Optical spectroscopy – probing the size, shape and single-particle properties of exotic nuclei

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Outline

- What is optical spectroscopy?
- What can it tell us about nuclear structure?
- Shape coexistence in the *A*=100 region
- New charge radii results for Ag, Pd
- Summary

What is optical (laser) spectroscopy?

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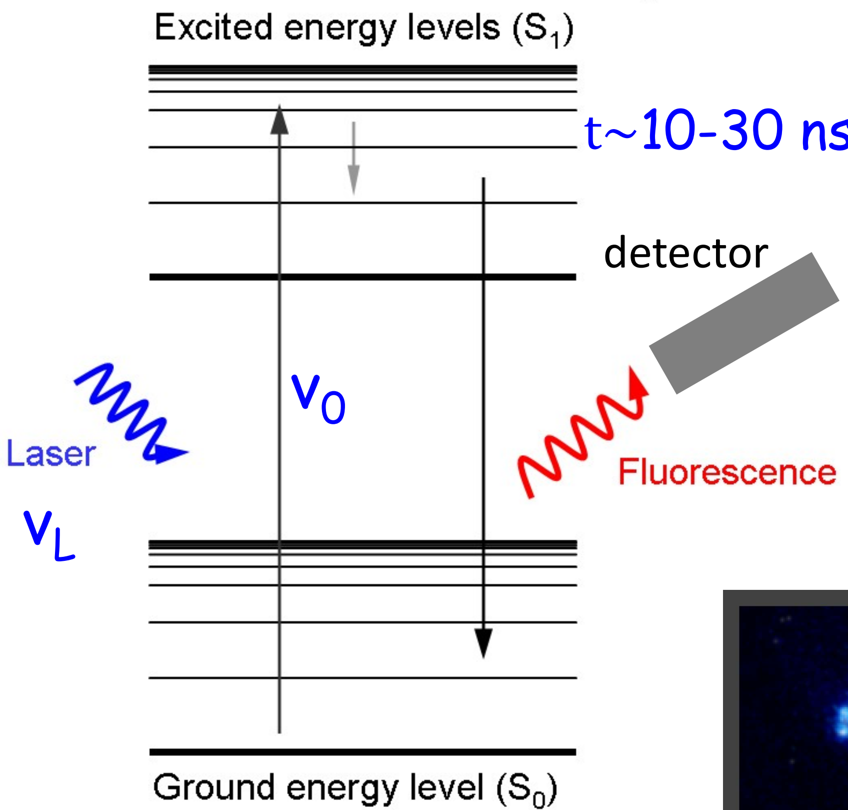
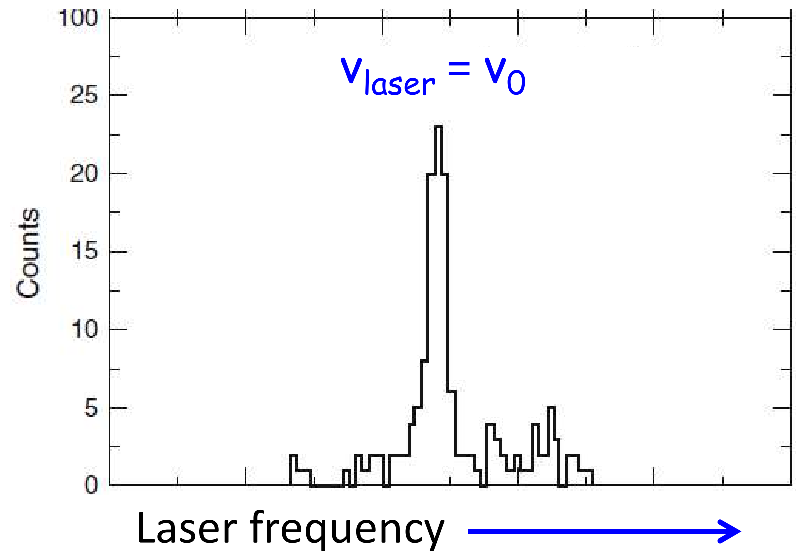
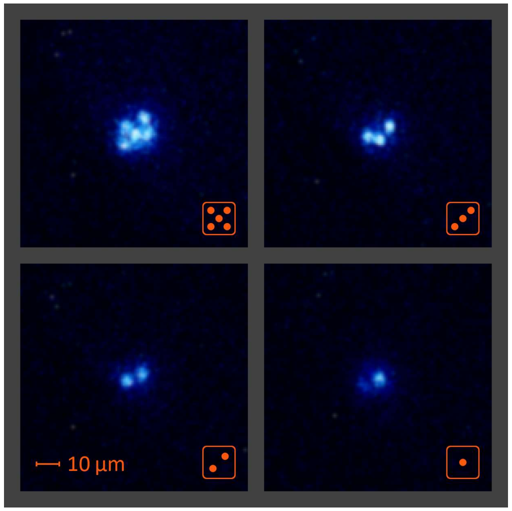




When $\nu_L = \nu_0$, resonant absorption.

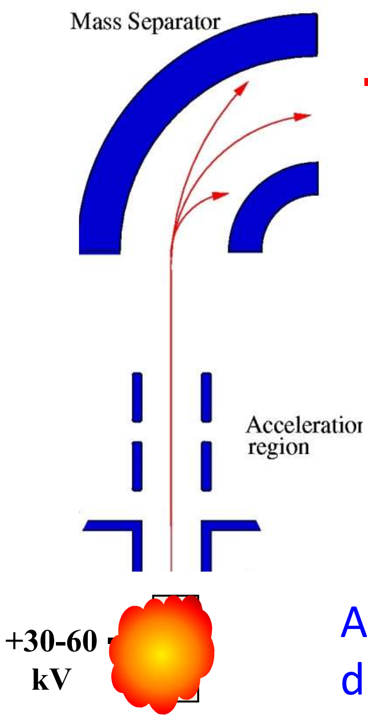
$\sigma \approx \lambda^2/2\pi$

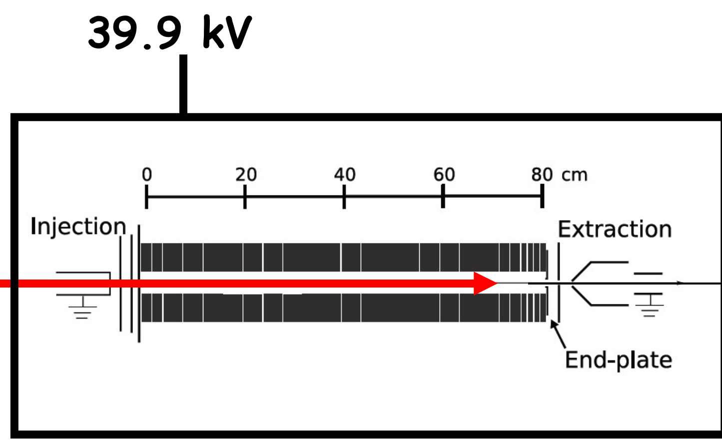


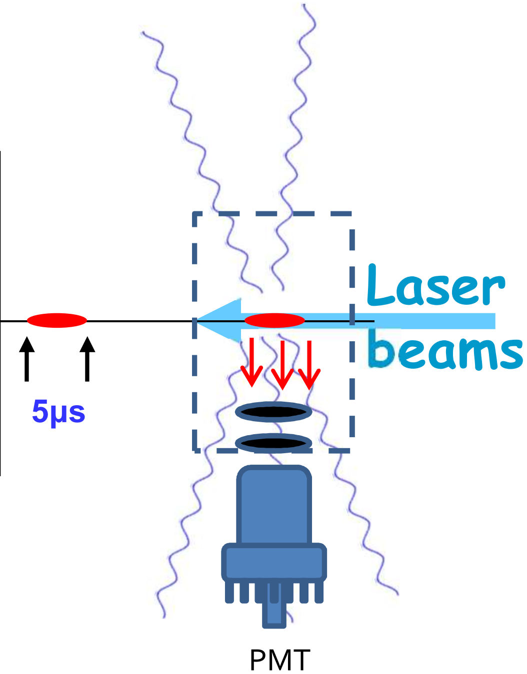
Individual trapped laser-cooled Ba^+ ions

(Courtesy of the TRIµP group, KVI)

