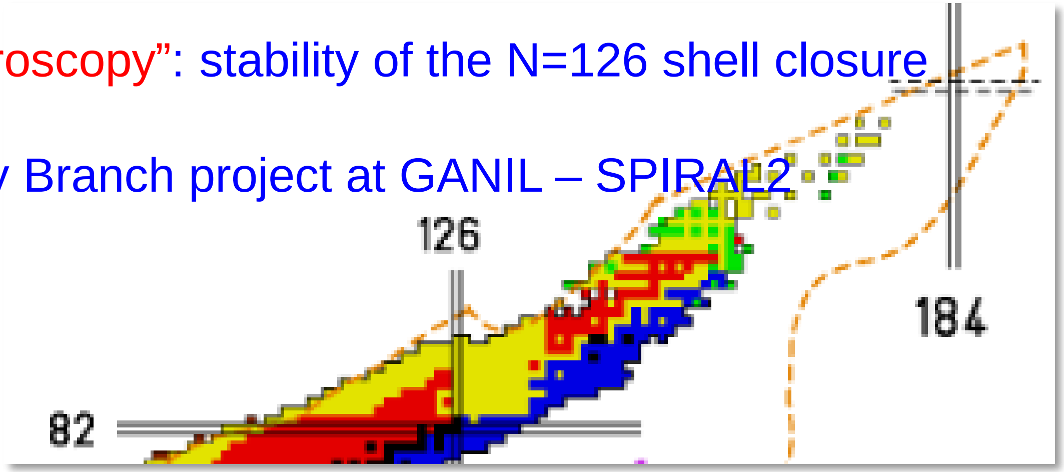
Shape coexistence along Z=82 and the stability of the N=126 shell closure studied using laser ionization spectroscopy

Piet Van Duppen
KU Leuven, Belgium

- Basics of laser spectroscopy
- Shape coexistence in the neutron-deficient mercury isotopes studied with "In Source Laser Spectroscopy"
- Comparison with Mean-Field and with Monte Carlo Shell Model calculations
- "In-gas jet Laser Ionization Spectroscopy": stability of the N=126 shell closure
- Outlook with the S3 – Low Energy Branch project at GANIL – SPIRAL2
- Conclusion



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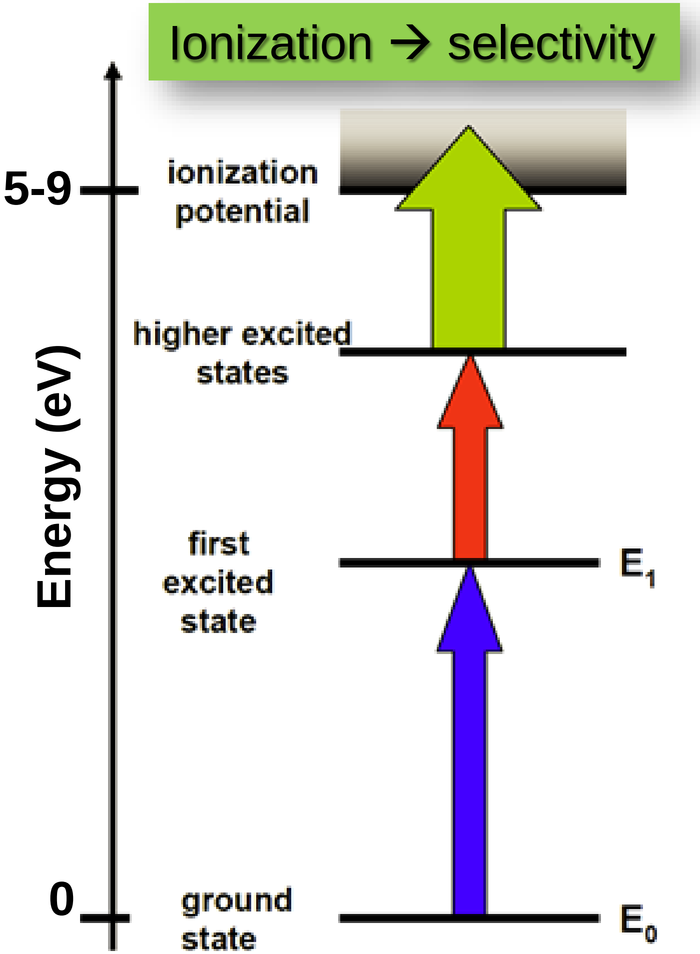
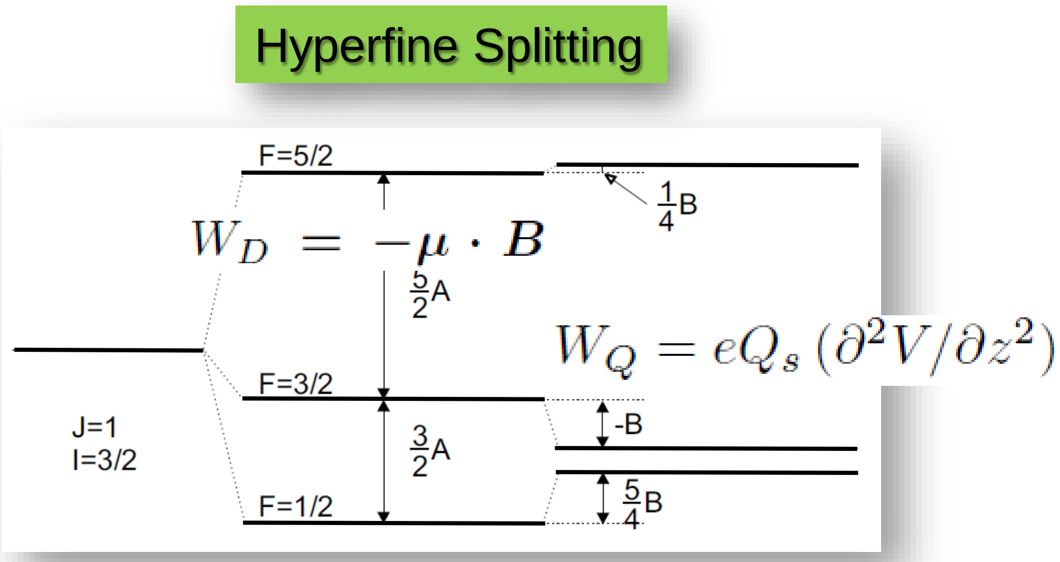
Laser Spectroscopy: basics



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



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

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

$$A = \mu_I B_e(0)/(IJ)$$

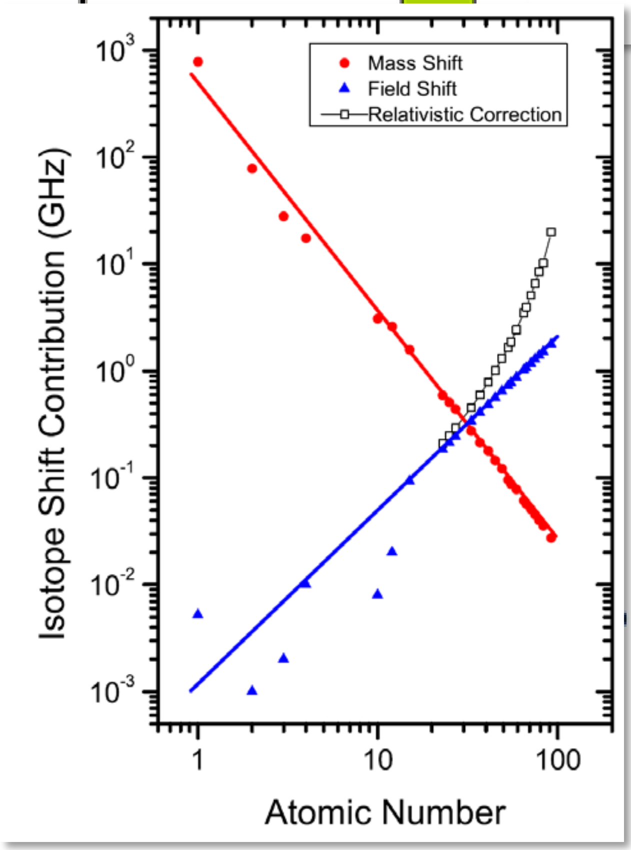
$$B = eQ_S V_{ZZ}(0)$$

 courtesy I. Moore

Laser Spectroscopy: basics

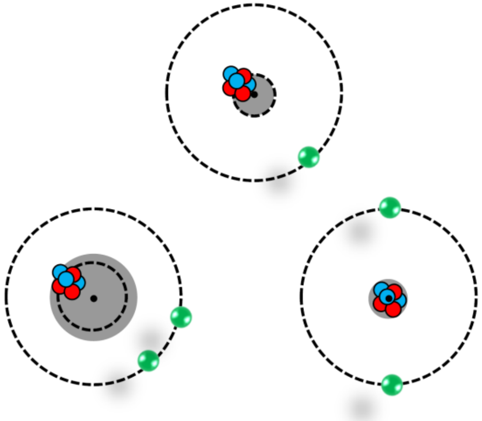
Isotope Shift

$$\delta\nu_{\mathrm{IS}}^{AA'} = K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + \frac{2\pi Z e}{3} \Delta \left|\Psi(0)\right|^2 \; \delta\left\langle r^2 \right\rangle^{AA'}$$

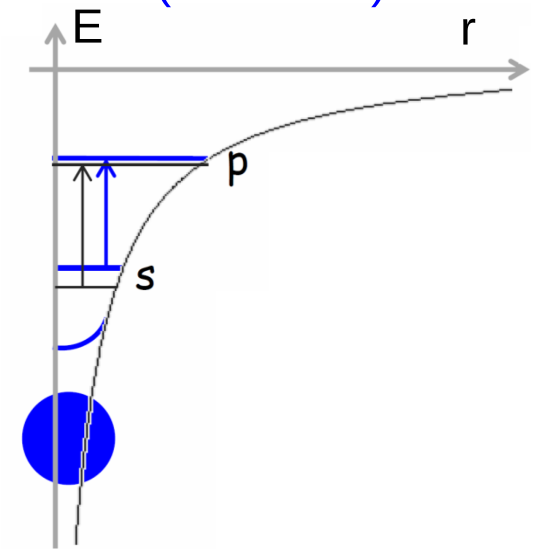


Blaum, Dilling, Nörtershäuser
Phys. Scr. T152 (2013)

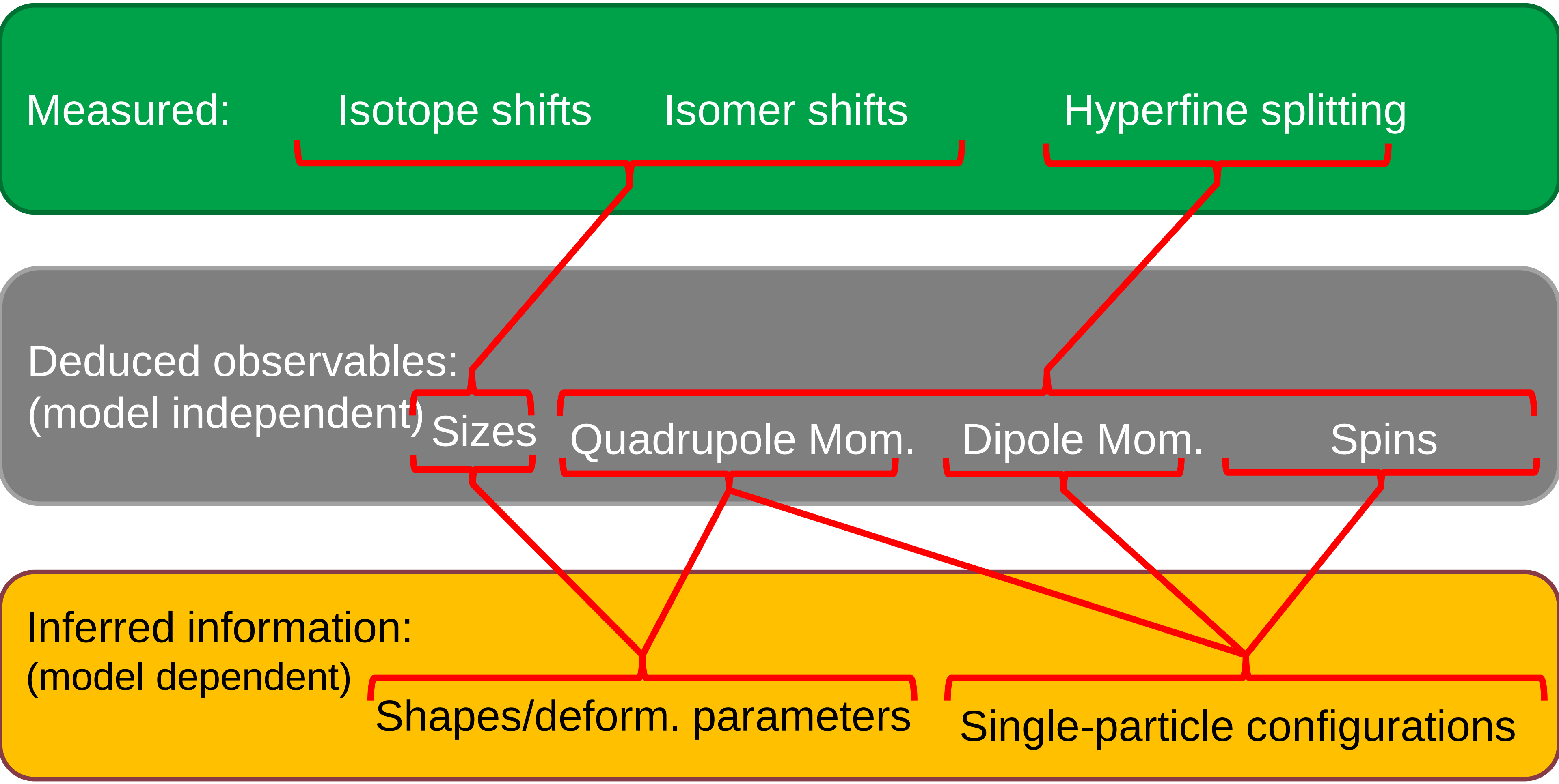
Mass shift
(center of mass motion)



