Super Separator Spectrometer

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Resonant ionization spectroscopy of ^{94}Ag and neutron-deficient Sn isotopes

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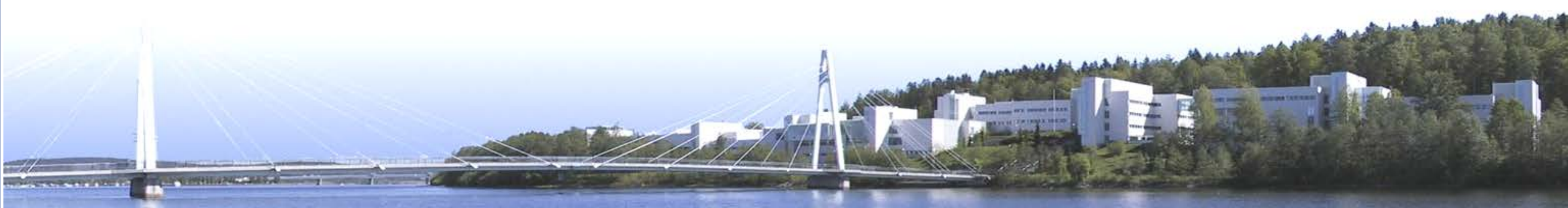
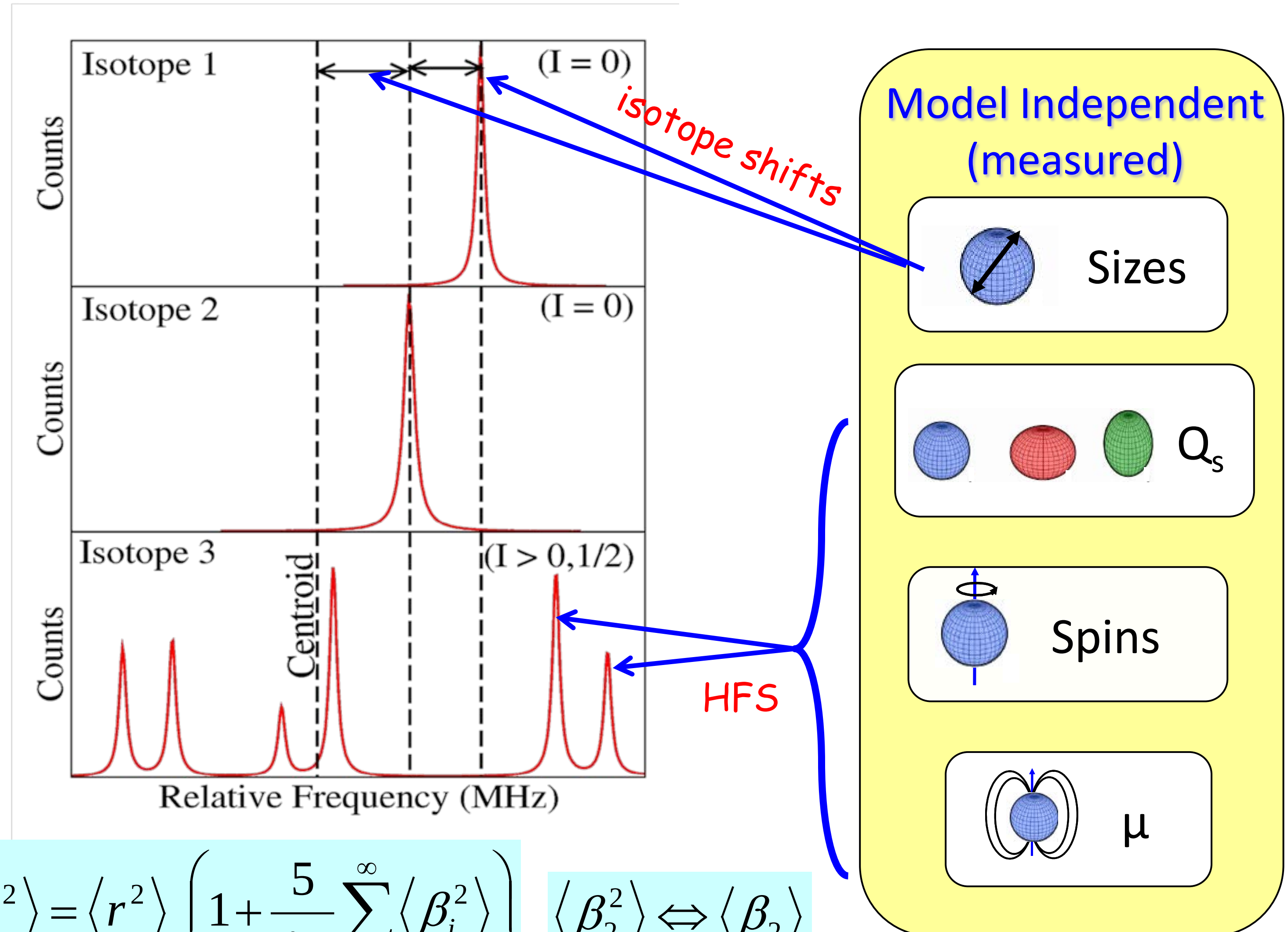


A nuclear fingerprint in the atomic levels



$$\langle r^2 \rangle = \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \sum_{i=2}^{\infty} \langle \beta_i^2 \rangle \right)$$

