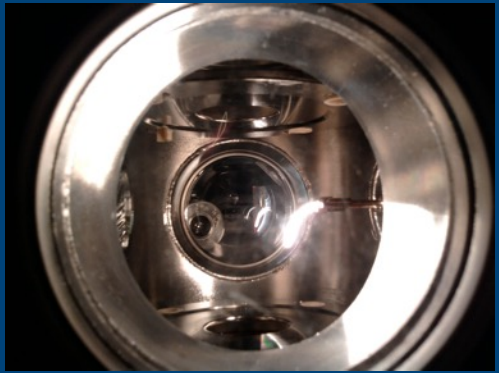
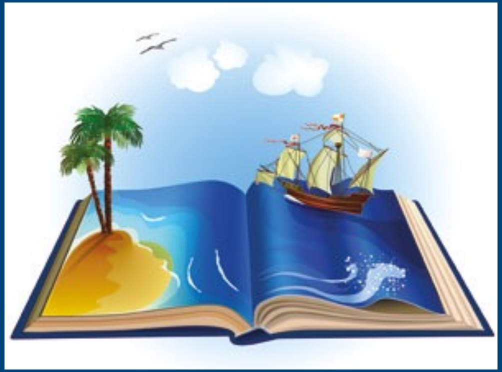
ANPC Conference, July 2019

Laser Spectroscopy Studies of Superheavy Elements





Michael Block

GSI Darmstadt

Helmholtzinstitut Mainz

Institut für Kernchemie der Universität Mainz

Outline

- Introduction
- Atomic and nuclear properties revealed by laser spectroscopy
- Results of the pioneering campaigns at GSI
- Recent results of the laser spectroscopy beamtime 2019
- Summary and Conclusions

RADRIS Collaboration

TECHNISCHE UNIVERSITÄT DARMSTADT
KU LEUVEN
UNIVERSITY OF LIVERPOOL
TRIUMF
GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3
cea
HELMHOLTZ ASSOCIATION
Helmholtz Institute Mainz
GSI
JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Superheavy Elements (SHE)

- What is the heaviest element that can exist?
- What are SHE‘s atomic, chemical and nuclear properties?

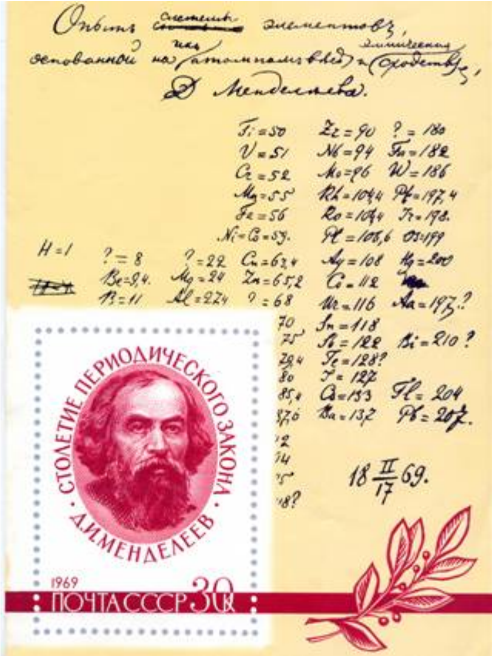
United Nations Educational, Scientific and Cultural Organization

2019 IYPT International Year of the Periodic Table of Chemical Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf 1964	105 Db 1968	106 Sg 1974	107 Bh 1981	108 Hs 1984	109 Mt 1982	110 Ds 1994	111 Rg 1994	112 Cn 1996	113 Nh 2004	114 Fl 1999	115 Mc 2004	116 Lv 2000	117 Ts 2010	118 Og 2006

Discovered at GSI

		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	



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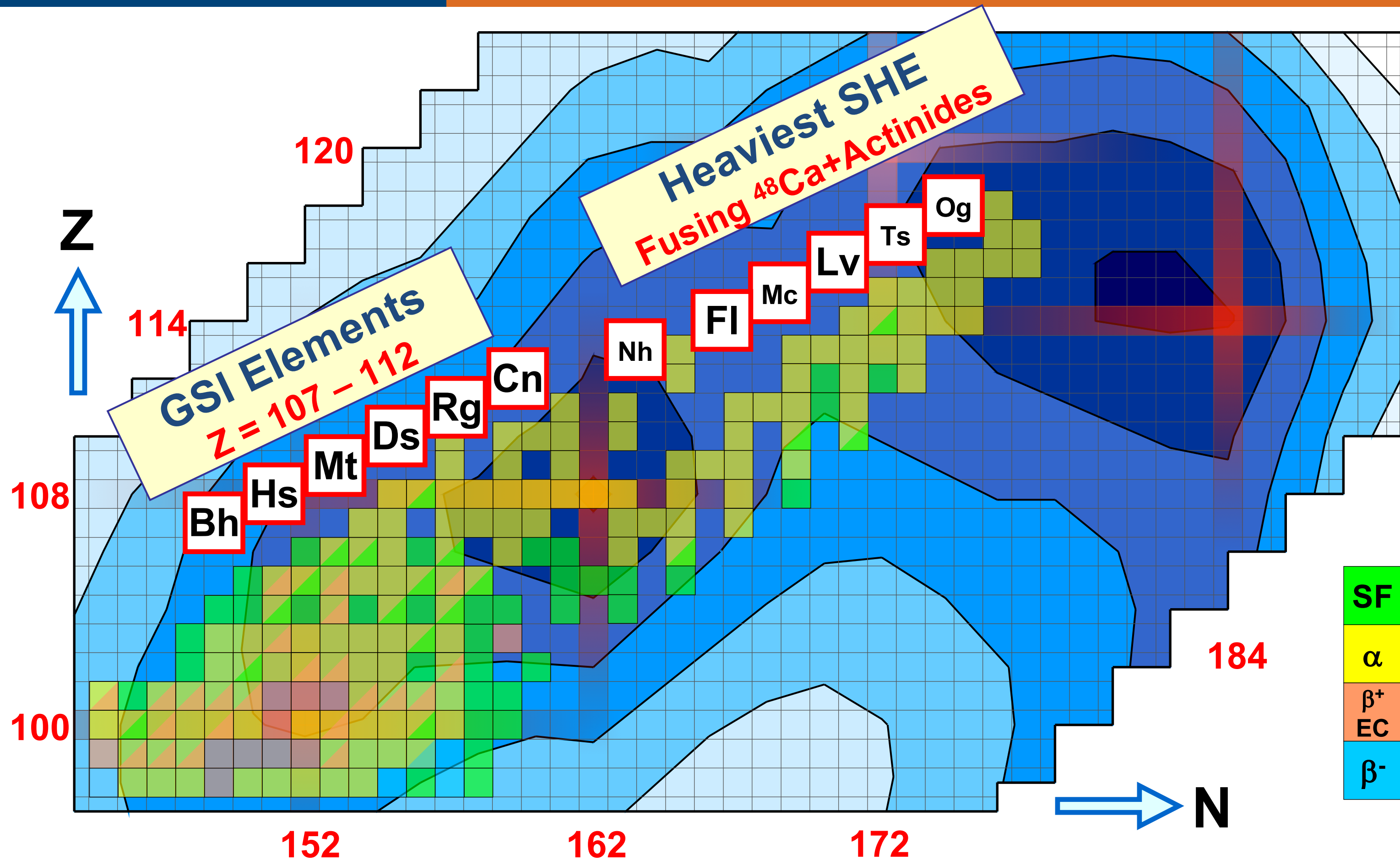
Superheavy Element Research – Status



