



Laser spectroscopy studies at Jyväskylä

Iain Moore
Department of Physics,
University of Jyväskylä, Finland

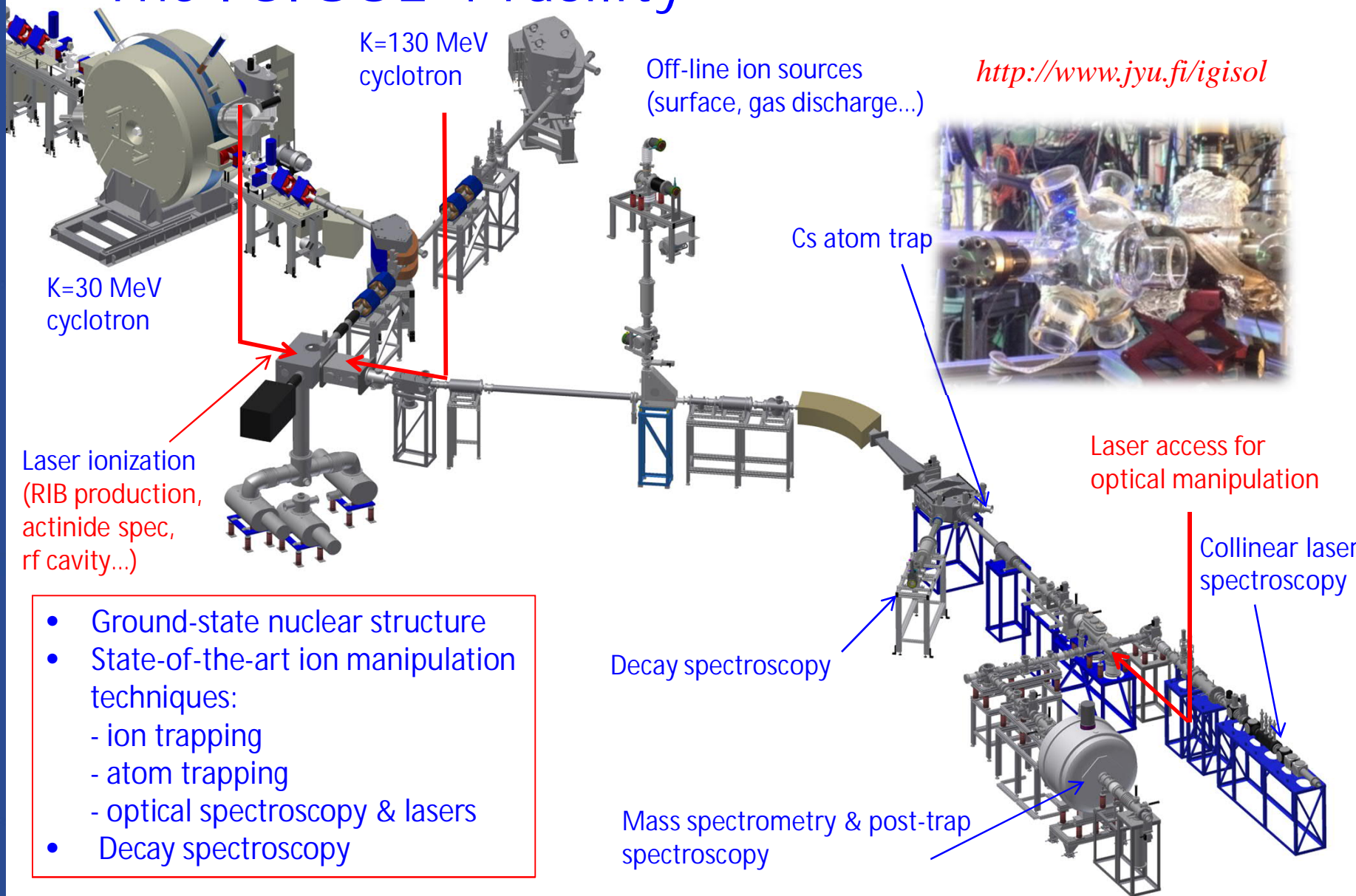
Outline

- The IGISOL facility – a short introduction
- Recent results:
 - ❖ Shape coexistence in the $A=100$ region
 - ❖ Collinear laser spectroscopy of neutron-rich Pd and Ag
 - ❖ In-source resonance ionization of neutron-deficient Ag
- Future prospects
 - ❖ Towards the light actinides
 - ❖ (RAPTOR/MORA/MARA-LEB/RF spectroscopy...lots of fun developments!)



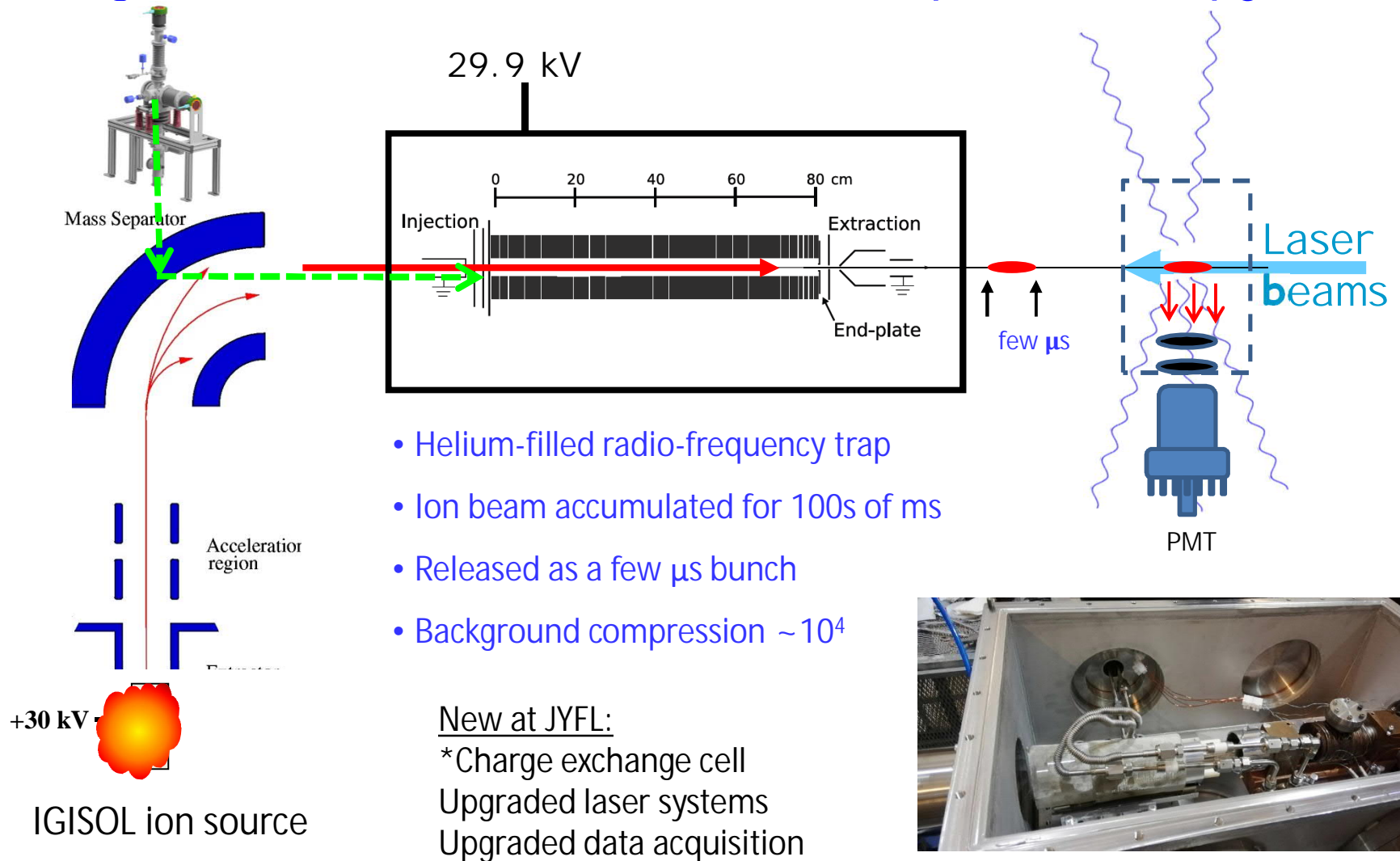


The IGI SOL-4 facility



- Ground-state nuclear structure
- State-of-the-art ion manipulation techniques:
 - ion trapping
 - atom trapping
 - optical spectroscopy & lasers
- Decay spectroscopy

High resolution collinear laser spectroscopy

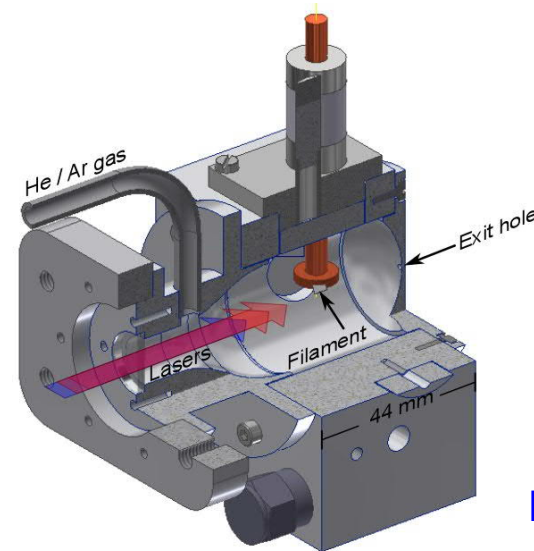
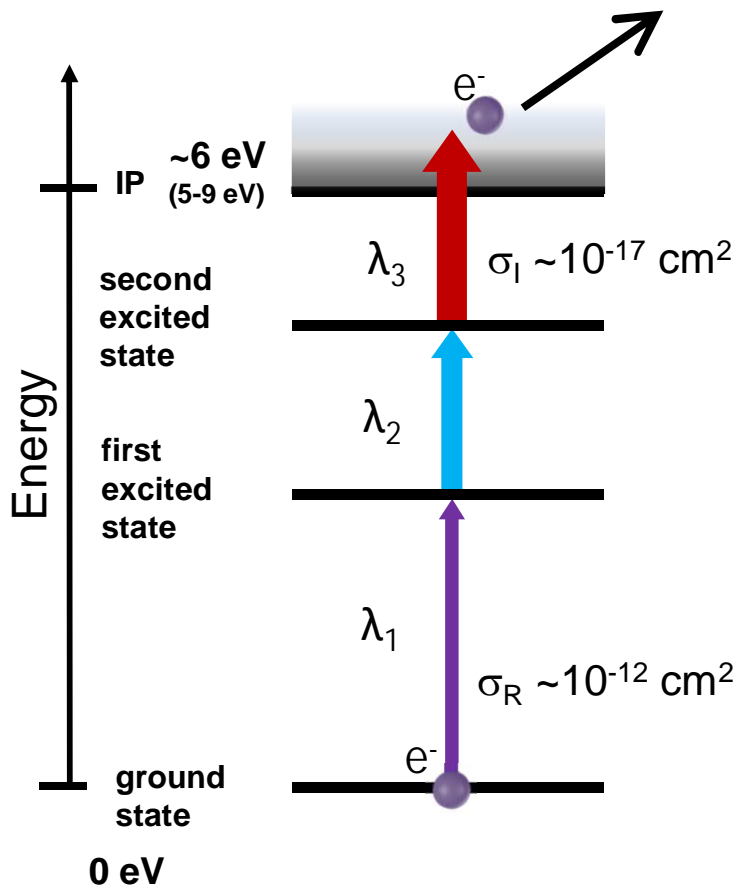


R.P. de Groote, et al., NIMB, <https://doi.org/10.1016/j.nimb.2019.04.028>

*Thanks to W. Noertershauser + team

L.J. Vormawah, M. Vilén et al., Phys. Rev. A 97 (2018) 042504

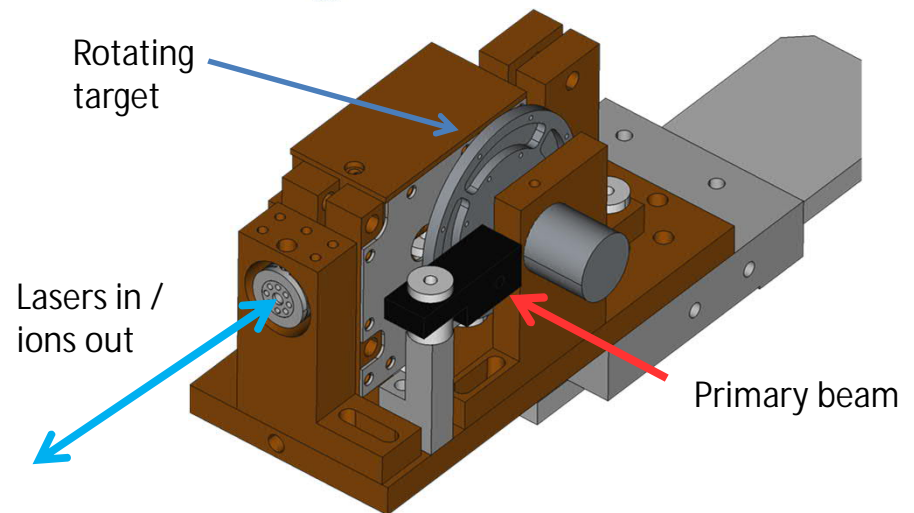
In-source resonance ionization spectroscopy



A variety of gas cell geometries:

- dual-chamber
- actinide (filaments)
- MARA-LEB (S^3 -LEB)

RF heated hot cavity

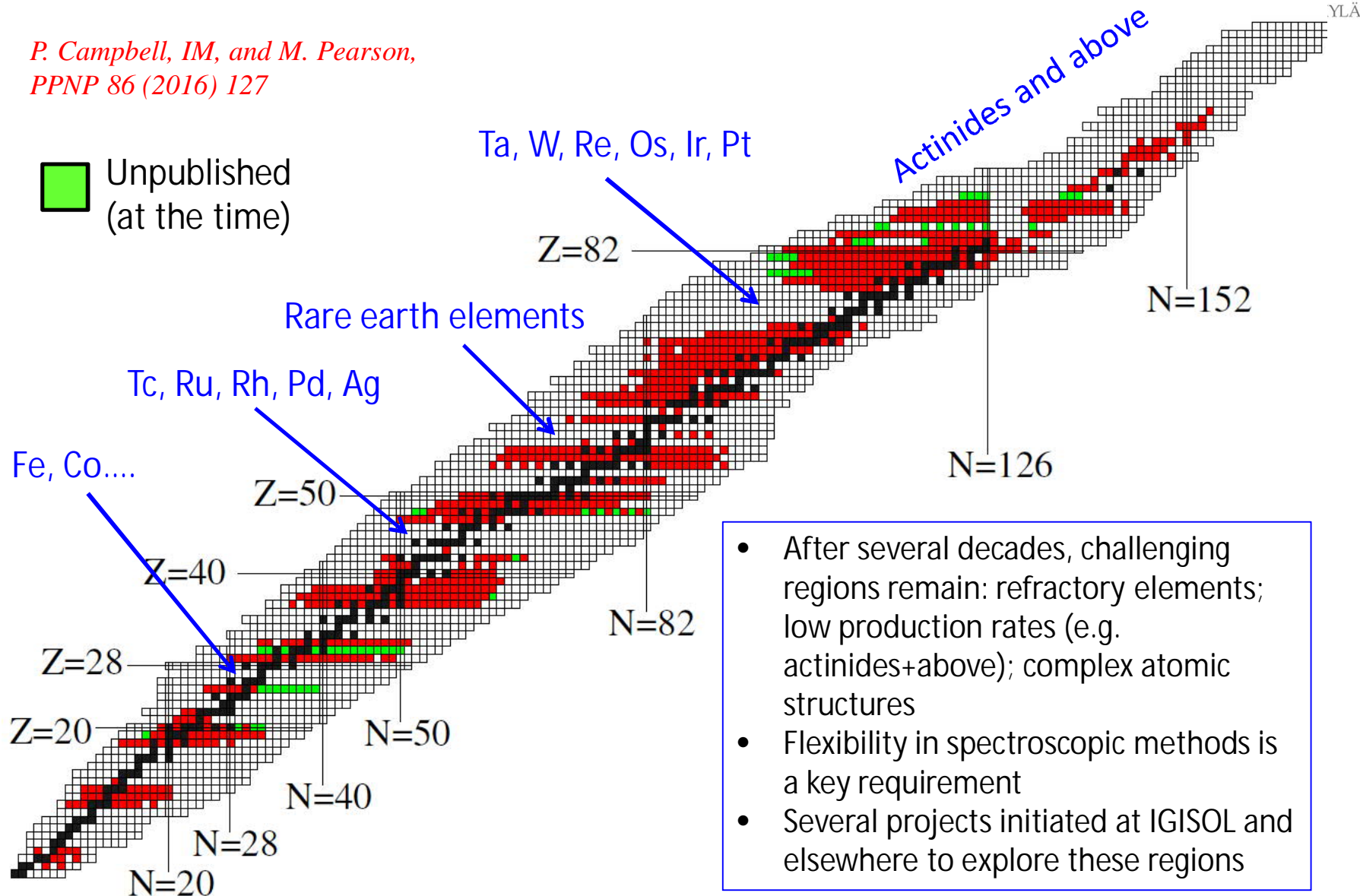


A selective and efficient spectroscopic method. Combine with mass separator (+ Penning trap!). Shorter lifetimes achievable. Lower resolution wrt collinear alleviated by in-gas jet method.

