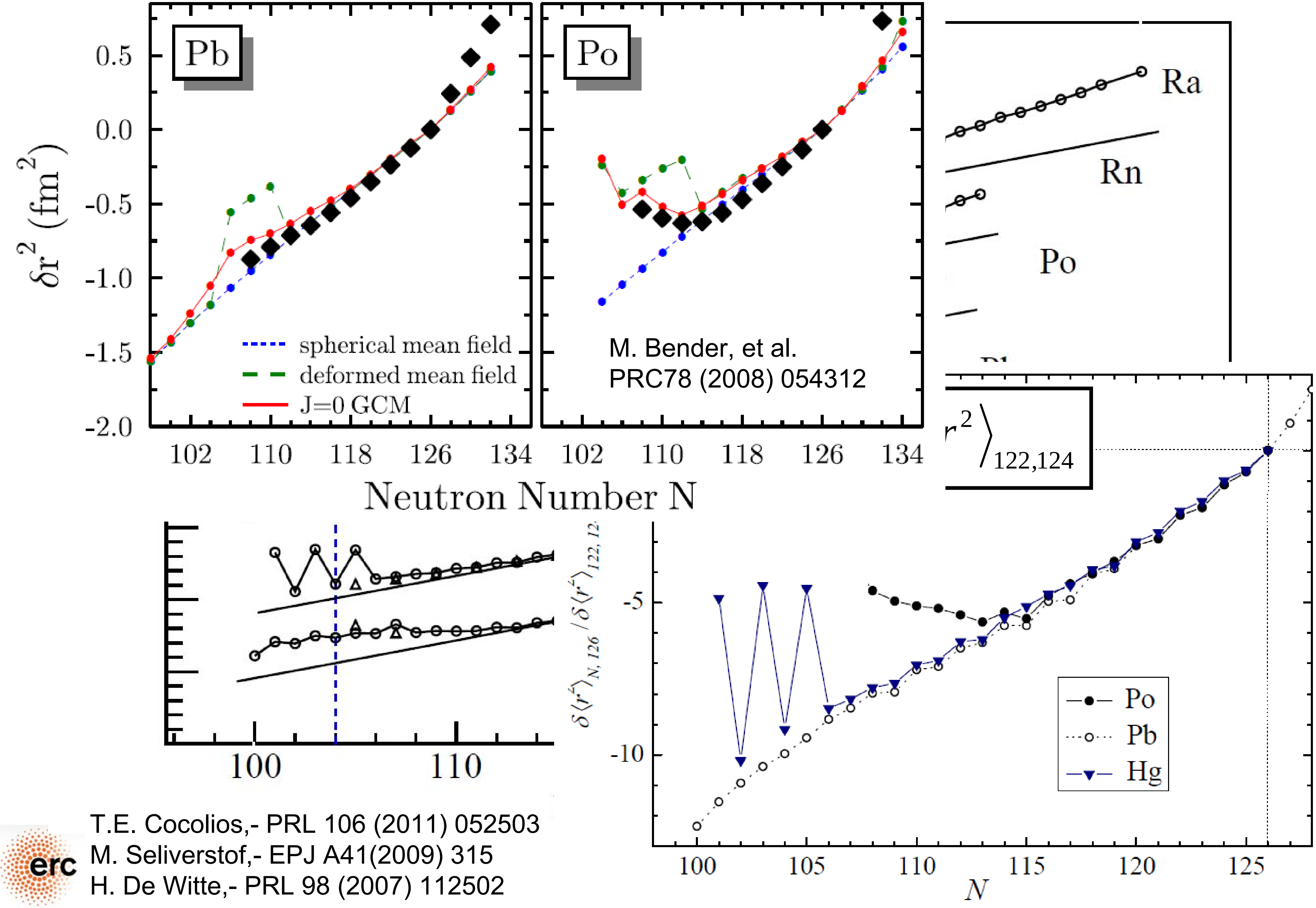
- ➢ $B_e(0)$: magnetic field at the nucleus
- ➢ $V_{ZZ}(0)$: electrical field gradient at the nucleus

Hyperfine Splitting



Laser spectroscopy ⇒ $\delta\langle r^2 \rangle$, μ_I, Q_S, I

In-source laser spectroscopy: charge radii



M. Bender, et al.
PRC78 (2008) 054312

T.E. Cocolios,- PRL 106 (2011) 052503
M. Seliverstof,- EPJ A41(2009) 315
H. De Witte,- PRL 98 (2007) 112502

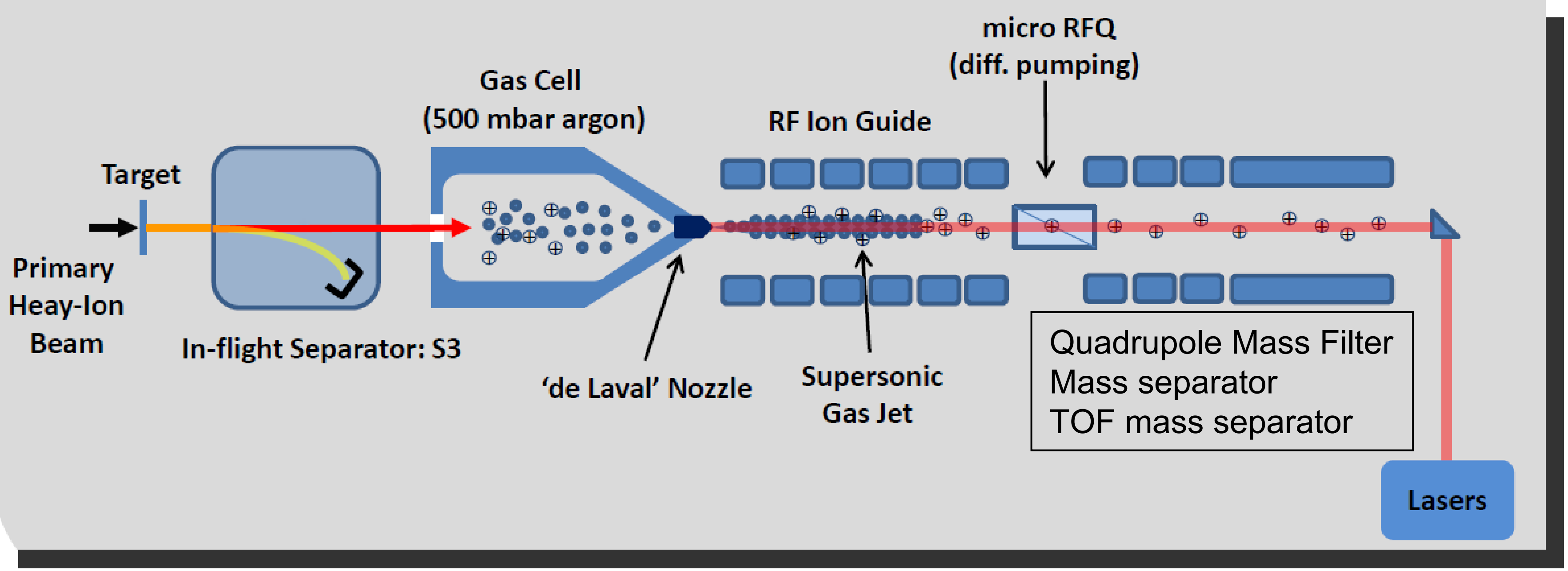
An alternative approach for laser spectroscopy of the heavy elements