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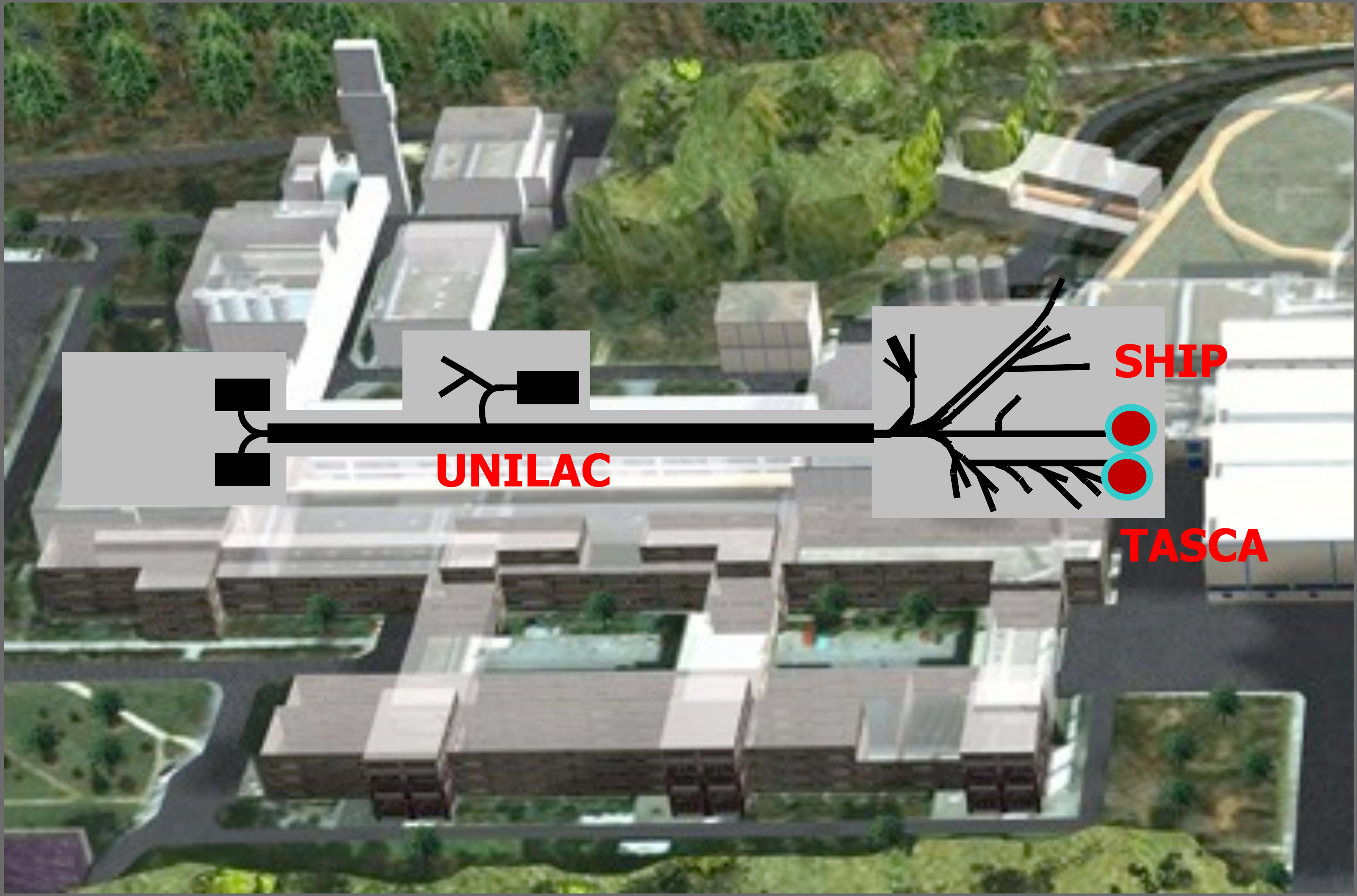


SHIP
UNILAC
TASCA

Superheavy Elements: Main Topics at GSI

- Production of “single-atom-only” elements with atomic number Z ≥ 100:

  nuclear reaction studies (element search on hold)

- Nuclear properties of heaviest elements

  Decay spectroscopy

  High-precision mass measurements

  Laser spectroscopy (hyperfine structure)

- Atomic properties of heaviest elements

  Laser spectroscopy of atomic levels

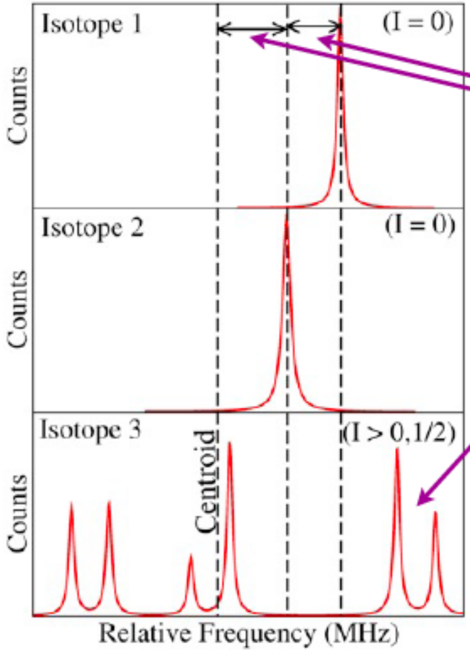
- Chemical properties

  Chemical reactions, surface interactions

Comprehensive approach to the study of the heaviest elements

Laser Spectroscopy of the Heaviest Elements

Methods:	Search for atomic levels	hyperfine spectroscopy	Measurement of isotopic shifts
Motivation:	**relativistic and QED effects**	**Nuclear moments & spins**	**changes in mean square charge radii**