A laser spectroscopists' nuclear landscape



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



Probing the nuclear size (and shape!)

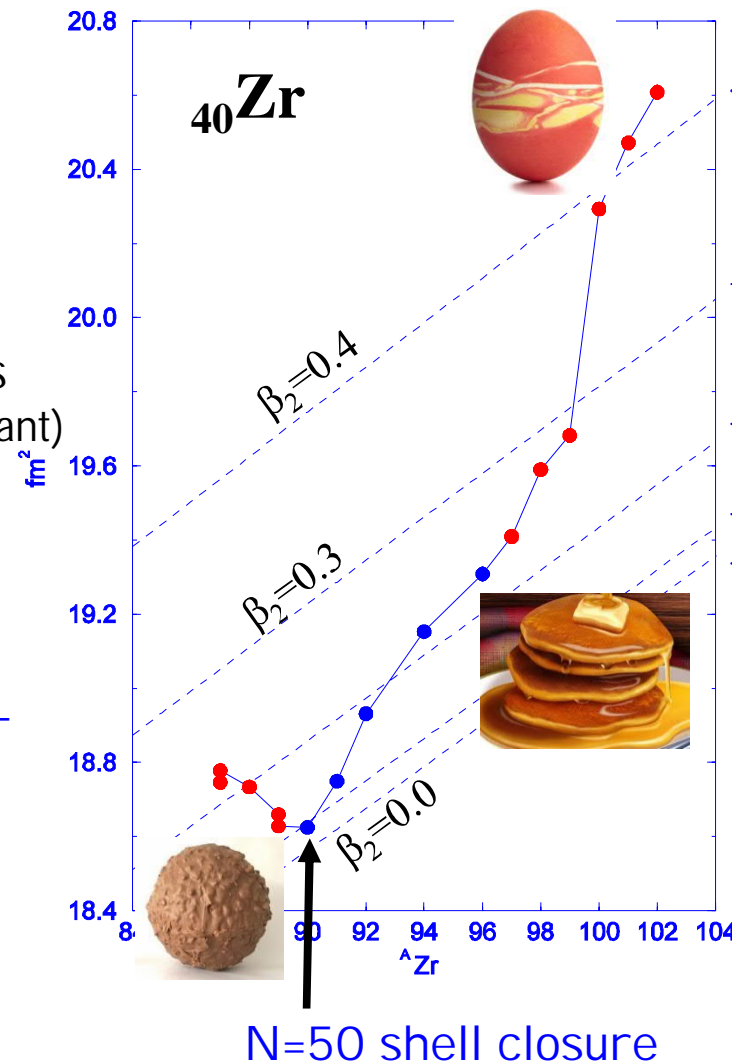
What can the charge radii tell us?

$$\langle r^2 \rangle = \langle r^2 \rangle_{sph} \left(1 + \frac{5}{4\pi} \langle \beta_2^2 \rangle + \dots \right) + 3\sigma^2$$

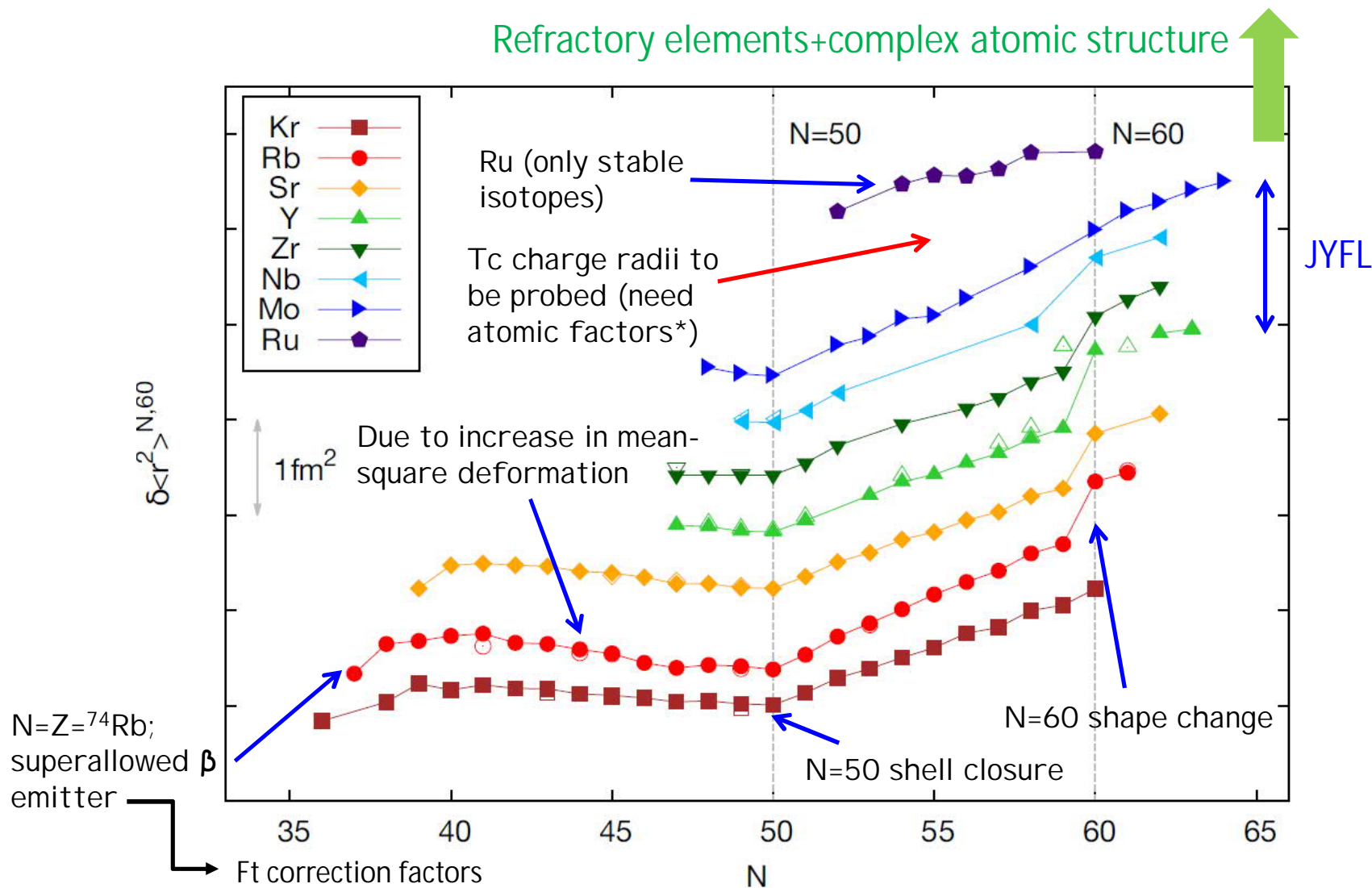
Size (droplet model)
Shape (Quadrupole term)
Diffuseness (assumed constant)

Comments/points for discussion:

- Dependence on higher order terms (deformations).
- Rigidity vs softness – comparison between charge radii and extrapolation from quadrupole moments – e.g. yttrium
- Is the conversion from Q_0 (intrinsic) to Q_s (spectroscopic) valid? Only if we have a rigid axial quadrupole deformation.
- Triaxiality? Can this be teased out from the charge radii? Is there a “smoking gun” for ground state properties?



Charge radii systematics near Zr

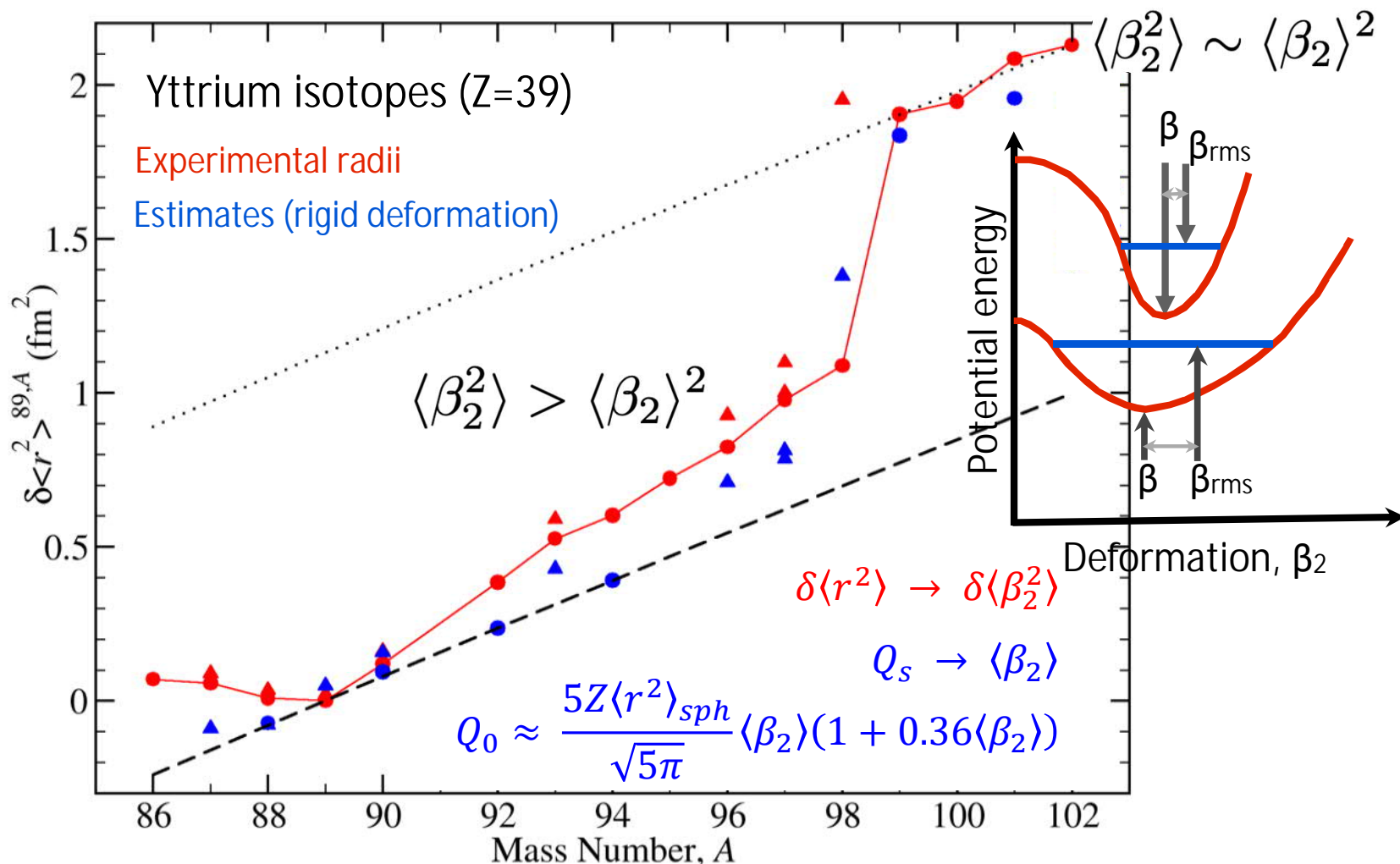


*S. Raeder et al., *Hyp. Int.* 238 (2017) 15



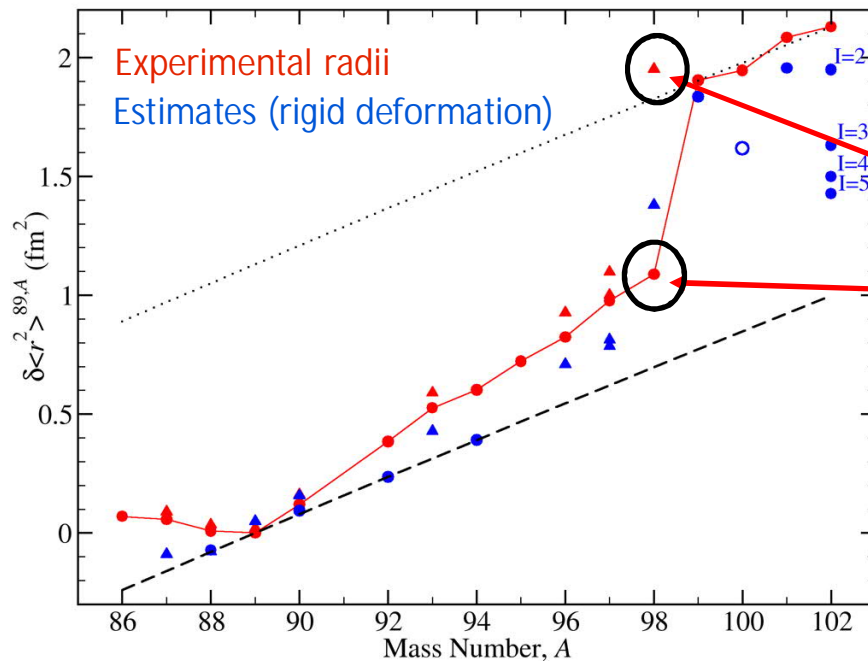
“Softness” vs “rigidity” in deformation

Comparison of estimates from quadrupole moments with results from charge radii.