$$\langle \beta_2^2 \rangle \Leftrightarrow \langle \beta_2 \rangle$$

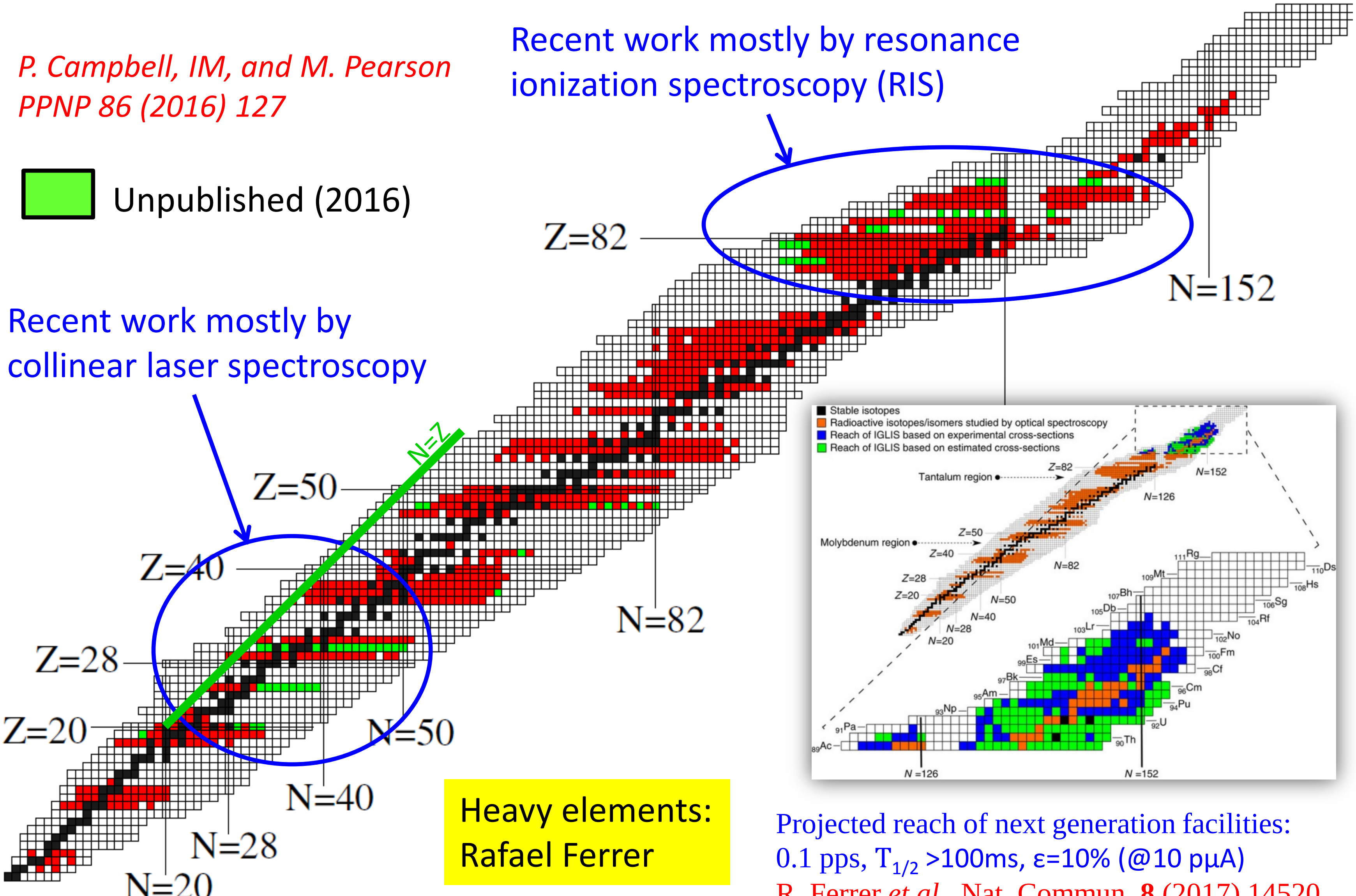
Laser spectroscopic (nuclear) landscape

P. Campbell, IM, and M. Pearson
PPNP 86 (2016) 127

Unpublished (2016)

Recent work mostly by resonance ionization spectroscopy (RIS)

Recent work mostly by collinear laser spectroscopy



Heavy elements: Rafael Ferrer

Projected reach of next generation facilities:
0.1 pps, $T_{1/2}$ >100ms, ε=10% (@10 pμA)
R. Ferrer *et al.*, Nat. Commun. **8** (2017) 14520

Selective resonant laser ionization

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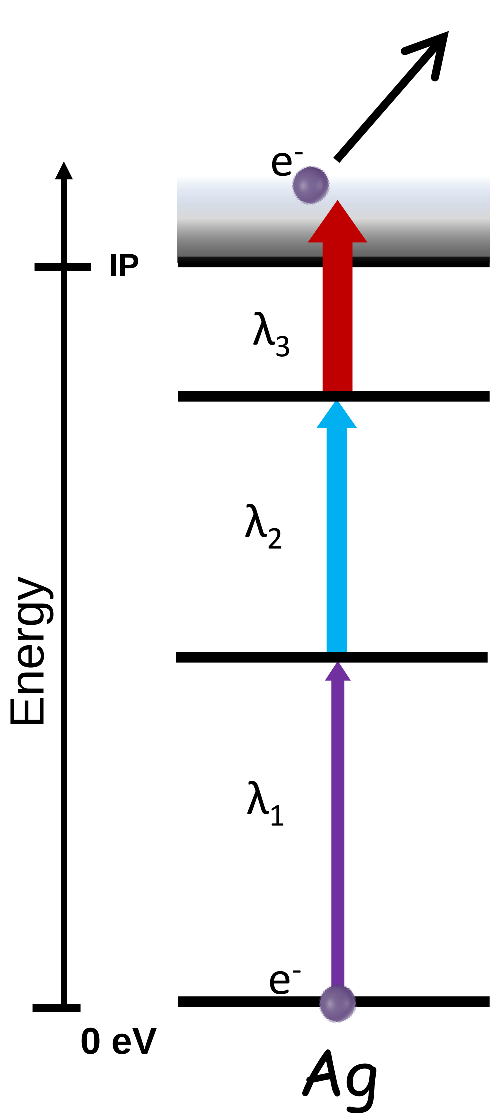