Isotope Shifts

➔ $\delta\langle r^2 \rangle$

➢ **size**

Hyperfine Structure

➔ μ

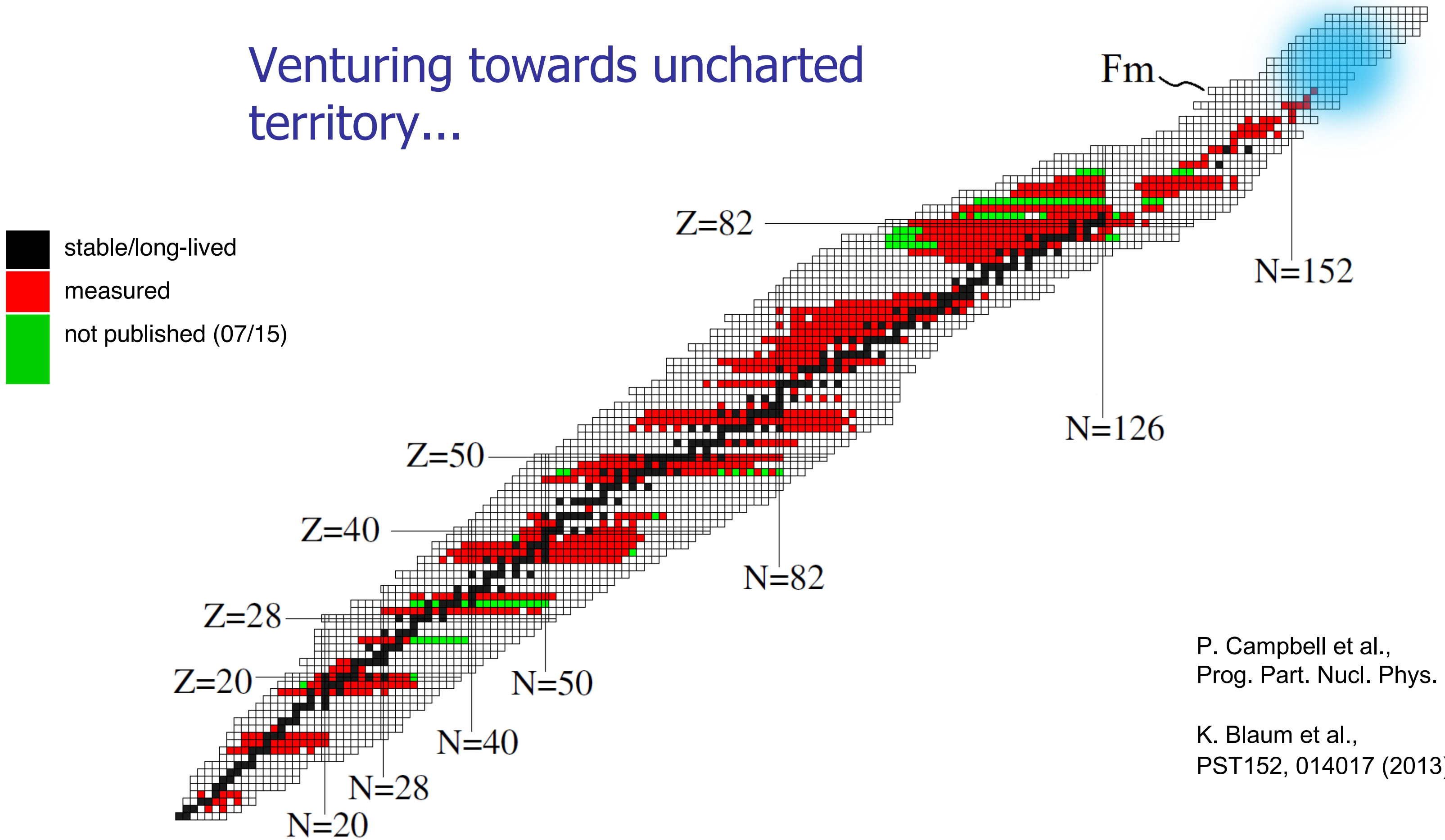
➔ Q_S ➔ $\langle\beta_2\rangle$

➔ Nuclear spin

➢ **deformation**

Laser Spectroscopy - Current Status

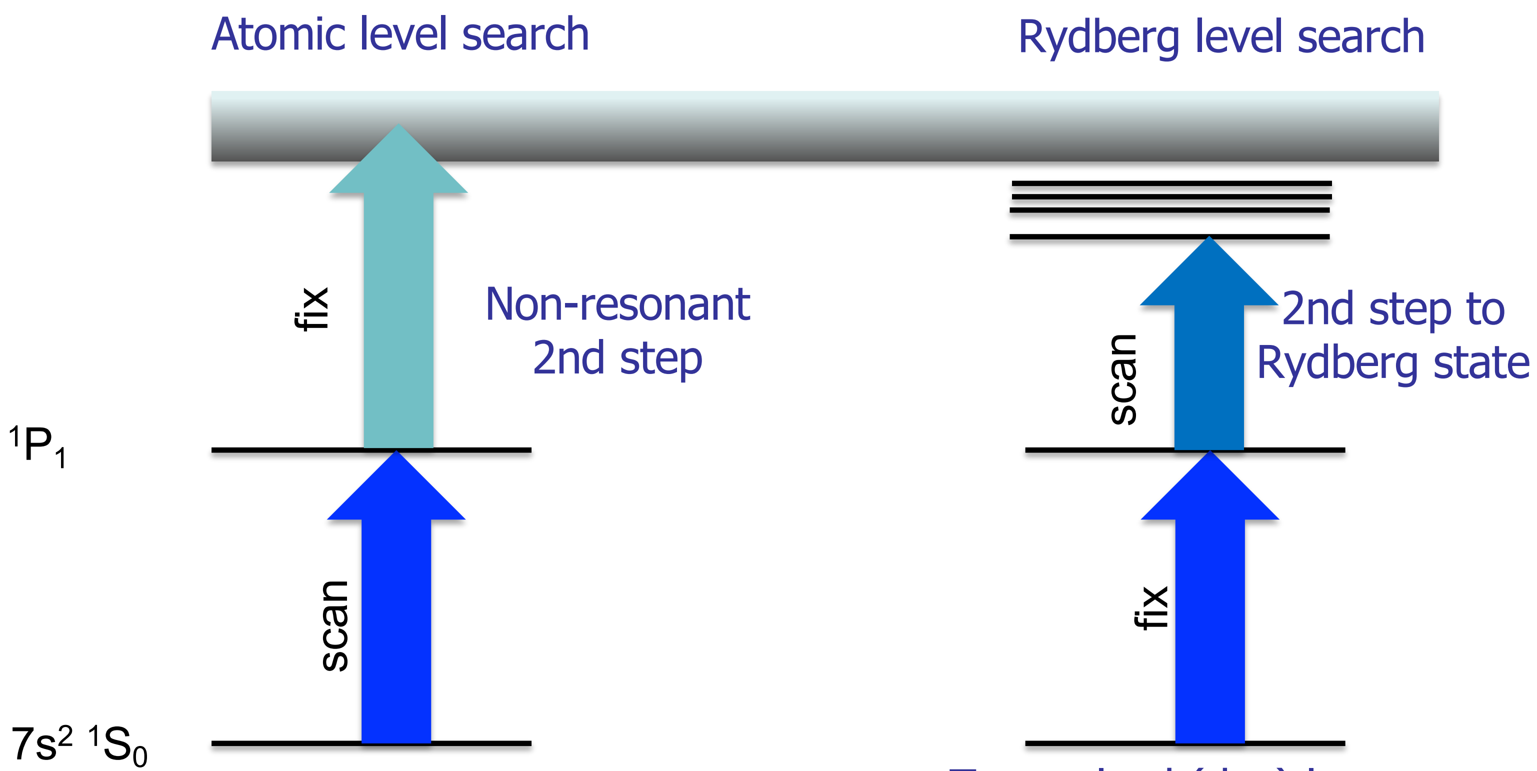
Venturing towards uncharted territory...