B. Cheal et al., Phys. Lett. B 645 (2007) 133.

Shape coexistence in ^{98}Y



B. Cheal et al., Phys. Lett. B 645 (2007) 133.

^{98}Y isomer ($T_{1/2} = 2.36 \text{ s}$; $E_{\text{exc}} = 465.7(7) \text{ keV}$ from JYFLTRAP)

^{98}Y ground state, $I=0$ ($T_{1/2} = 0.548 \text{ s}$)

- Largest deformation of all Y isotopes
- Earlier laser spectroscopy used $J=0 \rightarrow J'=1$ transition (limited sensitivity to nuclear spin)
- Tentative spin $I = (4,5)$
- New decay spectroscopy data indicates possible $I = (6,7)^+$
- Role of $9/2^+[404]$ neutron extruder orbital in odd-odd nucleus to explain large deformation

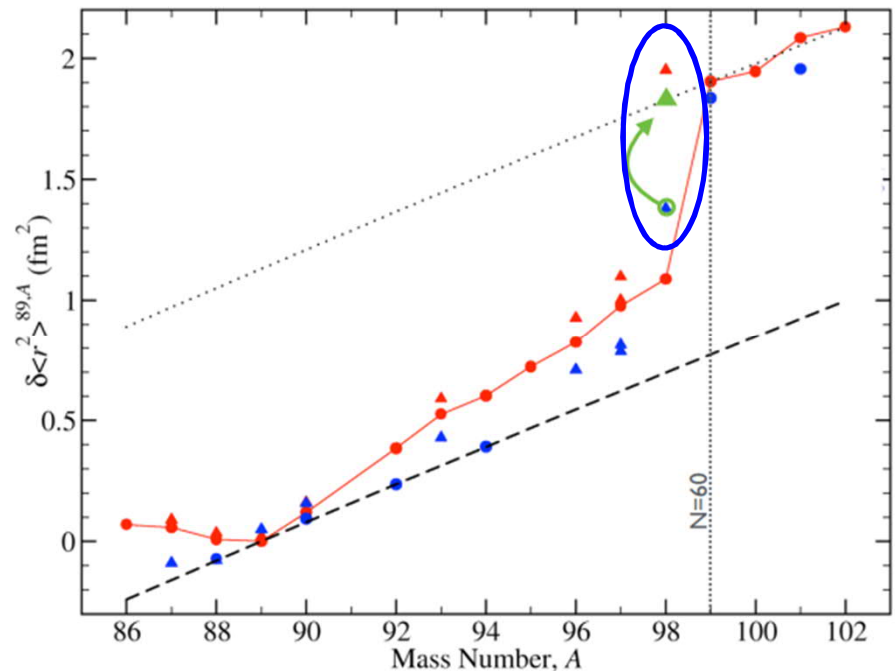
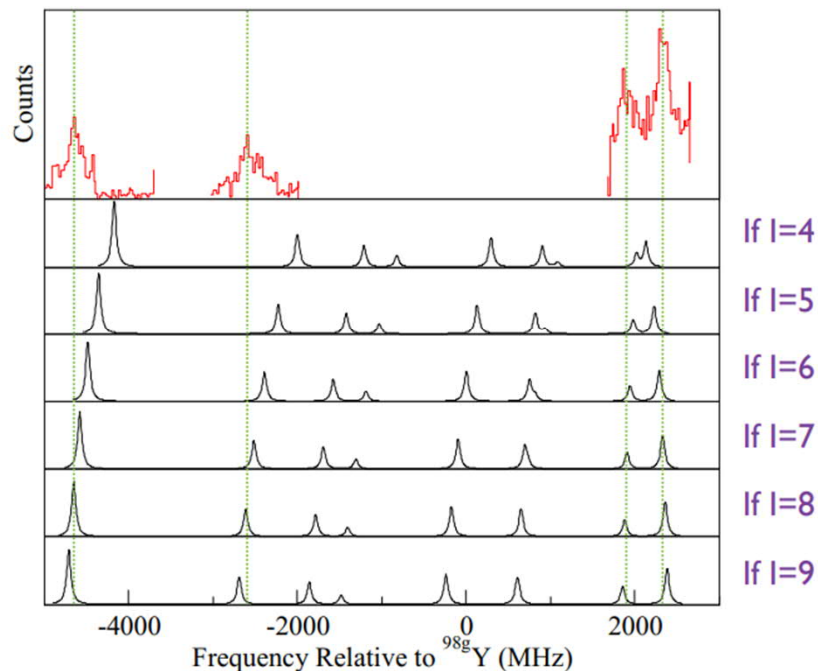
PHYSICAL REVIEW C **96**, 044333 (2017)

Shape coexistence in the odd-odd nucleus ^{98}Y : The role of the $g_{9/2}$ neutron extruder

W. Urban,¹ M. Czerwiński,¹ J. Kurpeta,¹ T. Rząca-Urban,¹ J. Wiśniewski,¹ T. Materna,² Ł. W. Iskra,³ A. G. Smith,⁴ I. Ahmad,⁵ A. Blanc,⁶ H. Faust,⁶ U. Köster,⁶ M. Jentschel,⁶ P. Mutti,⁶ T. Soldner,⁶ G. S. Simpson,⁷ J. A. Pinston,⁷ G. de France,⁸ C. A. Ur,⁹ V.-V. Elomaa,¹⁰ T. Eronen,¹⁰ J. Hakala,¹⁰ A. Jokinen,¹⁰ A. Kankainen,¹⁰ I. D. Moore,¹⁰ J. Rissanen,¹⁰ A. Saastamoinen,¹⁰ J. Szerypo,¹⁰ C. Weber,¹⁰ and J. Äystö¹⁰

Re-visiting ^{98}Y with optical spectroscopy

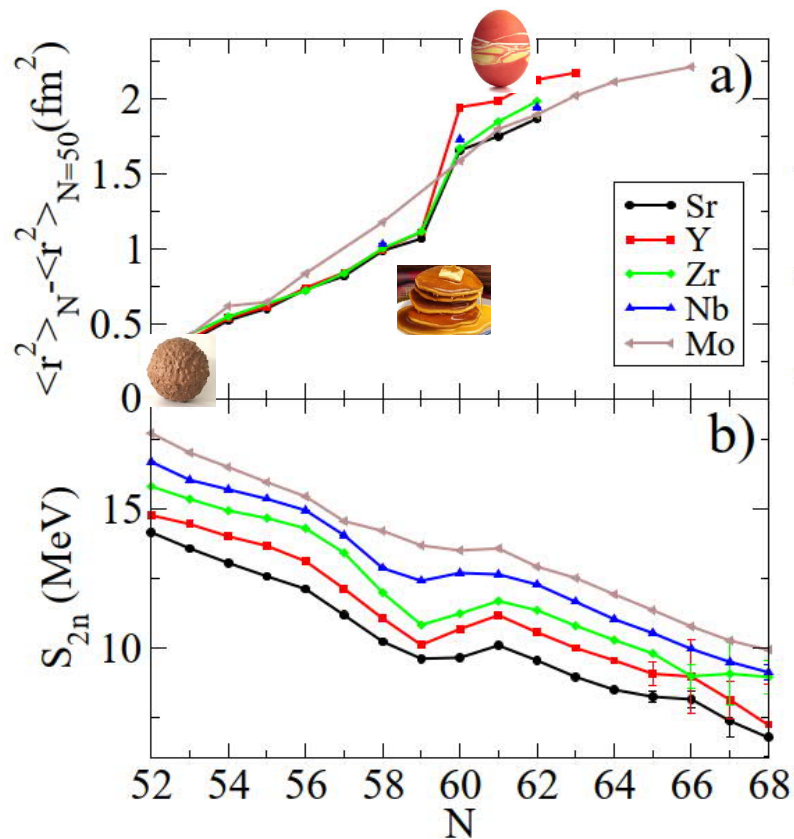
Use optical manipulation in the cooler-buncher to access a $J = 2 \rightarrow J' = 1$ transition to get sensitivity to higher nuclear spin



- New optical data obtained in 2019 indicates a nuclear spin of (7,8) for ^{98m}Y
- **Preliminary results:** $Q_s = +3.05(33)$ b and $\mu = +2.62(2) \mu_N$
- The isomer has a much larger quadrupole moment with strong prolate deformation which is very **rigid**

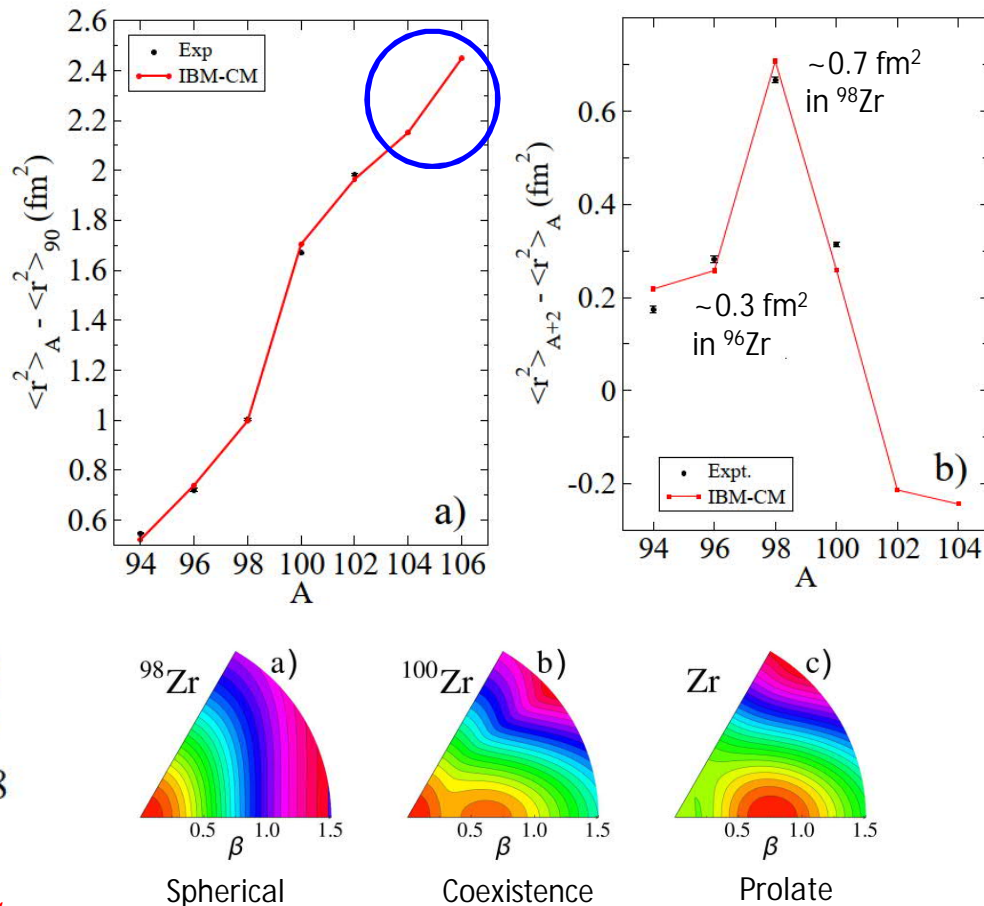
The quest for shape coexistence in Zr

"...we emphasize the importance of both electromagnetic properties, isotopic shifts, S_{2n} separation energies as well as data on two-nucleon transfer reactions..."

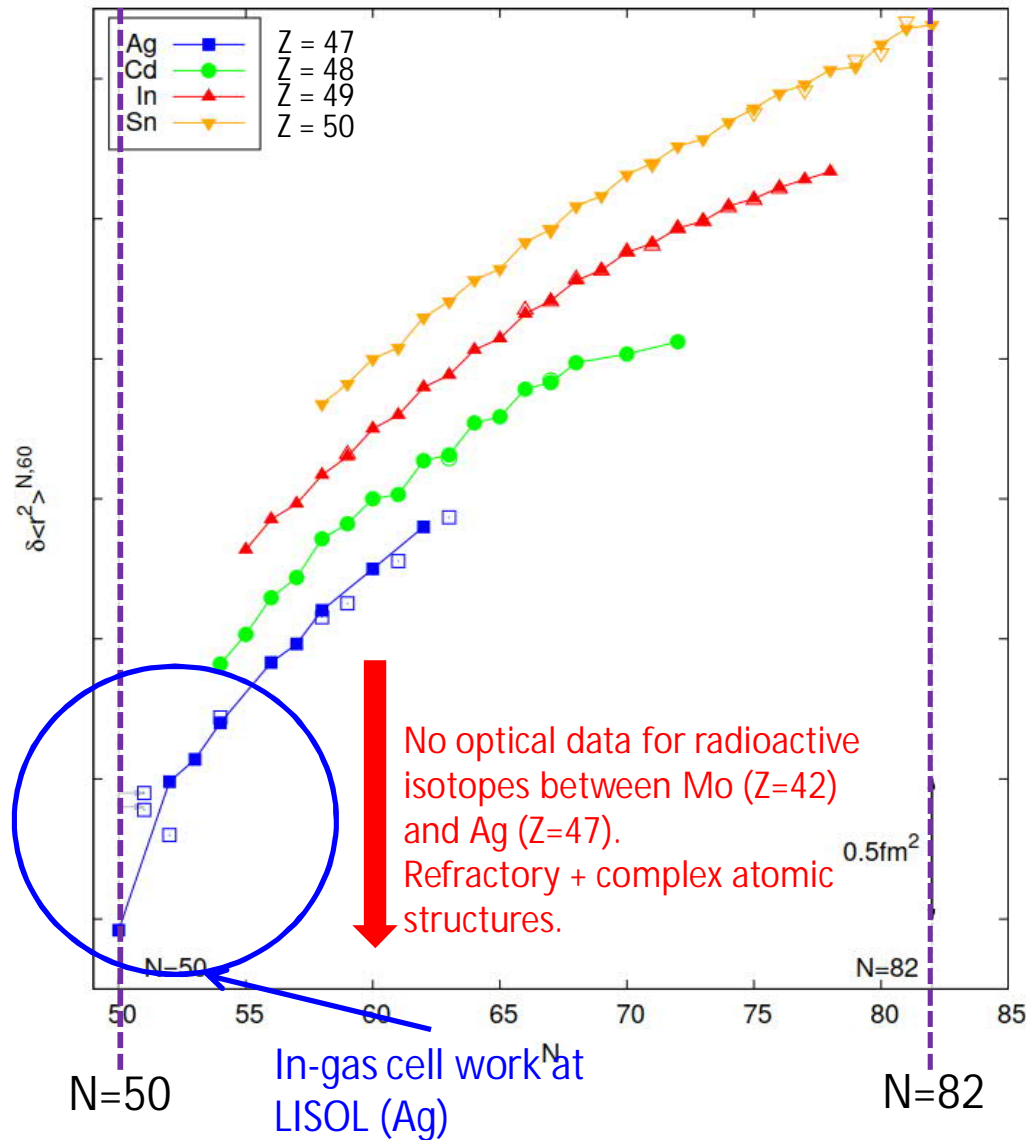


J.E. Garcia-Ramos and K. Heyde, arXiv:1909.00824

IBM-CM model



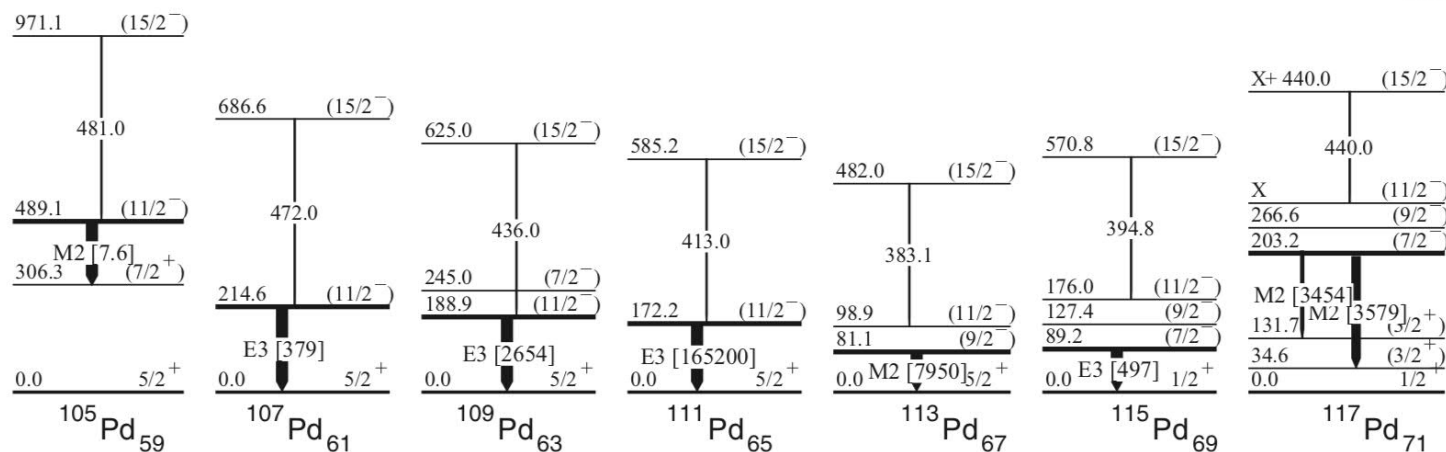
Charge radii near the Sn region



- Persistent and regular trends throughout the major shell (valence space of 32 neutrons)
- Quadrupole contribution, proportional to product of particles and holes, with constant odd-even staggering, added to linearly increasing $\langle r^2 \rangle$
- 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