High resolution collinear laser spectroscopy

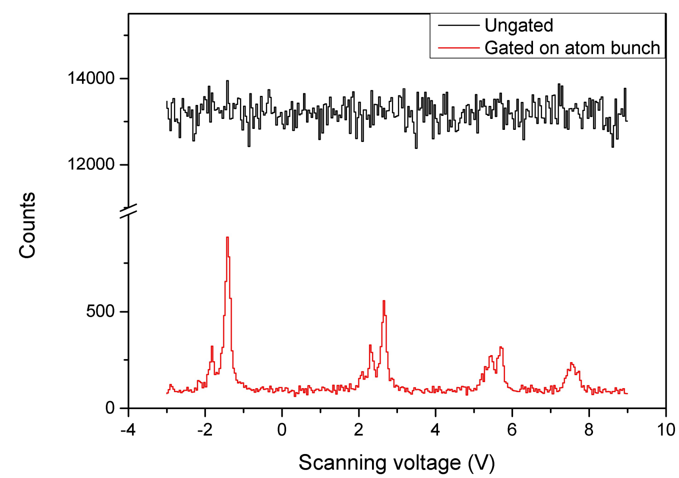






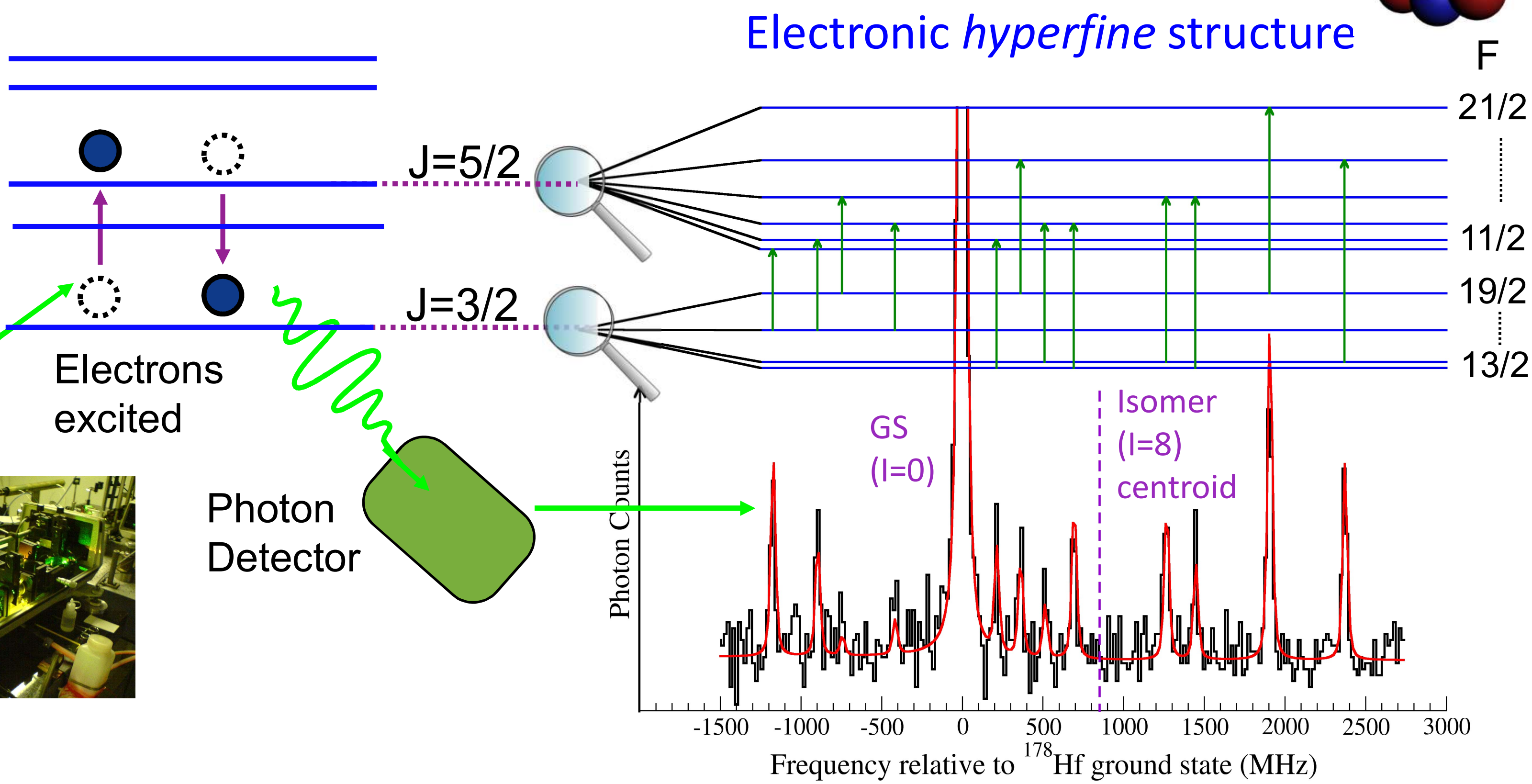
- Helium-filled radio-frequency trap
- Ion beam accumulated for 100s of ms
- Released as a few μs bunch

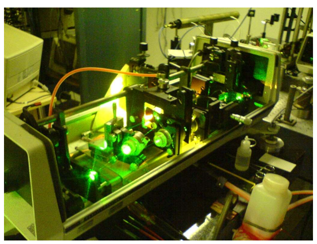
Accept photons in a time window during which the bunched beam passes. Background compressions of ~10^4 routinely achieved.



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

The hyperfine interaction





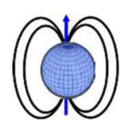
- Extract hyperfine factors A and B from fitting the peak positions:

$$A = \frac{\mu_I B_e(0)}{I\,J}$$

Magnetic dipole interaction

$$B = e Q_s \left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$$

Electric quadrupole interaction




A measurement of nuclear spin

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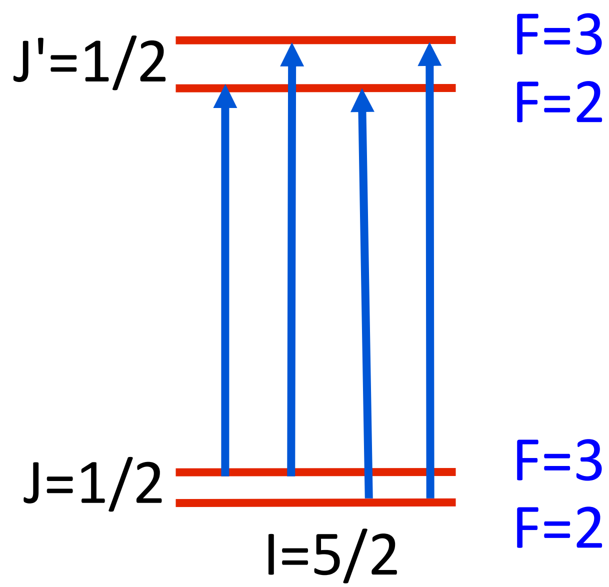
Recent example: ^{107}Mo

- Tentatively assigned ($5/2^+$) in ENSDF
- *Recent decay spectroscopy indicates a spin 1/2

**J. Kurpeta et al., Phys. Rev. C, accepted 23 Aug. 2019*



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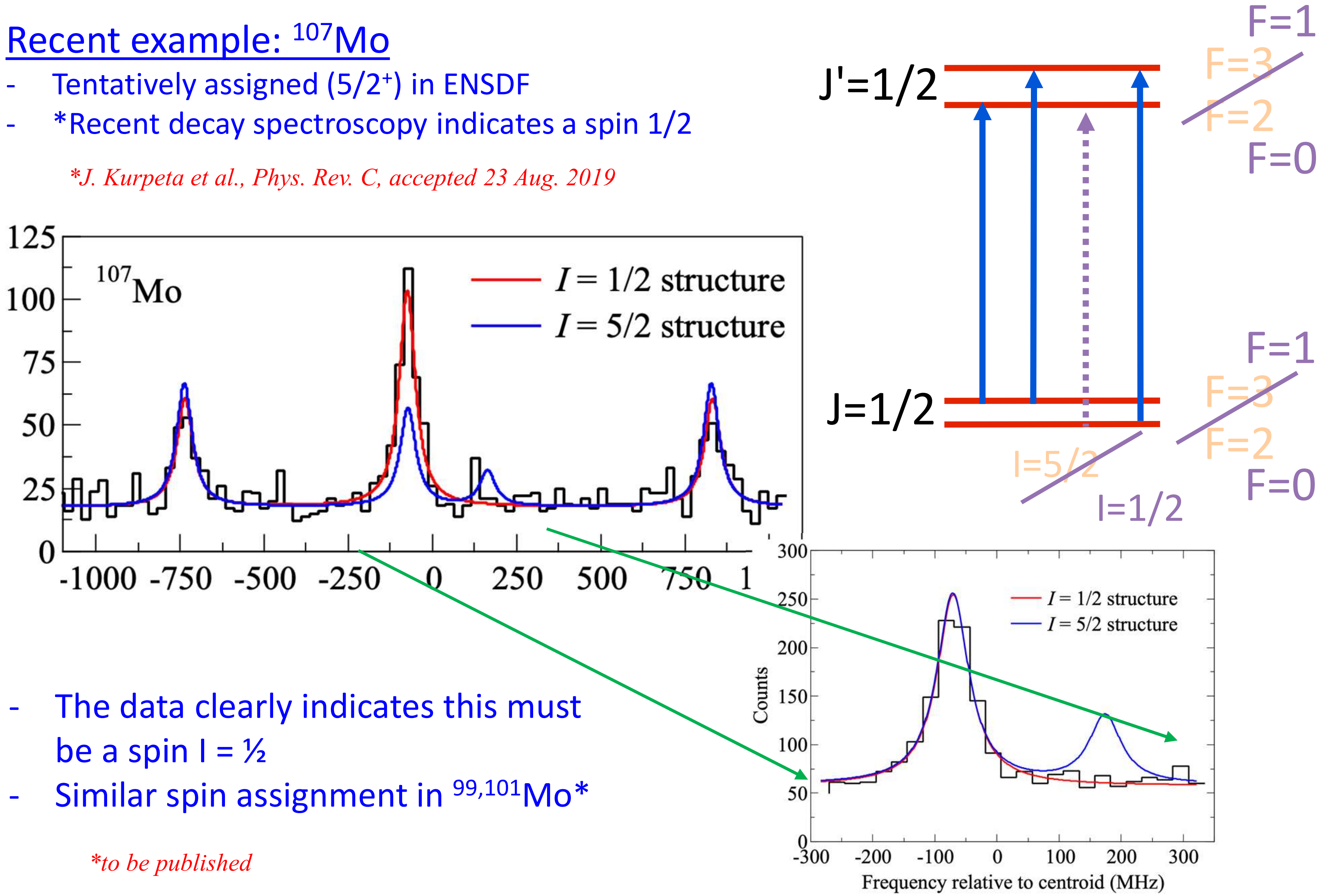