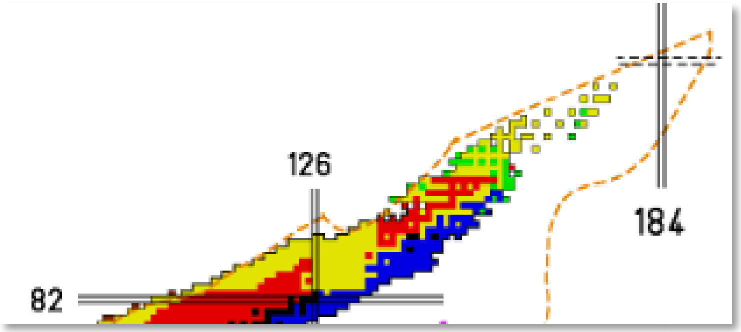
Field shift
(finite size)



Laser Spectroscopy: basics

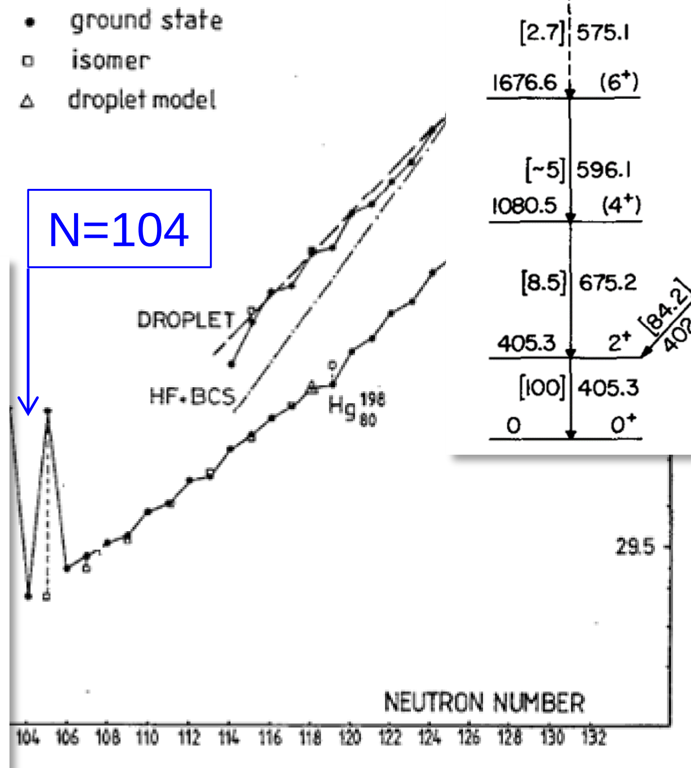


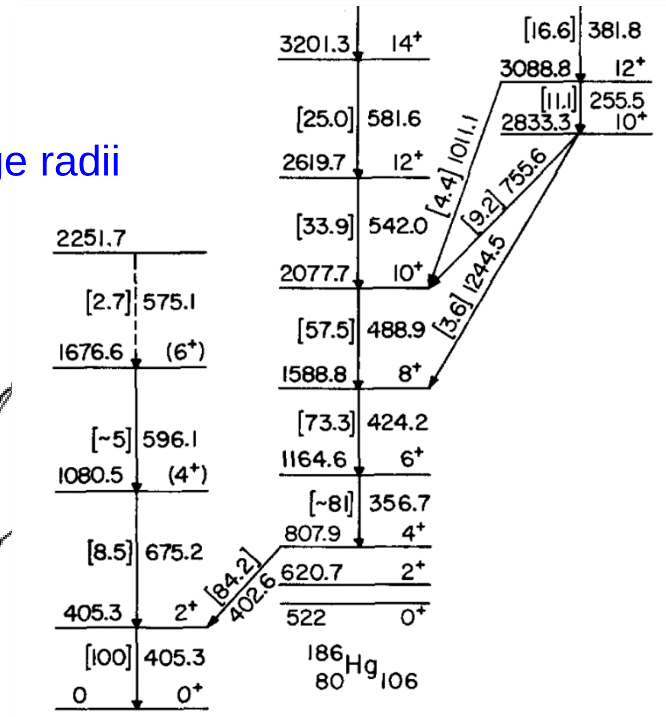
- Shape coexistence in heavy nuclei: initial indications



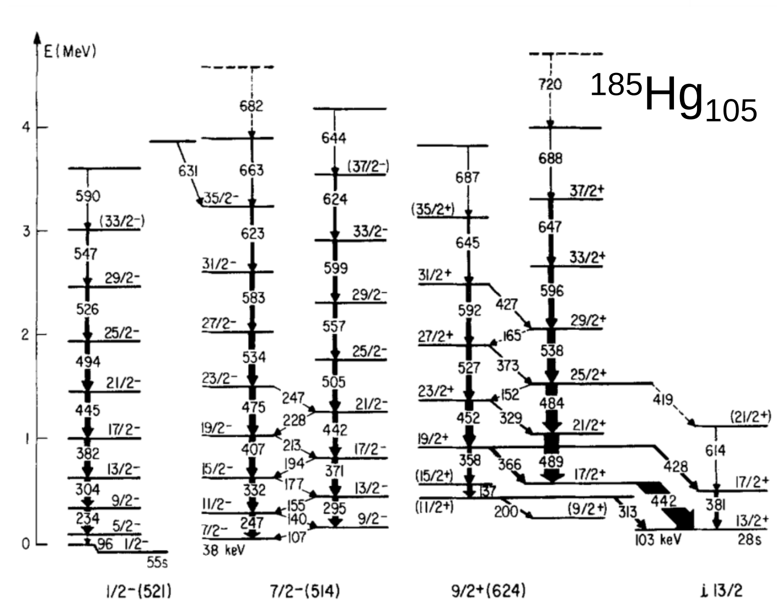
Hg (Z=80)

isotope shifts → charge radii



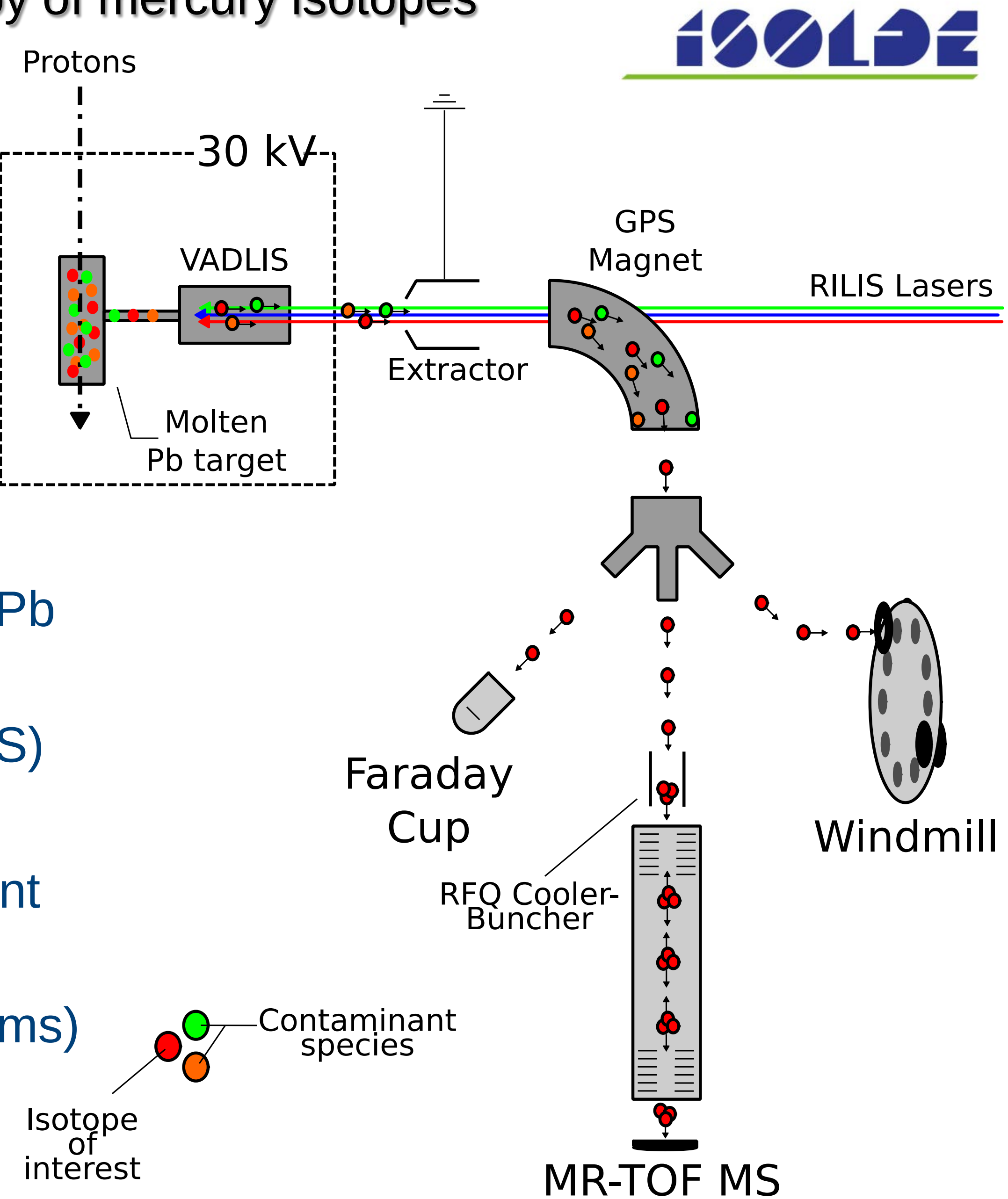


N=104

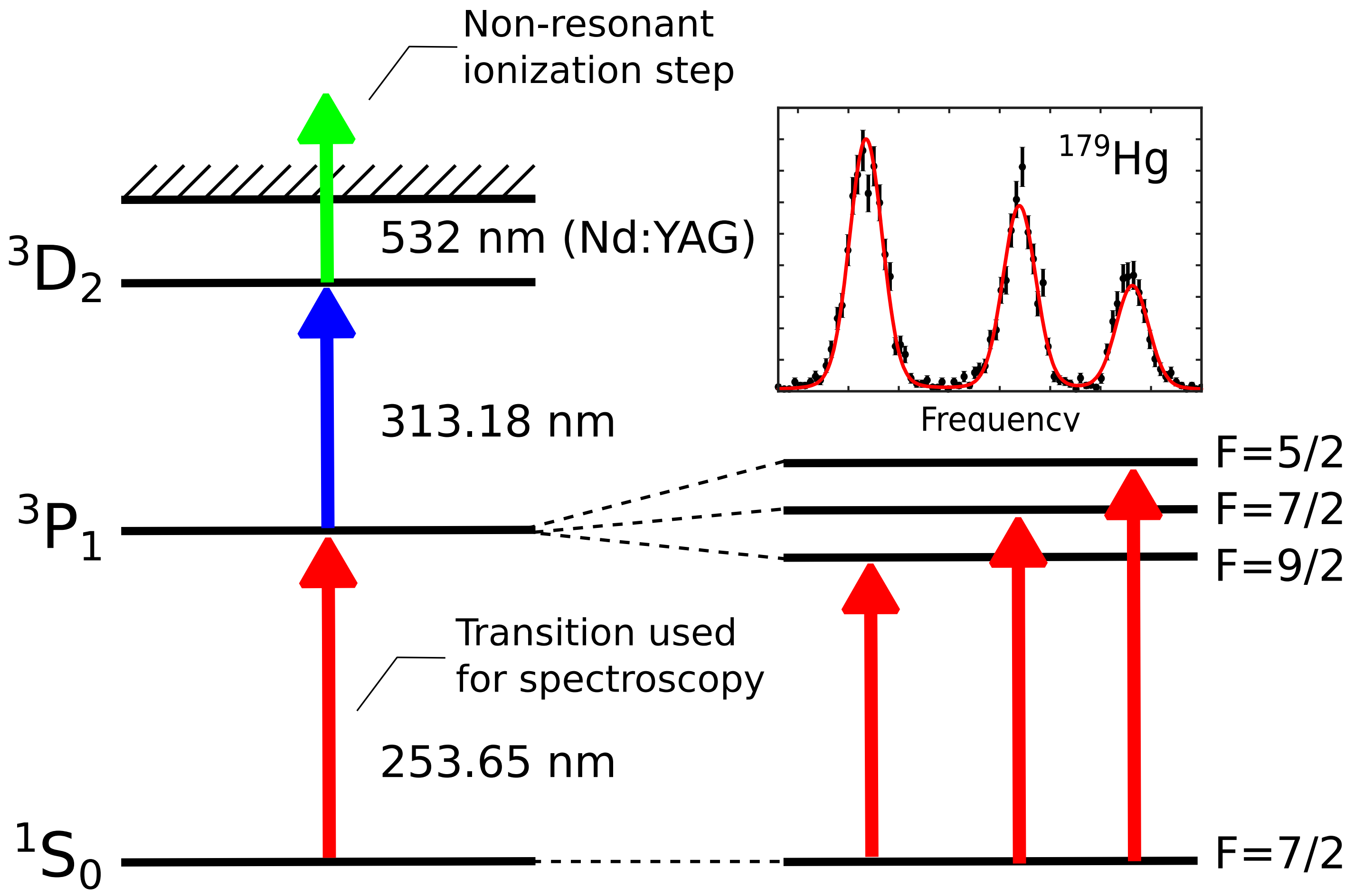


Bonn,- PLB 38 (1972), Hannachi,- ZP A370 (1988), Ma,- PLB167 (1986)
Janssens,- PLB131 (1983), Cole,- PRL37 (1976)

