What can we learn about nuclear structure from charge radii & electromagnetic moments

Lecture 4

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Outline of Lecture 4

- Back to some basics for charge radii
- Charge radii of exotic nuclei - light atoms, shell closures and deformation
- Magnetic moments – a reminder
- Example – the Zinc isotope chain*

*Links to the discussion paper: Wraith *et al*, Phys Lett. B (2017).

The nuclear radius: back to basics

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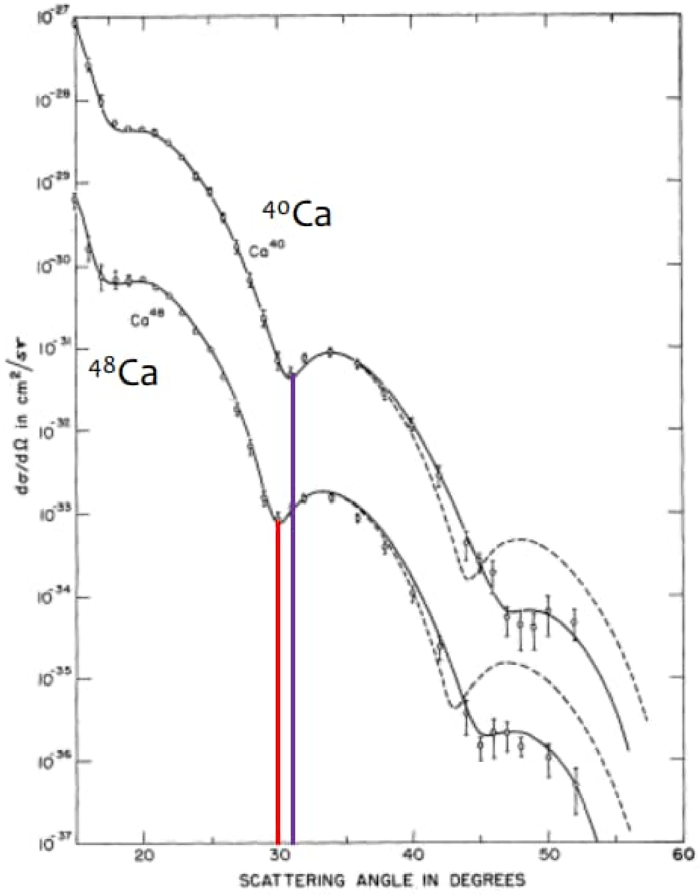
The majority of modern day experiments apply electromagnetic probes to obtain (absolute) nuclear radius information – preferably point-like, e.g., electrons and muons.



J.B. Bellicard et al., Phys. Rev. Lett. 19 (1967) 527

- In (elastic) electron scattering experiments, a precise spectrometer is used to analyze the electrons scattered from a nuclear target.
- Diffraction-like minima seen (similar to plane waves in optics).

Robert Hofstader: Nobel prize in physics in 1961:
Pionering studies of electron scattering on atomic nuclei.

Elastic electron scattering

<u>General analysis procedure:</u>

In Rutherford scattering: non-relativistic; interaction between electric charges, point like (and spinless)

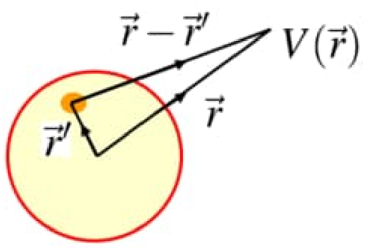
$$\left(\frac{d\sigma}{d\Omega}\right)_R = \frac{\alpha^2}{16E_k^2 \sin^4\left(\frac{\theta}{2}\right)}$$

Mott scattering adds a correction term to account for relativistic electron energies:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{16E^2 \sin^4\left(\frac{\theta}{2}\right)}\left(1 - \beta^2 \sin^2\left(\frac{\theta}{2}\right)\right)$$