- The data clearly indicates this must be a spin I = ½
- Similar spin assignment in ^{99,101}Mo*

**to be published*

A more general case (= more complicated)

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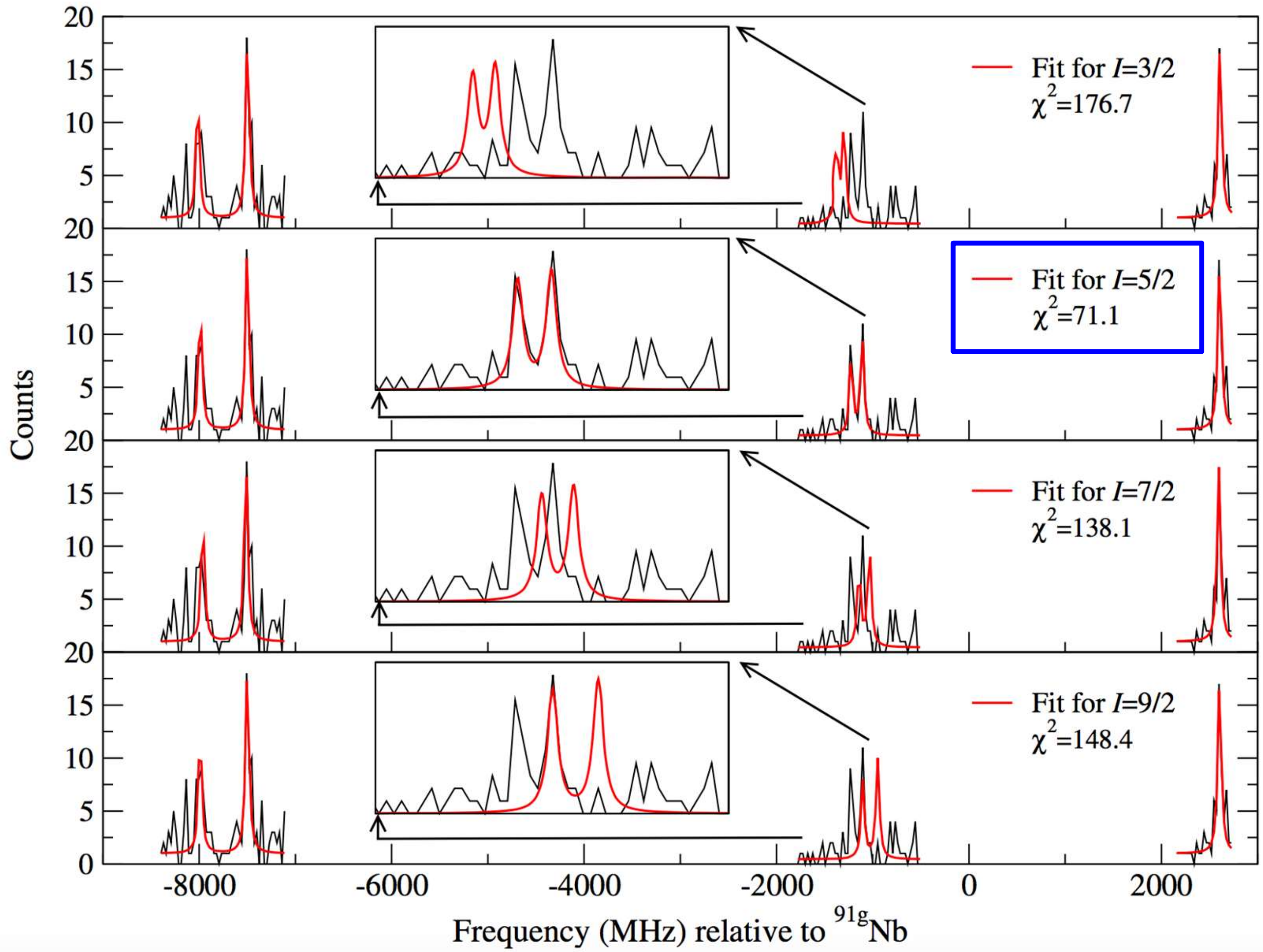
^{101}Nb
I=5/2

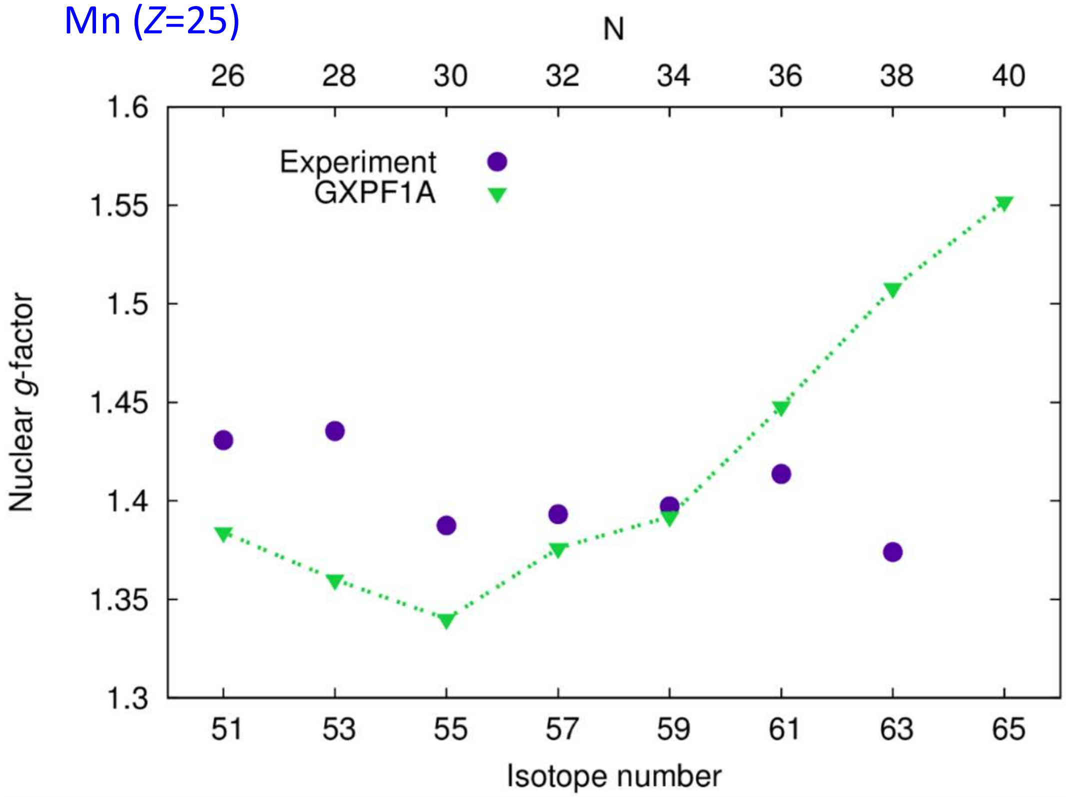


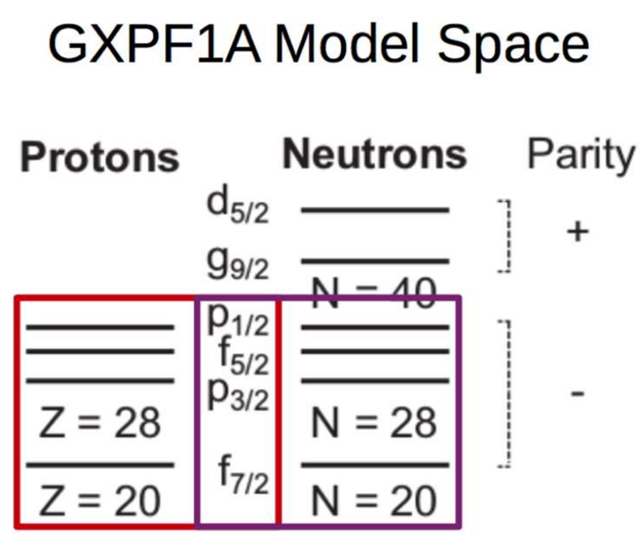
J = 1 → J' = 1 line

The frequency pattern can give the spin unambiguously

Magnetic moments and nuclear structure

- Looking at systematics, a sudden change of nuclear spin is reflected in the magnetic dipole moment – these parameters are importantly coupled
- Nuclear moments provide an exceptionally sensitive probe of the nuclear wave function and the different orbitals involved during the onset of collectivity (deformation)
- For example, suggestions of collectivity towards *N*=40 in Cr, Fe; test via optical spectroscopy in Mn (*Z*=25)