- efficient (heavy elements are produced in very small quantities)
- selective (suppression of unwanted isotopes)
- fast (short life time)
- sufficient spectral resolution (determine the isotope/isomer shift and hyperfine structure)

structure)

The HELIOS concept

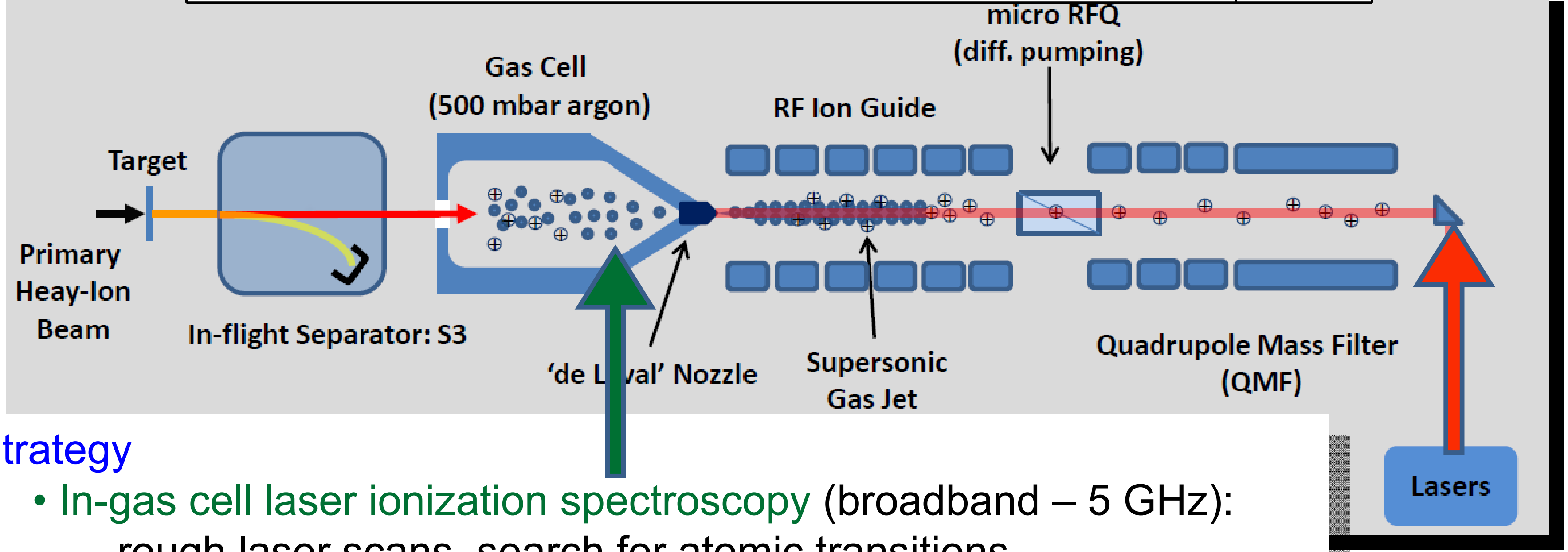
- Production of the heavy elements: heavy-ion fusion evaporation reactions
- Separation of the primary and secondary beam: e.g. S3-GANIL
- Thermalization in the gas cell
- Repelling unwanted ions
- Formation of a cooled atomic beam through e.g. a ‘de Laval’ nozzle (gas jet)
- Resonant laser ionization: high-repetition rate laser system (>10 kHz)
- Ion capture and transport in the RF Ion Guide followed by mass separation
- Detection of the ions: radioactivity / ion counting



Heavy Element Laser IOnization Spectroscopy - HELIOS

- Expected performances

Transport through the in-flight separator	50 %
Thermalization, diffusion and transport towards the exit hole	90 %
Neutralization in to the atomic ground state	30 %
Formation of the gas jet	90 %
Laser ionization	50 %
Capturing efficiency	80 %
Detection efficiency	85 %
Total efficiency	**4 %**



- Strategy
  - In-gas cell laser ionization spectroscopy (broadband – 5 GHz): rough laser scans, search for atomic transitions
  - In-gas jet laser ionization spectroscopy (narrow band – 200 MHz)

Strategy - Expected Rates

- Expected production rates:

  $^{208}\mathrm{Pb}(^{48}\mathrm{Ca},2n)^{254}\mathrm{No}$: ~150 pps (10 p$\mu$A primary beam intensity)

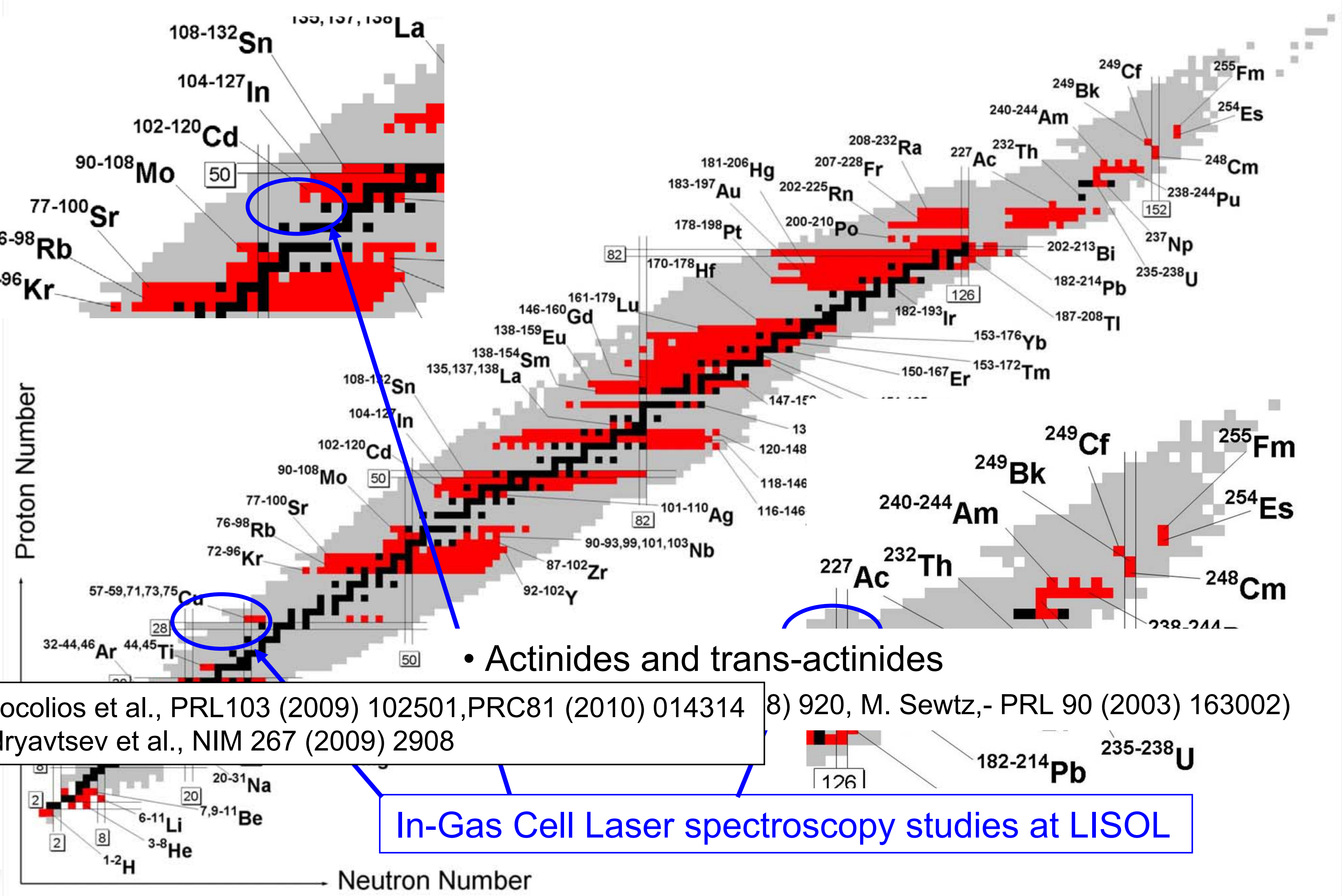
- Laser frequency scan:
- 100 points, 60s/point, 50 MHz/point: 5 GHz range in 100 minutes