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

K. Blaum et al.,
PST152, 014017 (2013)

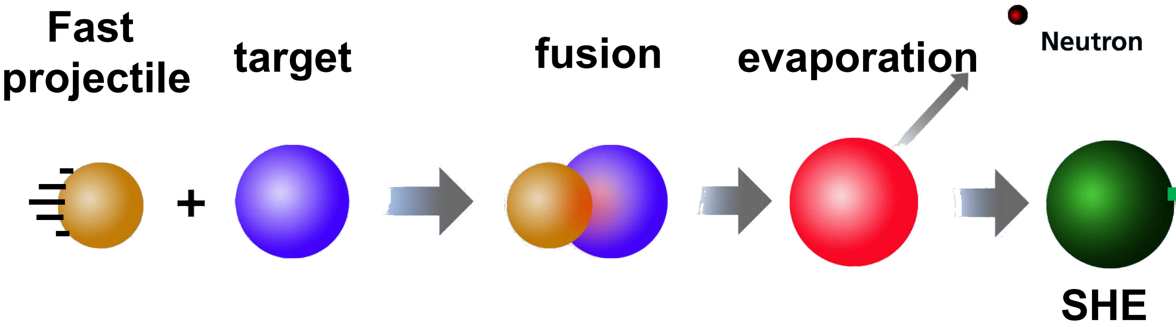
Resonant Laser Ionization – Excitation Schemes

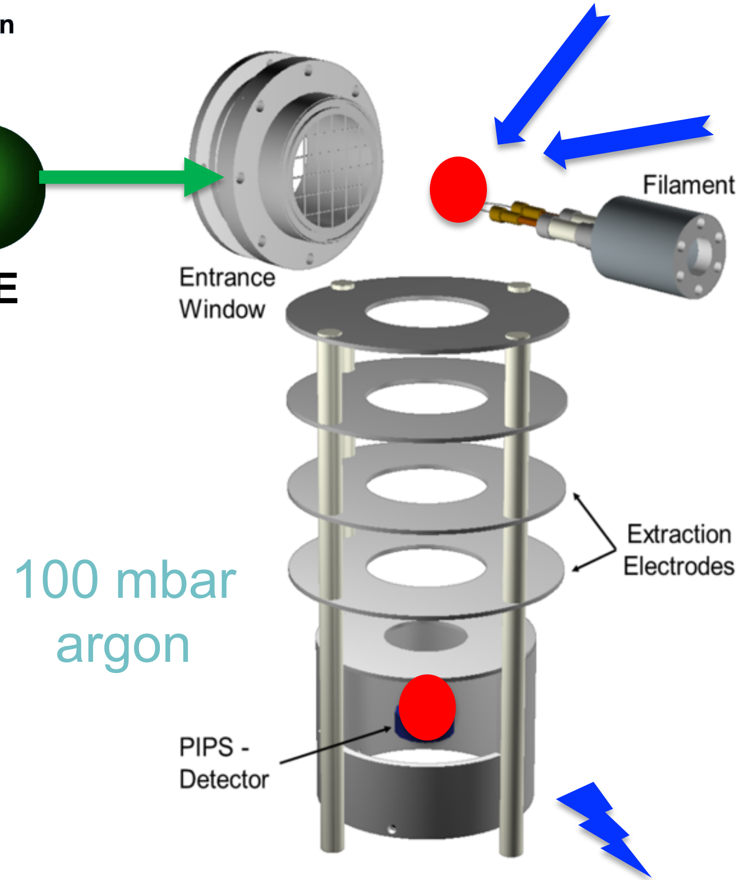


High power in 2nd step (>30mJ/pulse) for high efficiency

Two pulsed (dye) lasers, temporal overlap important

Radiation Detected Resonance Ionization Spectroscopy Method





- separate from primary beam
- slow down and neutralize particles
- evaporate atoms
- ionize by laser light
- transport to detector
- register alpha decay

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

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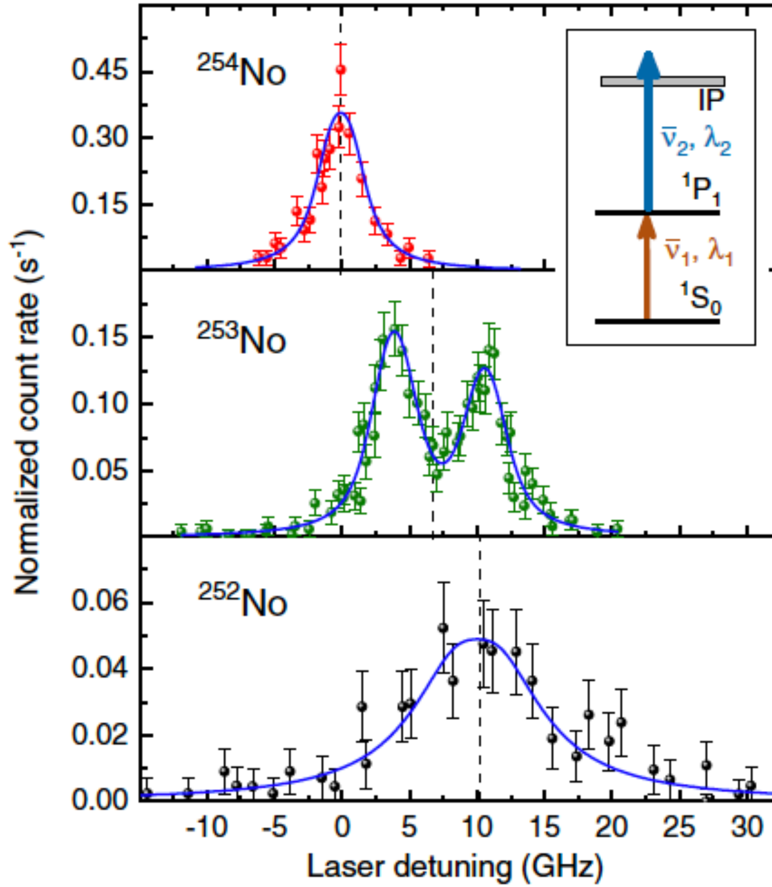
Laser Spectroscopy of Nobelium Atoms

- First optical spectroscopy beyond Z=100 despite low yields on the atom-at-a-time scale
- Half-life range 2.4 s – 55 s
- Several atomic and nuclear properties determined



M. Laatiaoui *et al.*, Nature 538, 495 (2016)
S. Raeder et al., Phys. Rev. Lett. 120 (2018) 232503

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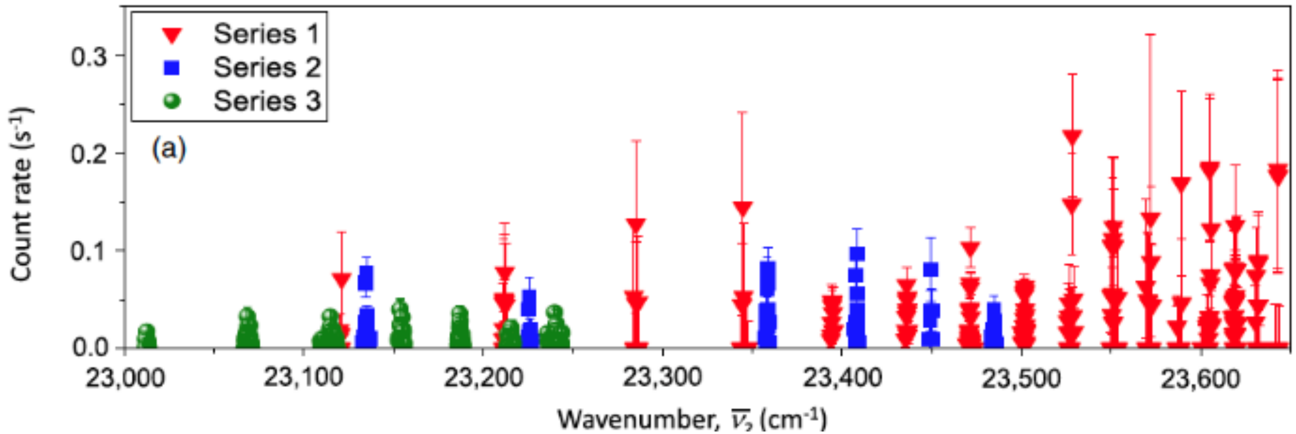
Nobelium Ionization Potential from Rydberg Series