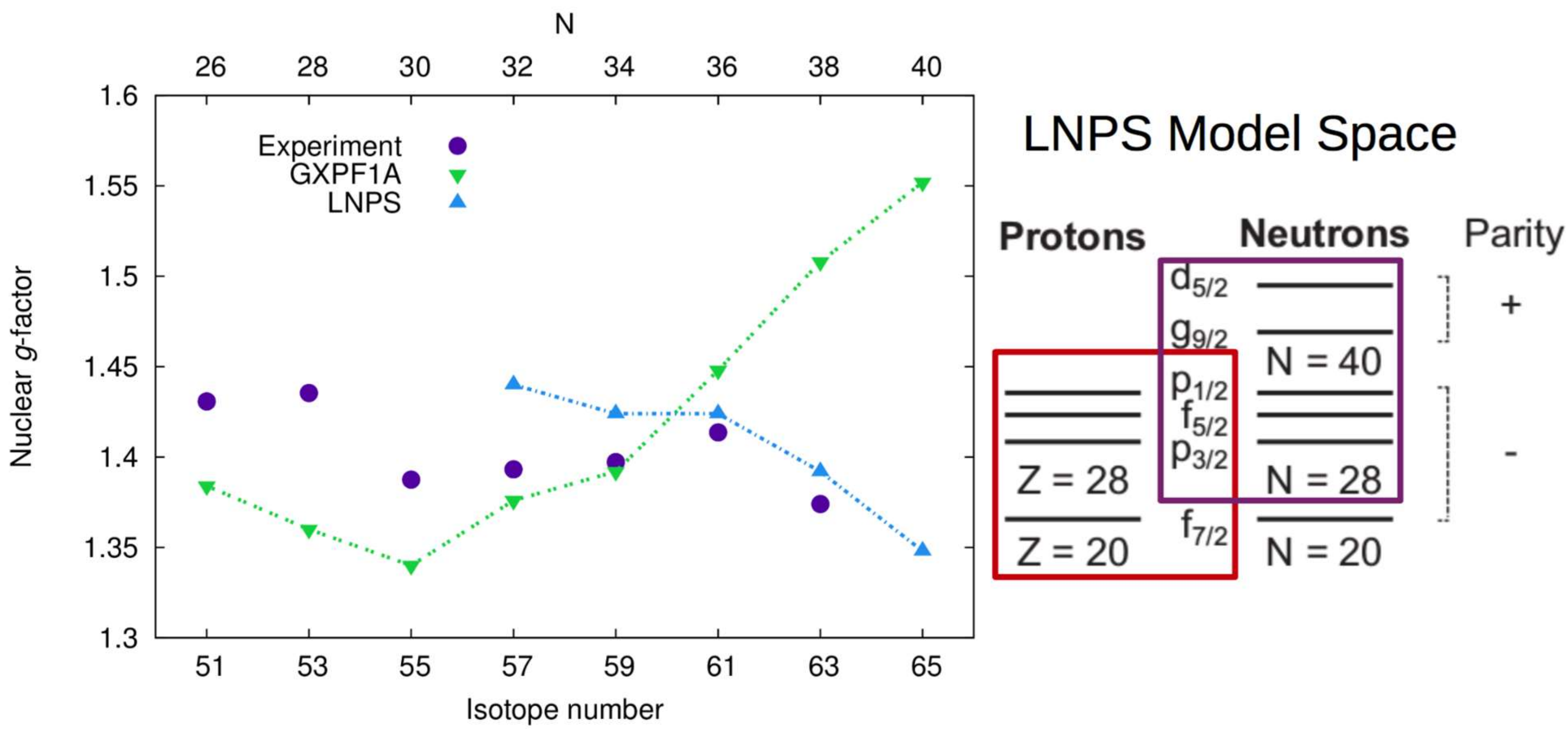




A model space with p and f shells alone cannot explain the data.

C. Babcock, H. Heylen et al., Phys. Lett. B 715 (2015) 176

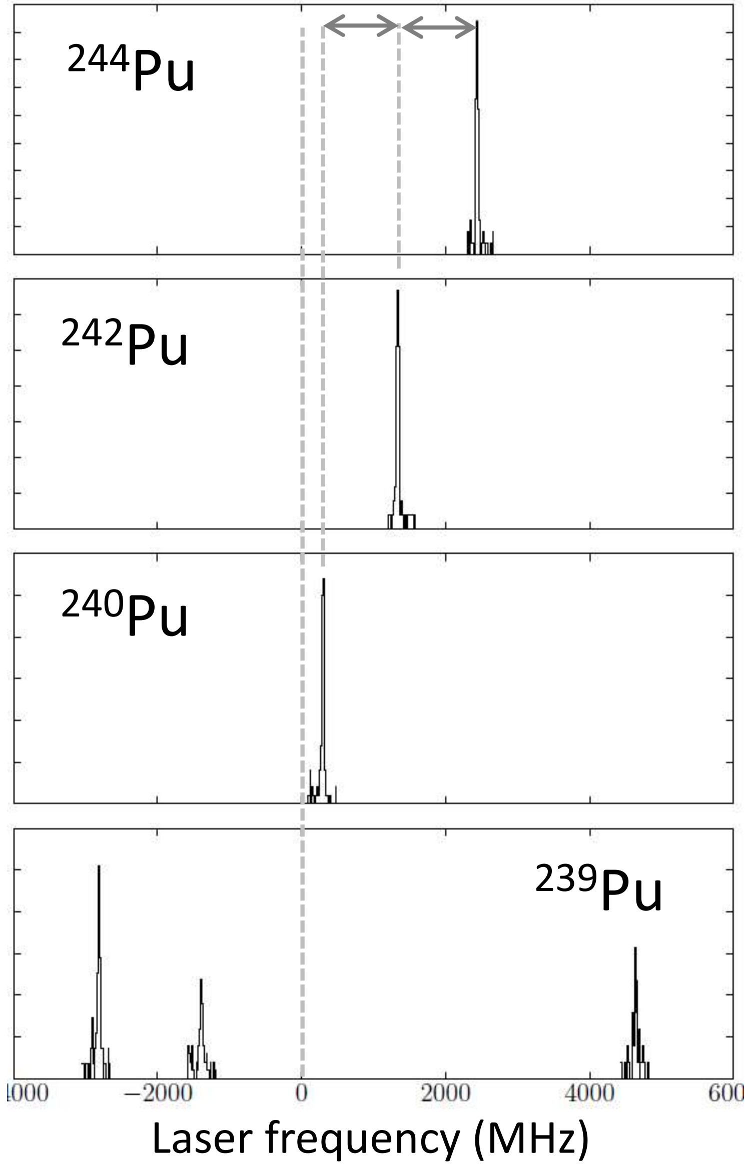
Magnetic moments and nuclear structure



- Extend the model space to include higher neutron orbitals (excitations indeed take place long before N = 40)
- Similarly, one can do the same probing using electric quadrupole moments!