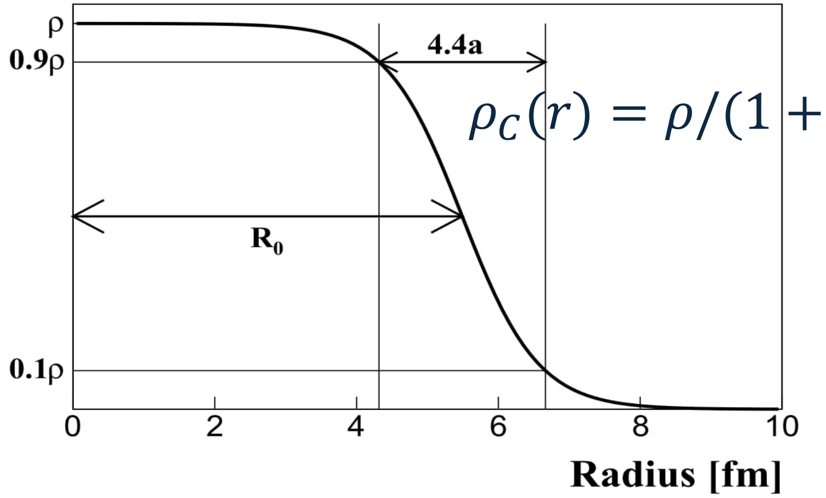
The nuclear Form factor accounts for the fact that the nucleus is not point-like, it has a finite size charge distribution.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left|F\left(\mathbf{q}^2\right)\right|^2$$



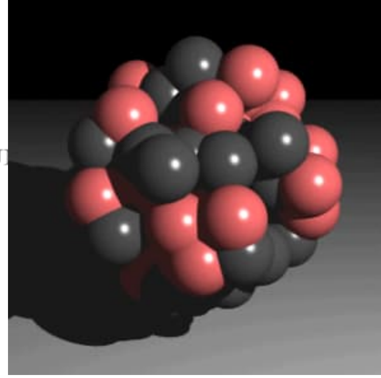
$$F\left(\mathbf{q}^2\right) = \int d^3\mathbf{r}\ \rho(\mathbf{r}) \cdot e^{i\mathbf{qr}}$$

Woods-Saxon charge distribution commonly used.



$$\rho_C(r) = \rho/(1 + e^{(r-R)/a})$$

Charge distributions from scattering



Extensive studies of stable nuclei with electron scattering experiments revealed:

- Nuclei are approximately a spherical ball of fixed density
- Scattering data agree well with a Fermi-type (Woods-Saxon) model of the nucleus
- The scattering minima occur at the same position….R ~$A^{1/3}$

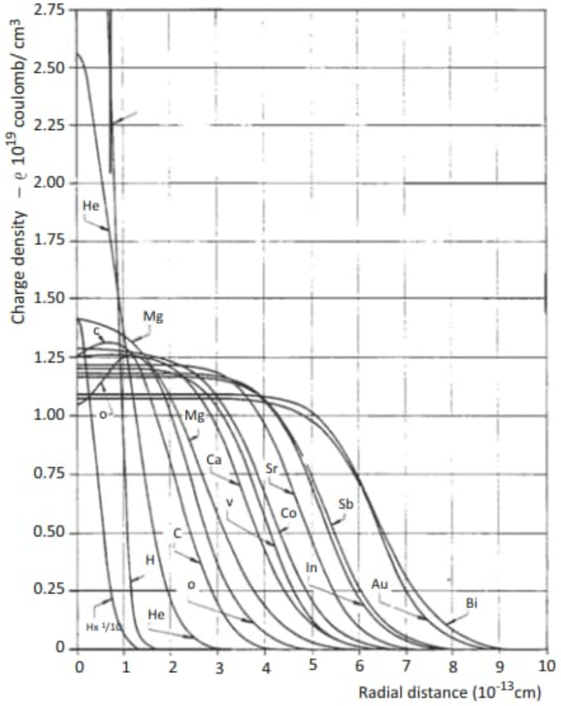


Figure from Hofstadter Nobel Prize lecture, 1961.

TABLE IV. Results of the analysis of nuclei in terms of the Fermi smoothed uniform charge distribution. All lengths are in Fermi units, charge densities in 10^{19} coulombs/cm^3. The accuracy of these results is thought to be: radial parameters, ±2%; surface thickness parameter, ±10%. For lighter elements, the errors are probably larger. The accuracy for gold is higher. *R* is the radius of uniform charge distribution having the same rms radius as the Fermi distribution.

taken from ref. [7]