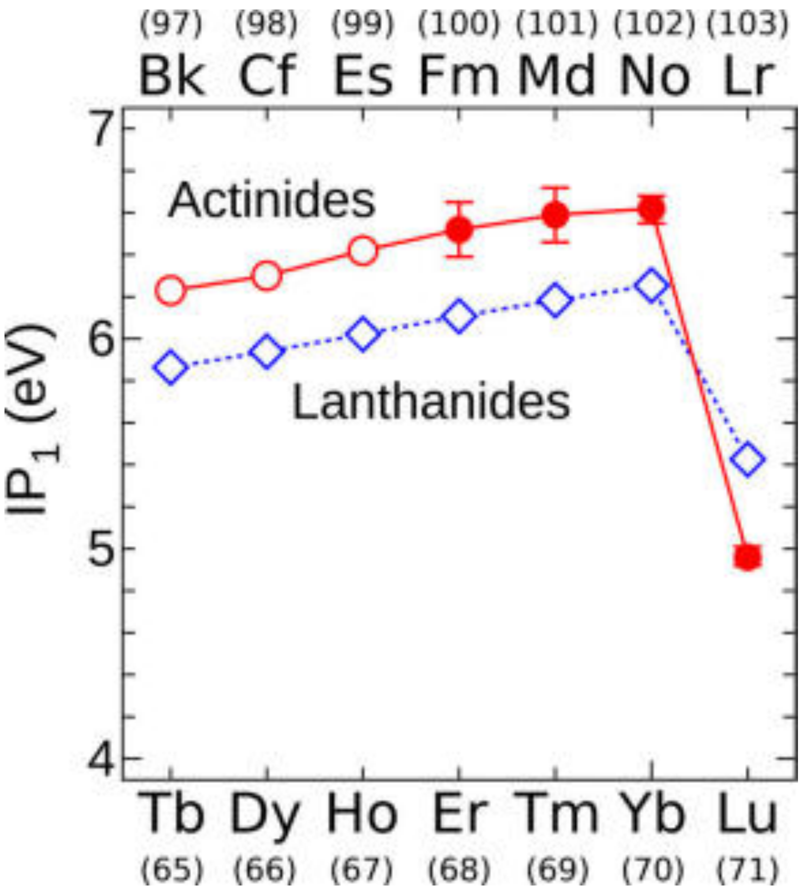


Method	IP (cm^{-1})	$^3D_3$ (cm^{-1})
Experiment (this work)	53 444.0 ± 0.4	29 652^{+8}_{-1}
IHFSCC [4]	53 489 ± 800	29 897 ± 800
CI+ all orders [5]	54 390 ± 1100	30 183 ± 1100
MCDF [6]	53 701 ± 1100	
Extrapolation [30]	53 600 ± 600	

- About 35 atomic states observed
- Good agreement with atomic theory predictions
- Accurate value for 1P1 state

P. Chhetri et al., Phys. Rev. Lett. 120 (2018) 263003

Ionization Potential of Actinides and Transactinides



	IP (eV)
Laser spectroscopy At SHIP / GSI	**6.62621(5)**
Theory (Borschevsky et al., RCC)	6.632
Extrapolation (Sugar)	6.65(7)

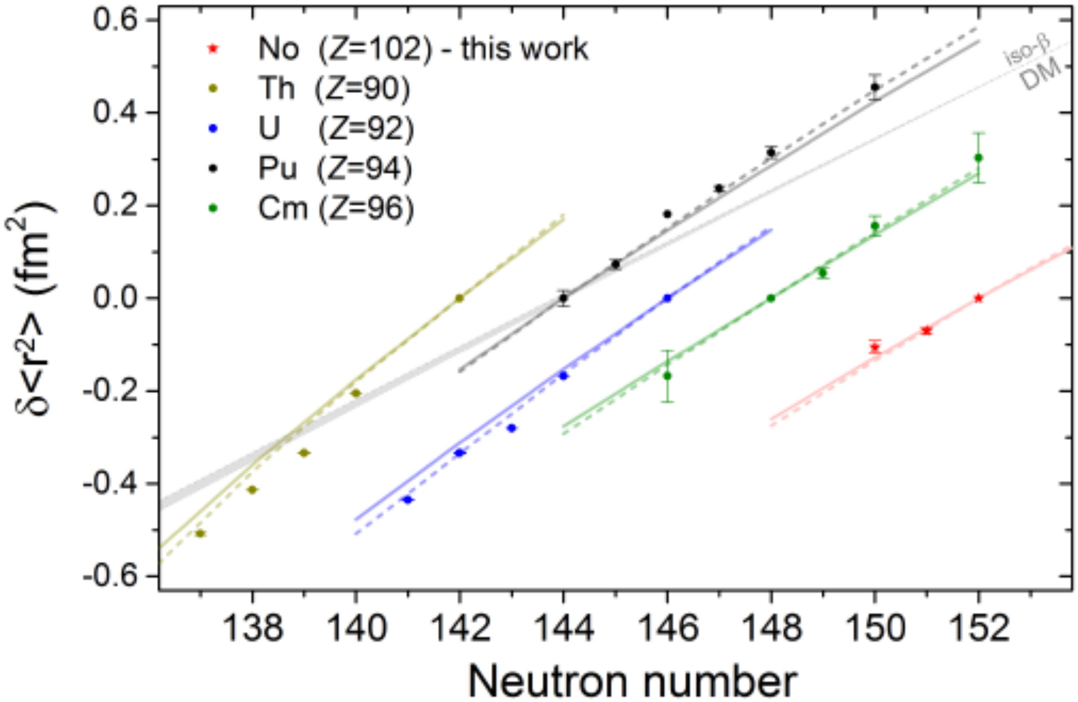
T. K. Sato *et al.*
Nature **520 (Apr.9)** (2015) 209-211.