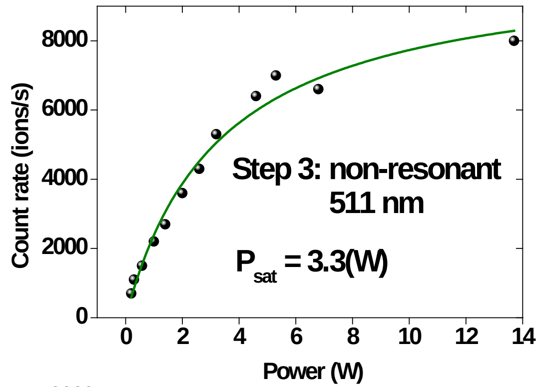

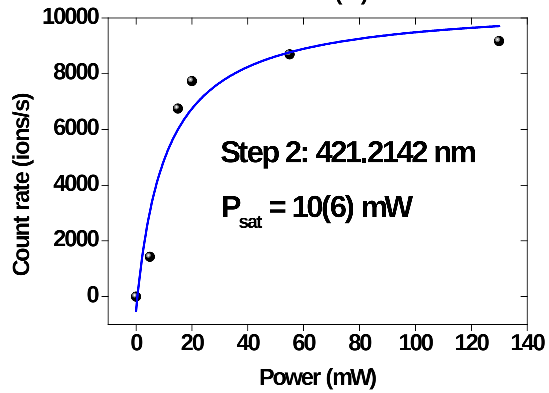

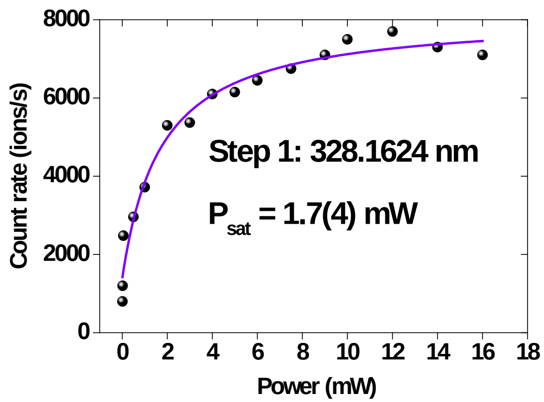

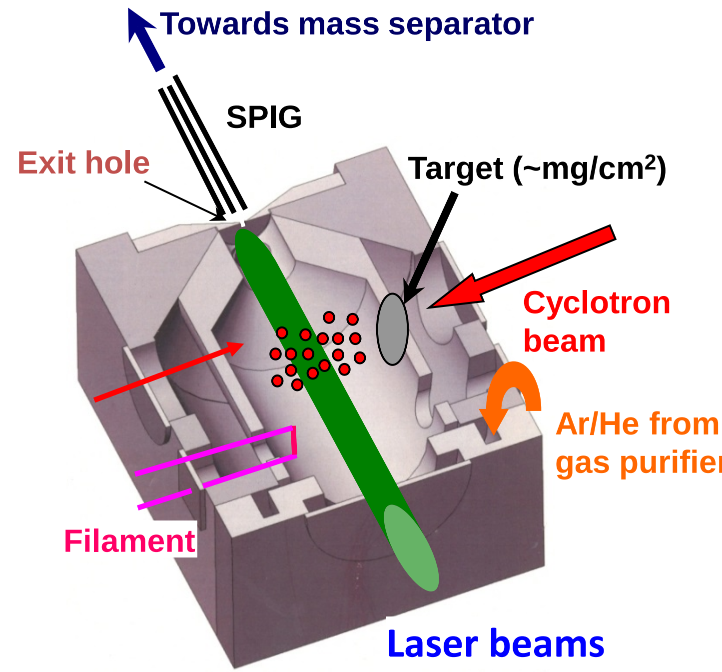

- ✓ Selective process
- ✓ Short lifetimes, low yields (<1 atom/s)
- ✓ High detection efficiency
- ✓ Poor resolution (100-1000× < collinear laser spectroscopy)

The study of $N=Z$ ^{94}Ag

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- Ground state (0^+), $T_{1/2}$ = 29 ms
- Low-spin (7^+) isomer, $T_{1/2}$ = 0.59(2)s
- High-spin (21^+) isomer, $T_{1/2}$ = 0.39(4)s

Schmidt et al., Z. Phys A (1994)
Commara et al., NPA (2002)
Mukha et al., PRC (2004), PRL (2005), Nature (2006)
Plettner et al., NPA (2004)

High-spin isomer (21^+):

- β decay (highest spin)
- β-delayed proton emission
- 1-proton decay
- Unexpected 2-proton decay

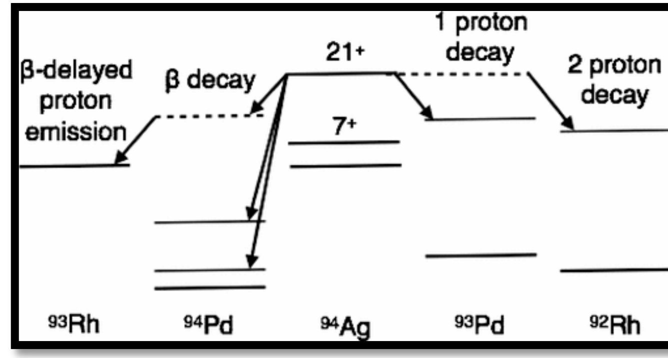
The conundrum:

- Non-observation of states in ^{92}Rh

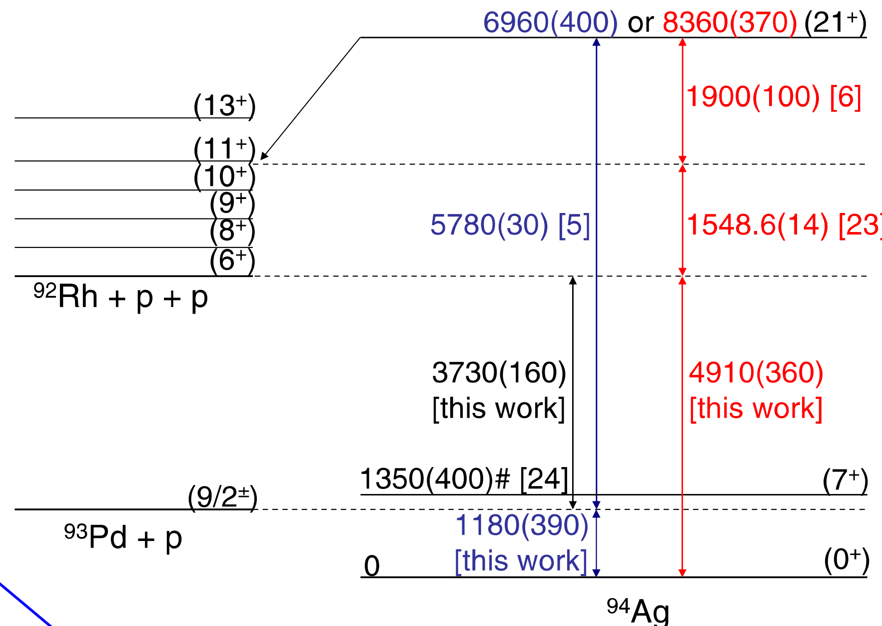
  Pechenya et al., PRC (2007)
- Contradiction from masses
- No sign of 2-proton decay