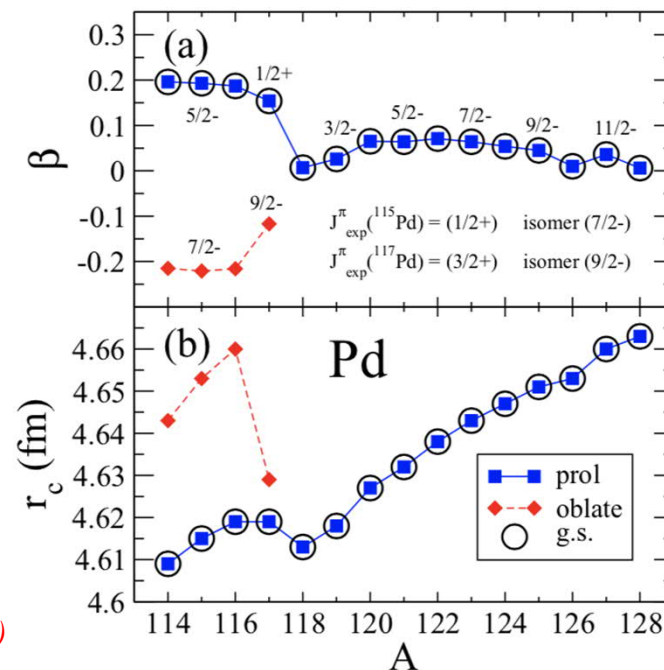
Motivation for the study of Pd (Z=46)



J. Kurpeta et al., Phys. Rev. C 98, 024318 (2018)

- Early spectroscopic information of odd-mass Pd obtained via prompt gamma-ray spectroscopy
- Need to confirm spin-parity assignments
- Theoretical analysis of the region performed by Sarriguren (microscopic approach based on a deformed QRPA calculation on top of a SLy4 Skyrme interaction)
- Potential energy curves for even-even nuclei show oblate and prolate minima in lighter isotopes (A=118)

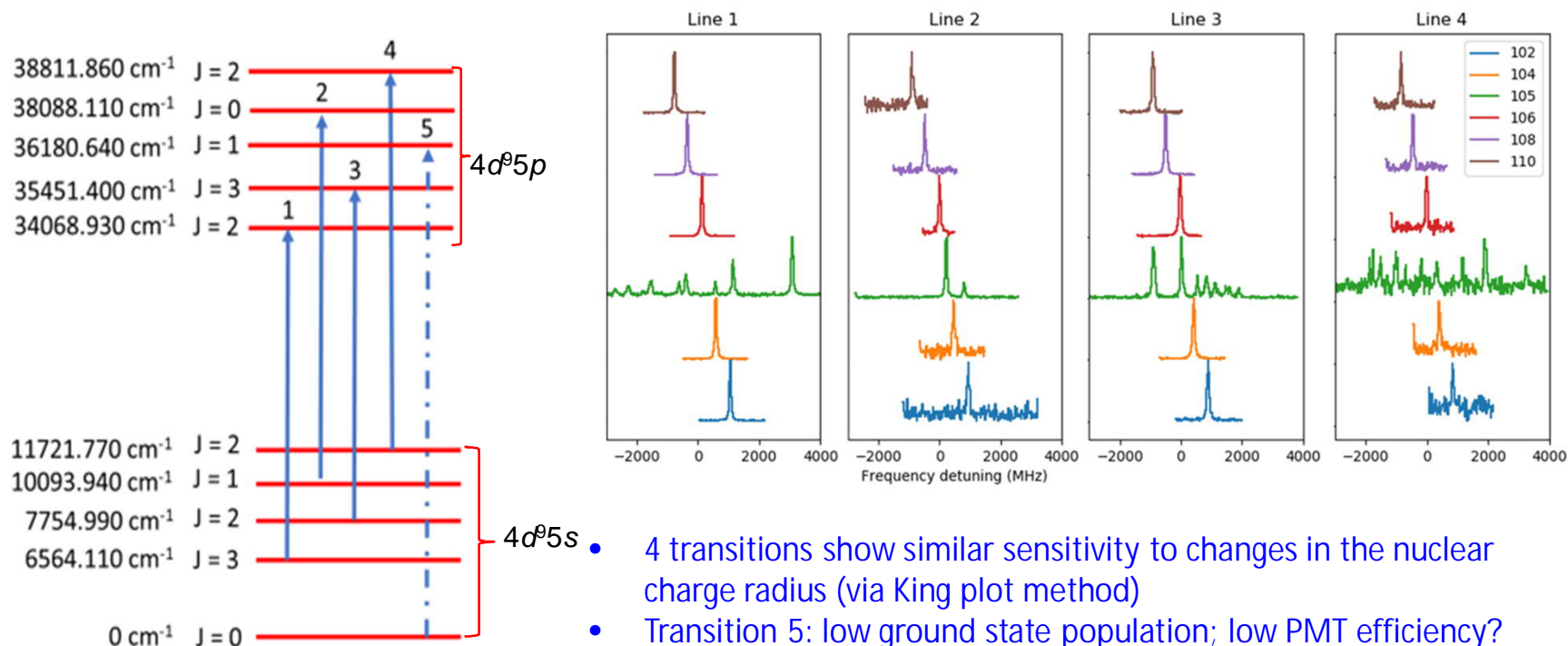
P. Sarriguren., Phys. Rev. C 91, 044304 (2015)



Collinear laser spectroscopy: stable Pd

No ionic transitions available.

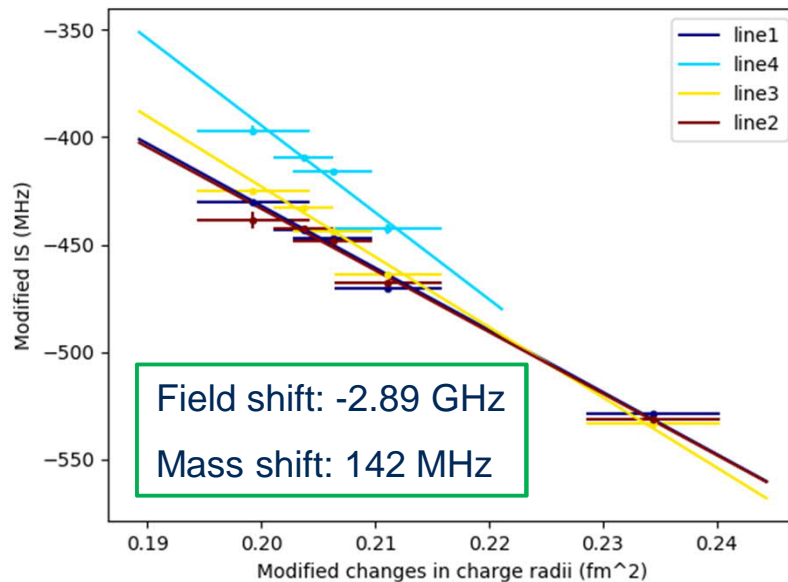
Different atomic transitions have been tested to determine the most efficient.



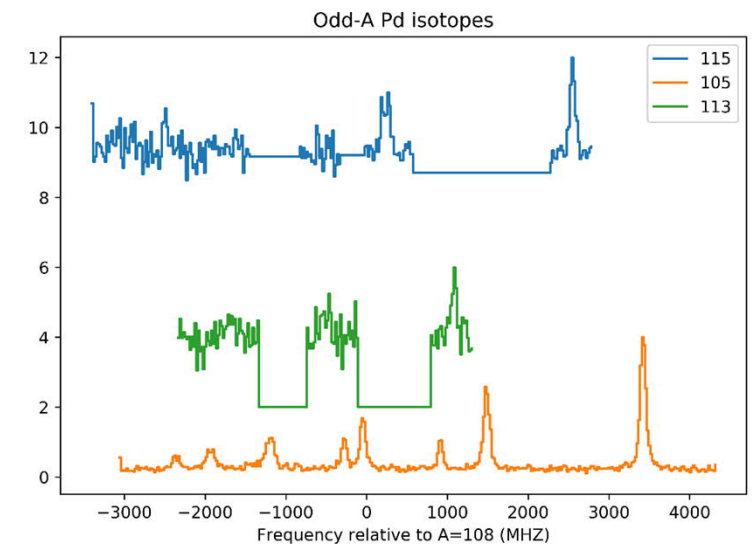
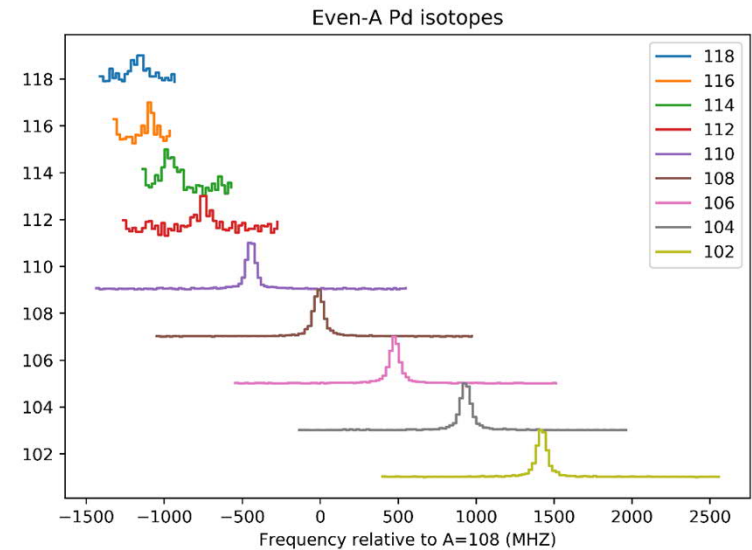
- 4 transitions show similar sensitivity to changes in the nuclear charge radius (via King plot method)
- Transition 5: low ground state population; low PMT efficiency?
- Line 1 (363.5726 nm) is the most efficient option although has relatively high atomic spins ($J=3 \rightarrow J'=2$)
- High-spin nuclear states in odd-A isotopes will be challenging (fragmented population, multiple hyperfine peaks to locate...)

S. Geldhof et al., PLATAN proceedings, to be submitted.

Online experiment: July 2019



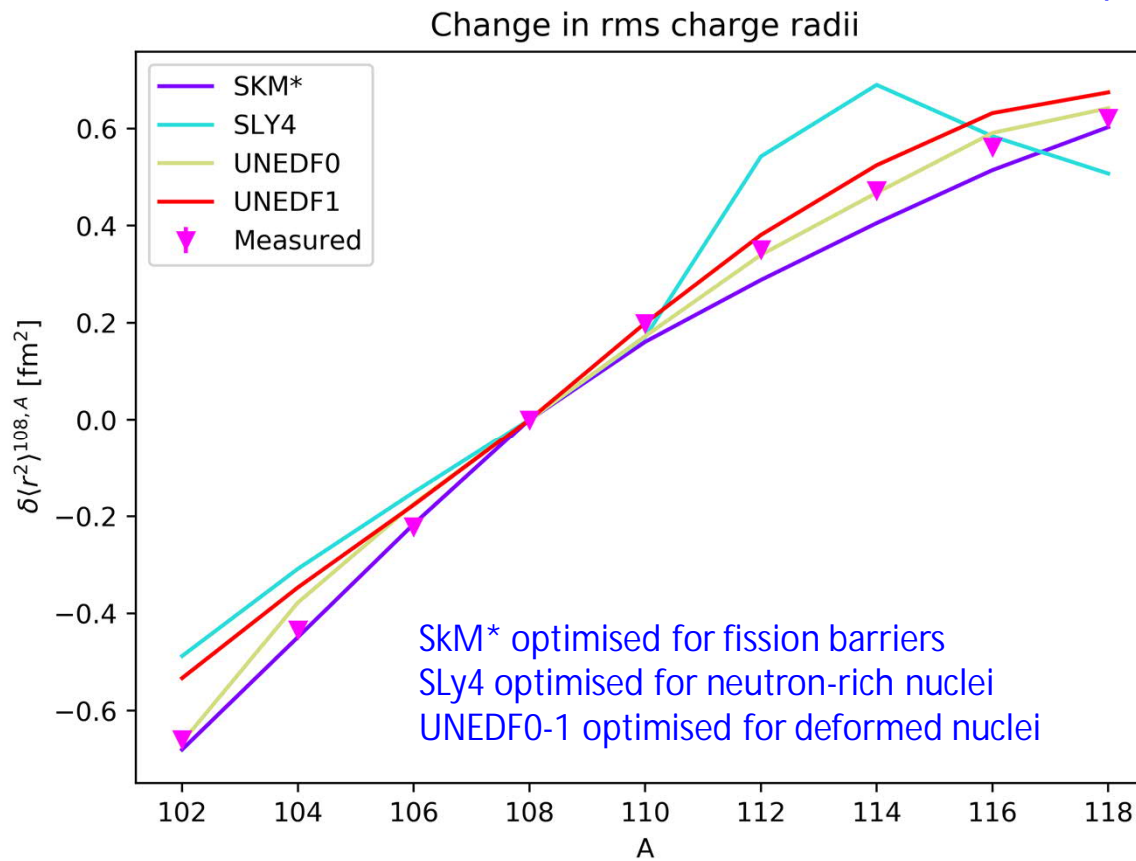
- King plot technique used to extract the atomic factors. Muonic data available.
- Even-A radioactive fission fragments for $^{112,114,116,118}\text{Pd}$ (spin 0 ground state, no isomers)
- Preliminary data on odd-A isotopes of $^{113,115}\text{Pd}$ (high nuclear spins, isomers, complex...)
- The odd-A cases are really at the limit of what we can do....Pd is also the "easiest" of the challenging refractory elements.



Charge radii and comparison to theory

Comparison of extracted changes in charge radii to nuclear Density Functional Theory with various Skyrme EDFs

<http://massexplorer.frib.msu.edu/>



Erler et al., Nature 486, 509 (2012)

SKM*:

Bartel et al., Nucl. Phys. A 386, 79 (1982).

SLy4:

Chabanat et al., Nucl. Phys. A 635, 231 (1998).