C. Babcock, H. Heylen et al., Phys. Lett. B 760 (2016) 387

Isotopic shifts of electronic transitions



Two contributions to the isotope shift:

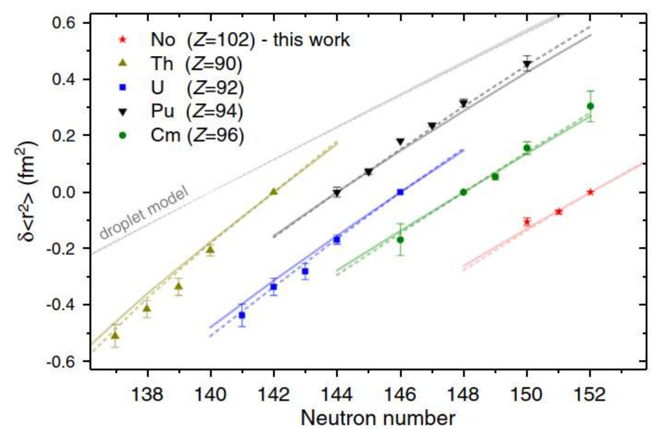
1) Finite nuclear mass
2) Finite nuclear volume (size)

Mass — Size

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

Depends on optical transition, i, only

Depends on isotopes only



S. Raeder et al., Phys. Rev. Lett. 120 (2018) 232503

Probing the nuclear size (and shape)

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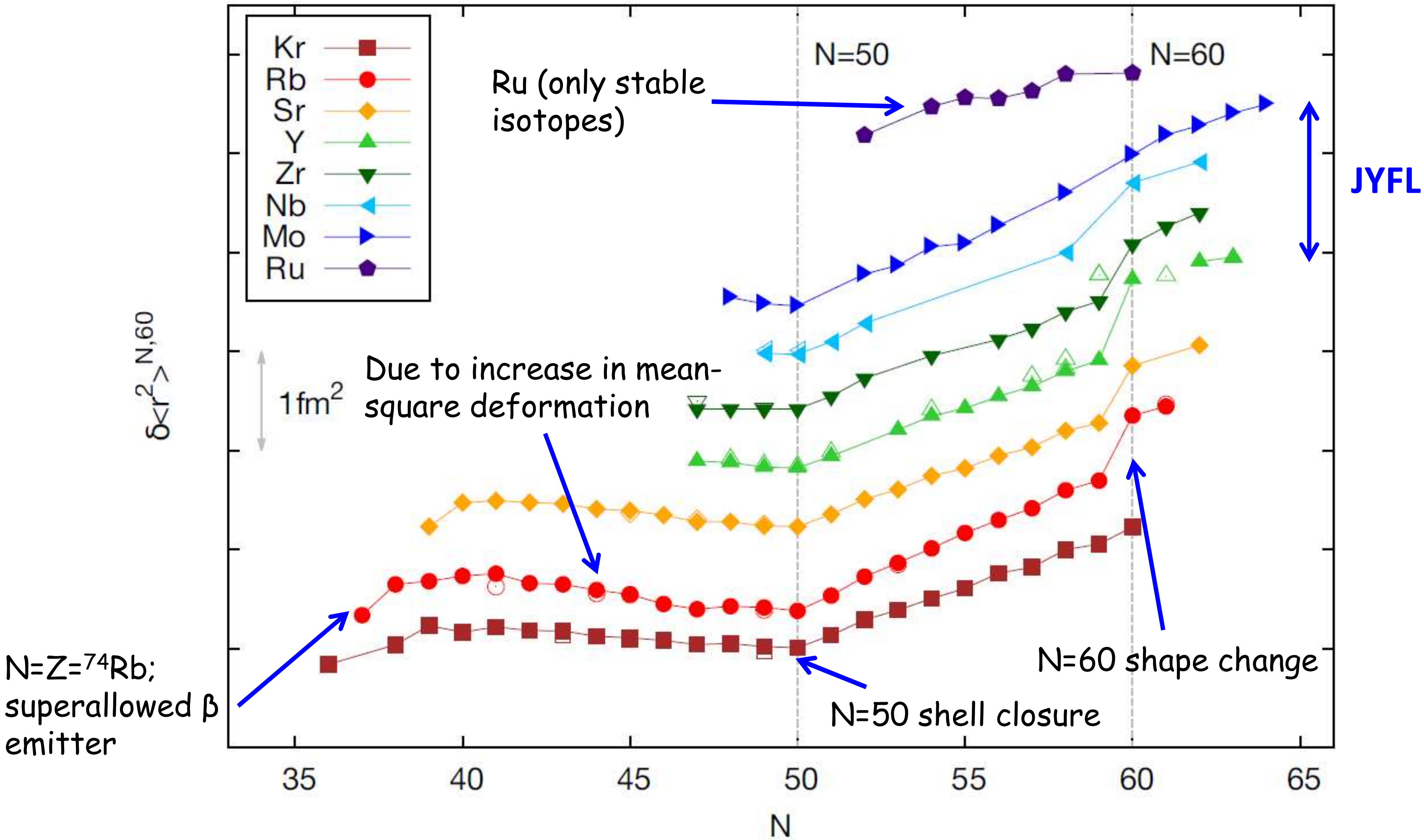
Size (droplet model)

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

Shape (Quadrupole term)



Complementarity: the nuclear mass surface

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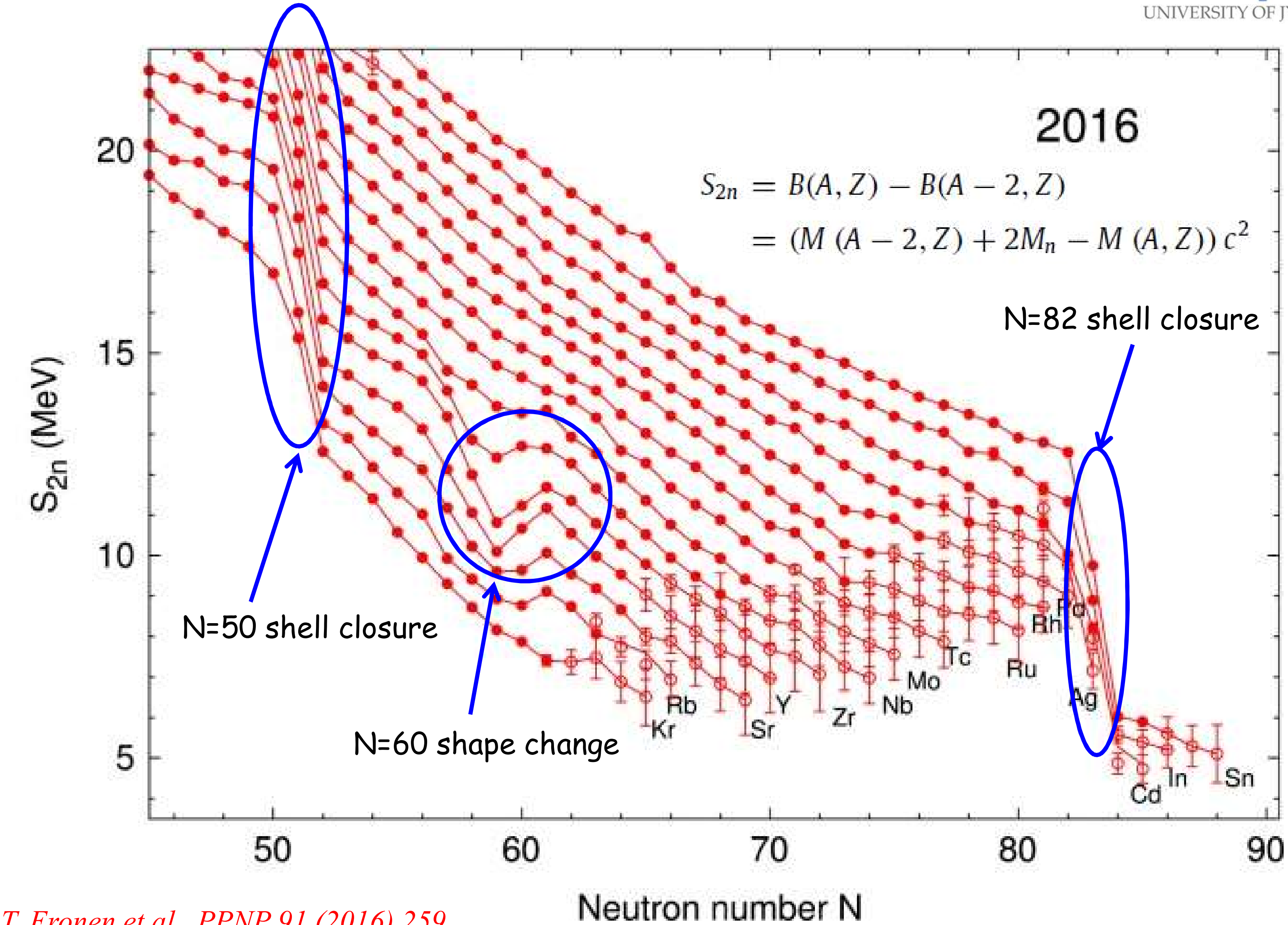
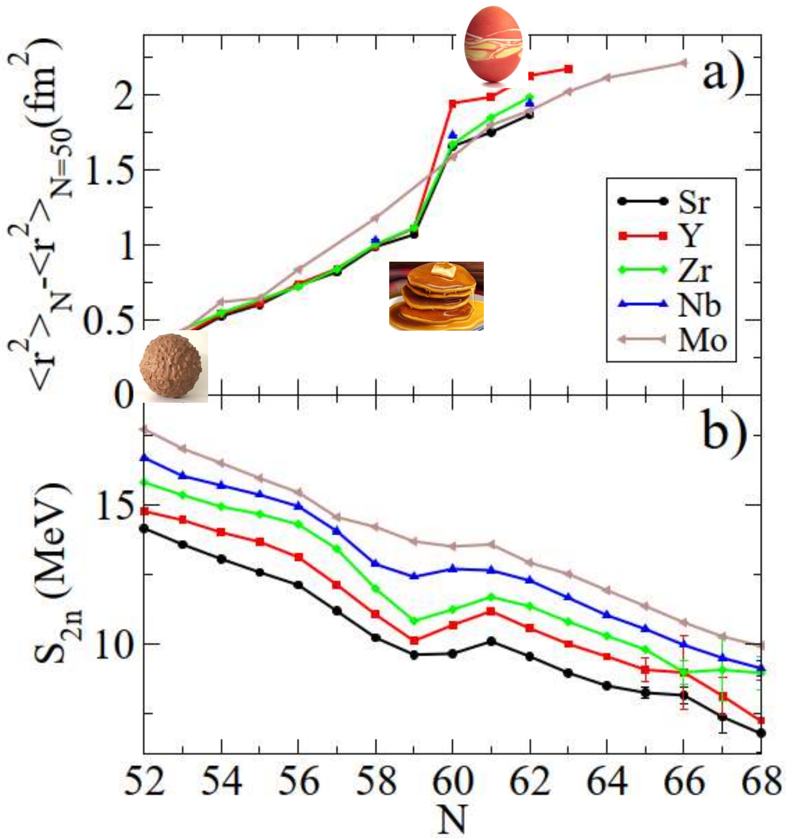