- 360 counts on resonance for ^{254}No (alpha detection – background free)

- Projects for in-gas cell or in-gas jet laser spectroscopy (not only heavy elements!):

  - HELIOS at KU Leuven (Belgium) and S3-SPIRAL (France)
    (T. Sonoda,- NIMB 267 (2009) 2918)
  - JYFL (Finland)
    (M. Reponen,- NIMA635 (2011) 24)
  - GSI (Germany)
  - RIKEN (Japan)
  - Dubna (Russia)
  - Berkeley (USA)

Feasibility: In-gas cell laser spectroscopy



- Actinides and trans-actinides

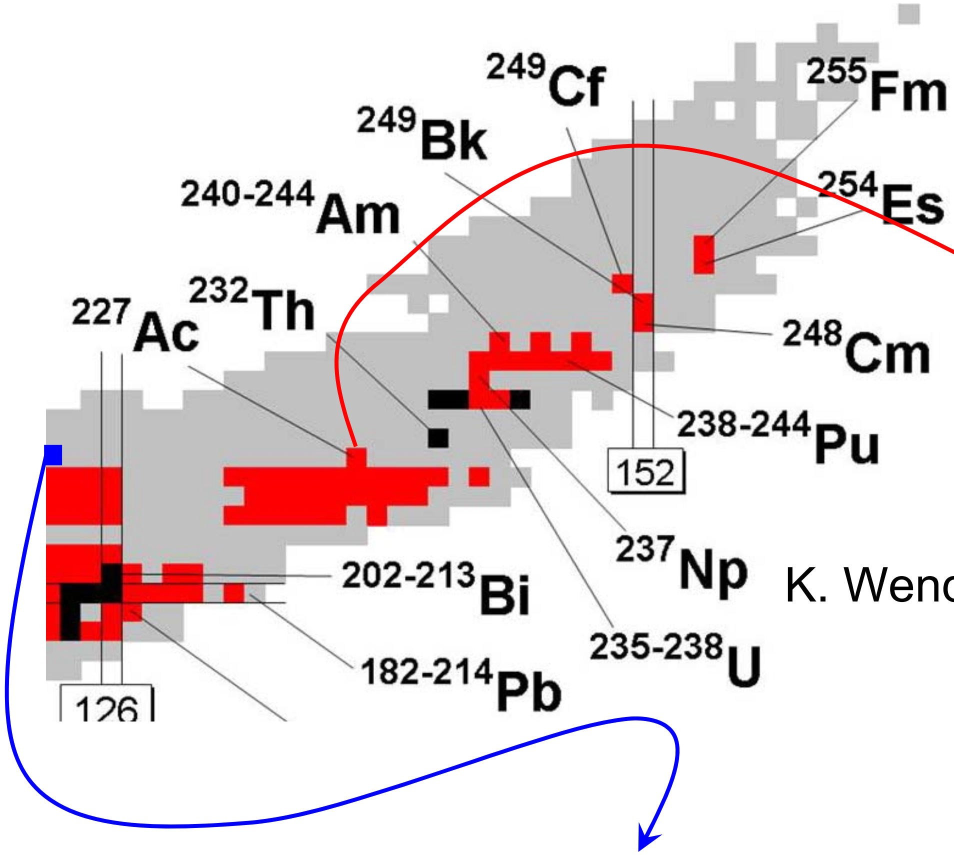
8) 920, M. Sewtz,- PRL 90 (2003) 163002)

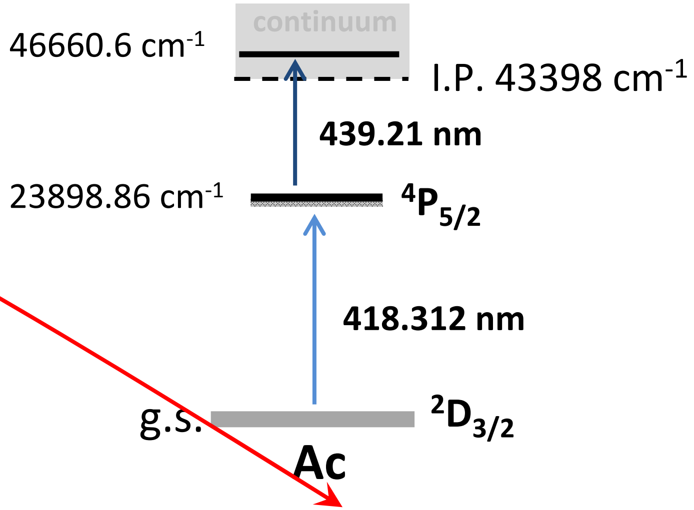
T.E. Cocolios et al., PRL103 (2009) 102501,PRC81 (2010) 014314
Y. Kudryavtsev et al., NIM 267 (2009) 2908

In-Gas Cell Laser spectroscopy studies at LISOL

W. Nörtershäuser et al., www.gsi.de/forschung/ap/projects/laser/survey.html

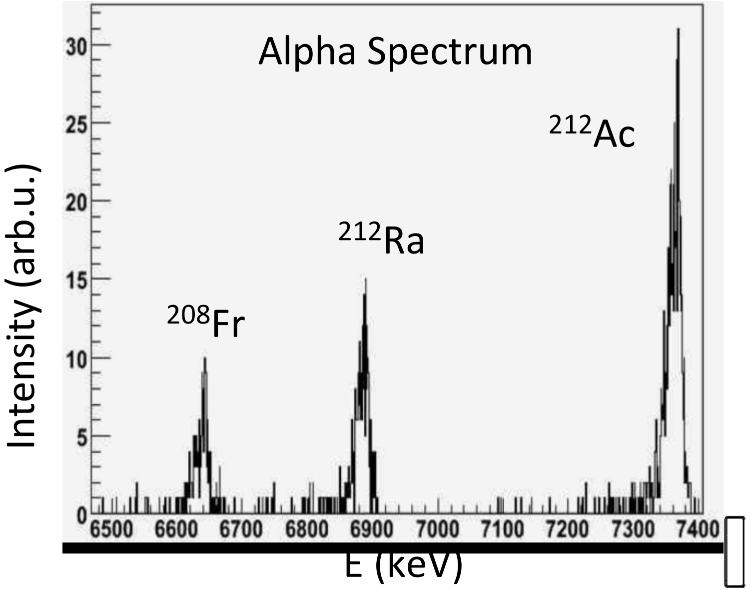
Broadband Laser Spectroscopy on ^{212}Ac