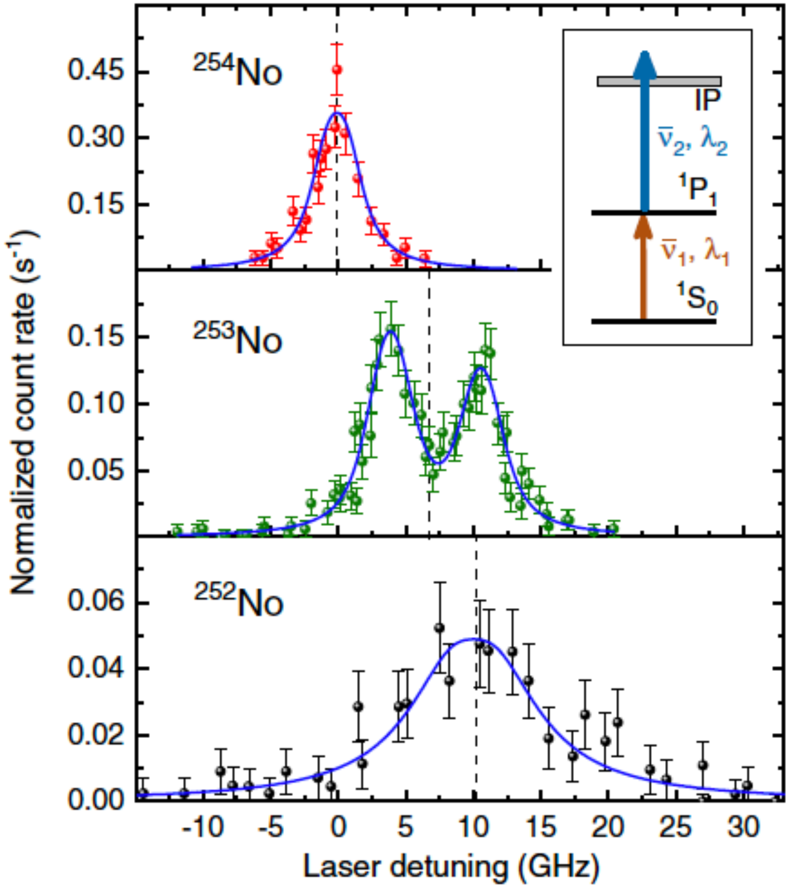
T. Sato et al. JACS 2018, 140, 14609

No: $IP_1(No) = 6.63 \pm 0.08$ eV

Lr: $IP_1(Lr) = 4.96 \pm 0.08$ eV
$\rightarrow$ Lr: $[Rn]5f^{14}7s^27p_{1/2}$

Charge Radii in Actinides





J. Maruhn et al. Phys. Commun. 185 2195 (2014)
P.-G. Reinhard, W. Nazarewicz, Phys. Rev. C 95 064328 (2017)

Exp. Date for No: S. Raeder et al., Phys. Rev. Lett. 120 (2018) 232503

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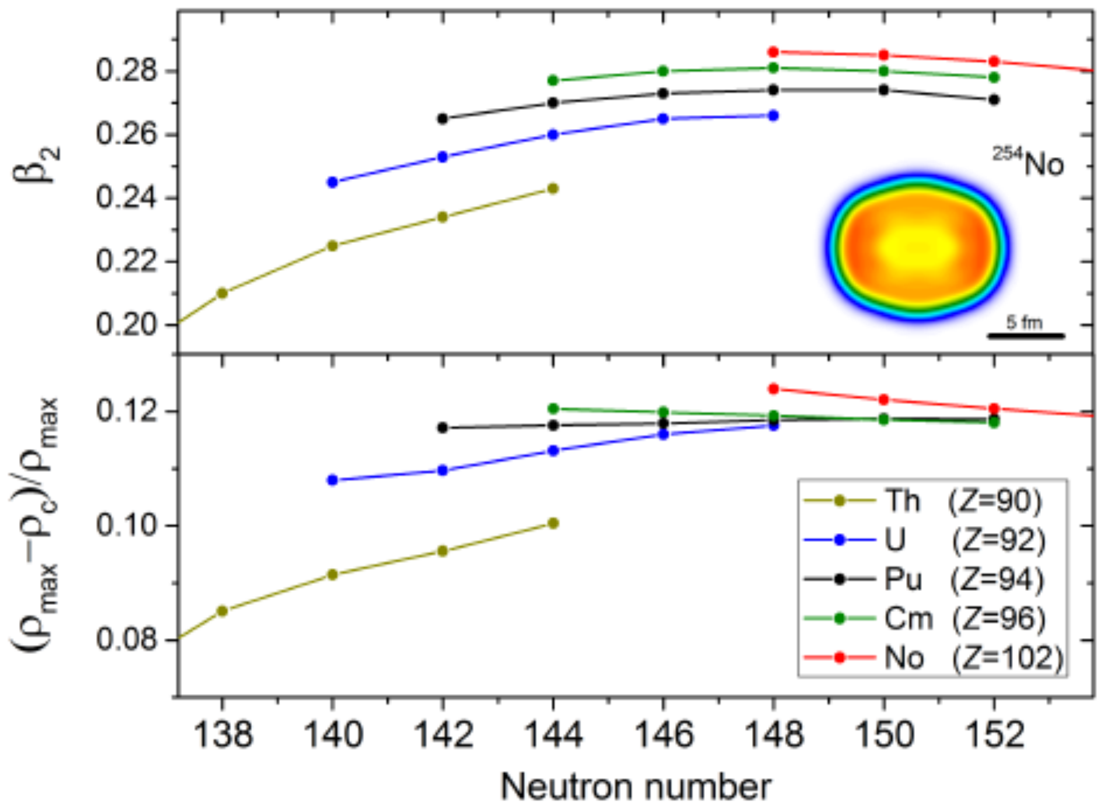
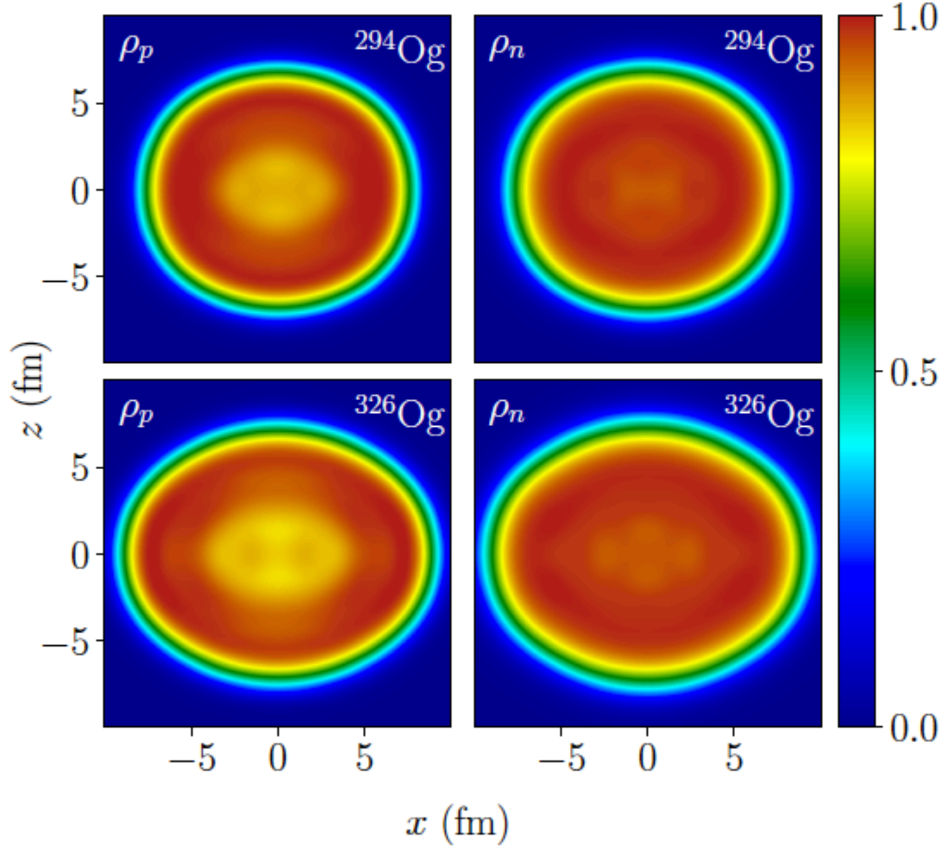
Deformation in Nobelium