UNEDF0:

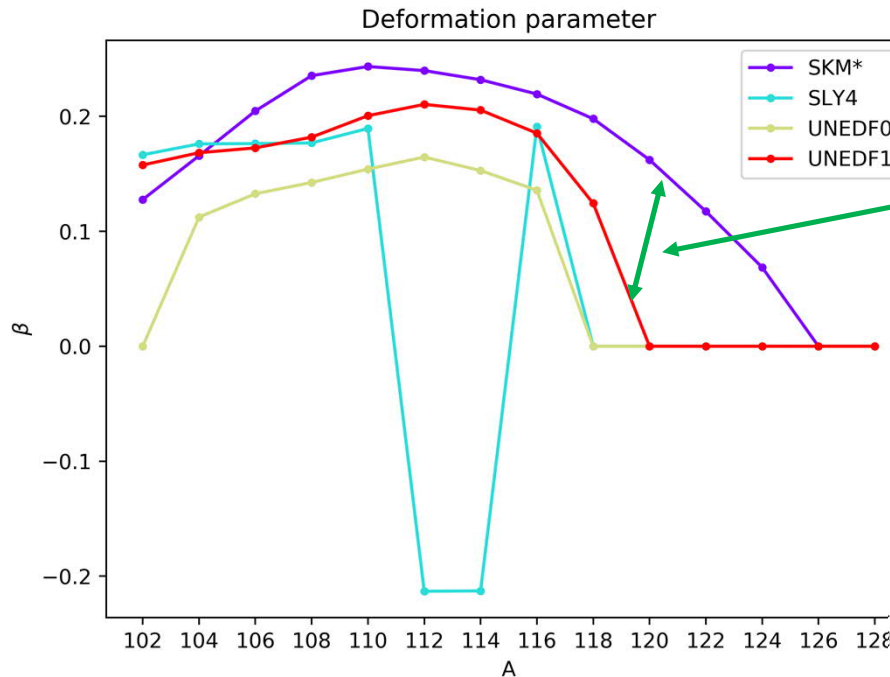
Kortelainen et al., Phys. Rev. C 82, 024313 (2010).

UNEDF1:

Kortelainen et al., Phys. Rev. C 85, 024304 (2012).

- General trend of data is well reproduced
- Fayans functional with axial solver to be tested (M. Kortelainen)

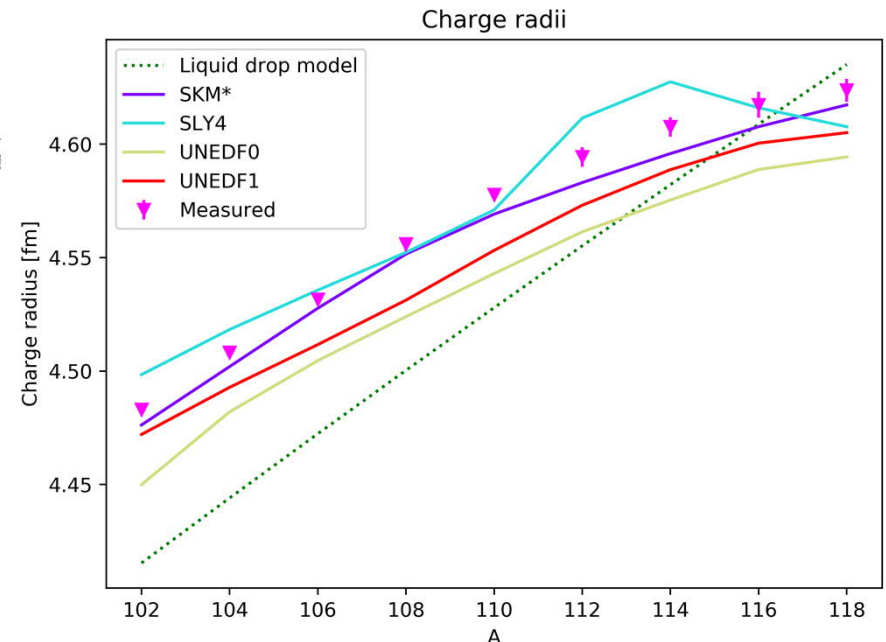
Charge radii and deformation



<http://massexplorer.frib.msu.edu/>

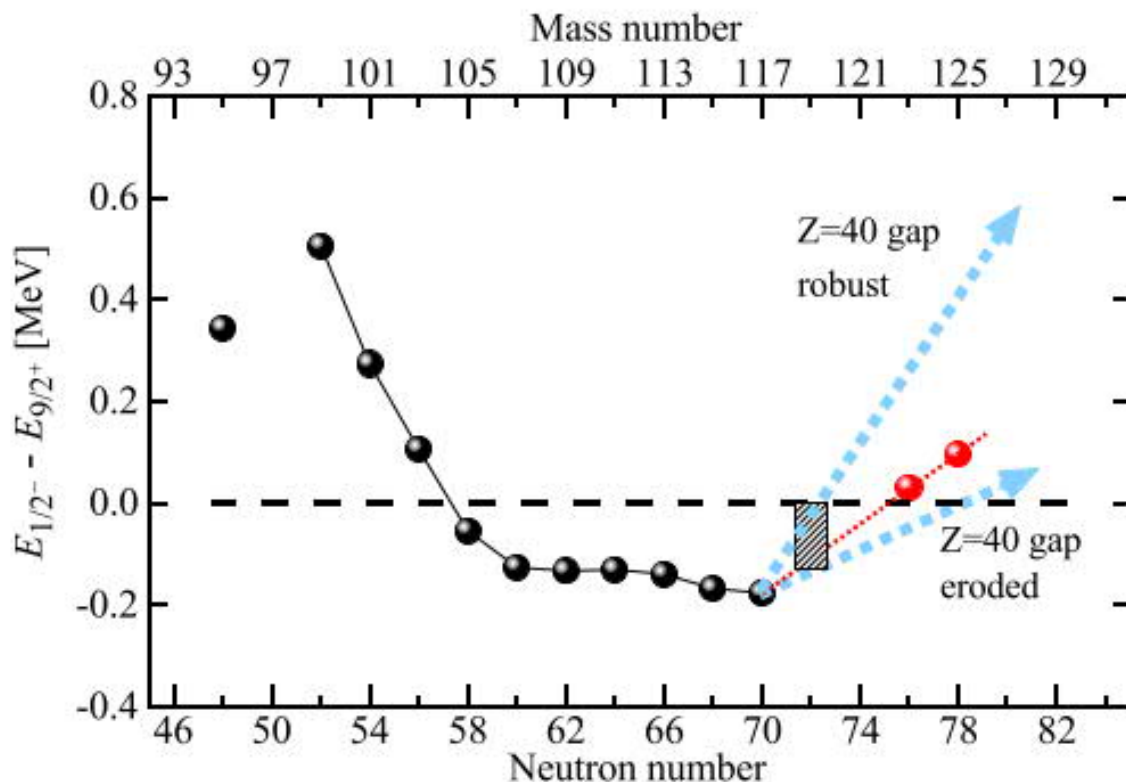
- Charge radii influenced by deformation
- Discrepancy in SLY4 –wrong state assumed for ground state (oblate)
- Same discrepancy seen in Gogny and relativistic EDFs.

- Different offsets seen in absolute charge radii – mainly due to deformation differences
- Saturation density important but its impact more clear in spherical systems
- SkM* appears to fit the absolute radii best.

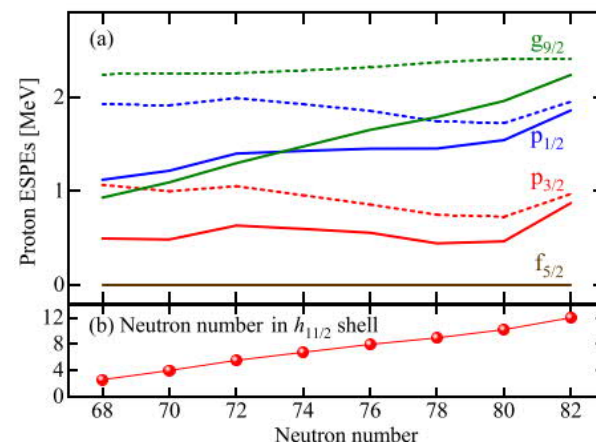


Probing the evolution of shells in Ag (Z=47)

n deficient ← → n rich



Z.Q. Chen et al., *Phys. Rev. Lett.* 122, 212502 (2019)

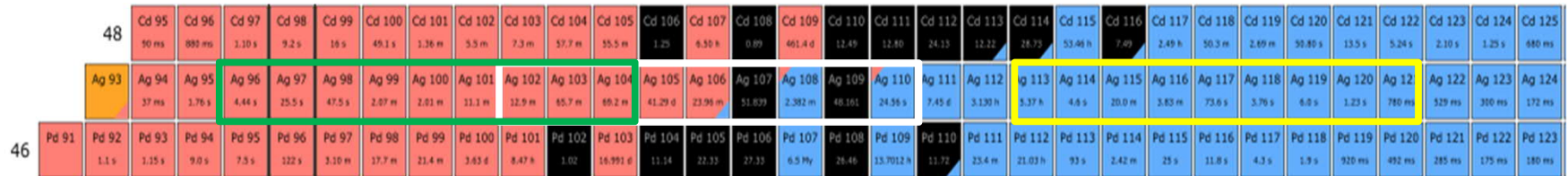


- Dashed line: central & spin-orbit
- Solid line, same but tensor added

- Odd-mass Ag isotopes feature a $\frac{1}{2}^-$ isomeric state which appears as the ground state for $N > 58$
- β -delayed γ -ray spectroscopy at RIKEN extended the systematic trend in the level spacing of the lowest $9/2^+$ and $\frac{1}{2}^-$ states up to $N=78$ (reduction of Z=40 subshell gap)
- Observed inversion around ^{123}Ag interpreted as a monopole shift of orbitals

Currently: isotopes from ^{96}Ag to ^{121}Ag

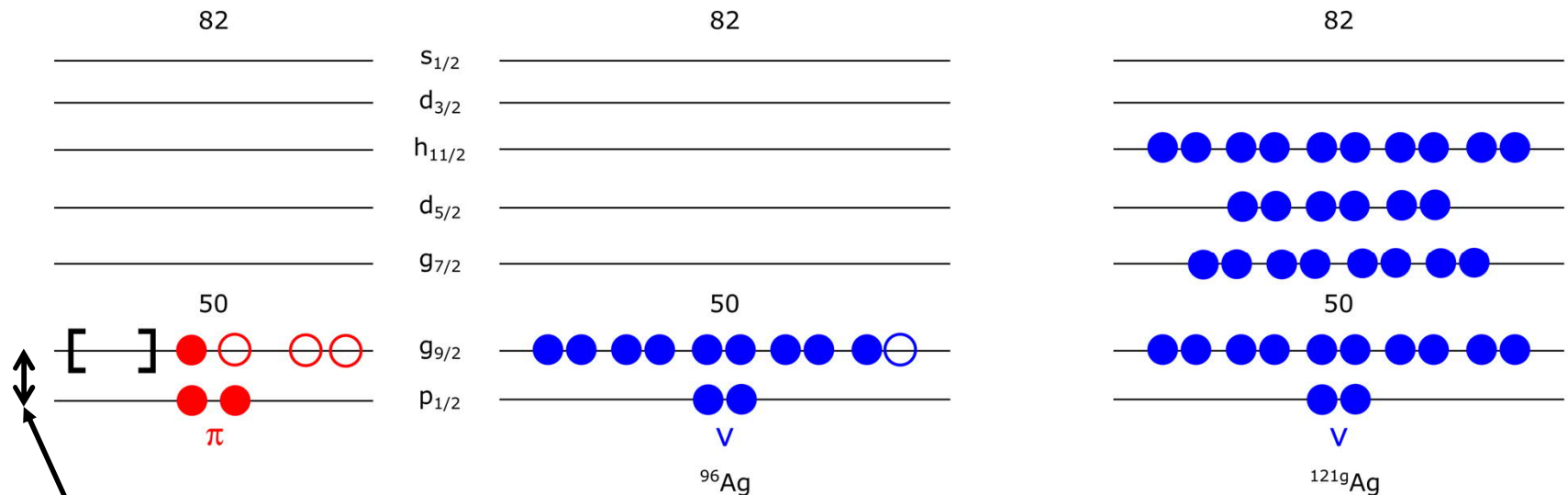
- JYFL proposal combining laser spectroscopy and mass spectrometry (JYFLTRAP)
- A variety of production mechanisms and RIB techniques (flexibility)



$\text{nat}, ^{92}\text{Mo}(^{14}\text{N}, 2\text{pxn})^{104-96}\text{Ag}$
Hot cavity+JYFLTRAP

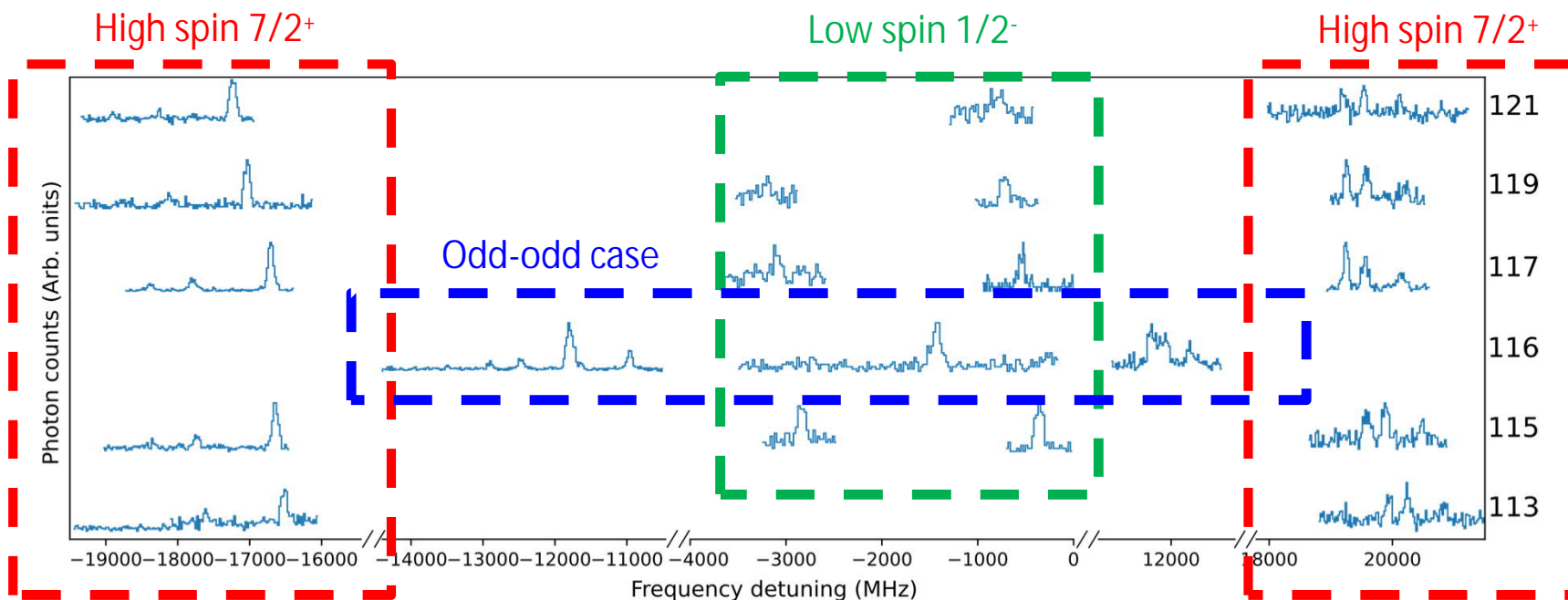
$\text{nat}\text{Pd}(p, \text{xn})$
(future proposal, L. Cacaes)

Fission – July/Dec. 2018
(more planned next week)



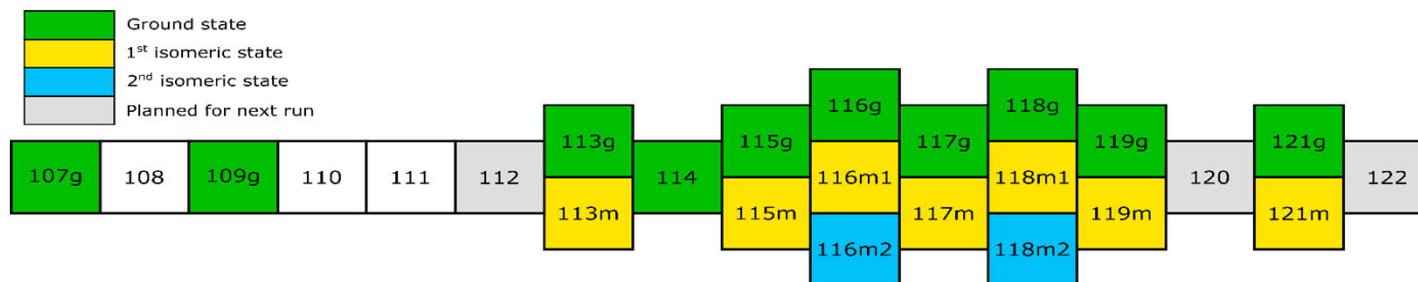
Z=40 sub-shell gap affected by addition of neutrons