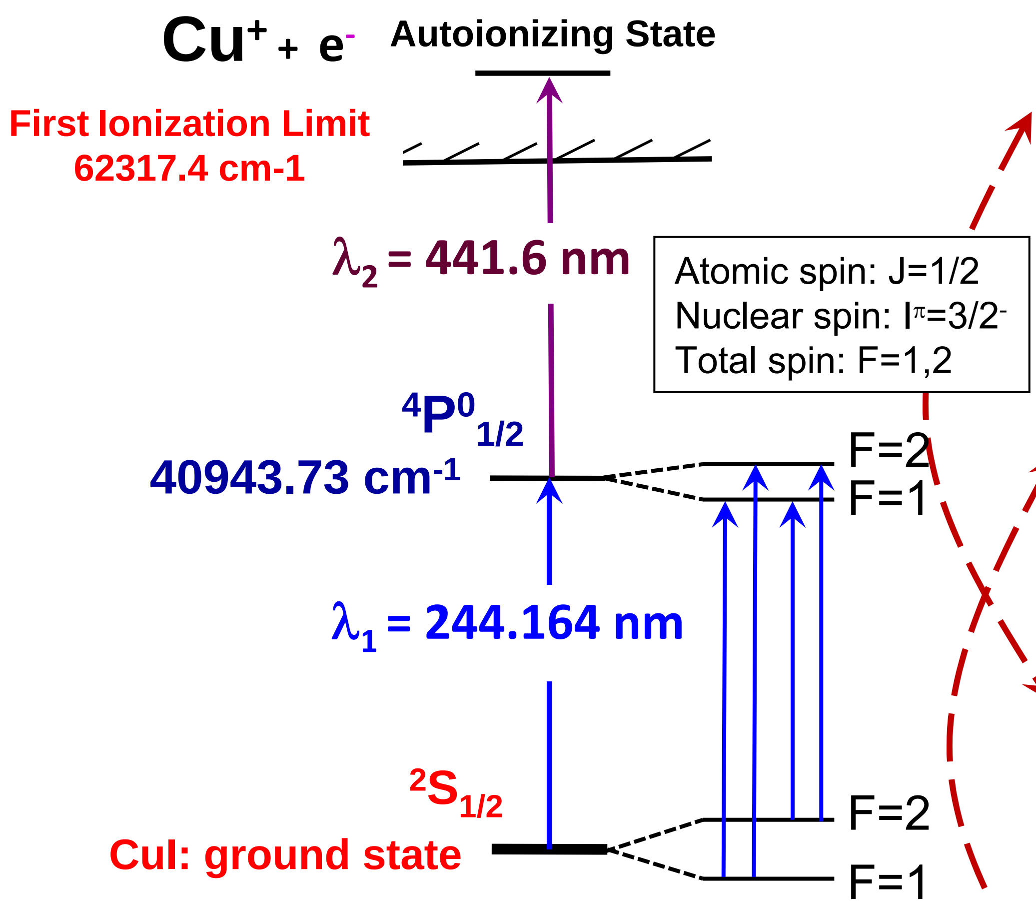


K. Wendt, N. Trautmann U.Mainz: ^{227}Ac ($T_{1/2}$=21.8 y)
J. Roßnagel, et al. PRA85 (2012) 012525

^{197}Au(^{20}Ne-145 MeV,5n)^{212}Ac$_{123}$ ($T_{1/2}$=0.9 s)