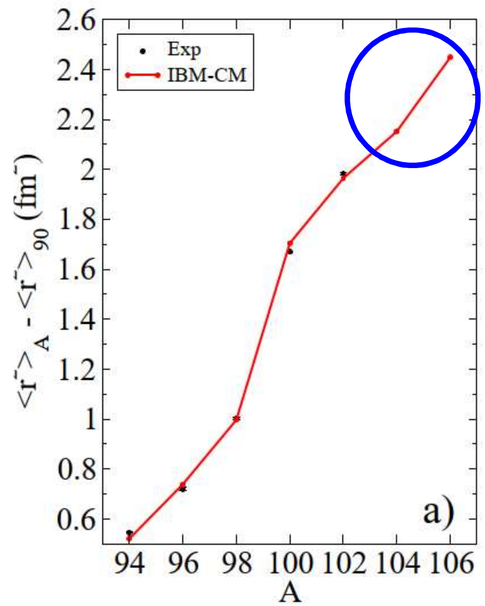
T. Eronen et al., PPNP 91 (2016) 259

The quest for shape coexistence in Zr isotopes

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



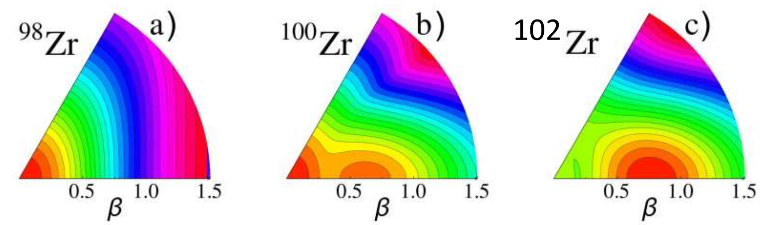
J.E. Garcia-Ramos and K. Heyde, arXiv:1909.00824



IBM-CM model

Max. change of isotopic shift:
~0.3 fm^2 in ^{96}Zr to
~0.7 fm^2 in ^{98}Zr

<u>Compare region of Pb</u>
Pt: ~0.07 fm^2
Hg: ~0.02 fm^2
Po: ~0.05 fm^2



Spherical *Coexistence* *Prolate*

Talk by A. Leviatan (Quantum phase transitions)

Deformation from the quadrupole moment

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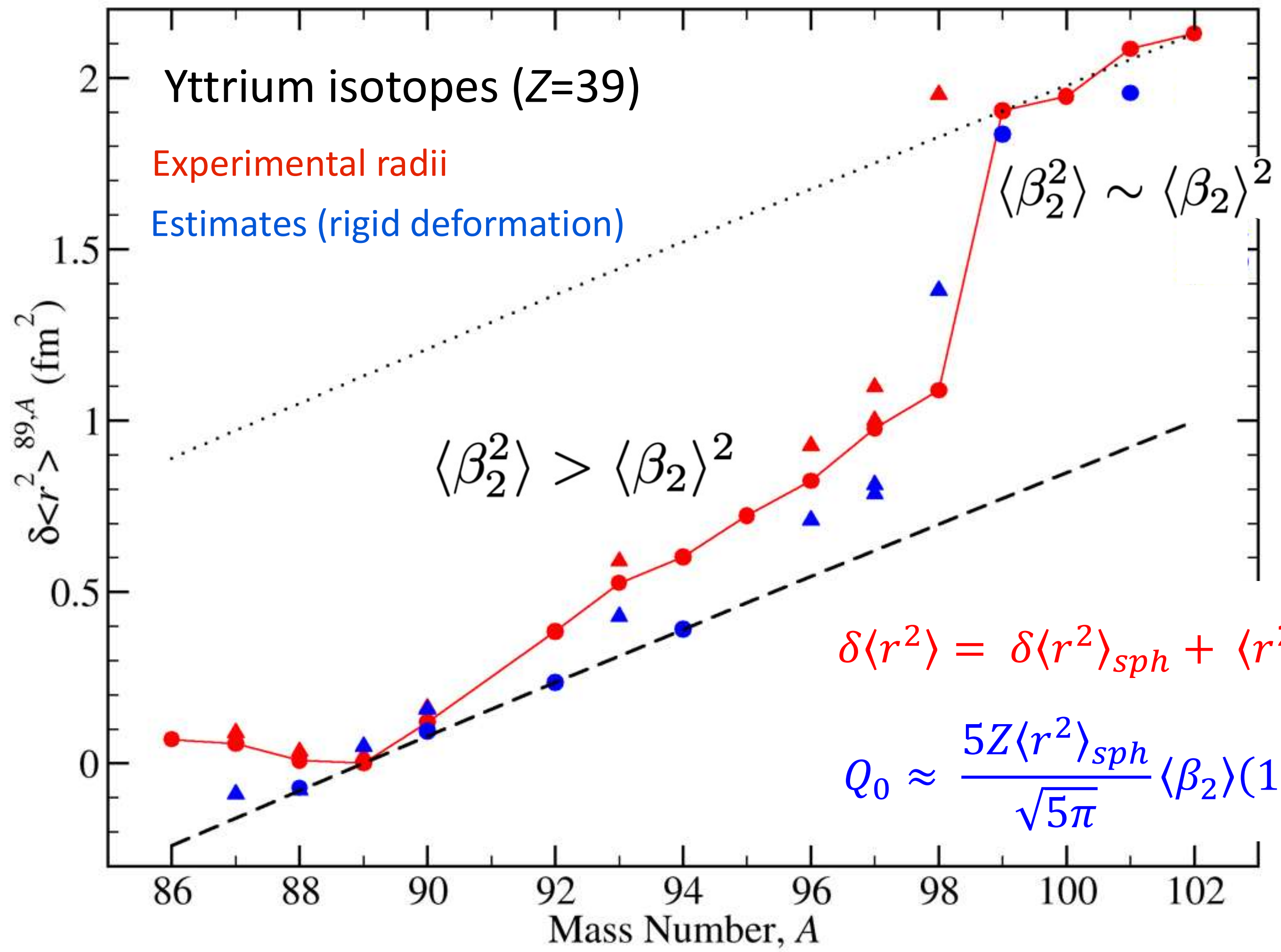
Compare estimates from quadrupole moments with results from charge radii.



$\delta\langle r^2\rangle \rightarrow \delta\langle\beta_2^2\rangle$

$Q_s \rightarrow \langle\beta_2\rangle$

$$\delta\langle r^2\rangle = \delta\langle r^2\rangle_{sph} + \langle r^2\rangle_{sph}\frac{5}{4\pi}\delta\langle\beta_2^2\rangle$$

$$Q_0 \approx \frac{5Z\langle r^2\rangle_{sph}}{\sqrt{5\pi}}\langle\beta_2\rangle(1+0.36\langle\beta_2\rangle)$$

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

Shape coexistence in ^{98}Y

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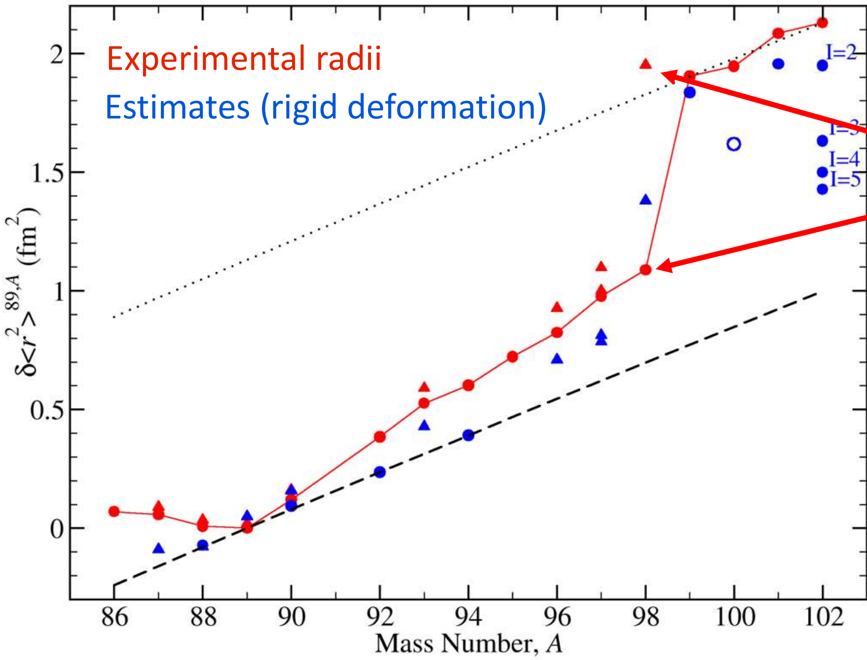