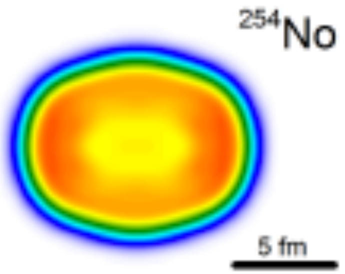
- Theoretical calculations using density functional theory predict:
- maximum deformation around $N=152$
- central depression in proton density already for nobelium

Calculations B. Schuetrumpf, W. Nazarewicz et al.

Central Depression in Nuclei



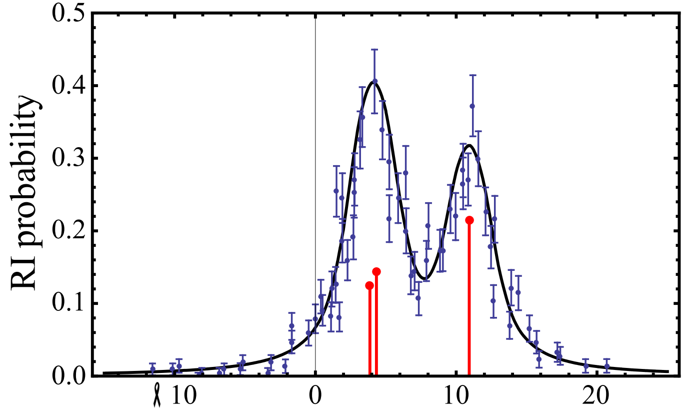
proton distribution

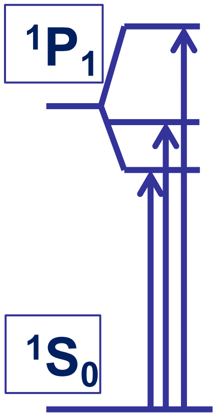


10% central depression

B. Schuetrumpf, W. Nazarewicz, and P.-G. Reinhard Phys. Rev. C **96**, 024306

Hyperfine Structure in ^{253}No





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

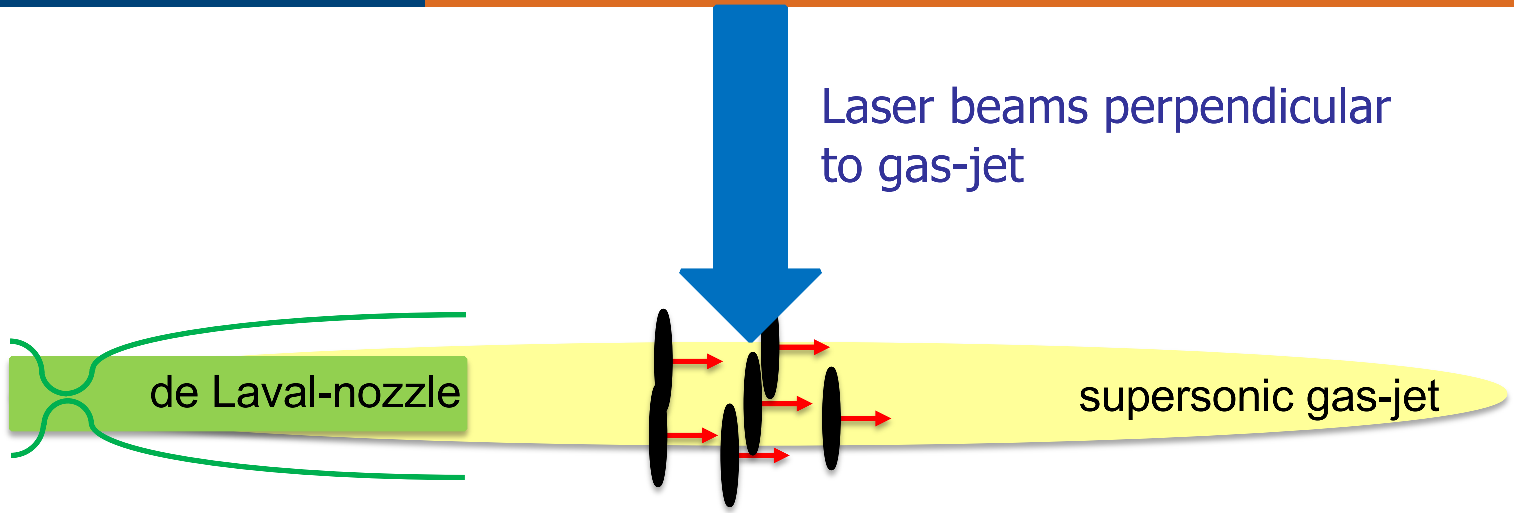
$$B = eQ_s \left\langle \frac{\delta^2 V}{\delta z^2} \right\rangle_{z=0}$$

Prolate shape + best fit to the experiemental data:

→ 7/2 nuclear spin can be excluded

→ A= 734(46) MHz; B= 2815(686) MHz

Improving Spectral Resolution by Supersonic Gas-Jet



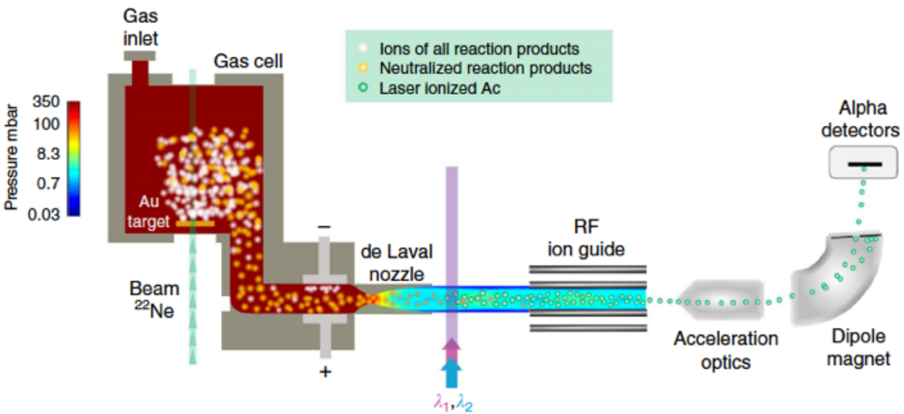
- Directed movement of the atoms in the gas-jet, perpendicular to laser beams