In-gas-cell laser spectroscopy of ^{57,59}Cu: a sample of spectra



Cu^{+} + e^{-} **Autoionizing State**

First Ionization Limit
62317.4 cm-1

λ_2 = 441.6 nm

Atomic spin: J=1/2
Nuclear spin: $I^{\pi}=3/2^{-}$
Total spin: F=1,2

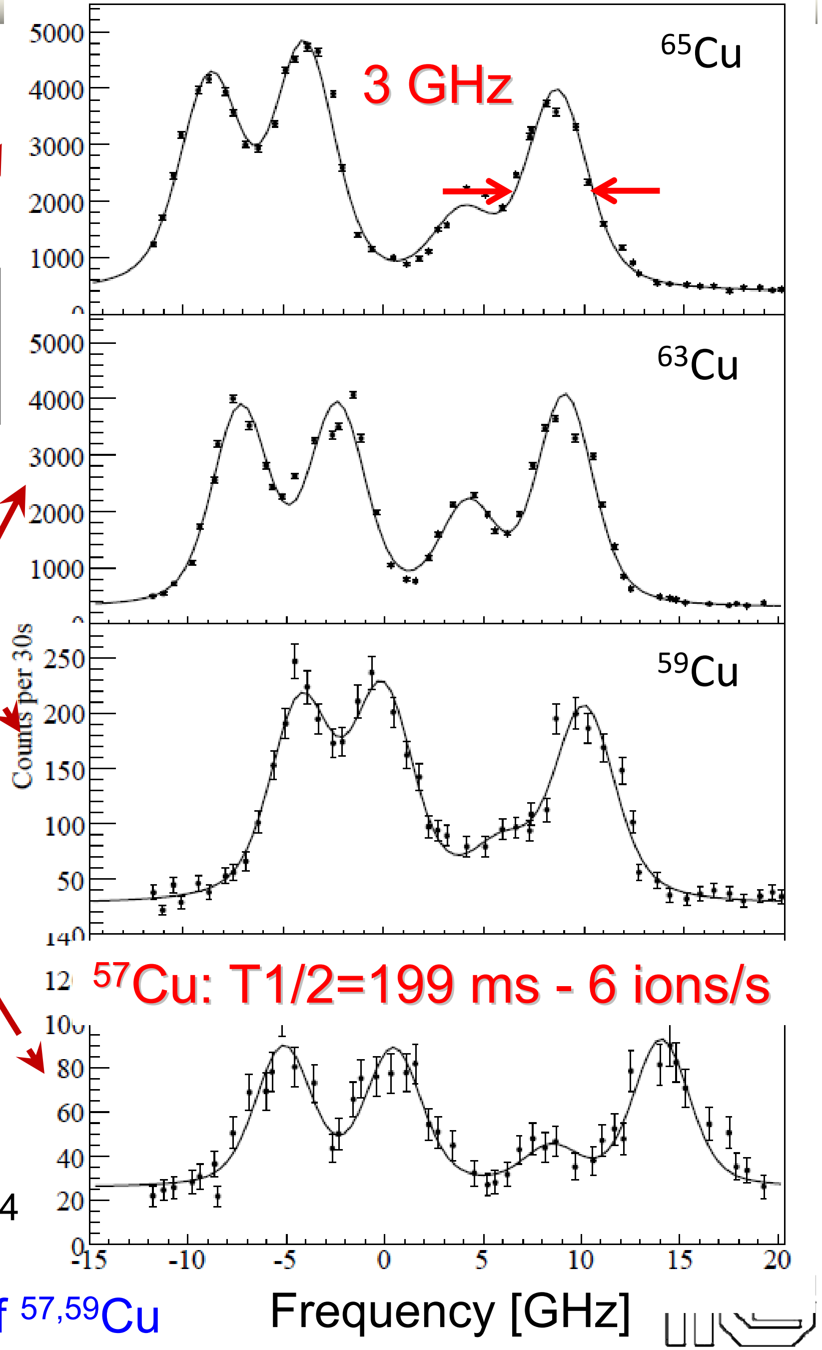
$^4P^0_{1/2}$
40943.73 cm^{-1}

F=2
F=1

λ_1 = 244.164 nm

$^2S_{1/2}$
CuI: ground state

F=2
F=1



^{57}Cu: T1/2=199 ms - 6 ions/s

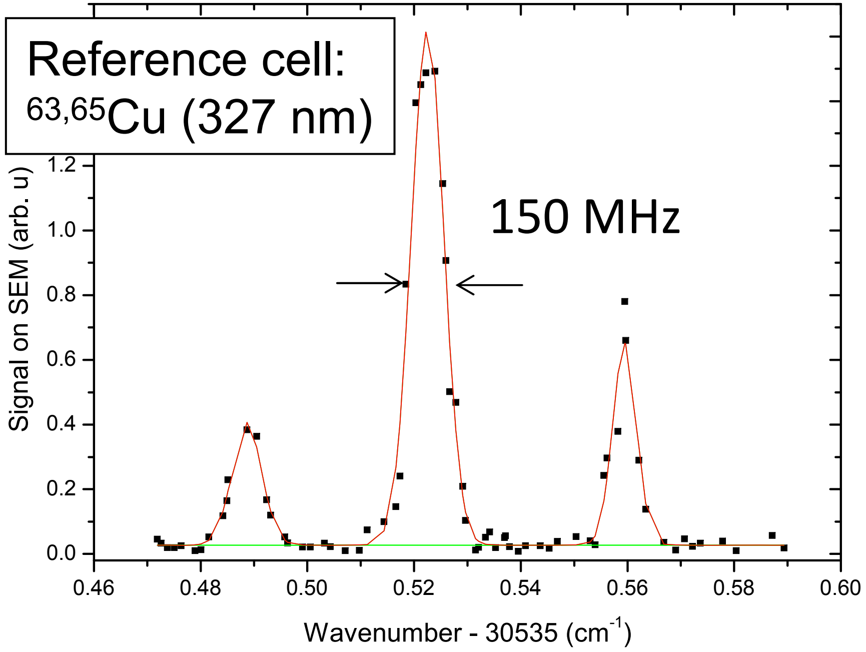
$$\mu(^{A}Cu)=\frac{A_{hf}(^{A}Cu)}{A_{hf}(^{63}Cu)}\mu(^{63}Cu)$$

T.E. Cocolios et al., PRL103 (2009) 102501,PRC81 (2010) 014314

In-gas jet laser spectroscopy

- High-resolution high-repetition-rate laser system:

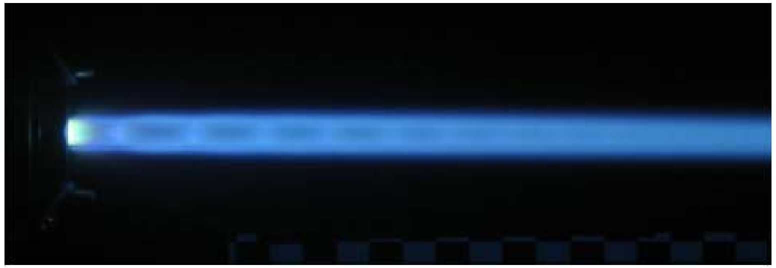
Amplification of CW Single Mode Diode Laser light in pulsed Dye Amplifier (excimer laser)