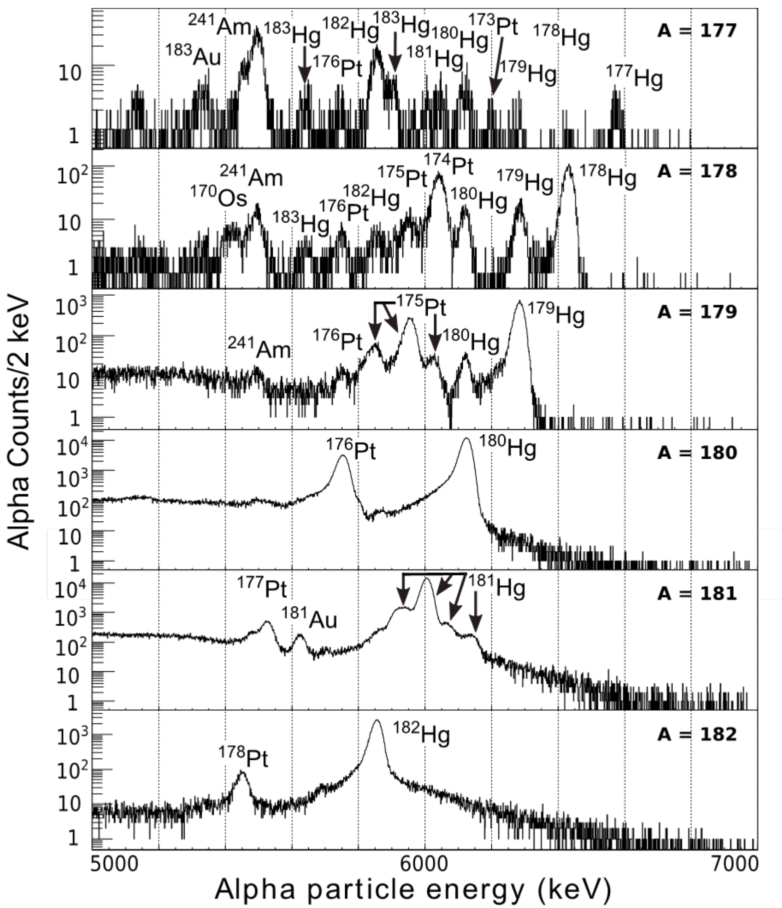
- Laser ionization spectroscopy of mercury isotopes

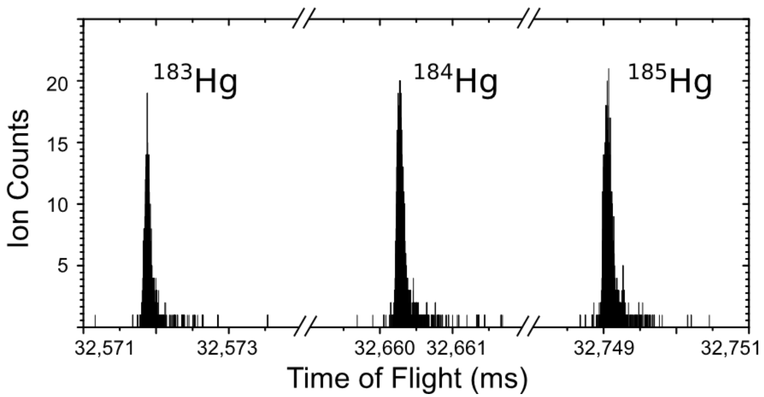


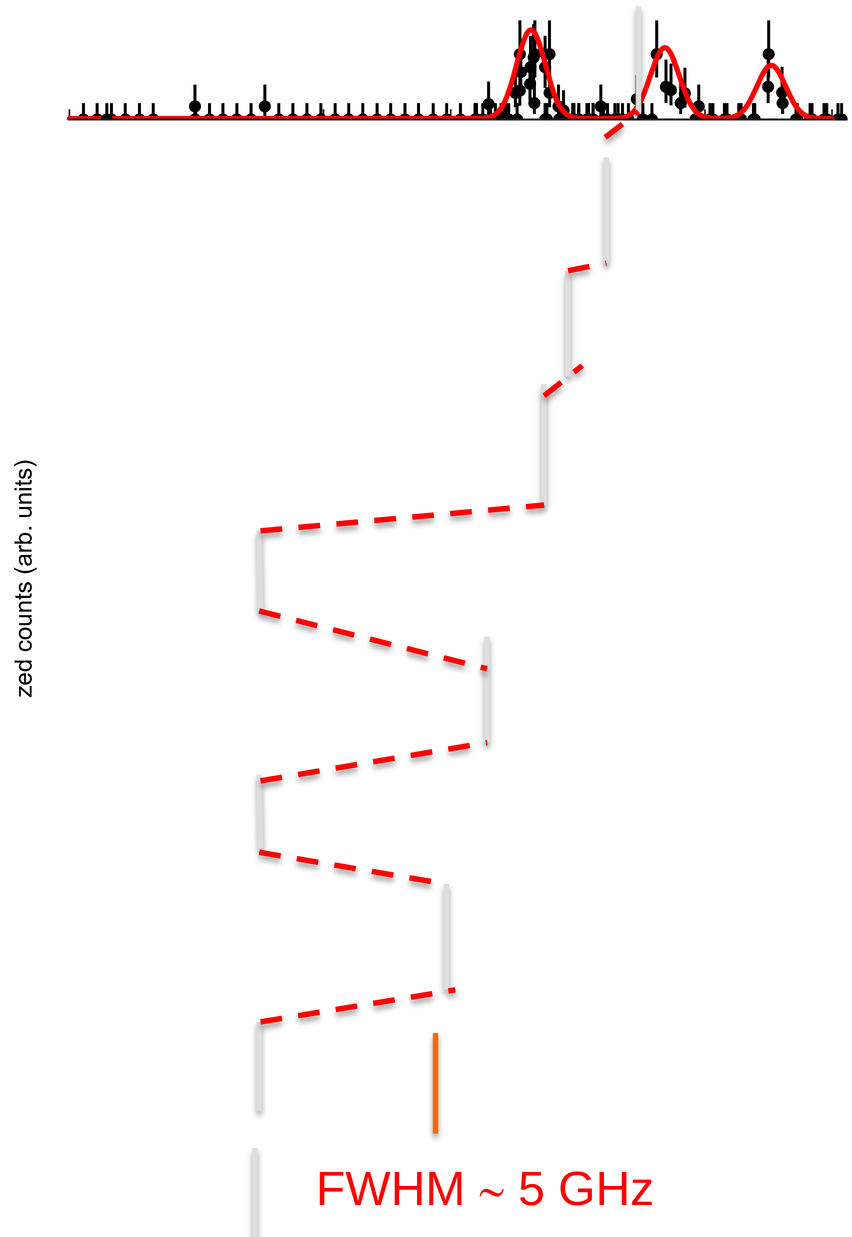
- 1,4 GeV protons on molten Pb
- Isotopes diffuse from target
- 3-step laser ionization (RILIS)
- Mass separation
- Ion detection using 3 different techniques
- Sensitive: ^{177}Hg ($T_{1/2}$ = 127 ms) 0.03 cps



Isotope shift,
hyperfine parameters → $\delta\langle r^2\rangle^{A,A'}$ $I, \mu, Q,$

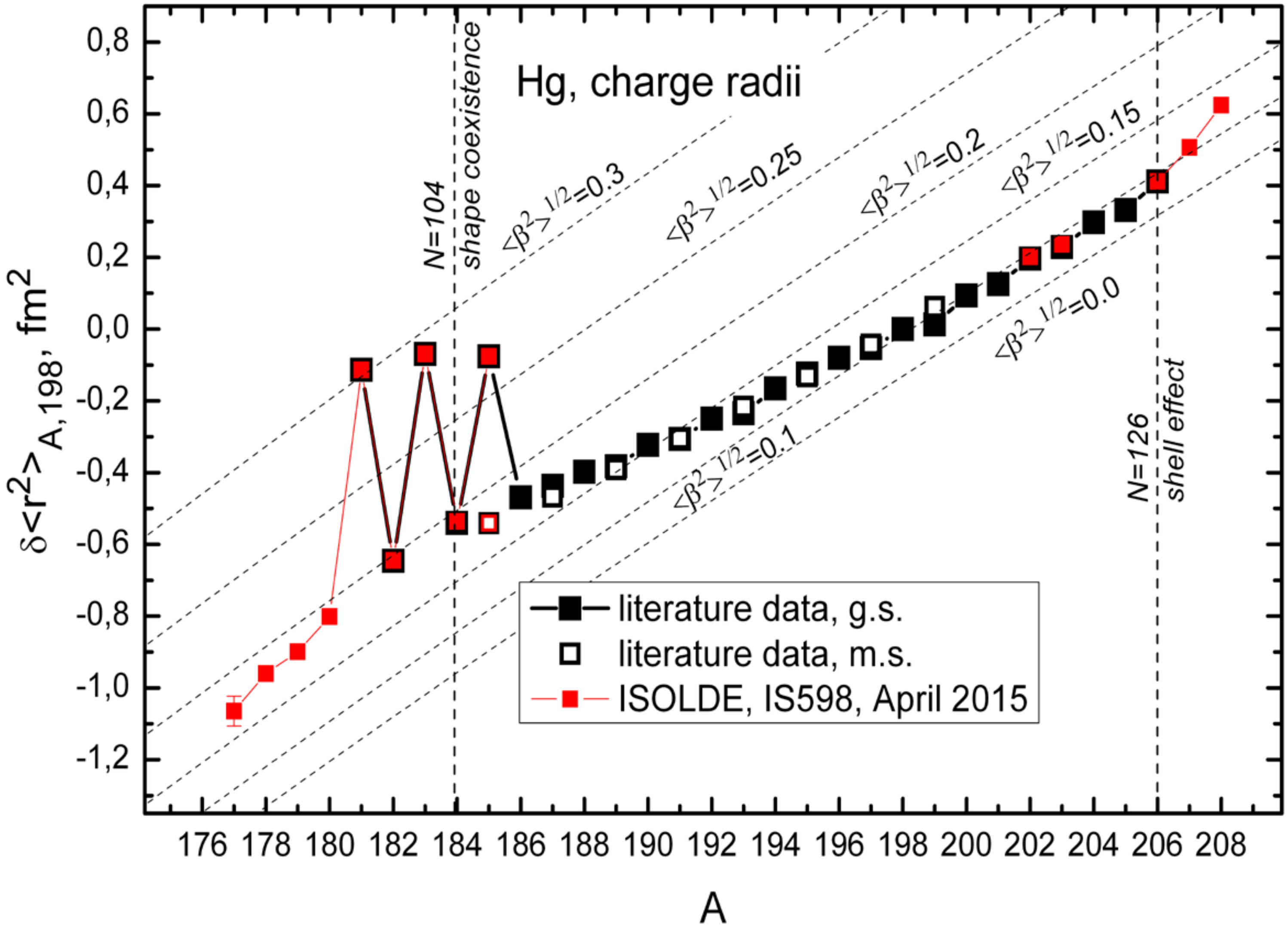

A = 177
A = 178
A = 179
A = 180
A = 181
A = 182
241Am 183Au 183Hg 176Pt 182Hg 183Hg 181Hg 180Hg 173Pt 179Hg 178Hg 177Hg
170Os 241Am 183Hg 176Pt 182Hg 175Pt 174Pt 180Hg 179Hg 178Hg
241Am 176Pt 175Pt 180Hg 179Hg
176Pt 180Hg
177Pt 181Au 181Hg
178Pt 182Hg
Alpha Counts/2 keV
5000
6000
7000
Alpha particle energy (keV)


183Hg
184Hg
185Hg
Ion Counts
20
15
10
5
32,571
32,573
32,660
32,661
32,749
32,751
Time of Flight (ms)


zed counts (arb. units)