Nucleus	c	t	R	$c/A^{\frac{1}{3}}=r_1$	$R/A^{\frac{1}{3}}=r_0$
$_{20}Ca^{40}$	3.64	2.5	4.54	1.06	1.32
$_{23}V^{51}$	3.98	2.2	4.63	1.07	1.25
$_{27}Co^{59}$	4.09	2.5	4.94	1.05	1.27
$_{49}In^{115}$	5.24	2.3	5.80	1.08	1.19
$_{51}Sb^{122}$	5.32	2.5	5.97	1.07	1.20
$_{79}Au^{197}$	6.38	2.32	6.87	1.096	1.180
$_{83}Bi^{209}$	6.47	2.7	7.13	1.09	1.20

Parameters from Fermi-model

The mean-square charge radius can be defined:

$$\langle r^2 \rangle = \frac{\int r^2 \rho_{ch}(r) dV}{\int \rho_{ch}(r) dV}$$

The trend of the mean-square charge radii has the form:

$$\langle r^2 \rangle = \frac{3}{5}\left(r_0 A^{\frac{1}{3}}\right)^2$$

Thus the rms charge radius $R = \sqrt{\langle r^2 \rangle}$ was seen to scale with $A^{\frac{1}{3}}$

Great! So we can all go home…..however….

Electron scattering vs optical spectroscopy

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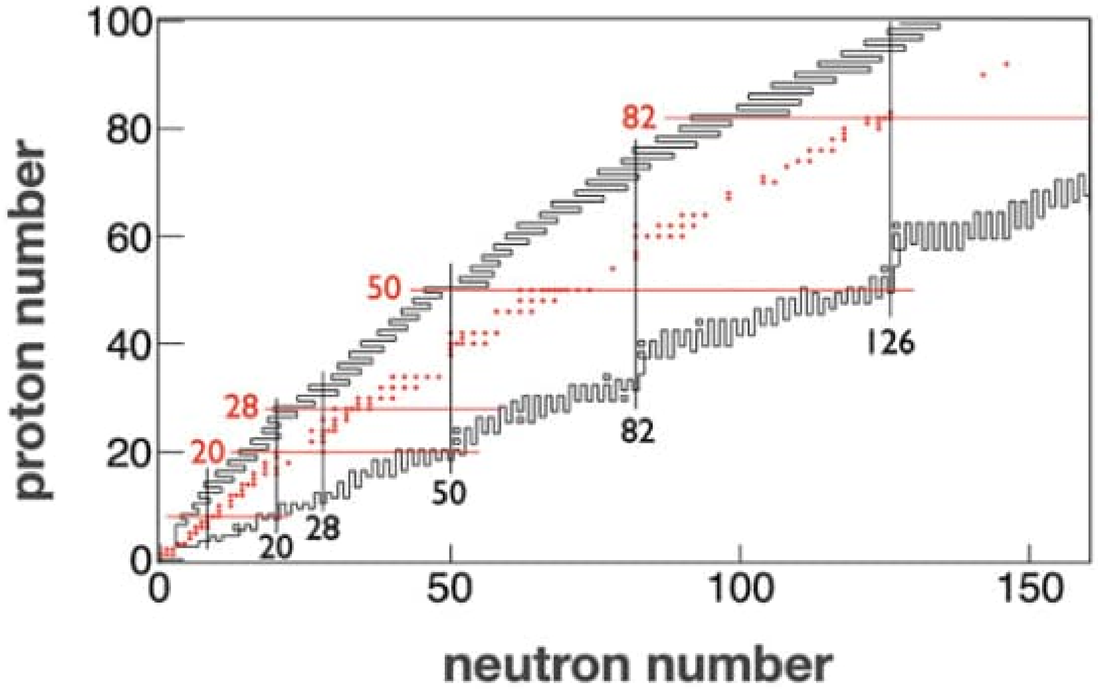
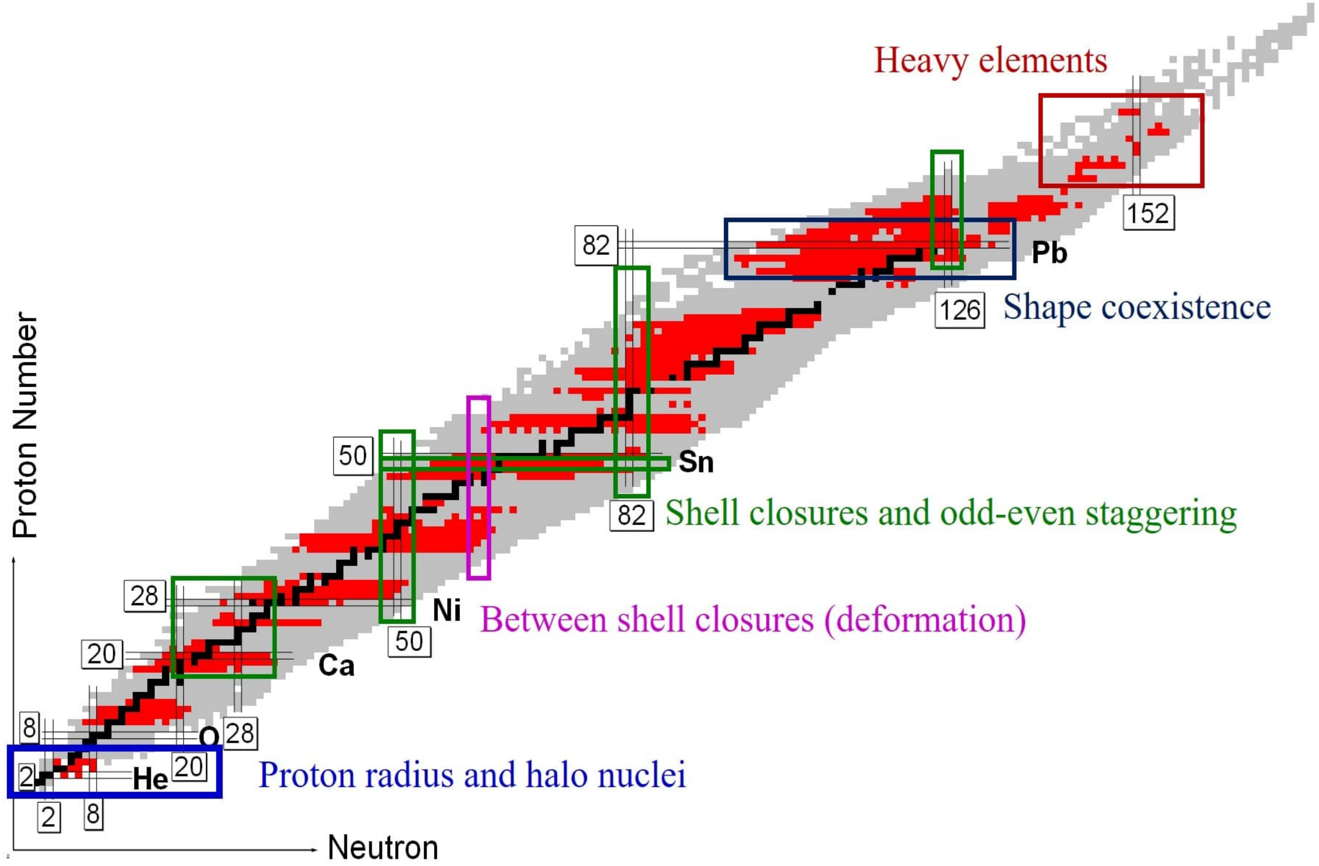