  Cerny et al., PRL (2009)
- Large-scale SM calculations do not accept large deformation picture

  Kaneko et al., PRC (2008)



1p sep energy & 1p decay **2p sep energy & 2p decay**



Kankainen *et al.*, PRL 101 (2008) 142503

In-gas-cell laser spectroscopy of Ag

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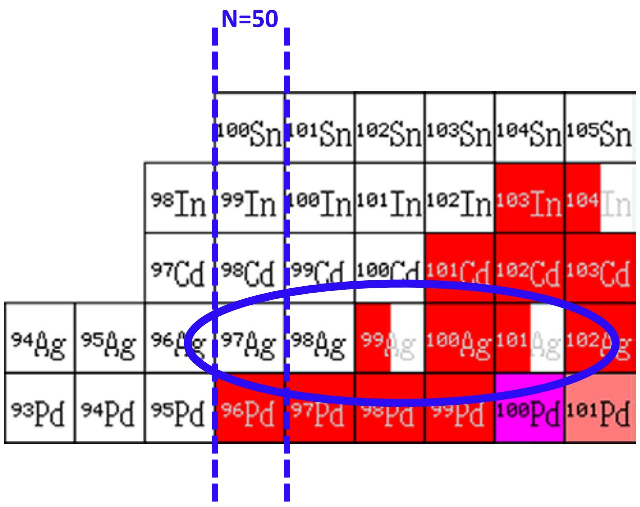
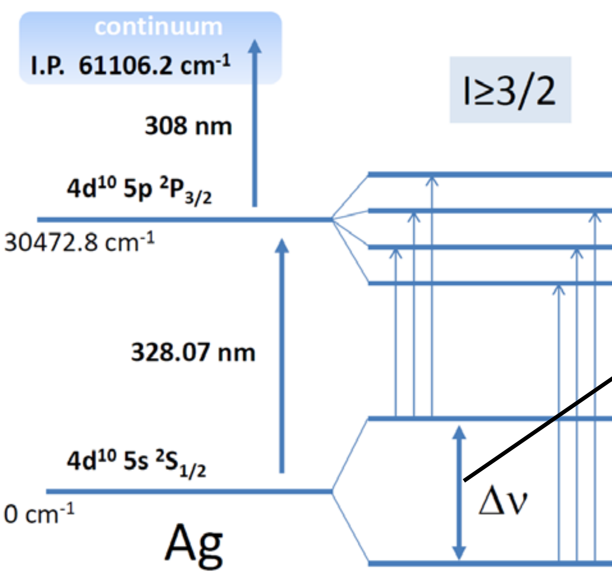
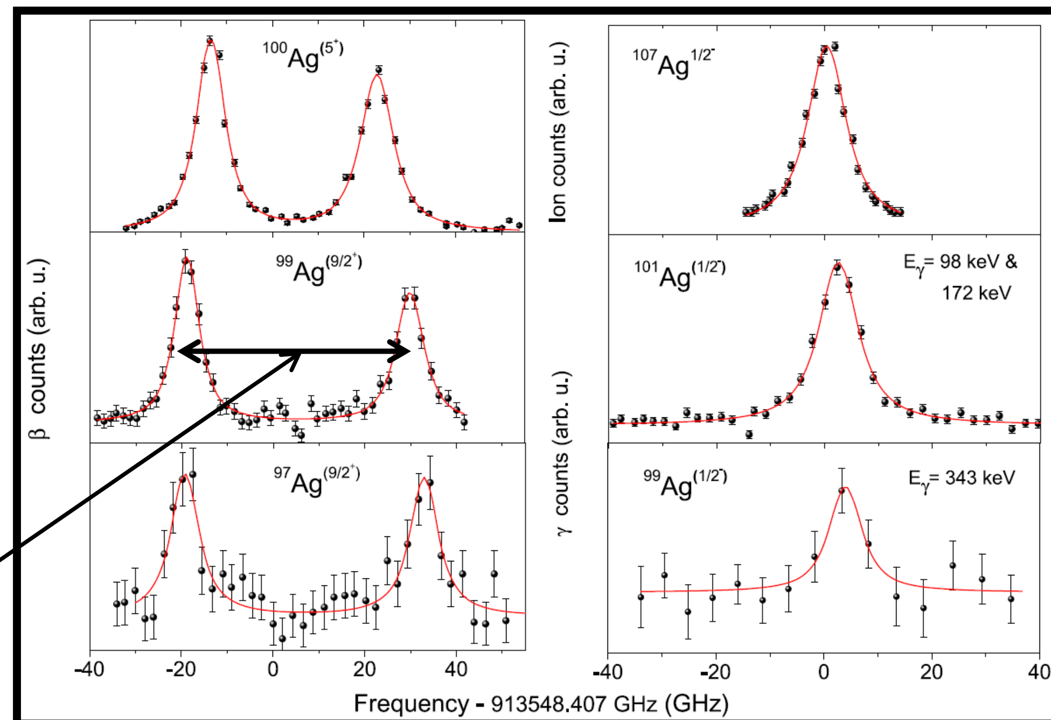


^{92}Mo(^{14}N – 130 MeV,2pxn)$^{104-x}$Ag
^{64,nat}Zn(^{36}Ar – 125 MeV,pxn)$^{101-x}$Ag