FWHM ~ 5 GHz

- Charge radii of mercury isotopes



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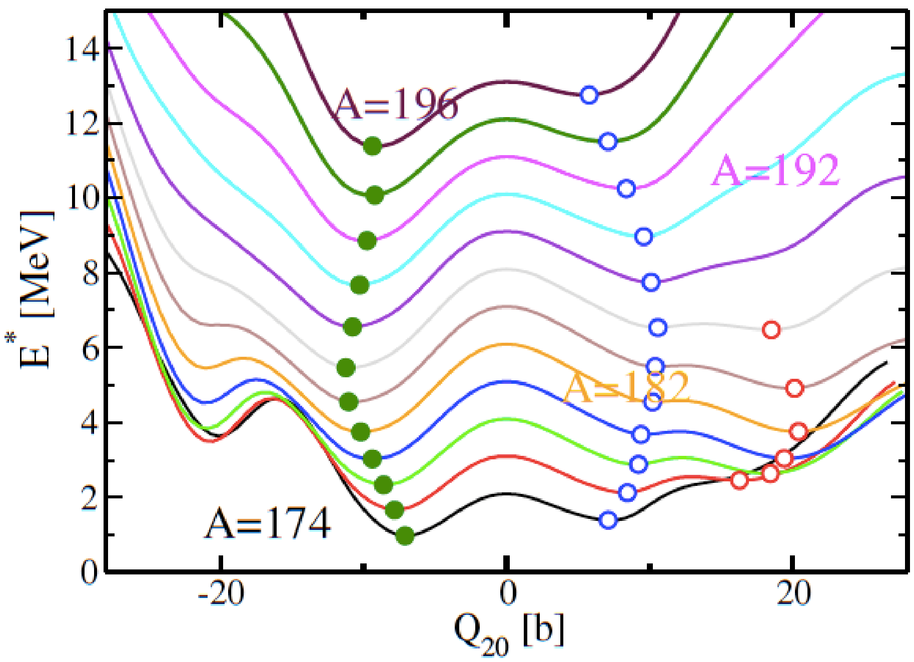
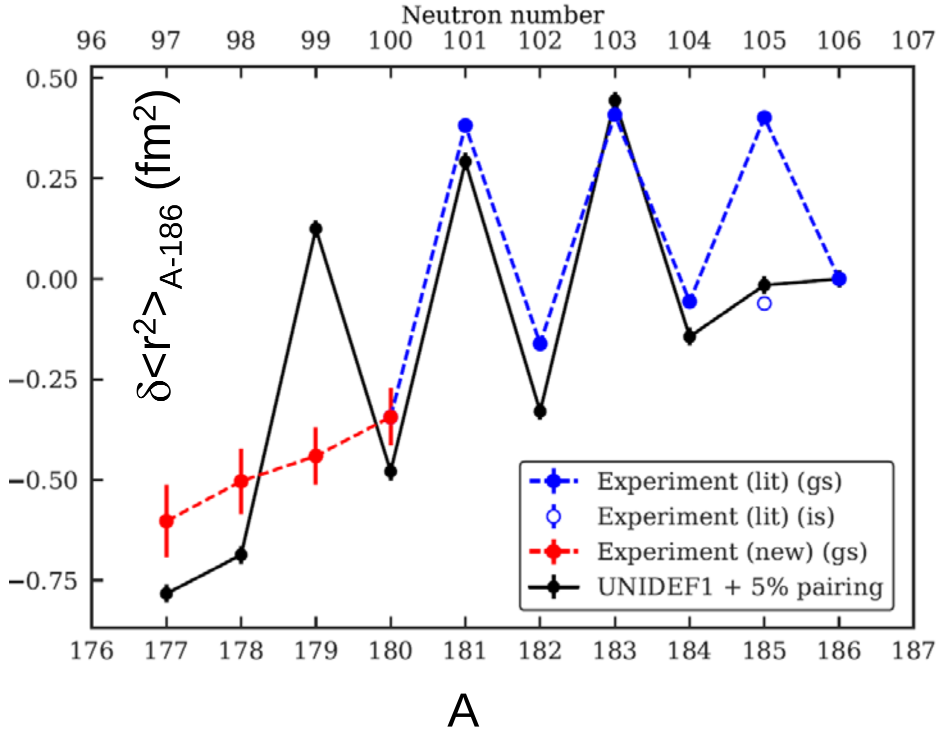
- DFT – UNEDF1

Energy surface



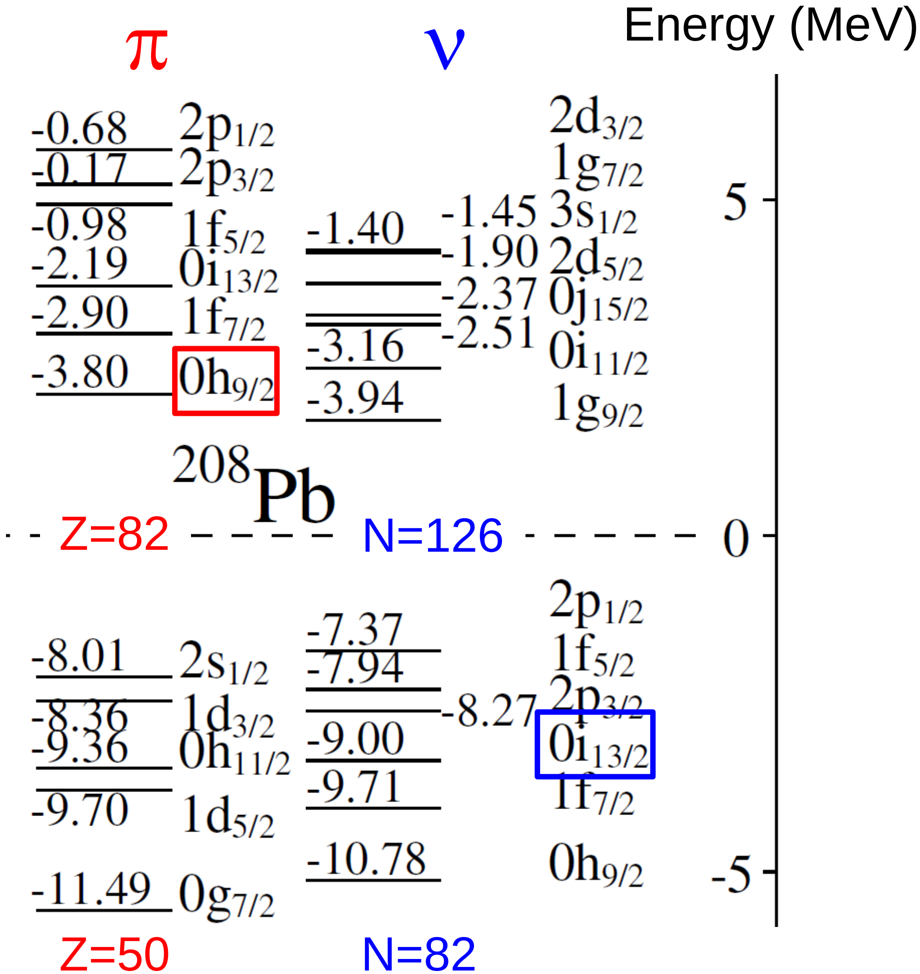
Charge radii



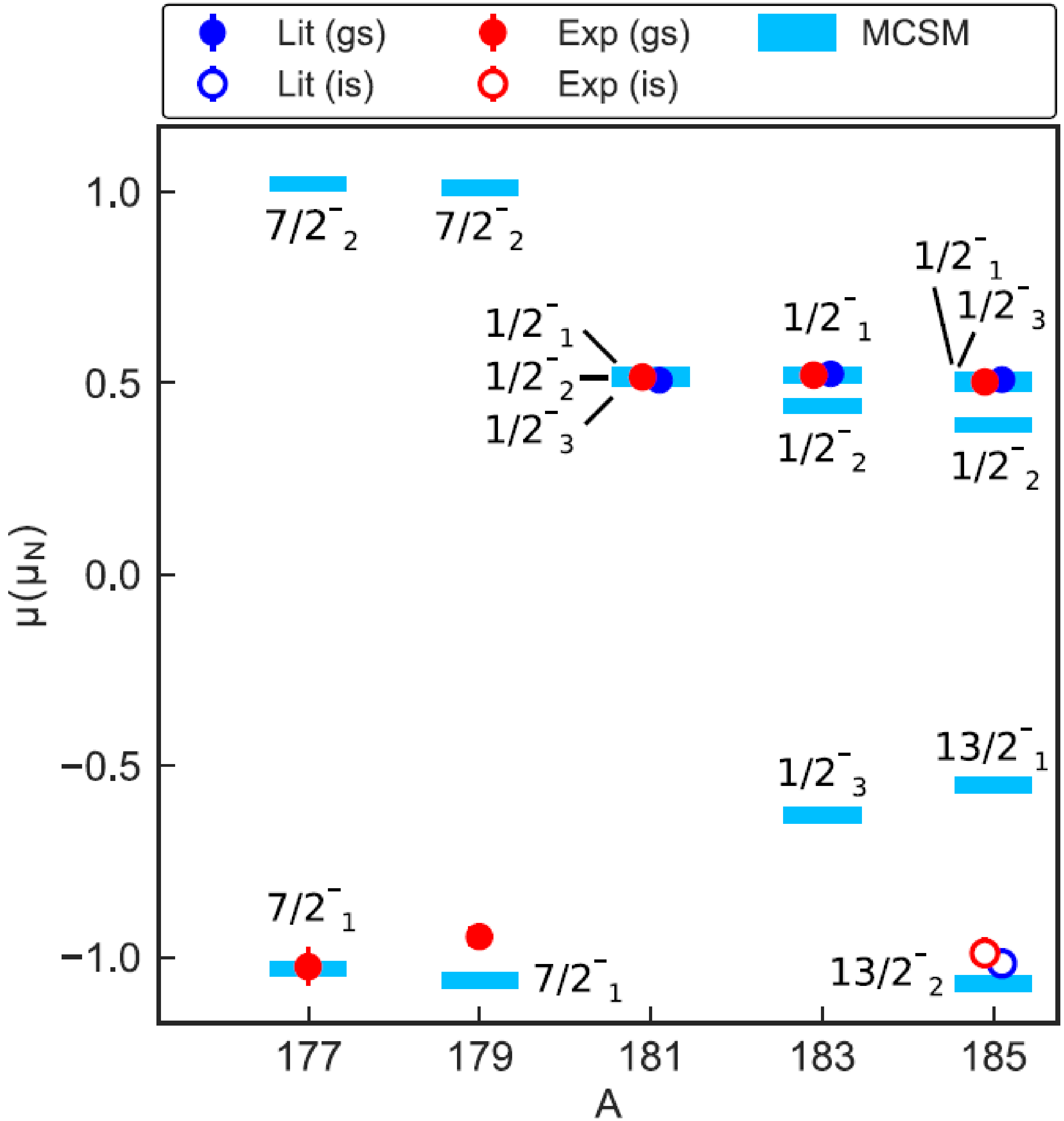
- Skyrme functional UNEDF1so [1]
  → Fine tuned SO and pairing to reproduce No spectroscopy

 [1] Yue Shi PRC 89, 034309 (2014)

- Monte-Carlo Shell Model calculation (Y. Tsunoda & T. Otsuka)
  - ^{132}Sn core – NN, PP[1], PN [2]
  - eff. ch. π = 1.6e / eff. ch. ν = 0.6e / spin quenching = 0.9
  - π: $1g_{7/2}$ → $1i_{13/2}$ (11 proton orbitals) / ν: $1h_{9/2}$ → $1j_{15/2}$ (13 neutron orbitals)



[1] B.A. Brown, Phys. Rev. Lett. 85, 5300 (2000).
[2] T. Otsuka et al., Phys. Rev. Lett. 104, 012501 (2010).



Lit (gs)
Lit (is)
Exp (gs)
Exp (is)
MCSM
1.0
0.5
0.0
−0.5
−1.0
μ(μN)
177
179
181
183
185
A
7/2⁻2
7/2⁻2
1/2⁻1
1/2⁻2
1/2⁻3
1/2⁻1
1/2⁻2
1/2⁻3
1/2⁻1
1/2⁻3
1/2⁻2
13/2⁻1
7/2⁻1
7/2⁻1
13/2⁻2

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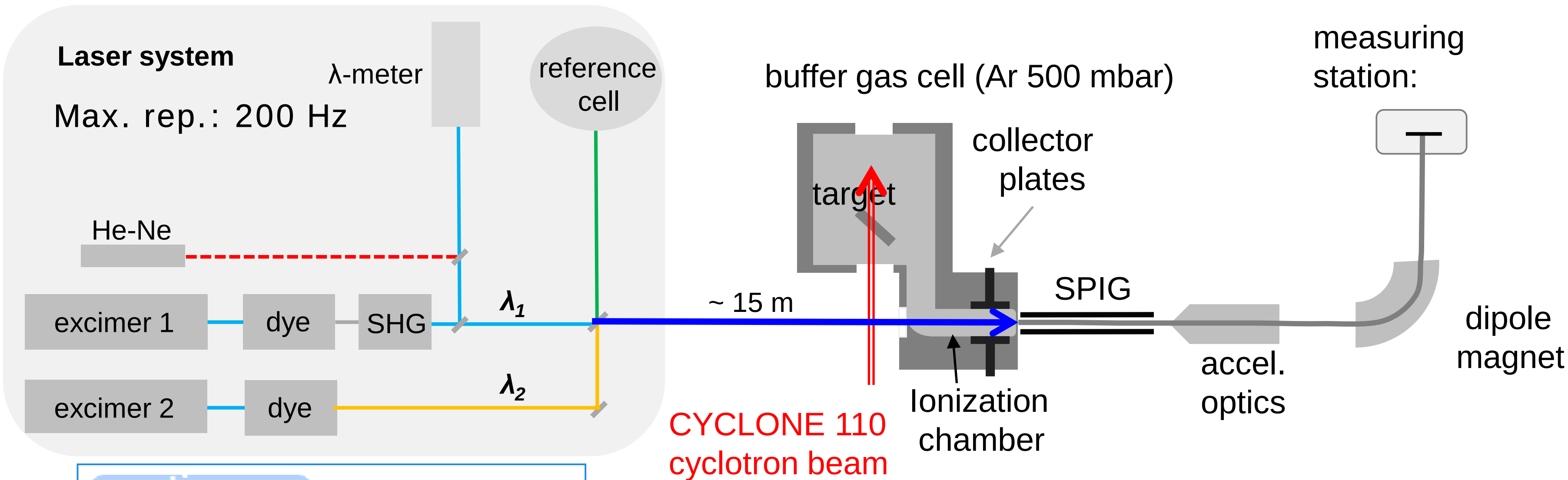
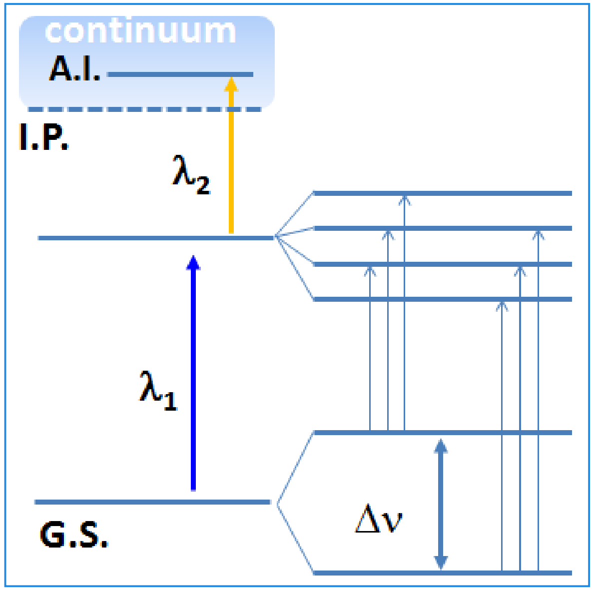
Leuven Isotope Separator On-Line (LISOL) facility: In-Gas Laser Ionization and Spectroscopy of RIBs (IGLIS)