Collinear laser spectroscopy: n-rich Ag



Data from fission – July 2018

(More data planned for A=115, 114, 116 and 121 low-spin state)

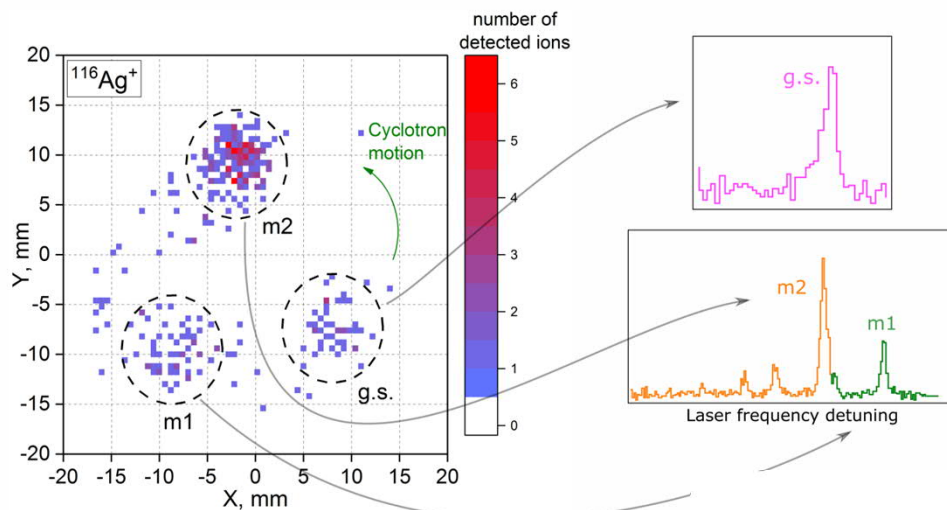


Mass spectrometry with PI-ICR method

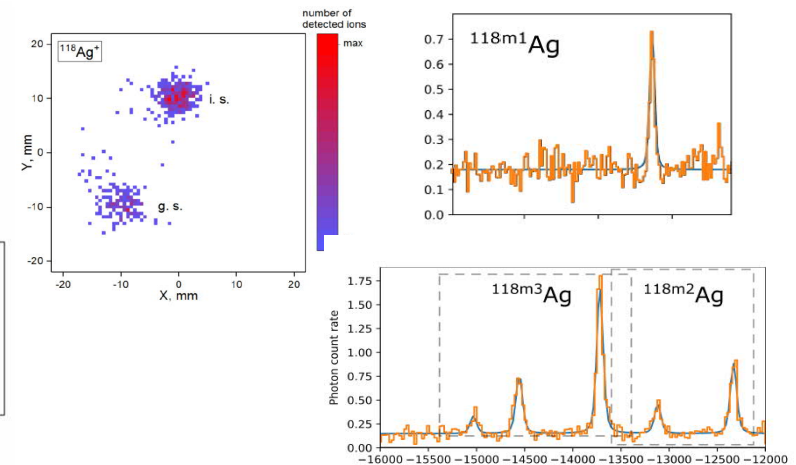
Challenging low-lying isomeric states identified with PI-ICR at JYFLTRAP
(not resolved in earlier TOF-ICR work at ISOLTRAP* - $^{112,114-124}\text{Ag}$)

*M. Breitenfeldt et al., PRC 81, 034313 (2010)

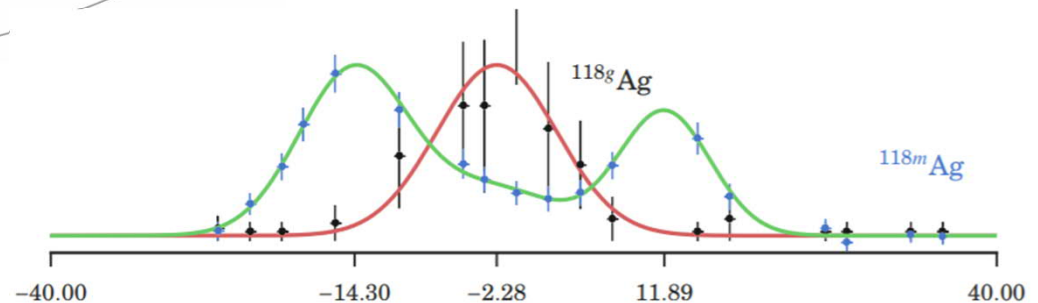
^{116}Ag (3 states observed both with trap and laser)



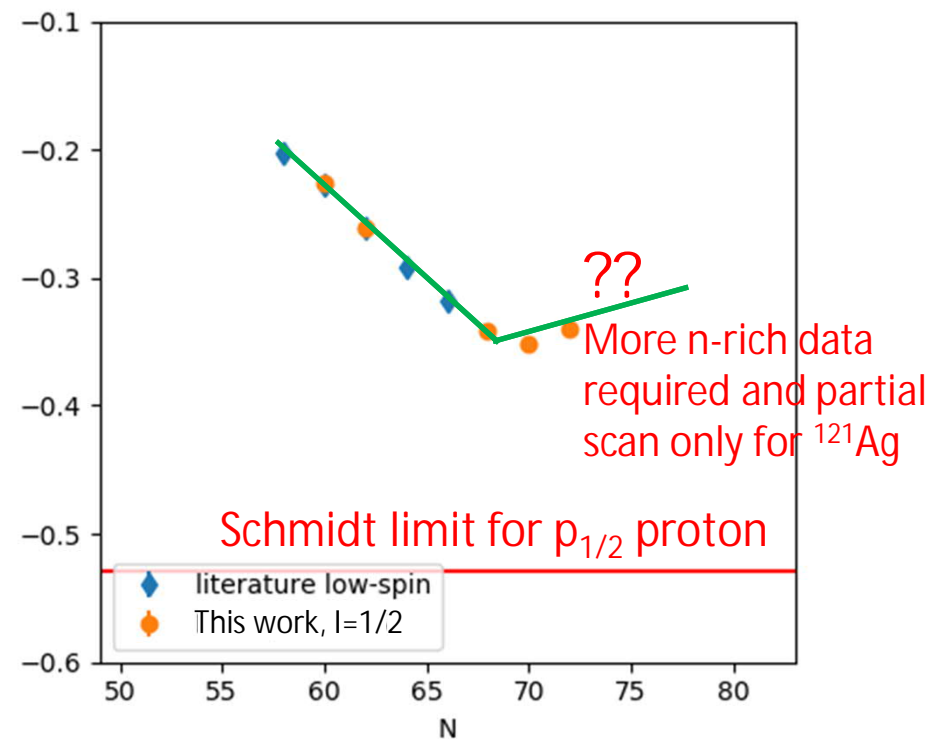
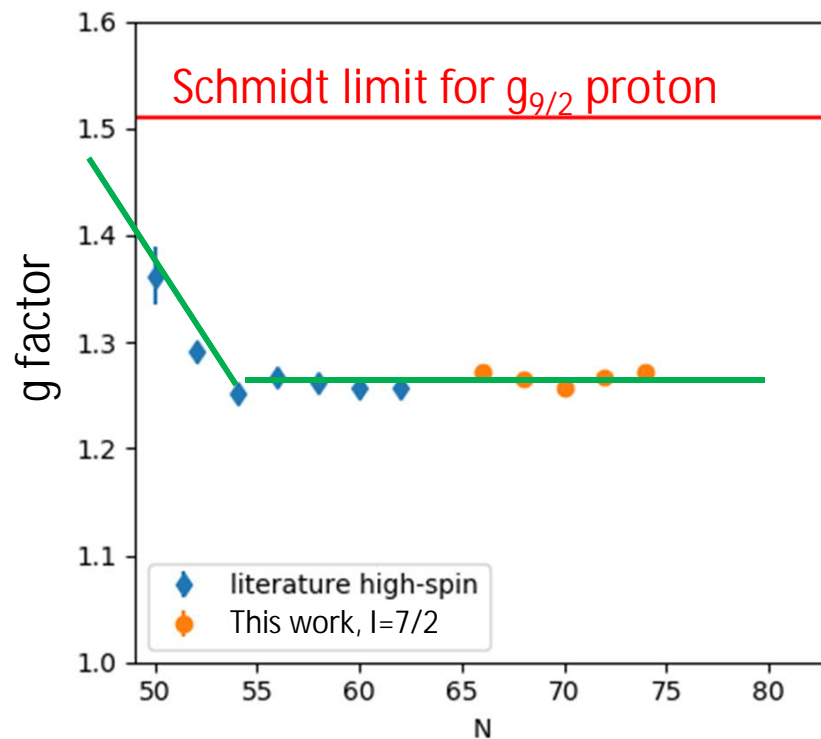
^{118}Ag (Trap: 2 states; laser: 3 states)
- could one be short-lived/low-lying?



In-source measurement on ^{118}Ag
performed at TRIUMF (PhD Thesis,
A. Teigelhoefer)



Magnetic moments of odd-A isotopes



- Near constant g factor for $l = 7/2$ ($9/2$) states with a shell effect towards $N=50$
- g factors of the low-spin $1/2$ state are not constant
- Similar trend observed in indium ($Z=49$)
- Mixing of configurations? But $p_{1/2}$ moments are insensitive to first order config. mixing*
- Link to Meson Exchange Currents (Jason – can you comment 😊?)

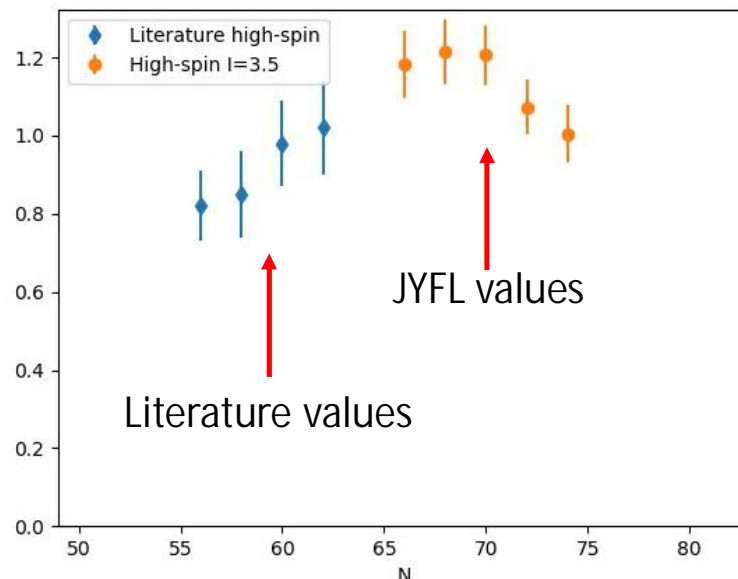
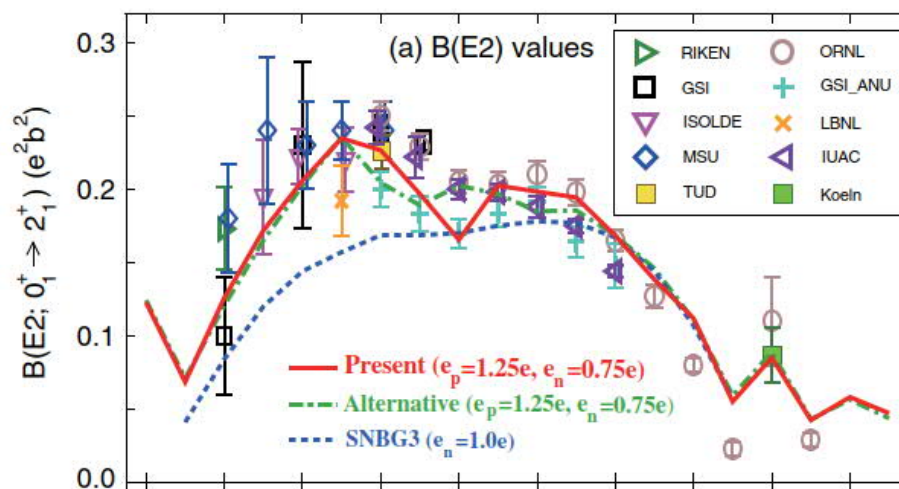
*A. Arima and H. Horie, *Prog. in Theor. Phys.* 12 (1954) 623

Quadrupole moments of odd-A isotopes

Quadrupole moments Q_s :

- Decrease towards N=50 and N=82
- $Q_0 = \frac{3}{\sqrt{5\pi}} ZeR^2 \langle \beta_2 \rangle (1 + 0.36 \langle \beta_2 \rangle)$
- Measurement of $^{107m,109m}\text{Ag}$ would reduce all errors by a factor of 3.

Example from Sn isotopes

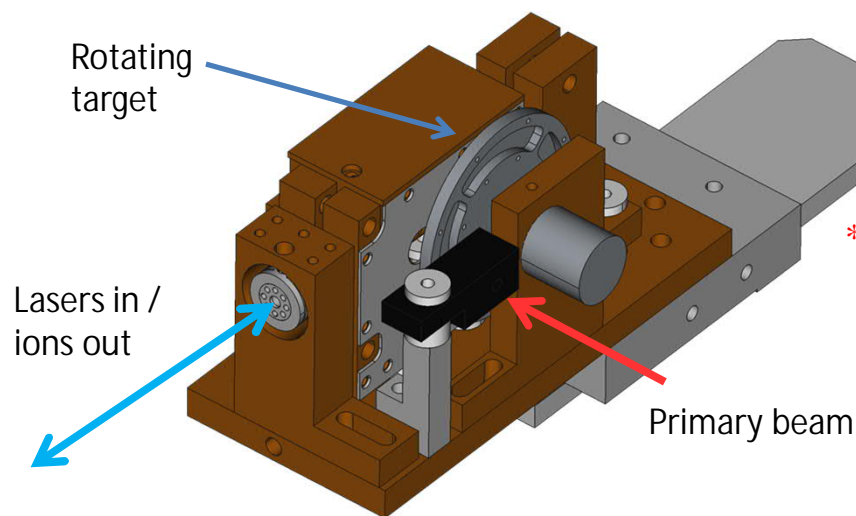


Similar trends observed in transition probabilities $B(E2)$ in the region as deformation parameter

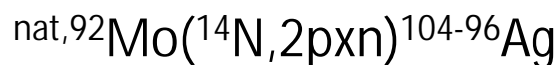
$$\beta_2 \approx \left(\frac{4\pi}{3ZeR_0^2} \right) \sqrt{B(E2)}$$