Count rates:
^{101}Ag = 2.3 pps
^{97}Ag = 0.9 pps

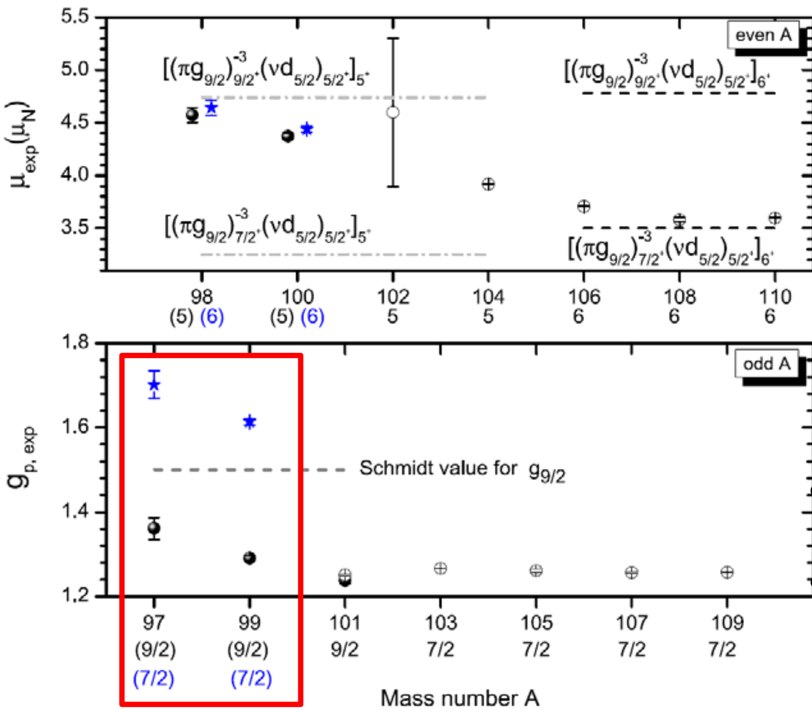
Overall ε_{total}~2%





R. Ferrer *et al*., Phys. Lett. B **728** (2014) 191

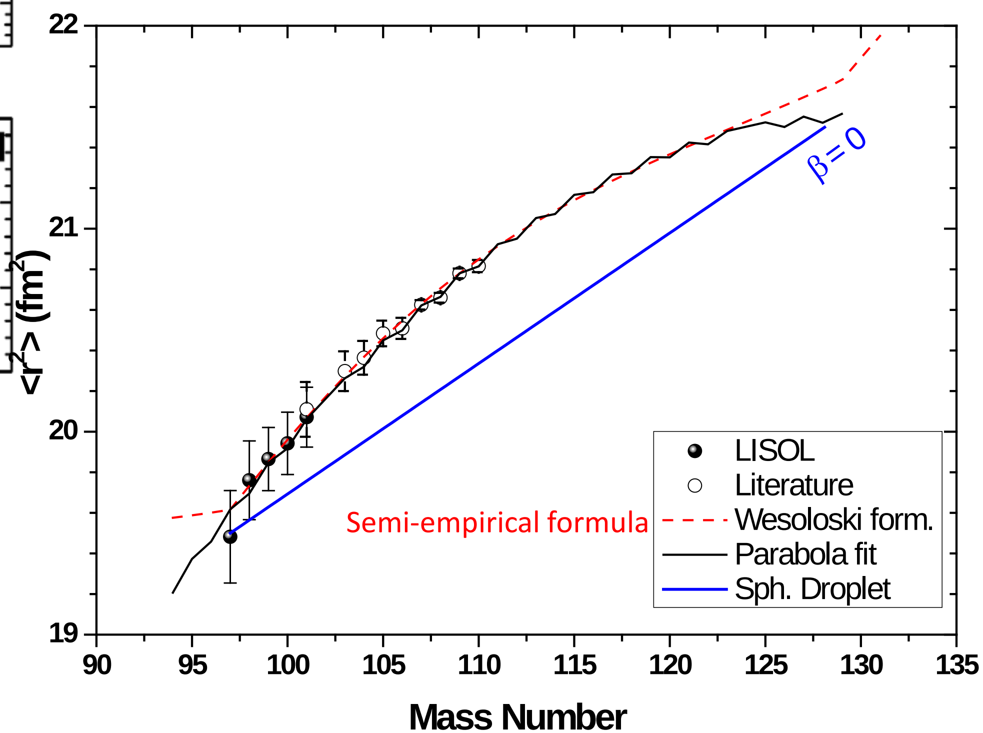
Results from the Ag data analysis



- Magnetic moments are a sensitive probe of configurations
- Tentative spin assignment of ^{97,99}Ag to 9/2 – approaching Schmidt value

R. Eder et al., PRC 31 (1985) 190
V. V. Golovko et al., PRC 81 (2010) 054323

- Mean charge radii show parabolic trend similar to isotopic chains of Cd, In and Sn
- In-gas cell results show trend towards spherical nuclear shape as predicted by droplet model



R. Ferrer *et al.*, Phys. Lett. B **728** (2014) 191

U. Dinger et al. NPA, 503 (1989) 331
W. Fischer et al. Z. Phys. A, 274 (1975) 79

The study of Sn isotopes

Darek, Lucia (^{100}Sn region)