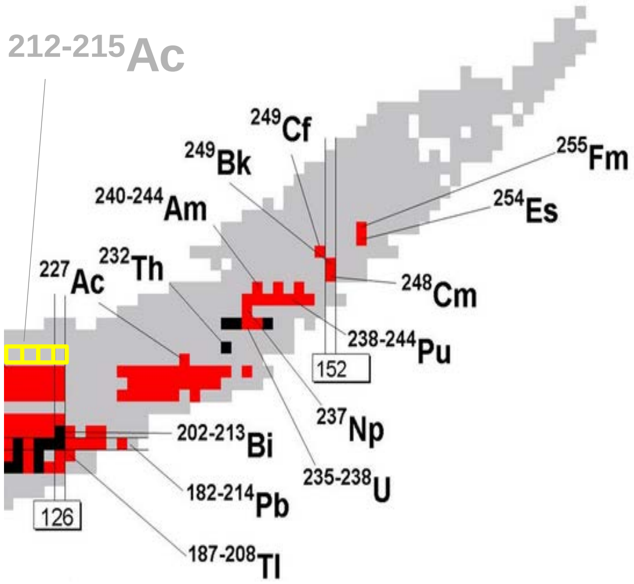
^{57}Cu(Z=29, N=28, $T_{1/2}$=196 ms)
Cocolios,- PRL 103 (2009) 102501

^{97}Ag (Z=47, N=50, $T_{1/2}$= 26 s))
Ferrer,- PLB 728 (2014) 191

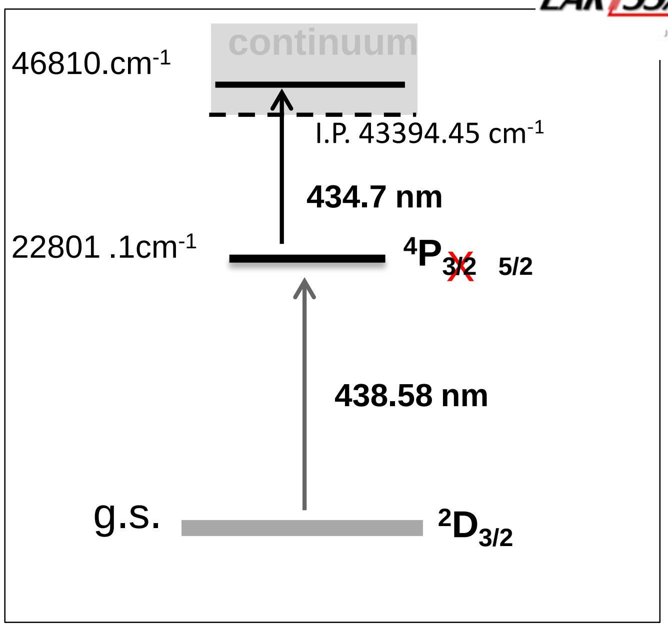
Yu. Kudryavtsev et al., NIM B 114 (1996) 350
M . Facina et al., NIM B 226 (2004) 401

Production & first laser spectroscopy tests of Ac

^{197}Au(^{20}Ne-145 MeV,4-5n)^{212,213}Ac
^{197}Au(^{22}Ne-143 MeV,4-5n)^{214,215}Ac



K. Blaum et al., Phys. Scr. T152 (2013) 014017



Limitations of in-gas cell laser spectroscopy:

- Pressure shift and broadening
- Doppler broadening
- Ion-gas interactions

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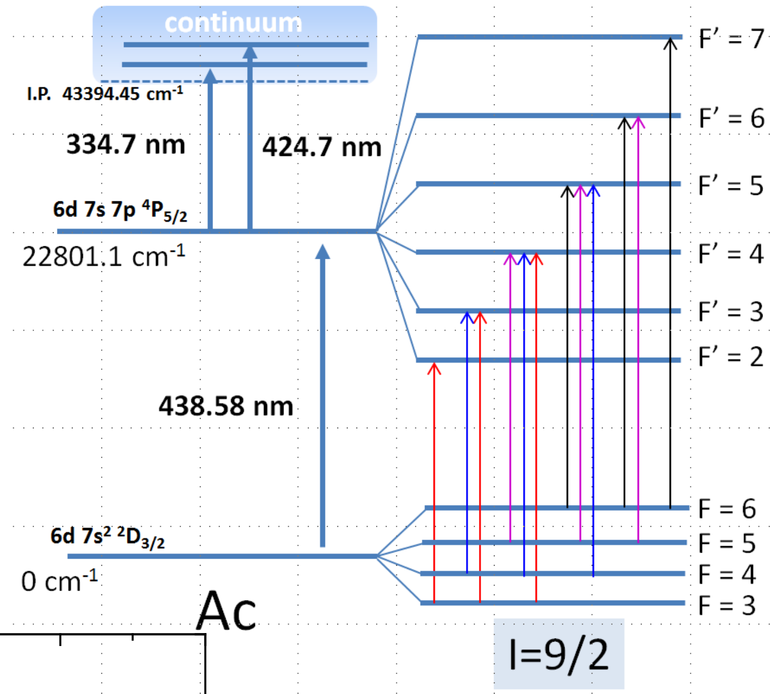
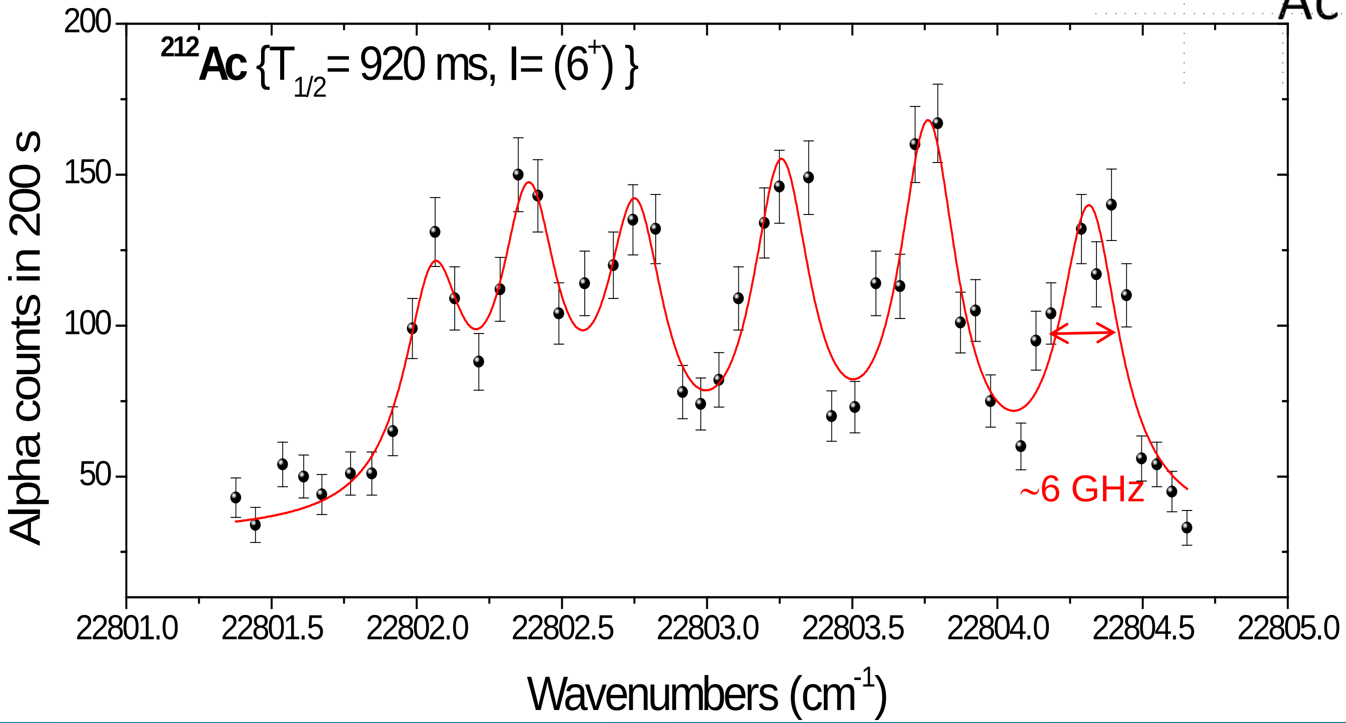
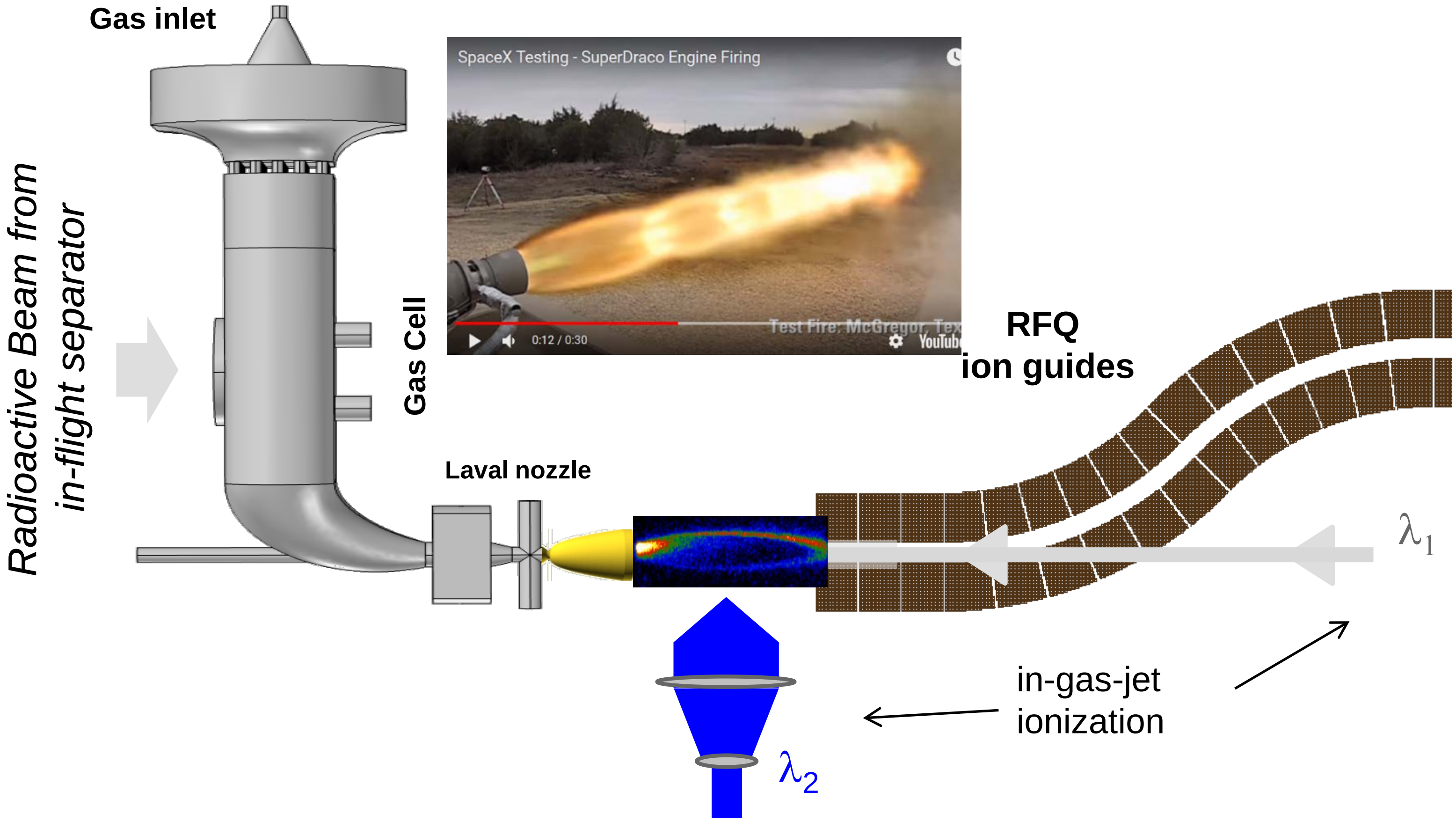

continuum
I.P. 43394.45 cm-1
334.7 nm
424.7 nm
6d 7s 7p 4P5/2
22801.1 cm-1
438.58 nm
6d 7s2 2D3/2
0 cm-1
Ac
F' = 7
F' = 6
F' = 5
F' = 4
F' = 3
F' = 2
F = 6
F = 5
F = 4
F = 3
I=9/2


212Ac {T1/2= 920 ms, I= (6+) }
Alpha counts in 200 s
Wavenumbers (cm-1)
~6 GHz
200
150
100
50
22801.0
22801.5
22802.0
22802.5
22803.0
22803.5
22804.0
22804.5
22805.0

In-Gas Jet Laser Ionization Spectroscopy

- stopping in the buffer gas cell
- formation of a gas jet through a 'de Laval' nozzle
- homogenous, low-density, cold get
- transport of the ions in Radio Frequency Ion Guides → detection system