T. Togashi et al., Phys. Rev. Lett. 121, 062501 (2018)

In-source laser spectroscopy of Ag



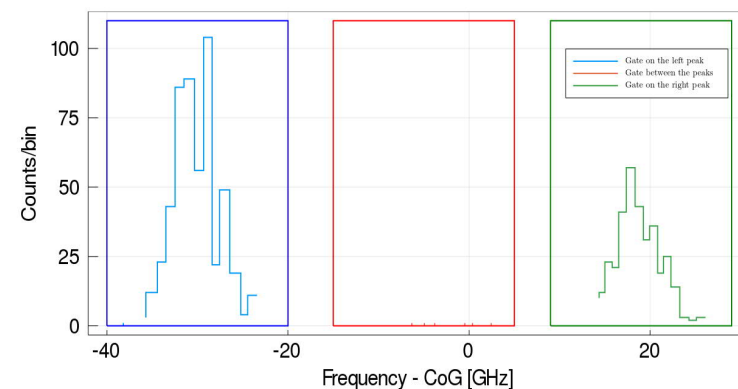
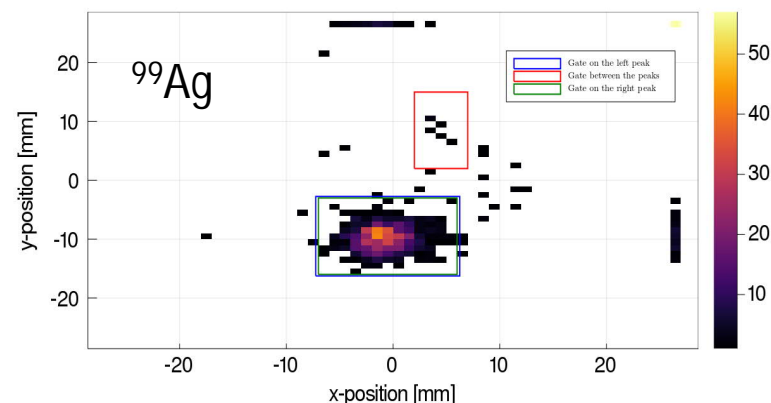
- 3-step resonance ionization spectroscopy
 - efficient (1% total) and selective
- Dual-etalon laser used (~ 1 GHz linewidth)
- Detection with PI-ICR method
 - ultra clean background conditions (rate << 1/hr)



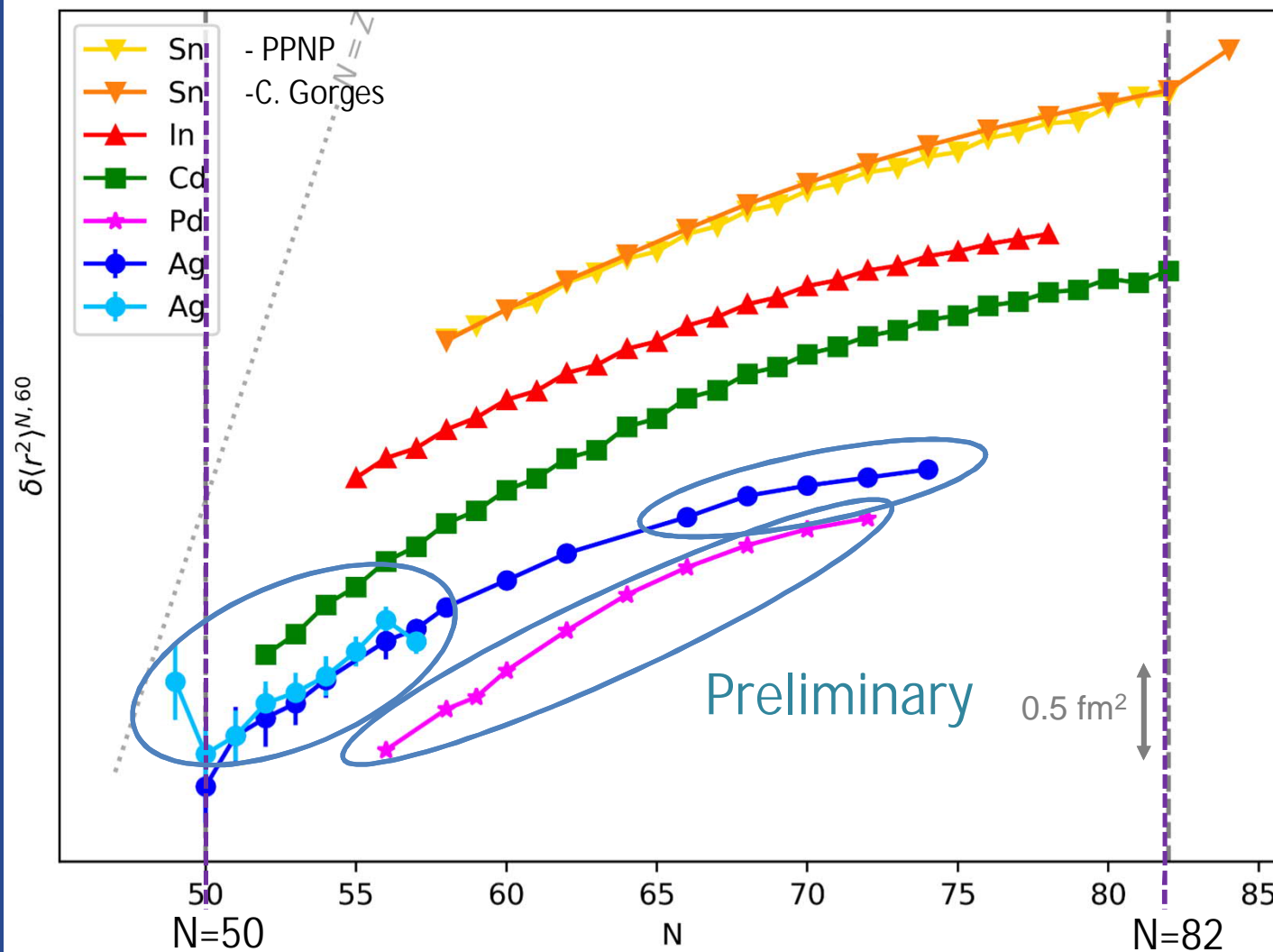
^{96}Ag studied with an "on resonance" detection rate of 1 ion per 5 mins.

Design of inductively-heated hot cavity catcher based on an upgrade from*:

*M. Reponen et al., *Rev. Sci. Instrum.* 86 (2015) 123501



New results from I G I SOL (2018-2019)



New data since
PPNP review (2016)

Cd: *M. Hammen et al.,
PRL 121 (2018)
102501*

Sn: *C. Gorges et al.,
PRL 122 (2019)
192502*

Talk by
D. Yordanov

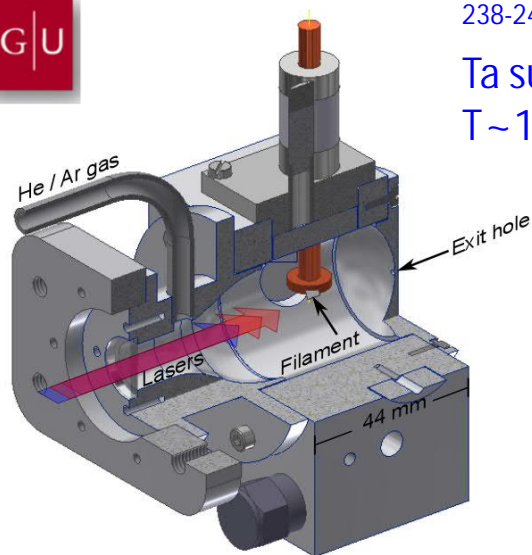
Collinear laser spectroscopy performed on neutron-rich Ag and Pd fission fragments;
In-source laser spectroscopy performed on neutron-deficient Ag (to ^{96}Ag)

I.D. Moore, Laser spectroscopy as a tool for nuclear theories, October 7-11, 2019

Filament-based studies and novel targets

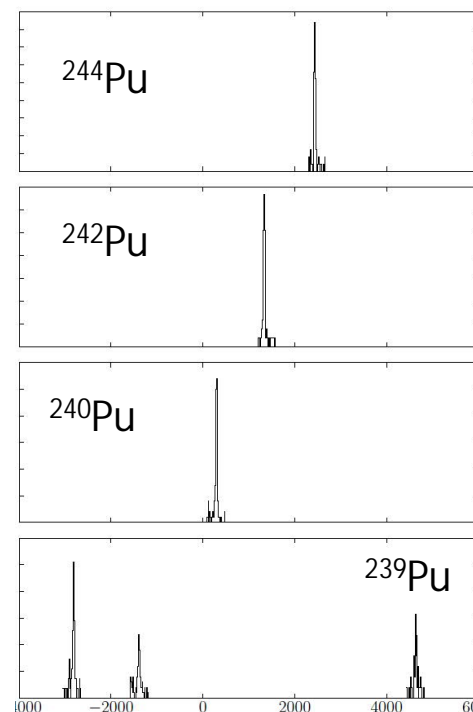
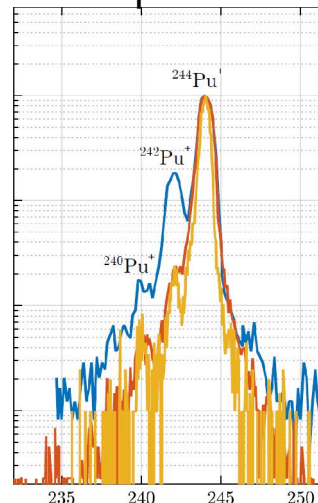


UNIVERSITY OF JYVÄSKYLÄ



$^{238-242,244}\text{Pu}$ ($10^{16} - 10^{12}$ atoms) on
Ta substrate
 $T \sim 1100^\circ\text{C}$

RIS of plutonium



I. Pohjalainen, I.M. et al., NIMB 376 (2016) 233

Further studies on thorium

I. Pohjalainen, I.M. et al., to be submitted.

A. Voss et al., Phys. Rev. A 95 (2017) 032506



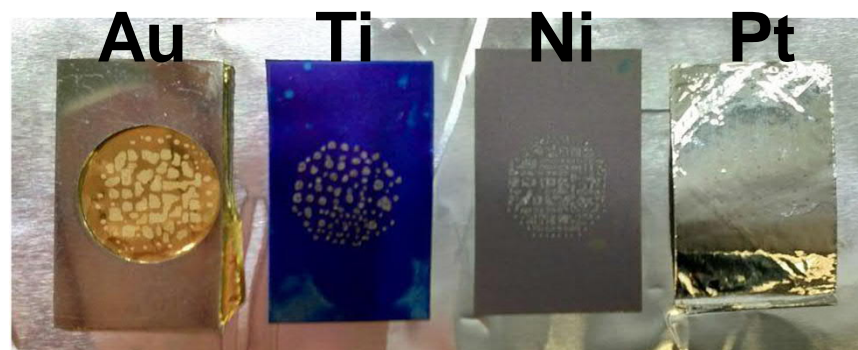
Development and characterization of a Drop-on-Demand inkjet printing system for nuclear target fabrication

R. Haas^{a,b,*}, S. Lohse^{a,b}, Ch.E. Düllmann^{a,b,c}, K. Eberhardt^{a,b}, C. Mokry^{a,b}, J. Runke^{a,c}

^a Johannes Gutenberg-Universität Mainz, Institut für Kernchemie, Fritz-Strassmann Weg 2, 55128 Mainz, Germany

^b Helmholtz-Institut Mainz, Staudinger Weg 18, 55128 Mainz, Germany

^c GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany

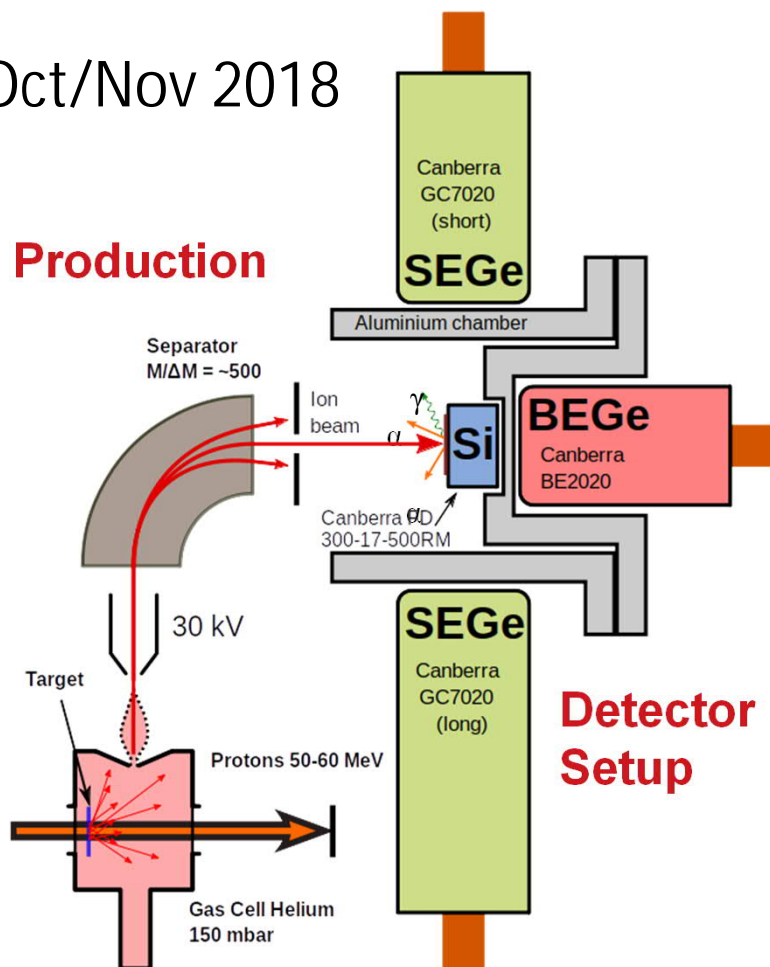


I.D. Moore, Laser spectroscopy as a tool for nuclear theories, October 7-11, 2019

Proof-of-principle experiment; $^{232}\text{Th}(p,X)Y$

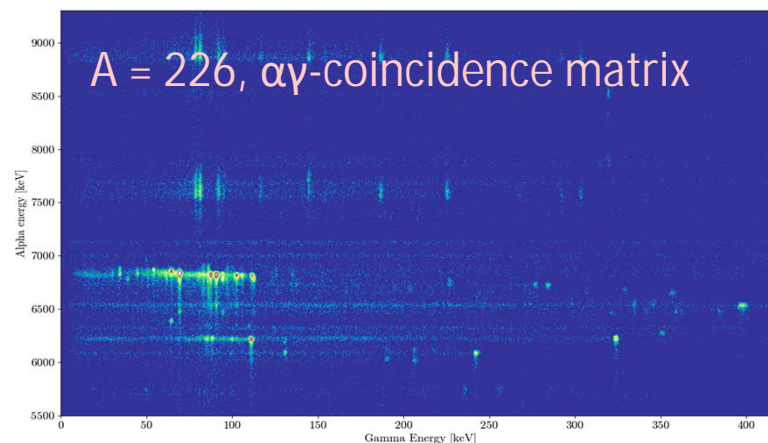
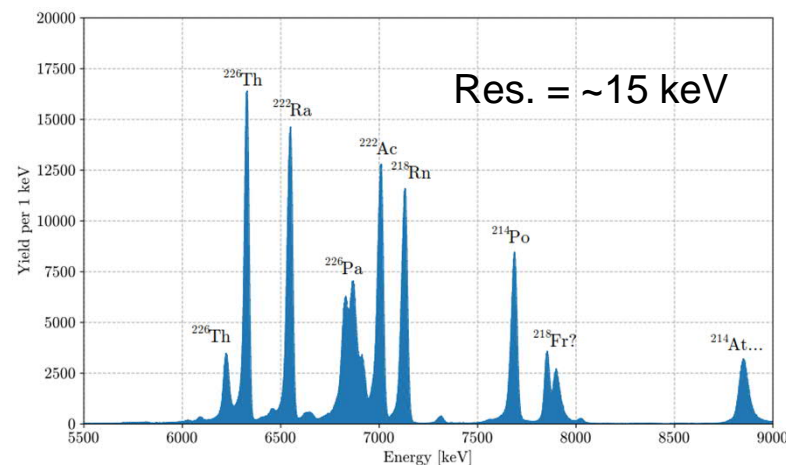
Oct/Nov 2018