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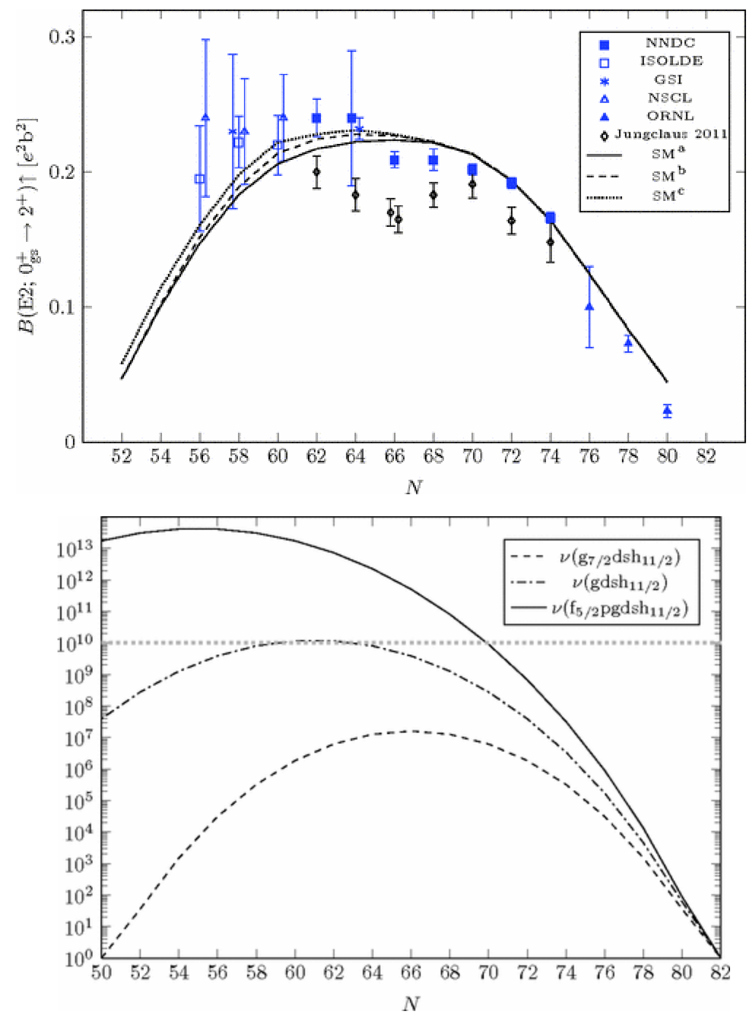
- Ideal laboratory for testing validity of shell model calculations
- Improving understanding of p-n interaction and related pairing effects (large spatial overlap between single-particle wavefunctions)
- Study evolution of *Z*=50 proton shell across a full neutron shell
- Study of beta decay/beta decay strengths (eg, "superallowed" GT decay in ^{100}Sn (Nature 2012)
- General astrophysical interest (rp process, X-ray burst light curves....)
- In-beam γ-ray, α-decay, lifetime measurements & Coulomb excitation
- Suggestion of enhanced B(E2) values as ^{100}Sn approached (strong correlation with deformation)



T. Bäck *et al.*, Phys. Rev. C **87** (2013) 031306

Mean-square charge radii (Ag to Sn)

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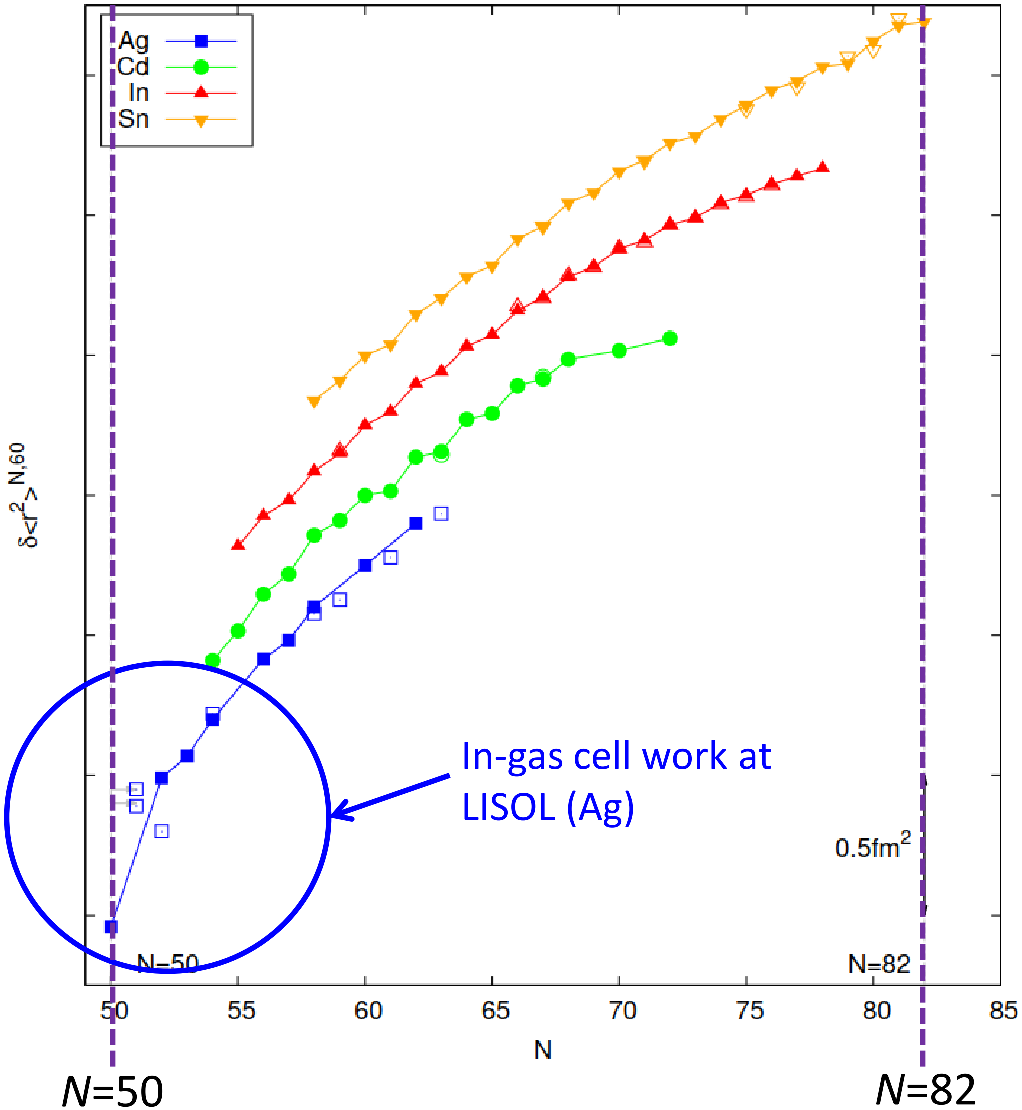

- Persistent and regular trends throughout the major shell (32 neutrons)
- Quadrupole contribution, proportional to product of particles and holes, with constant odd-even staggering, added to linearly increasing $<r^2>$
- Late d-shell systems are refractory, studies at exotic shell closures requires experimental sensitivity and selectivity beyond collinear laser spectroscopy