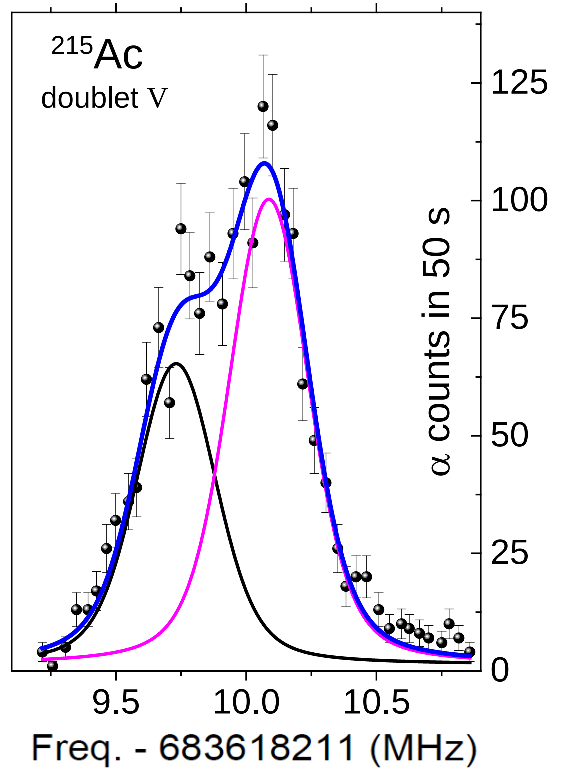


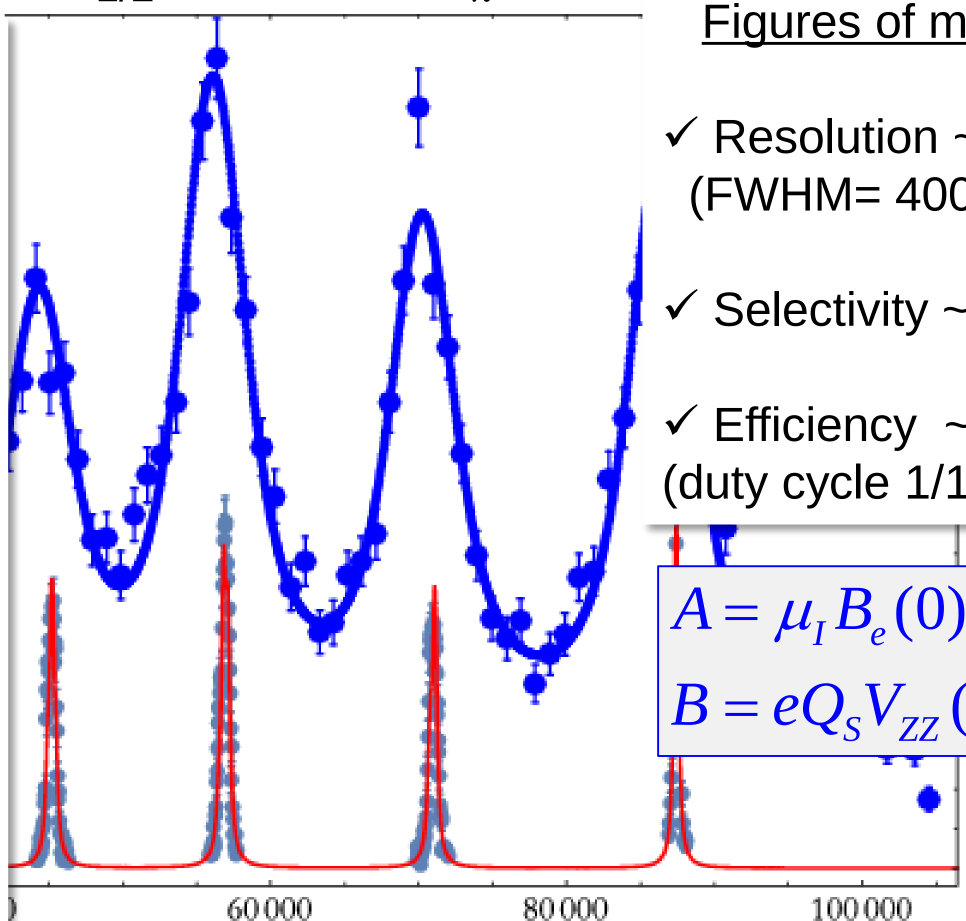
R. Ferrer et al, Nature Commun. 8, 14520 doi: 10.1038/ncomms14520 (2017)
Yu. Kudryavtsev et al, NIMB61724, (2016) pp. 345-352

LISOL's famous last action (*)

* 1/5/1974 - † 6/12/2014

^{215}Ac $T_{1/2} = 0.17$ s $J_\pi = (9/2^-)$





Figures of merit:

- ✓ Resolution ~ 5 10^{-7} (FWHM= 400 MHz)
- ✓ Selectivity ~ 200
- ✓ Efficiency ~ 0.5% (duty cycle 1/10)

$$A = \mu_I B_e(0) / (IJ)$$

$$B = eQ_S V_{ZZ}(0)$$

- in gas cell **- in gas jet**

R. Ferrer et al, Nature Commun. 8, 14520 doi: 10.1038/ncomms14520 (2017)
Yu. Kudryavtsev et al, NIMB61724, (2016) pp. 345-352

Nuclear Moments of Ac^{227}†

MARK FRED AND FRANK S. TOMKINS, *Chemistry Division, Argonne National Laboratory, Lemont, Illinois*

AND

WILLIAM F. MEGGERS, *National Bureau of Standards, Washington, D. C.*

(Received April 11, 1955) Phys. Rev. 98, 1514

The values derived for the moments from the conventional treatment of hfs in intermediate coupling are $+1.1$ nm and -1.7×10^{-24} cm². The experimental error is believed to be less than 10 percent, but it is difficult to estimate the total error because of the configuration interaction and the large relativity corrections. No correction for closed shell distortion was made.

It is hoped that improved values can be obtained, but meanwhile it appears useful to offer the present results. We should like to acknowledge helpful discussions with Dieter Kurath and R. E. Trees.

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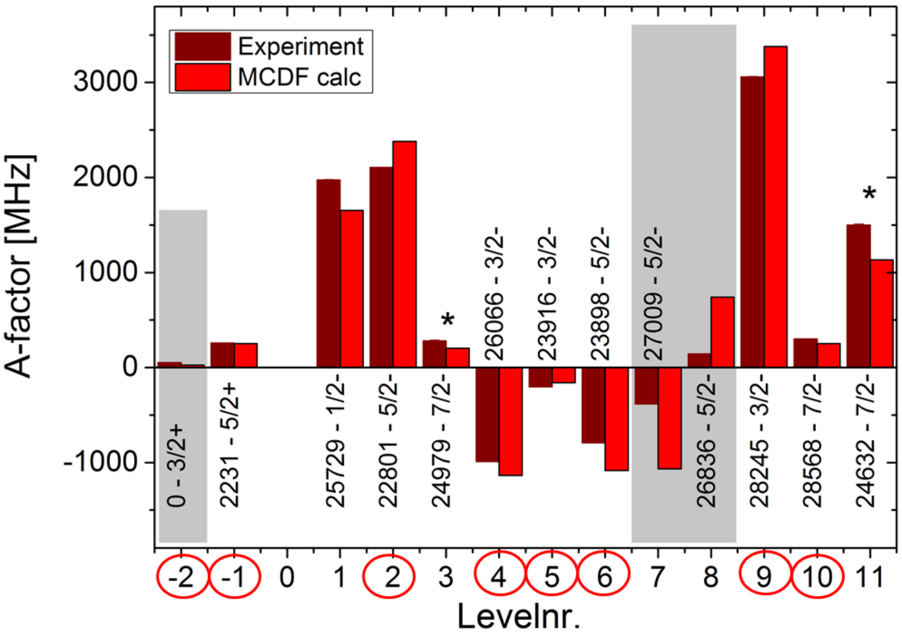
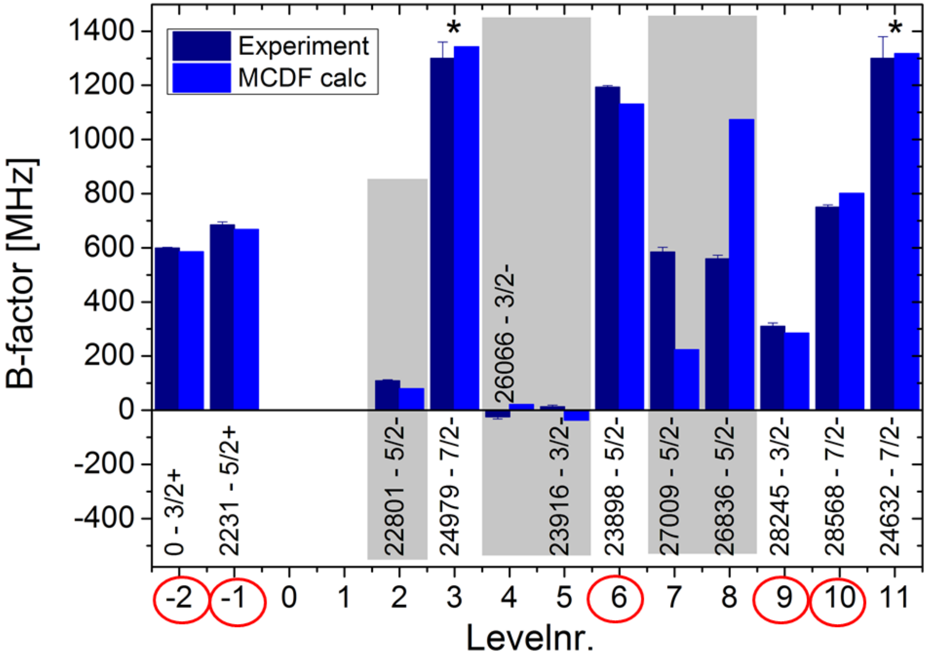
Multi-Monfiguration Dirac Fock atomic physics calculations: ^{227}Ac