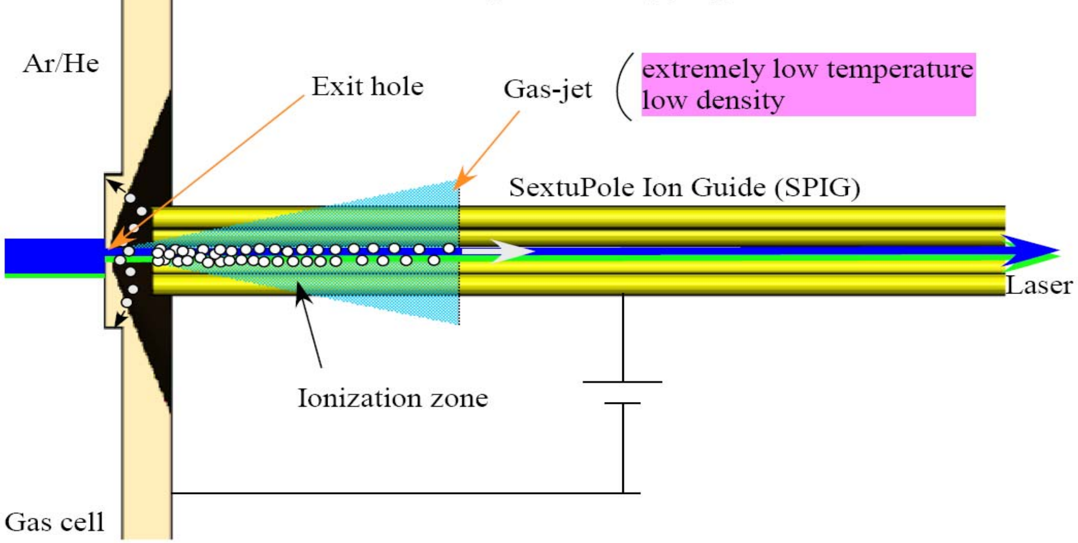
Proof of Principle

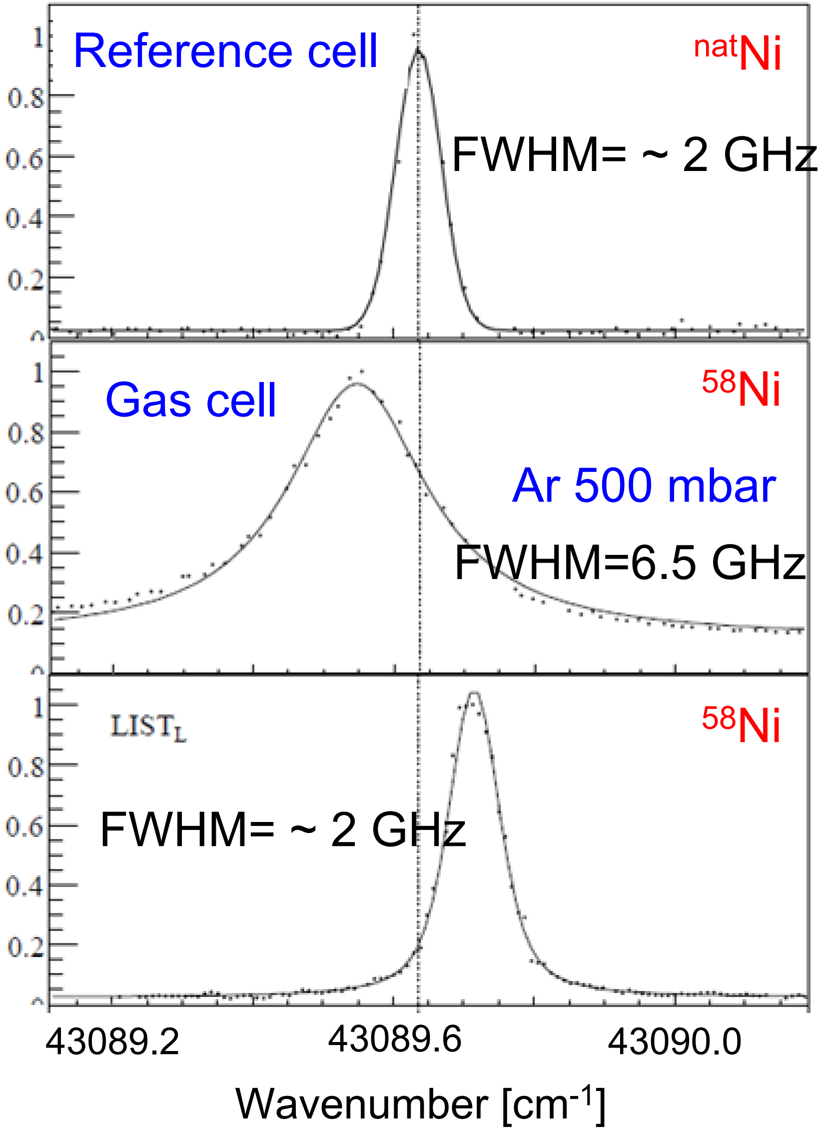
- Gas-jet formation and ionization

The Laser Ion Source Trap (LIST) coupled to a gas cell catcher (K. Blaum, et al., NIMB204 (2003) 331)