Production



Detector Setup

$A=226$, accumulated α spectra, 3 hours



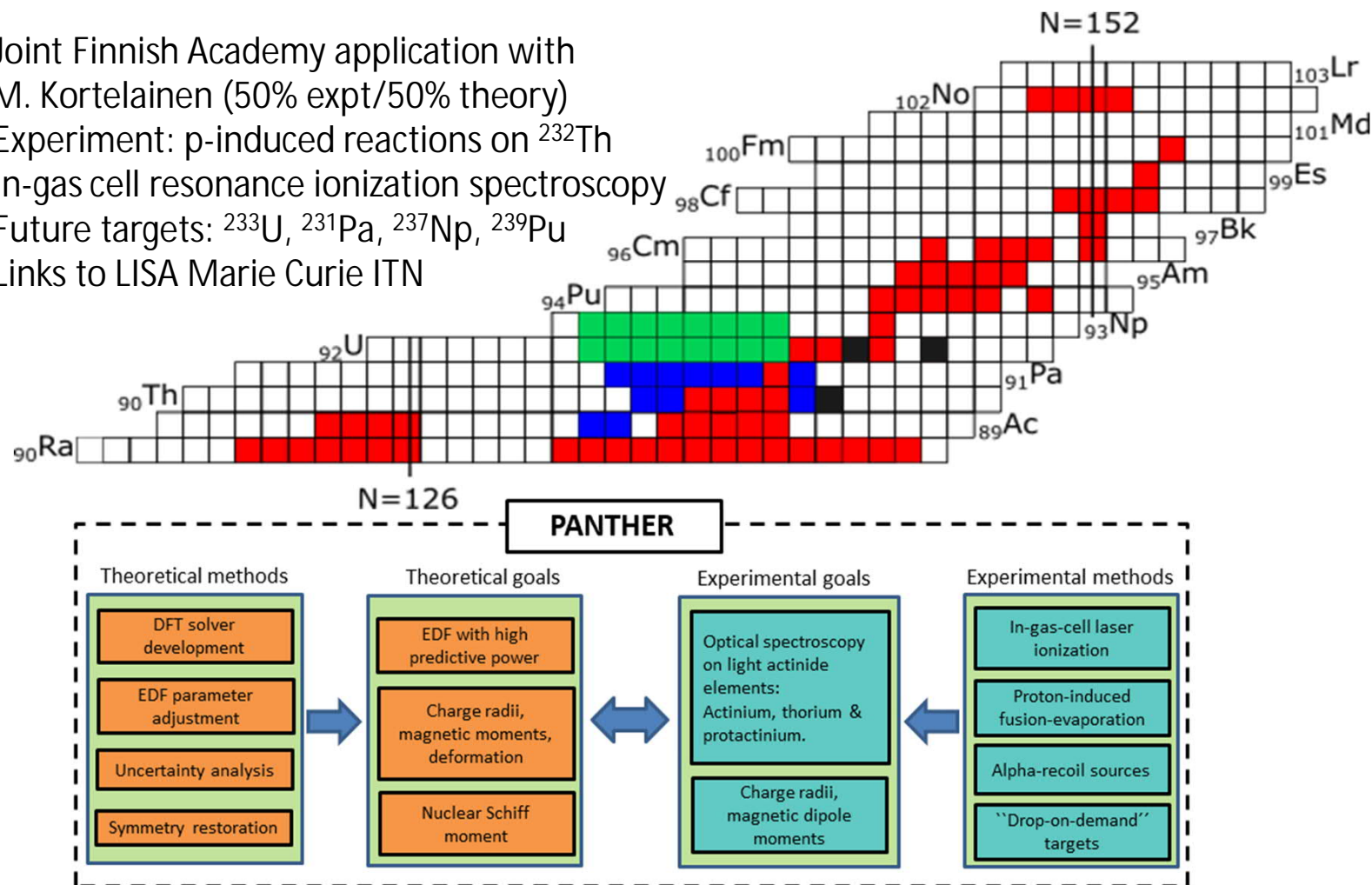
Similar spectra obtained for $A=225$, 224 , ...
Half-life determination (eg ^{226}Pa)
Yields: a few to $\sim 200/\text{s}$

Two accepted proposals: collaboration with
U-Mainz and M. Vandebrouck (Irfu, CEA)

PANTHER (submitted Sept. 2019)

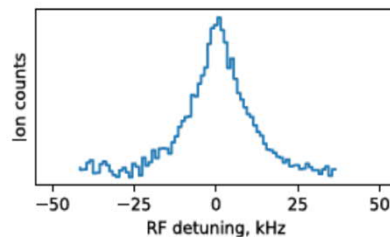
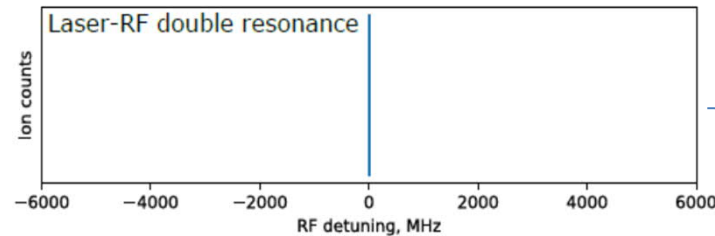
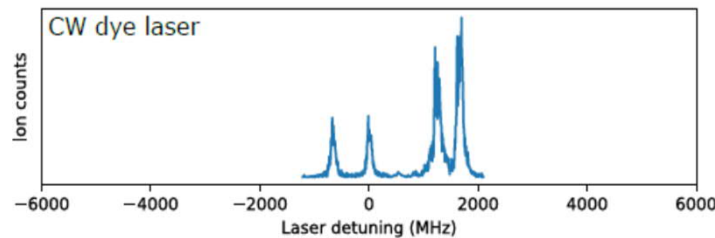
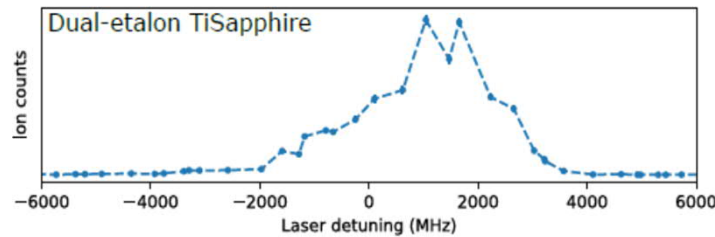
Probing the ActiNides: THeory and EExperiment of RRadioisotopes

- Joint Finnish Academy application with M. Kortelainen (50% expt/50% theory)
- Experiment: p-induced reactions on ^{232}Th
- In-gas cell resonance ionization spectroscopy
- Future targets: ^{233}U , ^{231}Pa , ^{237}Np , ^{239}Pu
- Links to LISA Marie Curie ITN



Laser-RF double-resonance spectroscopy

Example on stable Ag



Optical spec

Optical spectroscopy
(10's of MHz)

RF spectroscopy
(kHz linewidths)

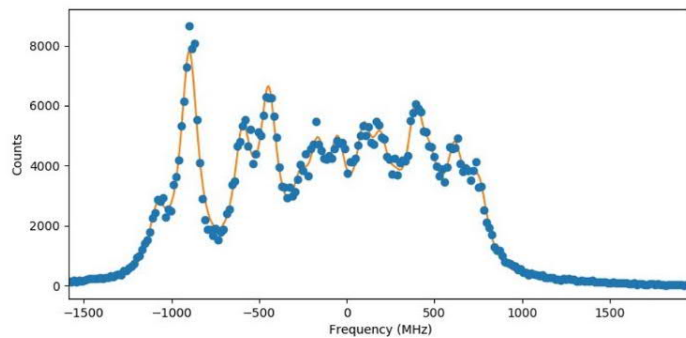
Hyperfine states

RF spec (centroid precision 100 Hz;
FWHM 20 kHz)

- Hyperfine anomalies (M. Bissell)
- Octupole deformation
- g factors

Scandium – a more complex system

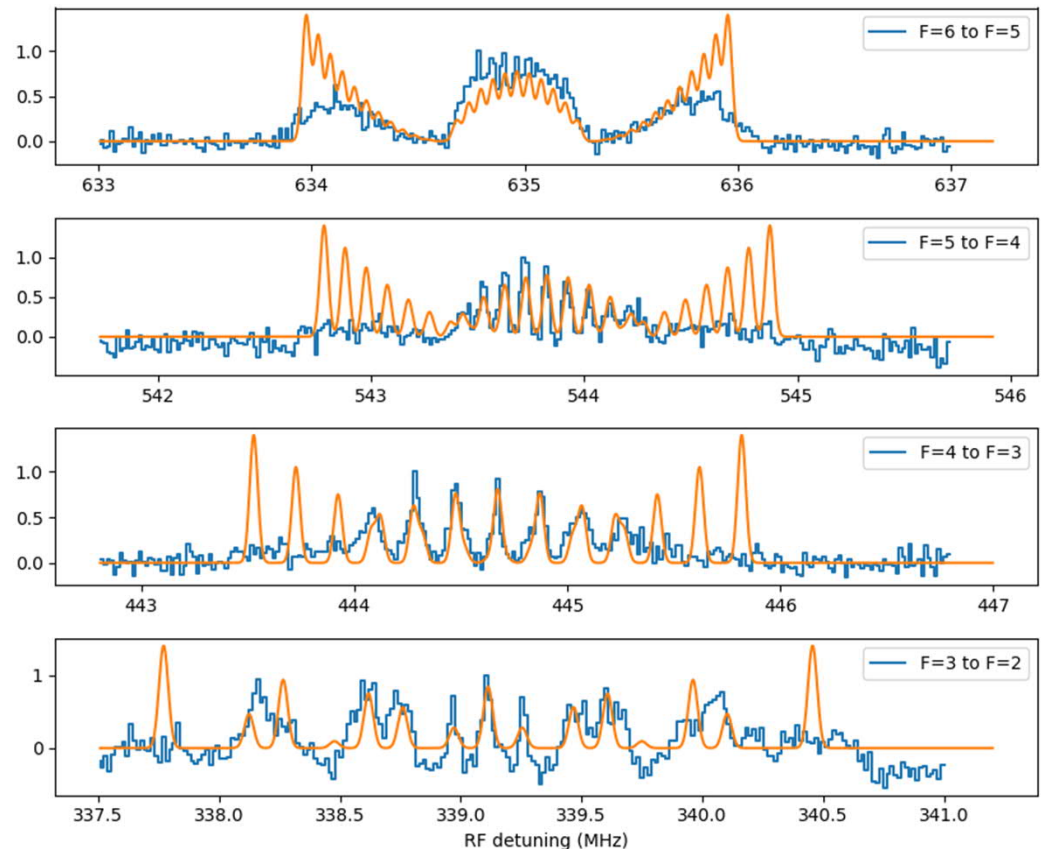
- ($J=5/2$, $I = 7/2$)
- Not fully resolved HFS with lasers



	This work		Childs et al	
A (MHz)	109.03213	0.0002	109.032	0.001
B (MHz)	-37.3889	0.003	-37.387	0.012
C (kHz)	0.96	under analysis	1.7	1

- Magnetic octupole parameter may be resolved using RF.

RF spectrum in magnetic field (Earth)

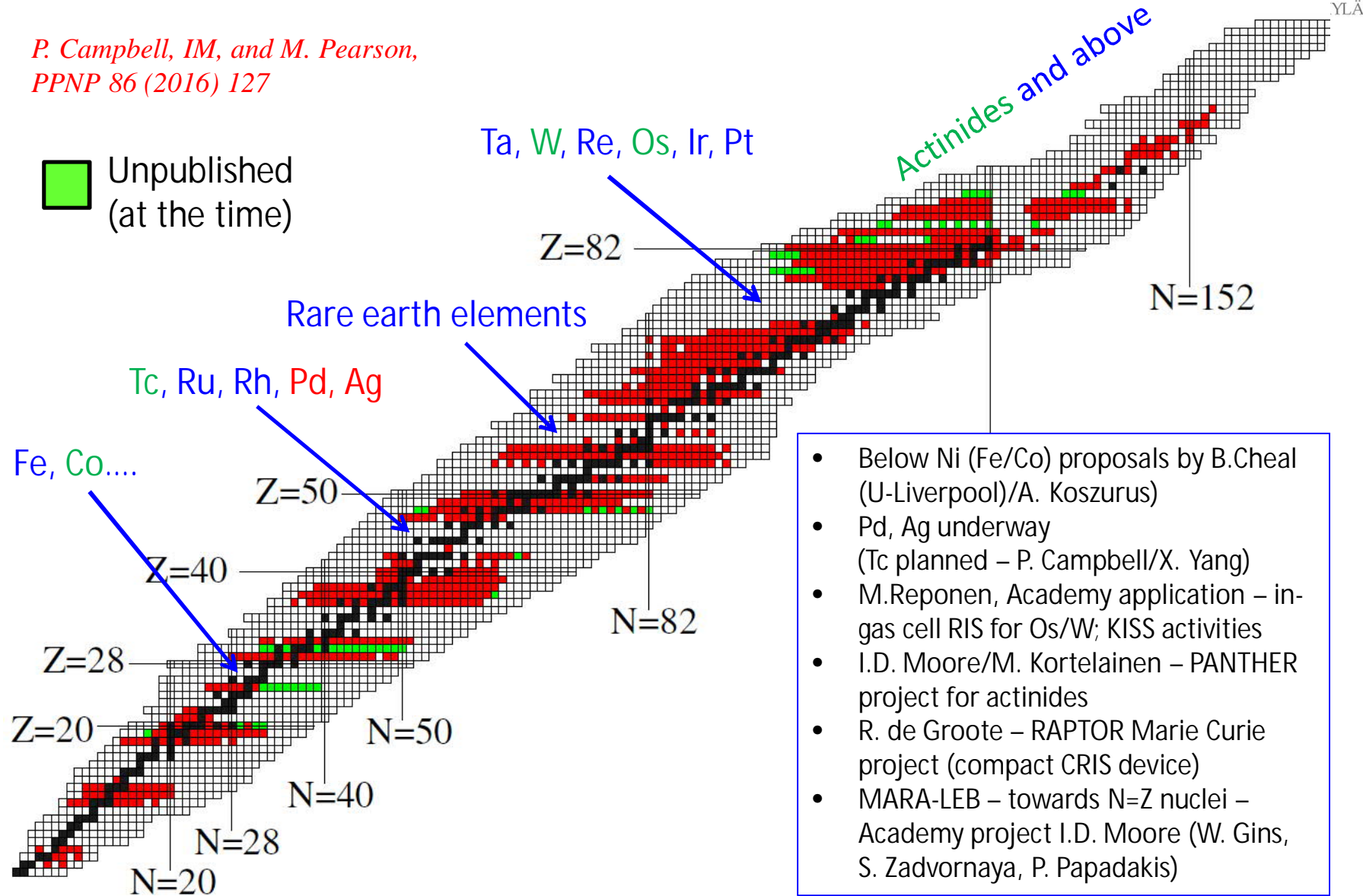


R. de Groote, unpublished.

Nuclear landscape and JYFL projects

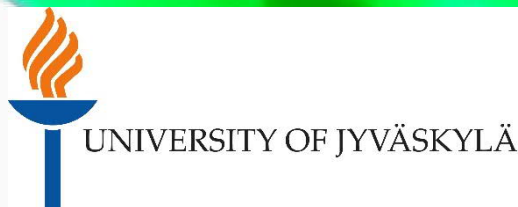


*P. Campbell, IM, and M. Pearson,
PPNP 86 (2016) 127*



- + MARA-LEB developments for in-gas cell / in-gas jet resonance ionization for isotopes towards the N=Z line
- + MORA (P. Delahaye et al., polarization of $^{23}\text{Mg}^+$ for D correlation measurement)

Thank you



**R. De Groote, S. Geldhof, W. Gins, I. Pohjalainen,
M.Reponen, S. Zadvornaya and the IGISOL team**



B. Cheal, C. Devlin



P. Campbell

<https://www.jyu.fi/igisol>