P. Campbell, IM, and M. Pearson PPNP 86 (2016) 127

A first attempt at spectroscopy of Sn

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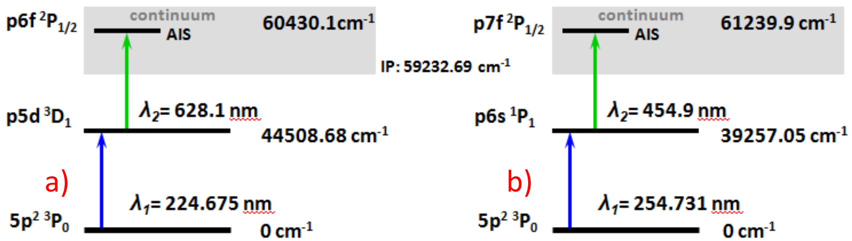
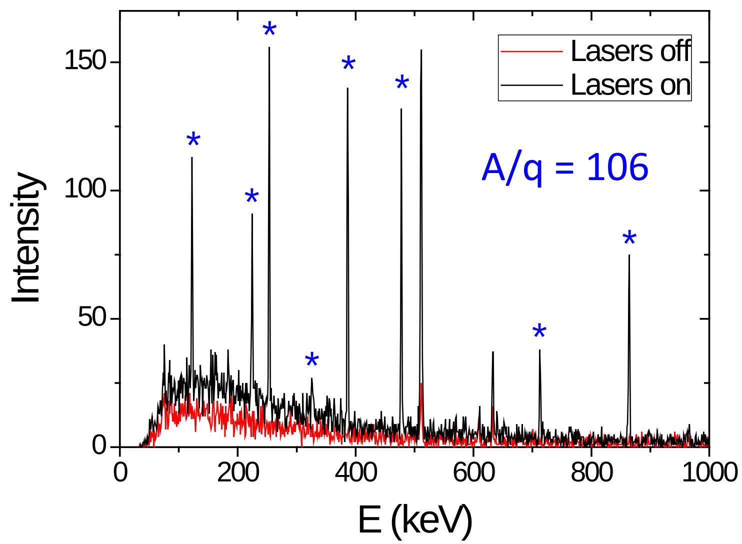


Scheme b)

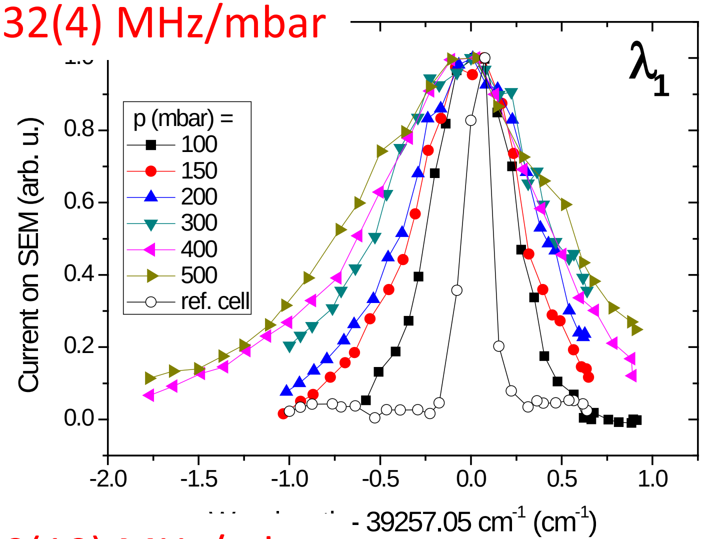
A. Nadeem et al., J. Phys. B 33 (2000) 3729.

^{92}Mo(^{16}O 100 MeV,2-3n)^{105,106}Sn

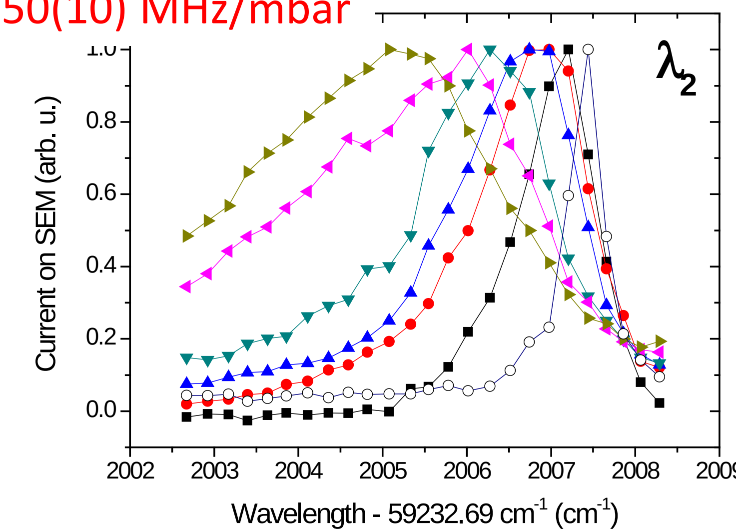
σ=3.7 mb for ^{106}Sn; **ε_{total} ~0.5%**