Jet-Laser Spectroscopy @LISOL

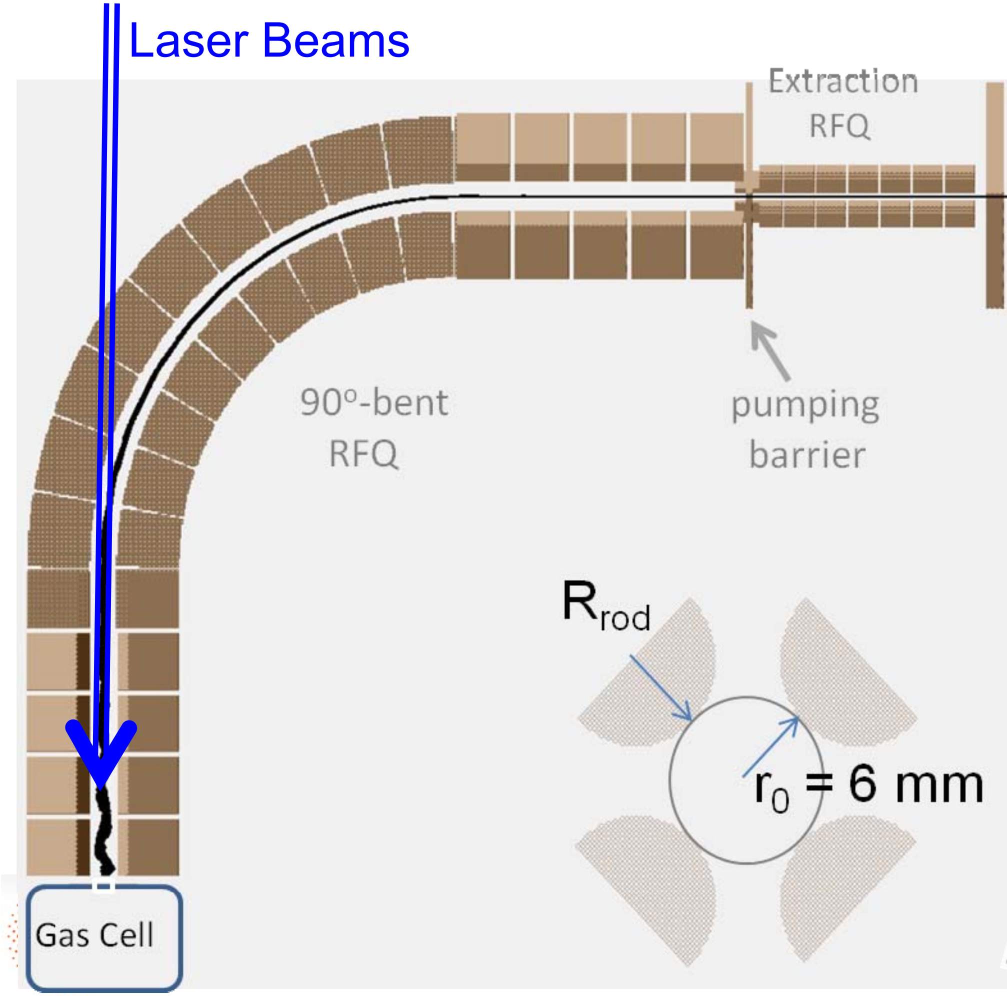


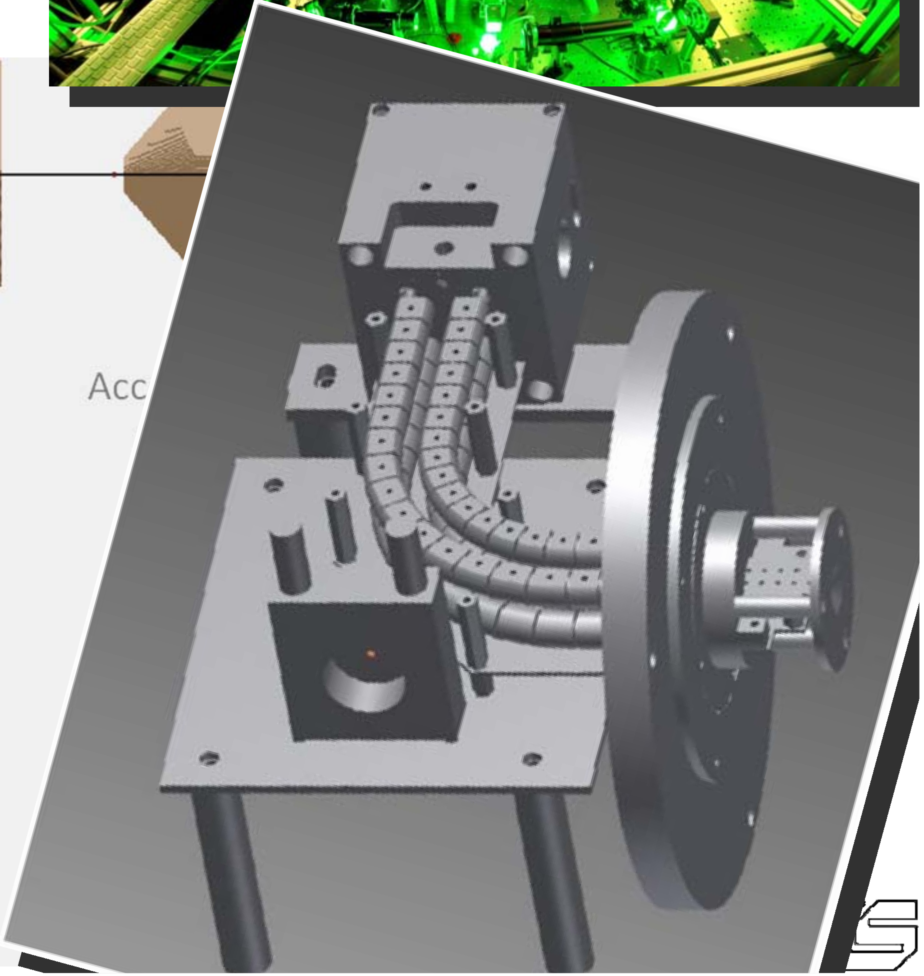


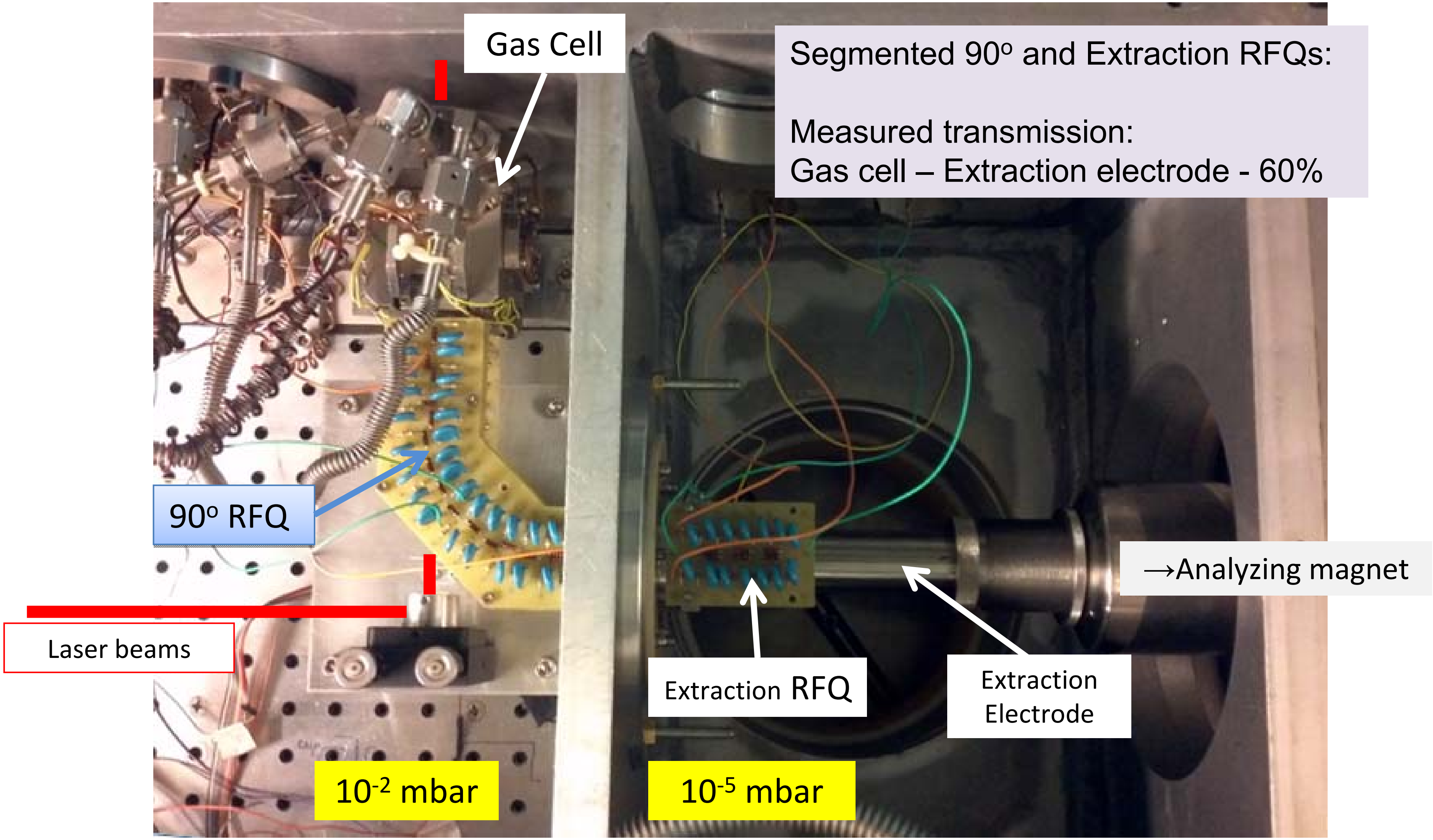
T. Sonoda et al. NIM B267 (2009) 2908
M. Reponen et al., NIMA635 (2011) 24

Off-line test facility

- New laser laboratory for off-line testing:
  - study gas-jet formation, RF ion guides to obtain the ultimate spectral resolution: estimated to reach 200 MHz
  - study chemical homologues