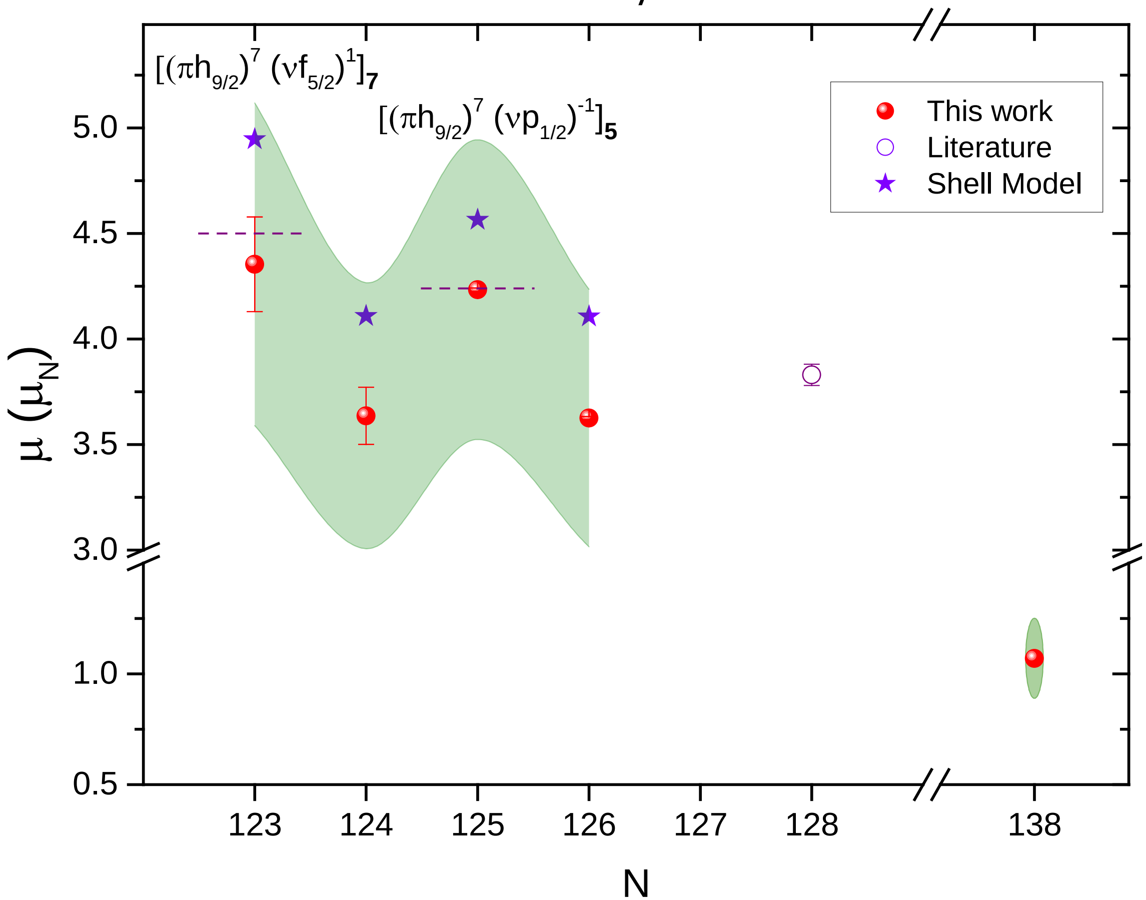




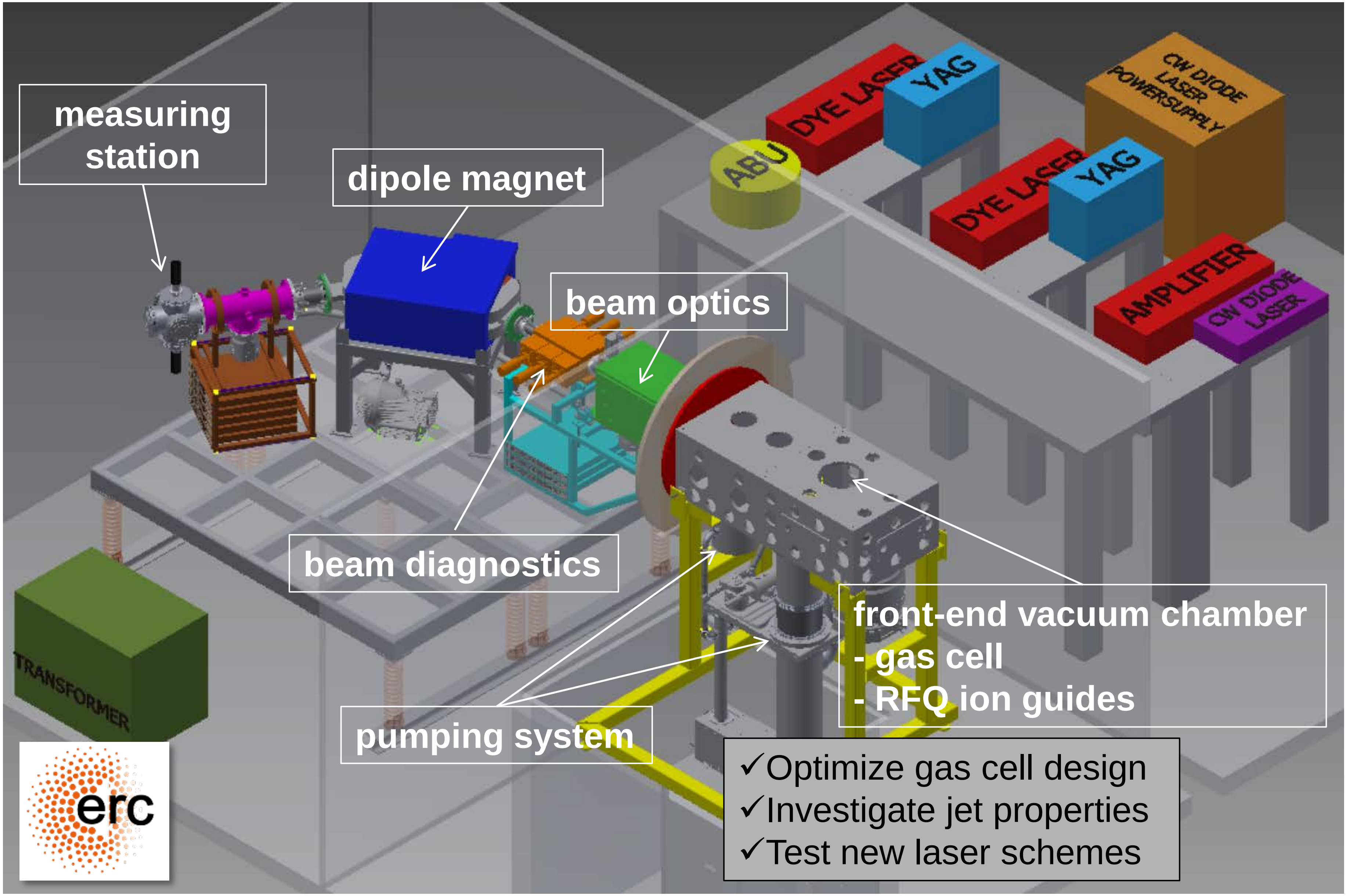
Fred,- Phys. Rev. 98 (1955)	MCDF calculations + experimental data on ^{227}Ac
$\mu_{lit.} = 1.1(1)\ \mu_N$	$\mu_{calc.} = 1.07(18)\ \mu_N$
$Q_{lit.} = 1.7(2)$ eb	$Q_{calc.} = 1.74(10)$ eb

Magnetic dipole moments and electical quadrupole moments

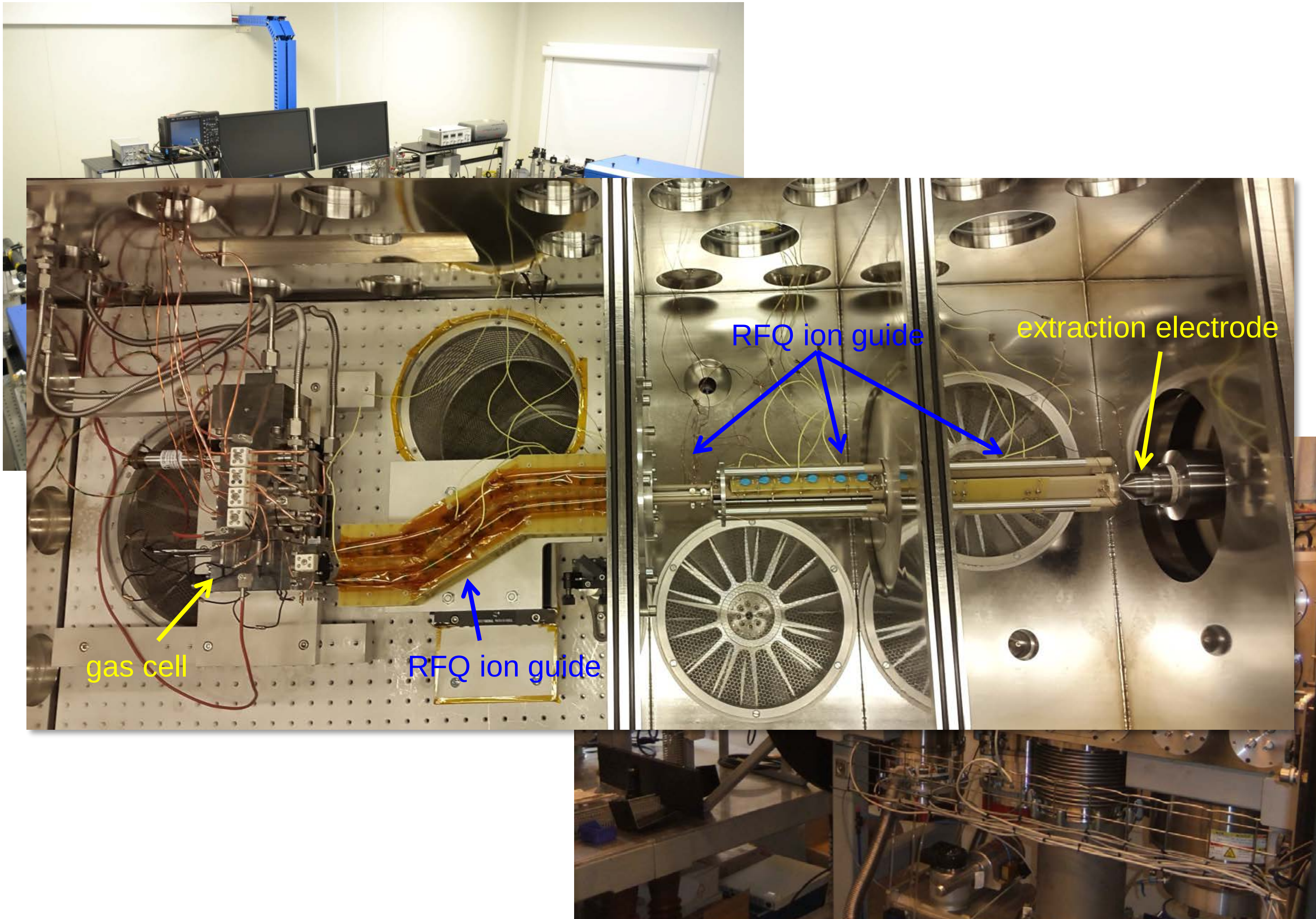
$$\mu^{exp.} = \frac{A^{exp} \cdot I^{exp}}{A^{227} \cdot 3/2} \cdot \mu^{227}_{calc.}$$



- Shell model calc. are in good agreement with experimental quadrupole moments (using atom. physics input) and magnetic dipole moments
- ^{208}Pb good core for shell model predictions (N=126)

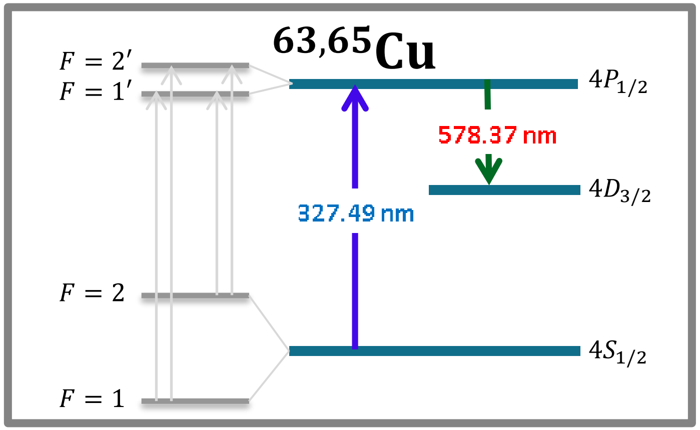


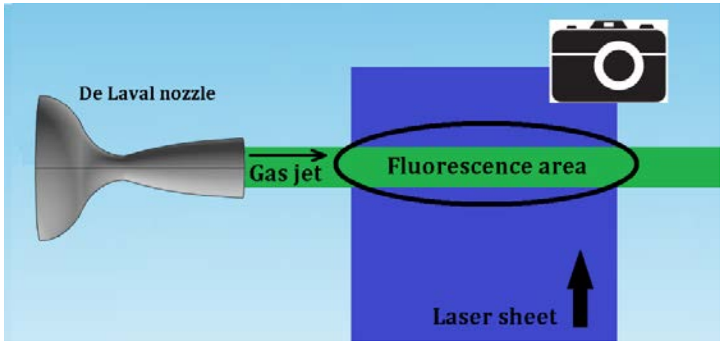
✓Optimize gas cell design
✓Investigate jet properties
✓Test new laser schemes

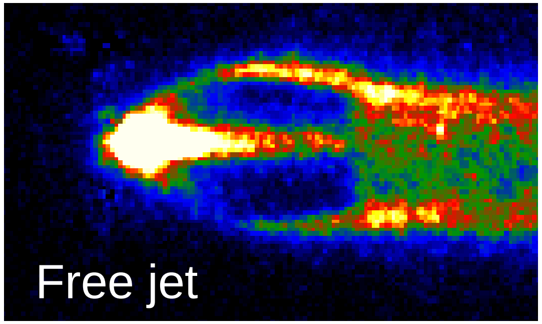

RFQ ion guide
extraction electrode
gas cell
RFQ ion guide

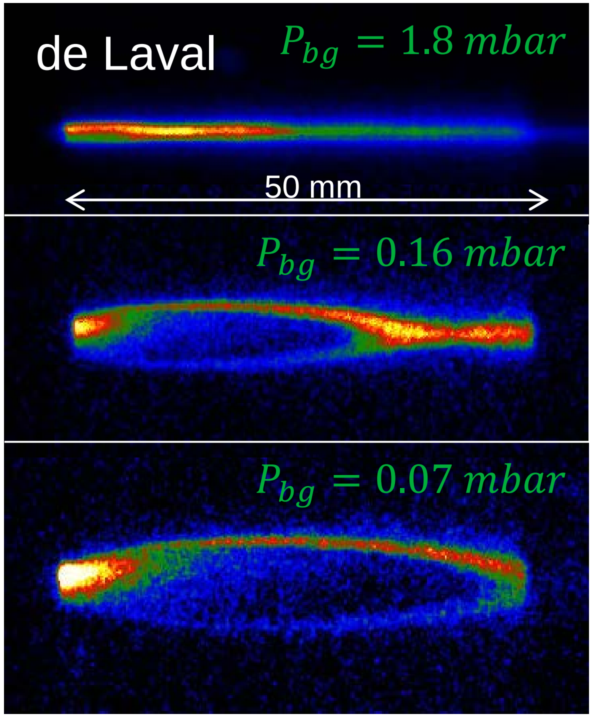
- Planar Laser Induced Fluorescence (PLIF) - technique