B. Cheal et al., Phys. Lett. B 645 (2007) 133.

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

^{98}Y ground state, I=0

- Largest deformation of all Y isotopes
- Earlier laser spectroscopy used J=0 → 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. Äystö[10]

Re-visiting ^{98}Y with optical spectroscopy

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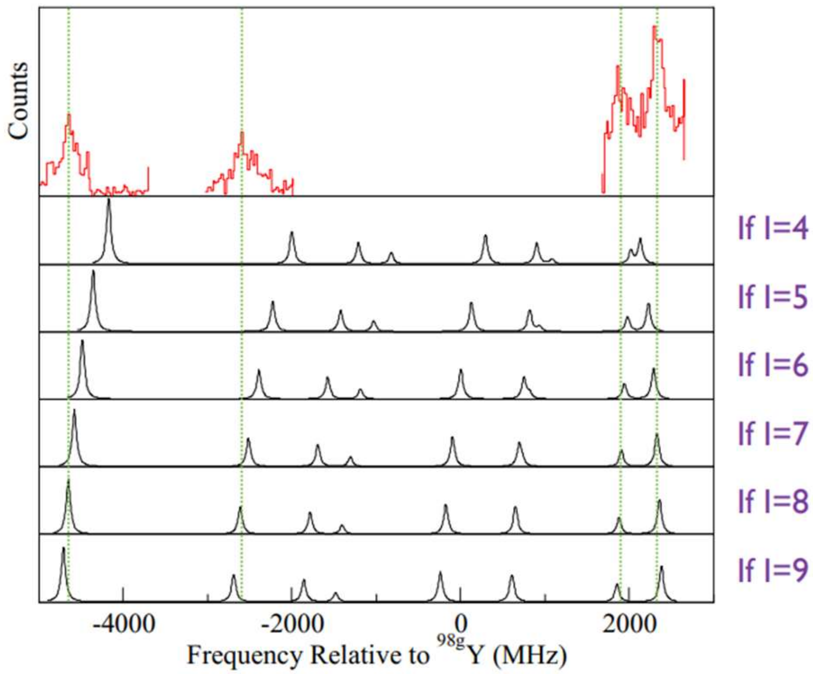
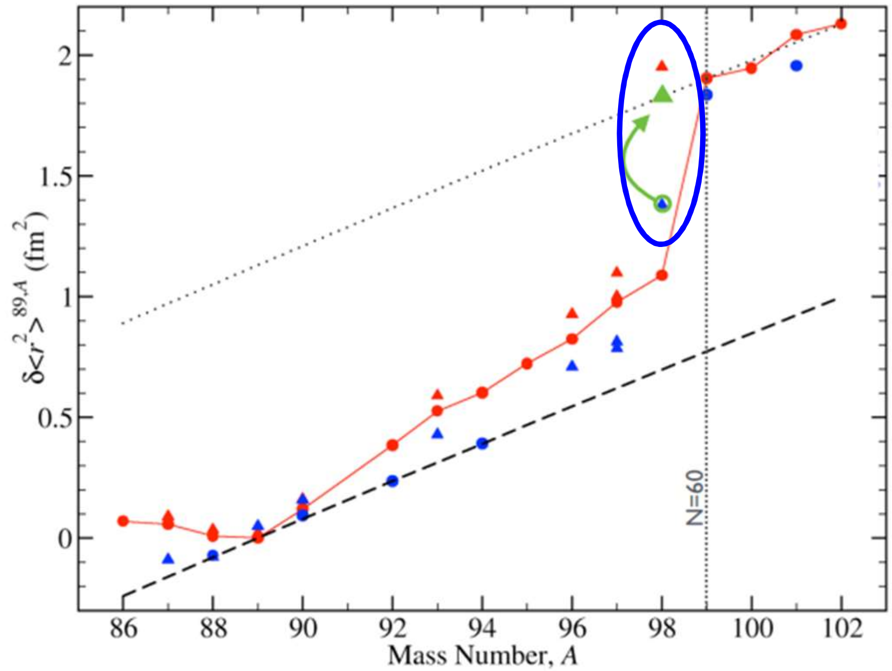
Use a different ionic transition (J = 2 → J' = 1)





- 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 μ = +2.62(2) μ_N
- The isomer has a much larger quadrupole moment with strong prolate deformation which is very rigid

Charge radii near the Sn region

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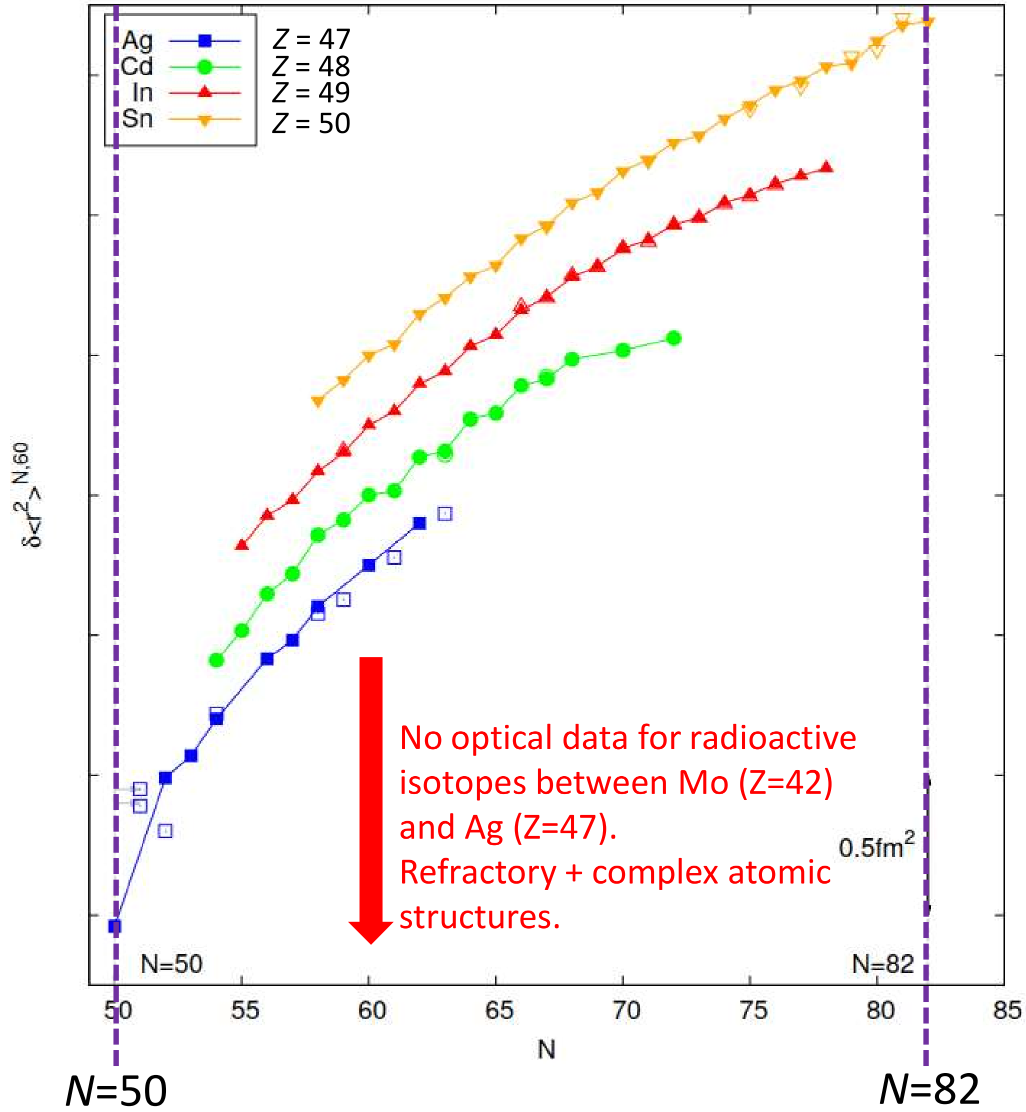

- Persistent and regular trends throughout the major shell (valence space of 32 neutrons)