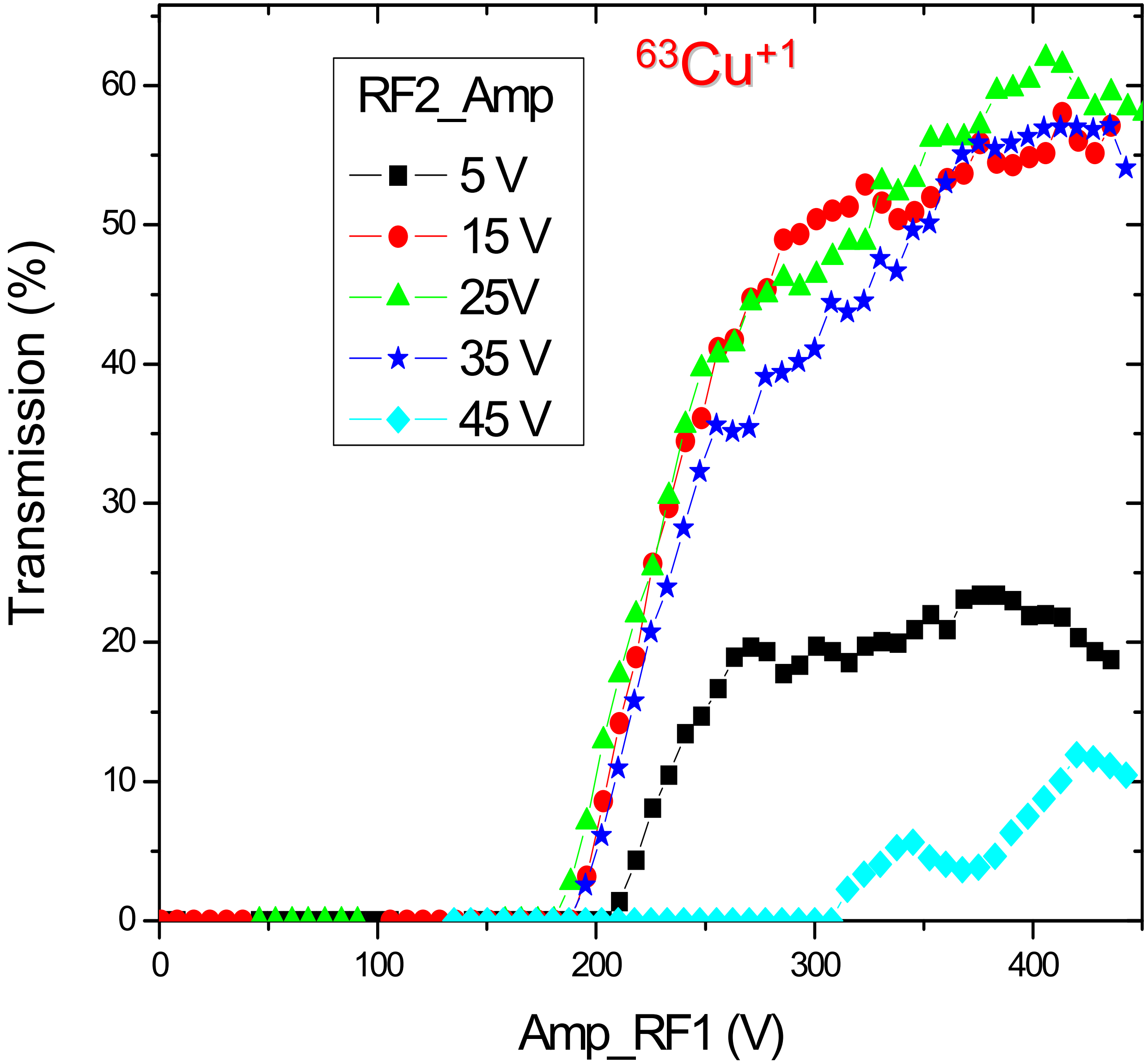




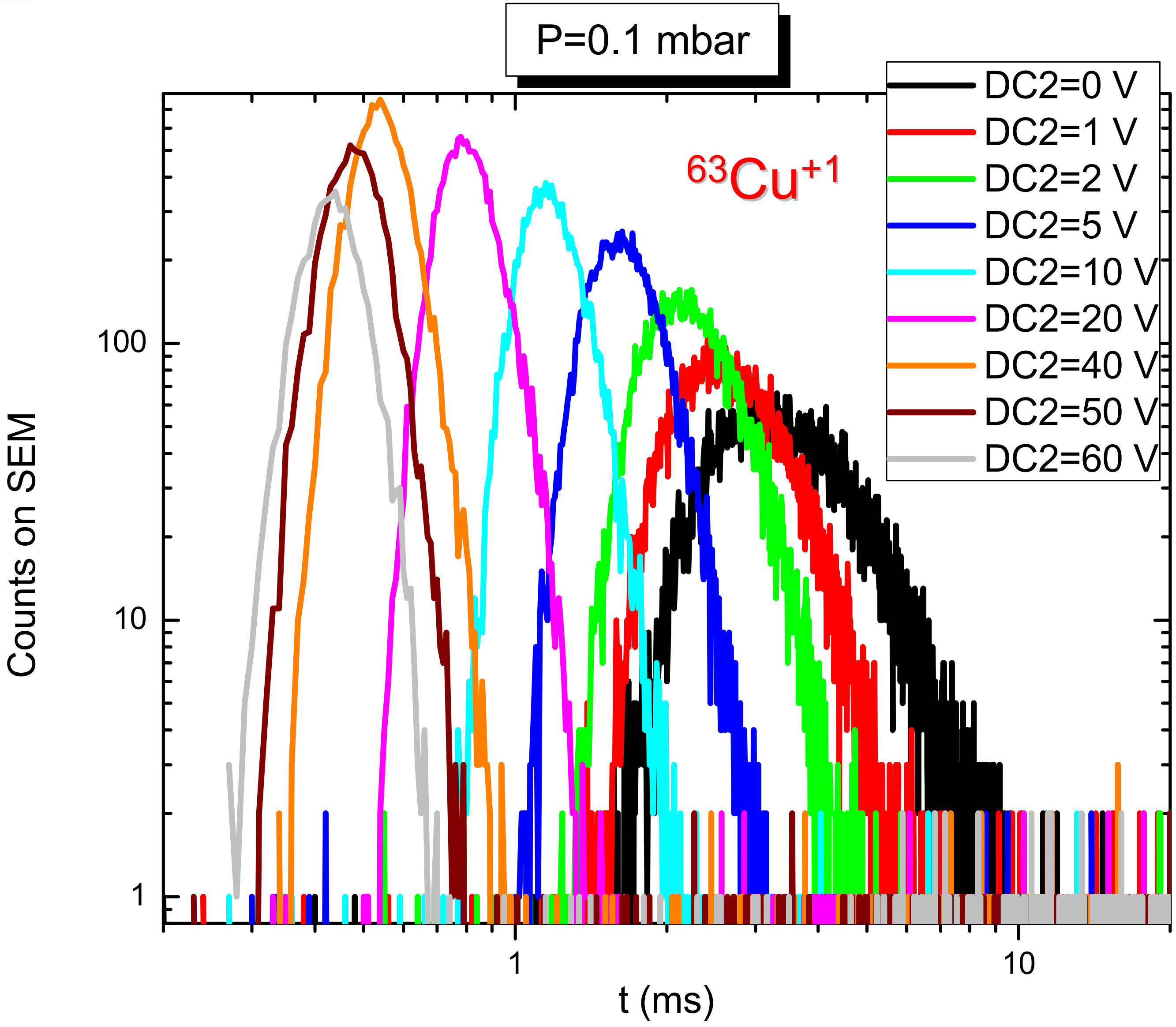
Segmented 90º and Extraction RFQs:

Measured transmission:
Gas cell – Extraction electrode - 60%

Good Transmission



Pulse Compression



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Conclusion and Outlook

BriX

- Need for solid experimental data on ground-state properties of isotopes in the super-heavy element **and** heavy region

- **Survey** of firmly established spins/parities/configurations (cf. mass evaluation tables) might be necessary

- New approaches for **laser ionization spectroscopy** combined with intense primary accelerators and high-transmission separators offer the possibility to obtain **isotope or isomer shift** data and to measure **the hyperfine structure** of the actinides and trans actinides and **atomic properties** of the SHE (up to No and beyond)

- From this charge radii, magnetic dipole or electrical quadrupole moments and spin/parities can be extracted in a **nuclear-model independent** way provided **atomic theory** is available

- Mass measurements using e.g. Penning traps and Laser ionization spectroscopy experiments will bring new **anchor points** with a great potential for further development

- Identify the **critical isotopes** in the heavy mass and SHE region that essential for progressing our understanding of the SHE region and the rest of the nuclear chart