→ *temperature, velocity and density jet 'maps'*









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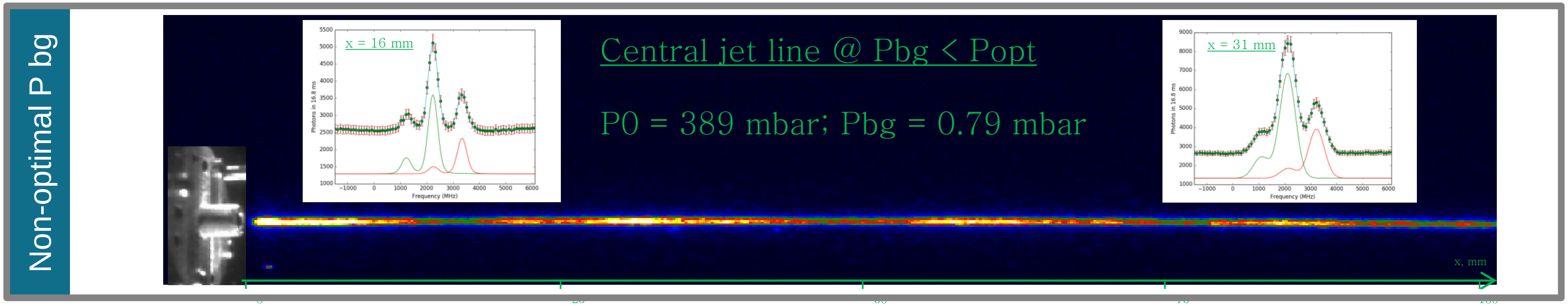
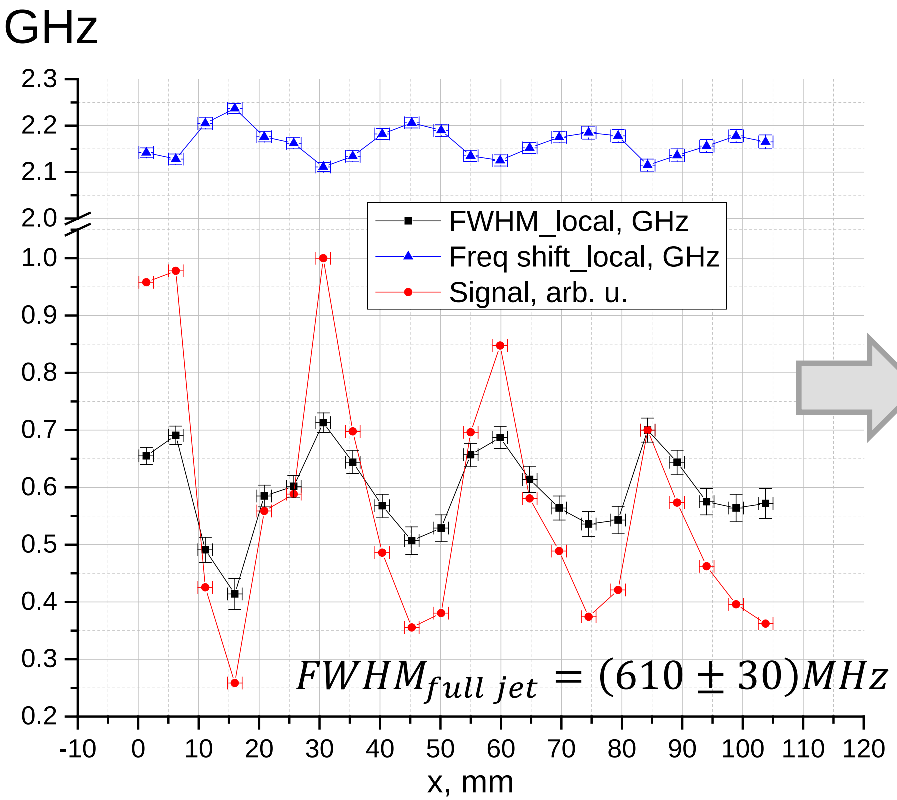
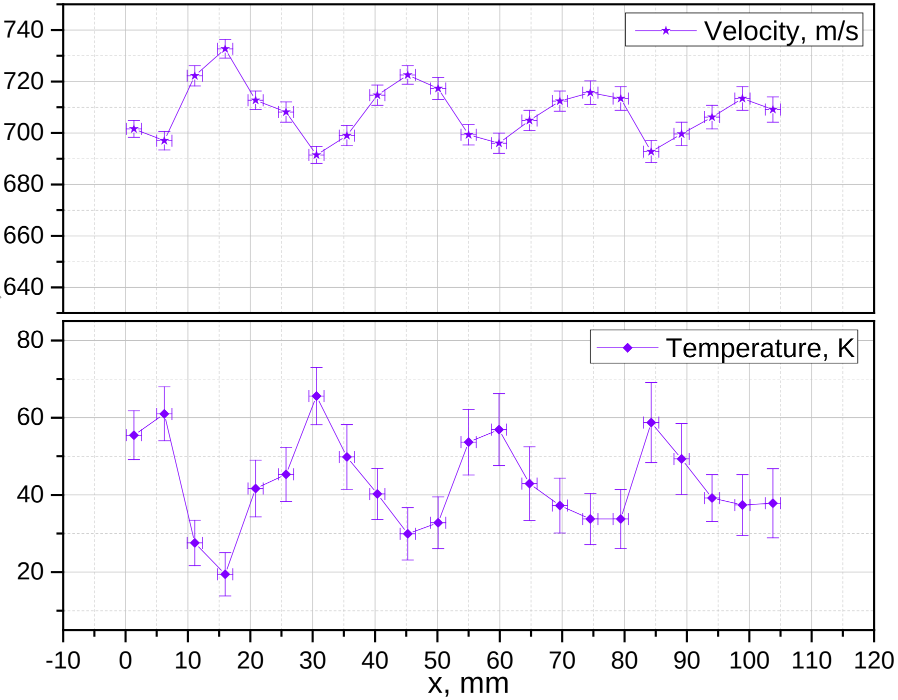
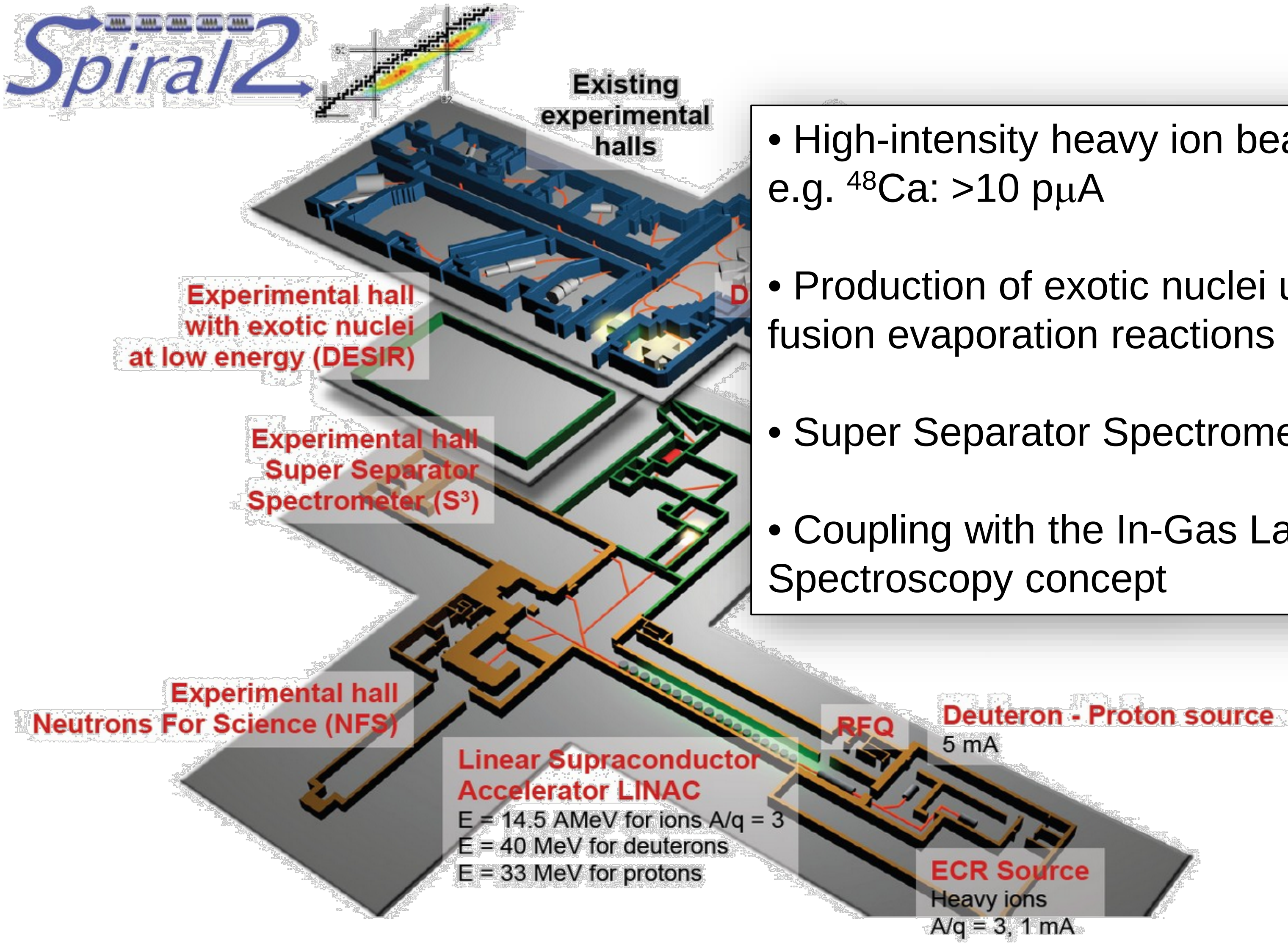
• ‘de Laval’ nozzle: Mach 5→ v and T jet ‘maps’







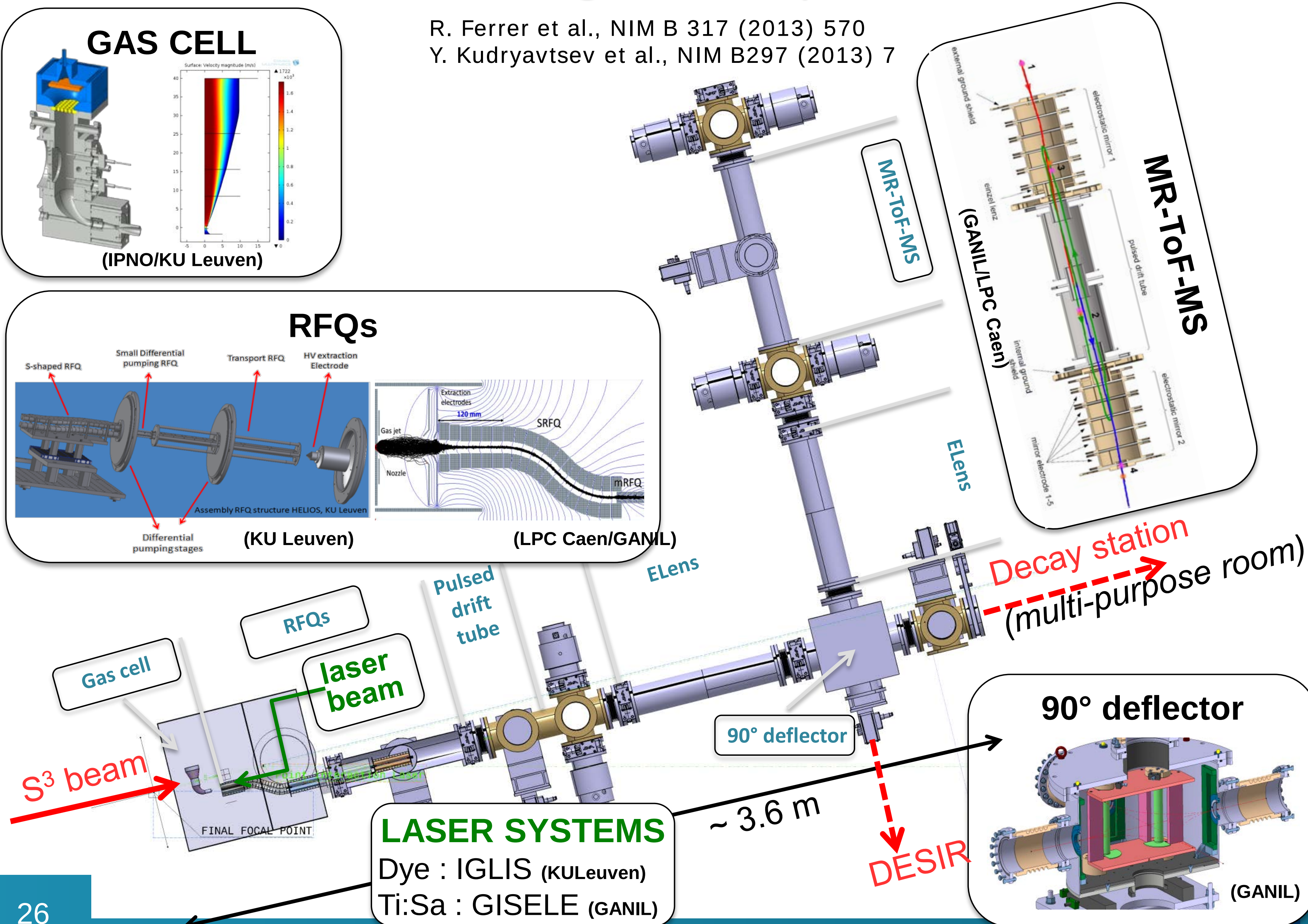
IGLIS @ S3LEB - SPIRAL2 - GANIL



- High-intensity heavy ion beams: e.g. ^{48}Ca: >10 pμA
- Production of exotic nuclei using heavy-ion fusion evaporation reactions
- Super Separator Spectrometer: S3
- Coupling with the In-Gas Laser Ionization Spectroscopy concept

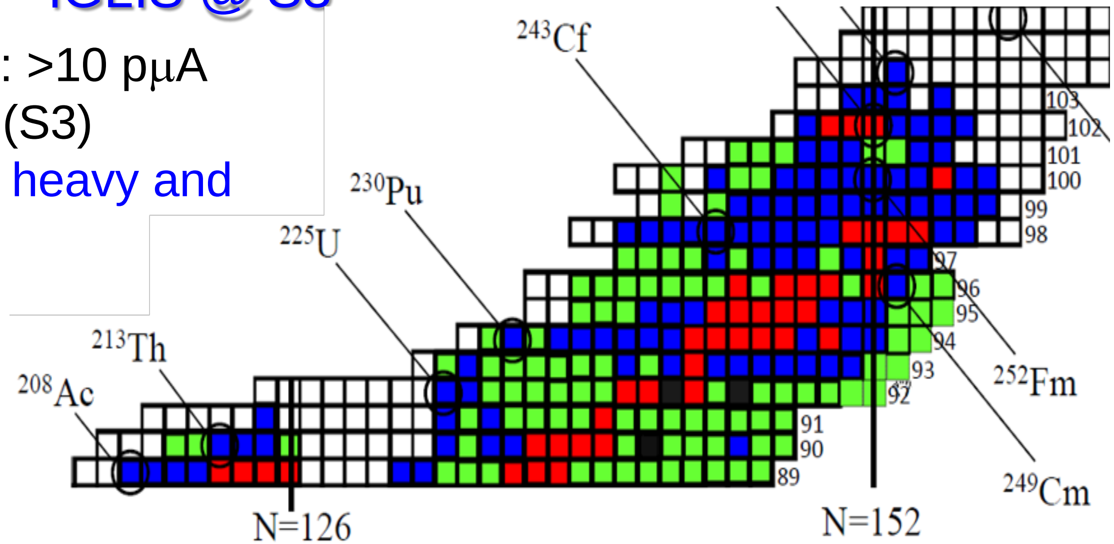
S³-LEB general layout

R. Ferrer et al., NIM B 317 (2013) 570
Y. Kudryavtsev et al., NIM B297 (2013) 7



IGLIS @ S3

- High intensity heavy-ion LINAC: >10 pμA
- Super Separator Spectrometer (S3)
- N=Z nuclei (towards ^{100}Sn) and heavy and Super Heavy Elements



Conclusion

- Shape coexistence in the neutron-deficient mercury isotopes
  - local phenomena
  - Monte Carlo Shell Model calculations: $\pi h_{9/2}$ and $\nu i_{13/2}$ orbitals

- In-gas jet Laser Ionization Spectrosopy
  - stability of the N=126 shell closure
  - improved spectral resolution and efficiency

- Exploration of the N=Z line and the heavy element region with the S3 – Low Energy Branch project at GANIL – SPIRAL2

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