- Quadrupole contribution, proportional to product of particles and holes, with constant odd-even staggering, added to linearly increasing <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

New results from IGISOL (2018-2019)

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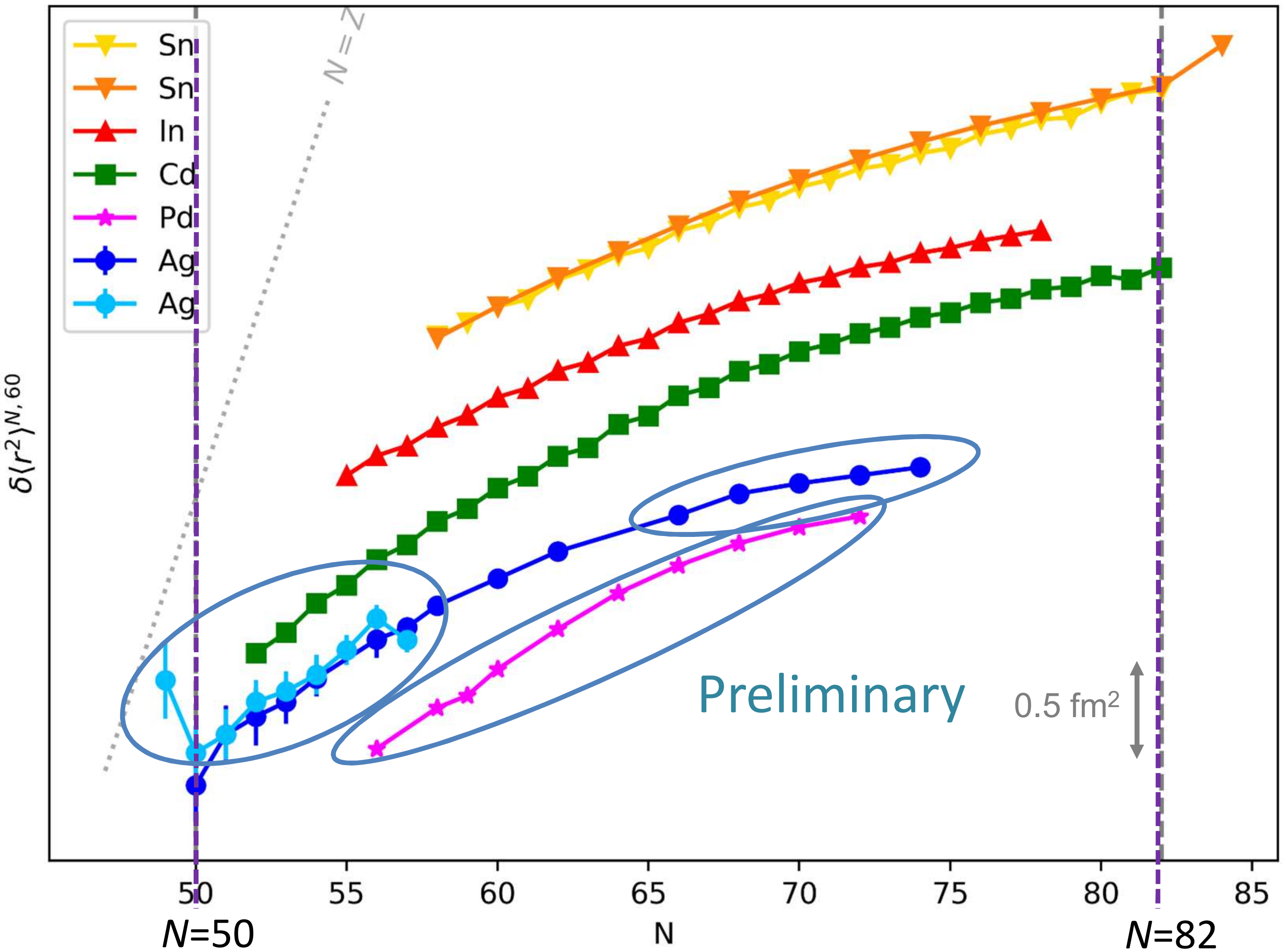


New data since PPNP review (2016)

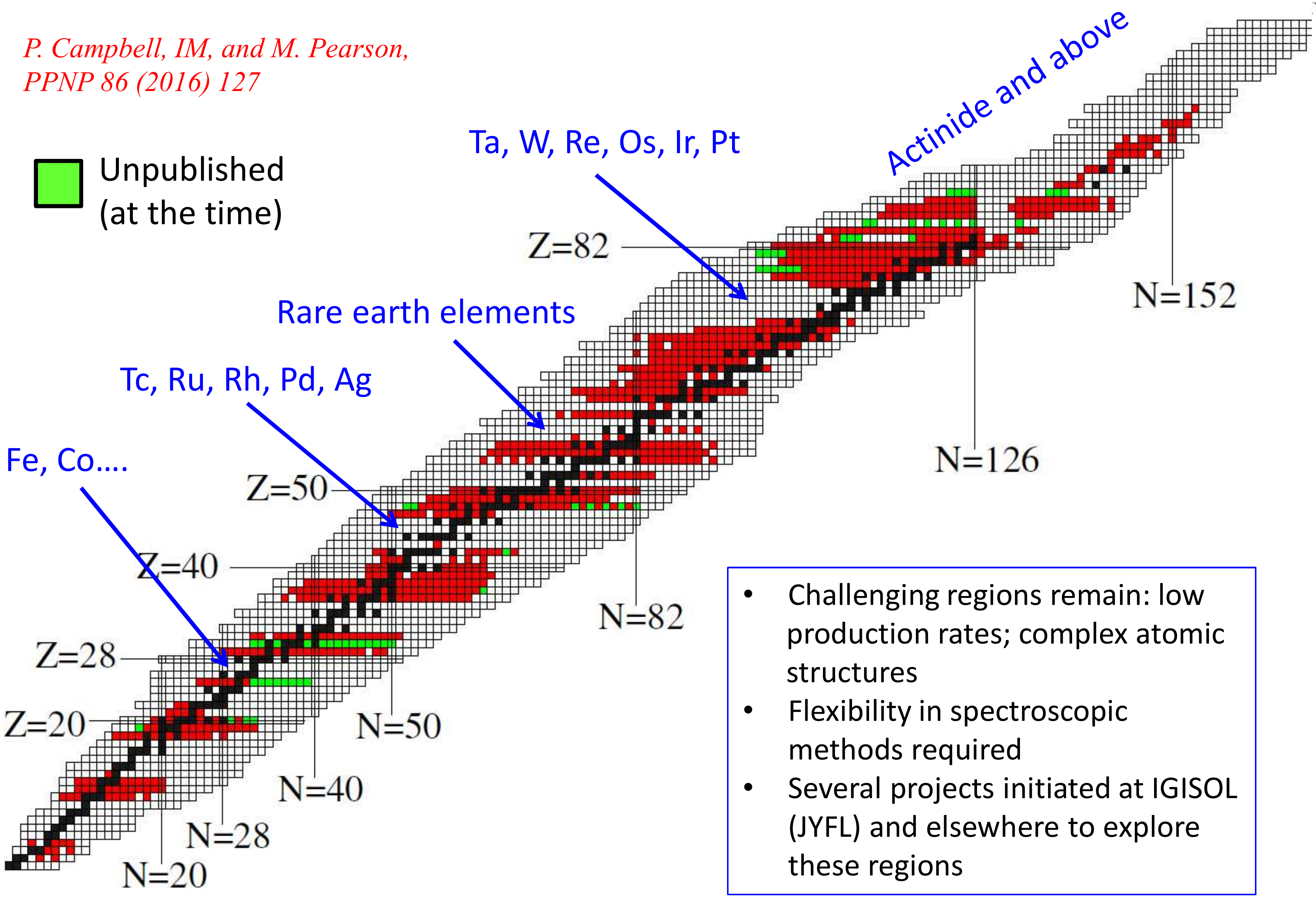
Cd: *M. Hammen et al., PRL 121 (2018) 102501*

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

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

A laser spectroscopists' nuclear landscape

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



- Challenging regions remain: low production rates; complex atomic structures
- Flexibility in spectroscopic methods required
- Several projects initiated at IGISOL (JYFL) and elsewhere to explore these regions

Summary & outlook

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- Laser spectroscopy is a powerful tool which provides access to fundamental ground (and isomeric) state nuclear structure, complementary to other methods but importantly free from model dependencies
- Extract nuclear spins, magnetic properties (single-particle), electric properties (collective), charge radii, nuclear state identification
- Testing theoretical models (shell model, density functional approaches, ab-initio….)

- Array of techniques, traditionally either high resolution OR highly sensitive (collinear, in-source laser resonance ionization)
- CRIS, in-gas-jet spectroscopy are aimed at combining these two properties
- Novel methods of production, ion/atom & optical manipulation required to access more challenging elements
- Future facilities (SPIRAL2, FAIR, FRIB….)

Thank you

P. Campbell

B. Cheal, C. Devlin

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

https://www.jyu.fi/igisol