γ_{br} =32(4) MHz/mbar

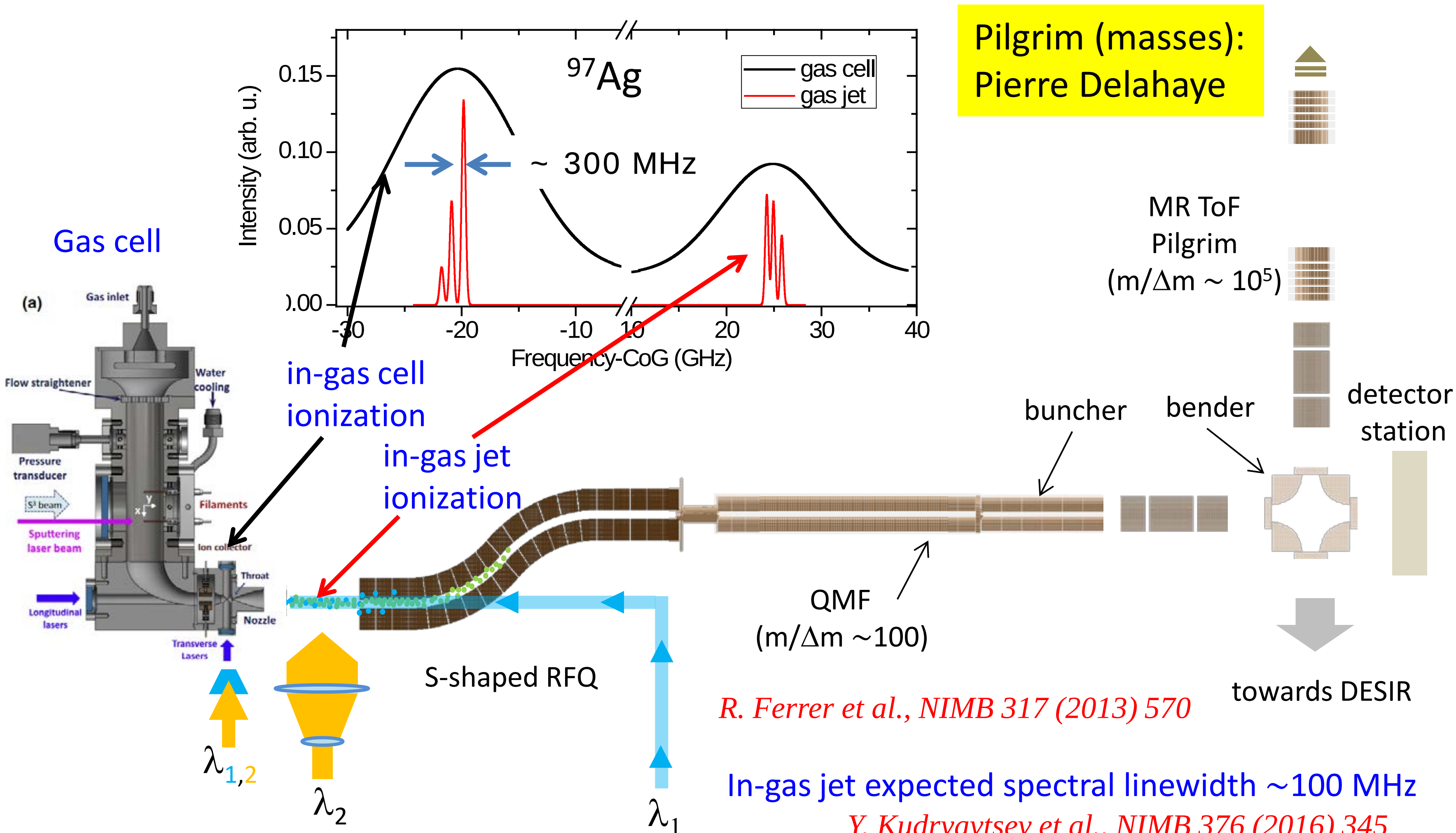


γ_{sh} = 150(10) MHz/mbar



R. Ferrer *et al.*, NIMB 317 (2013) 570

REGLIS³ @ SPIRAL2



R. Ferrer et al., NIMB 317 (2013) 570

In-gas jet expected spectral linewidth ~100 MHz

Y. Kudryavtsev et al., NIMB 376 (2016) 345

Expected efficiencies of REGLIS

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Process	Efficiency (%)
Transmission through S^3	50
Thermalisation, diffusion and gas cell transport	50
Neutralisation	50
In-gas jet laser ionization	50
Transport efficiency	80
Overall performance	**5 (”realistic” estimate)**

R. Ferrer *et al.*, NIMB 317 (2013) 570

In the following, please note:

- decay losses assumed to be negligible (optimization of gas cell in particular cases)
- Significant neutralization should be possible (due to in-flight cocktail)
- Additional neutralization to be studied (eg. beta source in gas cell, could be done at MARA)
- Conservative selectivity of 1000 (LoI assumes 10000, ^{215}Ac Nature Comm. paper projects >3000)

^{94}Ag & ^{105}Sn - expected rates (LoI uPdated)

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- ^{58}Ni(^{40}Ca – 4.78 MeV/nucl, p3n)^{94}Ag
- Assume >1 pμA of $^{40}Ca^{14+}$(**factor of 10 < LoI**), 500 μg/cm^2 enriched ^{58}Ni foil
- Estimated cross section (experimental & GSI HIVAP code)

Nucleus	Estimated σ	Half-life (ms)	Production (at/μC)	S3 image 4 focal plane (pps)	Detected ions (pps) after transport
^{94}Ag (J^π=21$^+$)	71 nb	590	0.009	0.6	**0.06 (need A/Q = 7)**
^{94}Ag (J^π=7$^+$)	579 nb	390	0.072	5	**0.5**
^{94}Pd	400 μb		460	3.2×10^4	26
^{94}Rh	4 mb		4600	3.2×10^5	256
^{94}Ru	40 mb		46000	3.2×10^6	2560

- High intensity(>1 pμA) of $^{58}Ni^{18+}$between 3.6 and 4.34 MeV/u on 500 μg/cm^2 enriched foils of ^{48}Ti and ^{50}Ti

Nucleus	Estimated σ (mb)	Half-life (s)	Production (at/μC)	S3 image 4 focal plane (pps)	Detected ions (pps) after transport
^{101}Sn	~10 nb*	1.7		0.2	**0.02 (need A/Q = 7)**
^{105}Sn	1.16	34	1.21×10^2	1.09×10^3	**100**
^{105}In	34		3.57×10^4	3.21×10^5	250
^{105}Cd	100		1.04×10^5	9.40×10^5	750

*La Commara et al., NPA 669 (2000) 43, ^{58}Ni(^{50}Cr,α3n)^{101}Sn

Summary

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- The Low Energy Branch at S^3 will provide a unique opportunity for the study of neutron deficient Sn isotopes and to solve the conudrum of the unique case of ^{94}Ag
- In-gas cell and in-gas jet spectroscopy with provide access to fundamental nuclear structure properties: I, μ, Q_s and $\delta\langle r^2\rangle$
- Isomerically enriched low-energy beams (eg of ^{94}Ag) may be sent to a decay spectroscopy station for further studies, or to the MR-TOF, Pilgrim, (several MeV between 7^+ and 21^+ isomeric states) for mass measurement
- High-resolution RIS for actinides (talk by R. Ferrer)
- ^{80}Zr and related isotopes of interest. Needs gas cell facilities due to refractory nature (study of shape coexistence, shape changes)

REGLIS @ S3

Participants for ^{94}Ag and Sn (LoIs)

The LISOL group at IKS KU Leuven
GANIL
IPN Orsay
JYFL
RIKEN