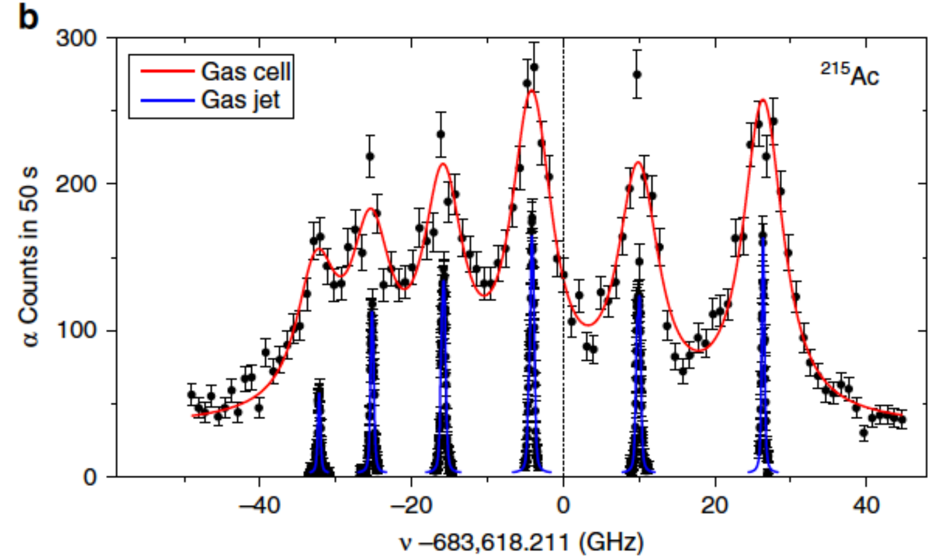
- High Mach-number for low pressures and low temperatures

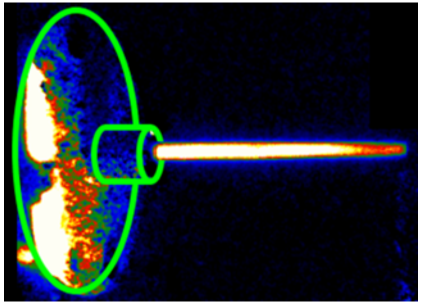
→ Reduction of the Doppler-effect results in smaller linewidths

Higher Resolution – Laser Spectroscopy in Jet

Perform laser spectroscopy in gas jet formed in de Laval nozzle



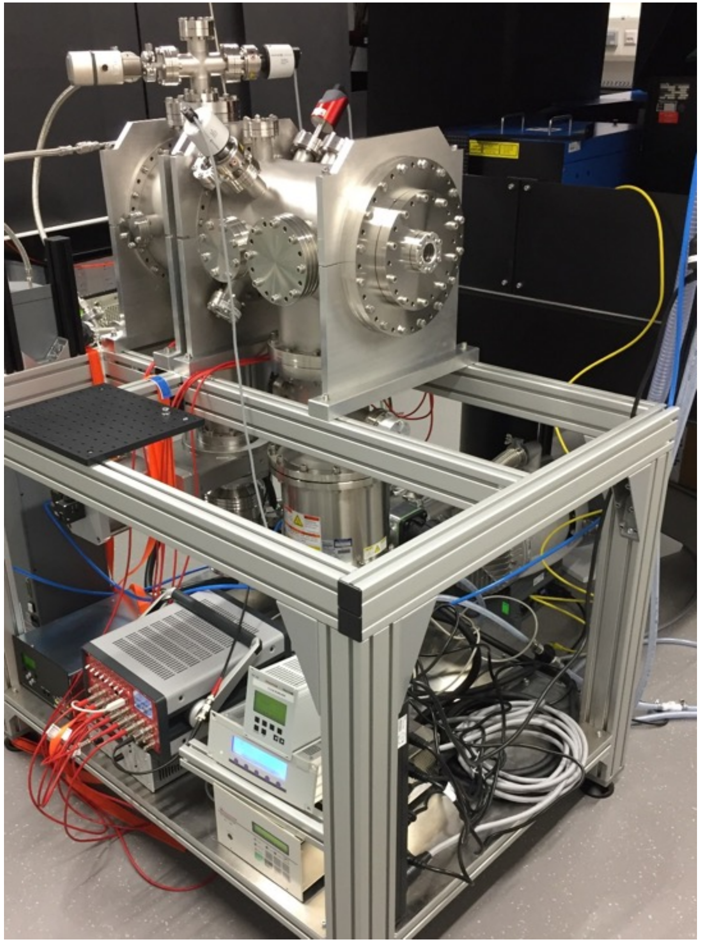


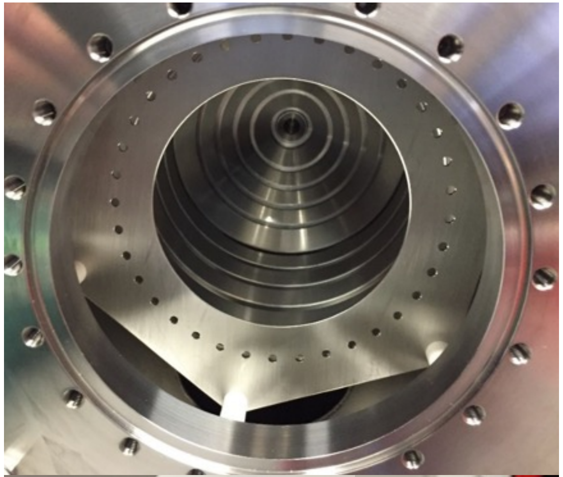


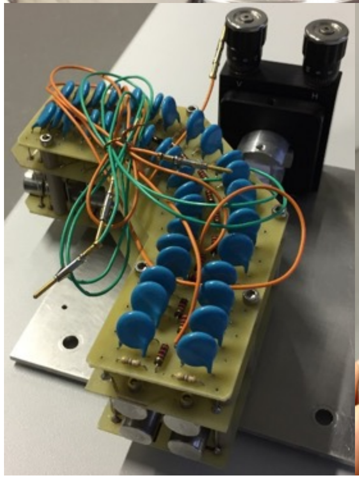
- Resolution improves by more than factor 10
- Efficiency comparable to in-gas cell approach

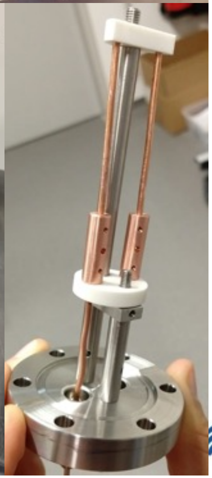
R. Ferrer et al., Nature Communications 8, 14520 (2017)

New Setup Built – Online Commissioning 2019









S. Raeder,
S. Nothhelfer et al.

In close collaboration with P. van Duppen's group

KU LEUVEN

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Summary

- Laser spectroscopy provides new opportunities to track the nuclear structure evolution in the heaviest nuclei getting access to their shape and size
- Differential charge radii and nuclear moments of 4 nobelium isotopes have been obtained from laser spectroscopy
- Experimental data are in good agreement with atomic theory calculations and nuclear EDF calculations that also predict central depression
- Technical and methodical developments for extension to heavier elements under way

Thank you for your attention !