Unfortunately, scattering experiments (generally) cannot be applied to exotic radioactive nuclei. Optical spectroscopy however provides us with the required sensitivity to probe changes in mean-square charge radii across long chains of isotopes far from stability.



T. Suda, Electron scattering off stable and unstable nuclei, Handbook of Nuclear Physics (2023)



Nörtershäuser and Moore, Nuclear Charge Radii, Handbook of Nuclear Physics (2023)

SCRIT – a world's first in the RIKEN RI factory

``Self-Confining Radioactive isotope Ion Target´´

- 150 MeV injector and storage ring for electrons (150-700 MeV)
- ISOL method for unstable nuclei

  Photofission of U / FEBIAD / Surface ionization

- Cooler & buncher for RI beams → 2*10^7 ^{137}Cs /pulse injected into SCRIT

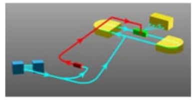
Featured in Physics | Editors' Suggestion

First Observation of Electron Scattering from Online-Produced Radioactive Target

K. Tsukada, Y. Abe, A. Enokizono, T. Goke, M. Hara, Y. Honda, T. Hori, S. Ichikawa, Y. Ito, K. Kurita, C. Legris, Y. Maehara, T. Ohnishi, R. Ogawara, T. Suda, T. Tamae, M. Wakasugi, M. Watanabe, and H. Wauke

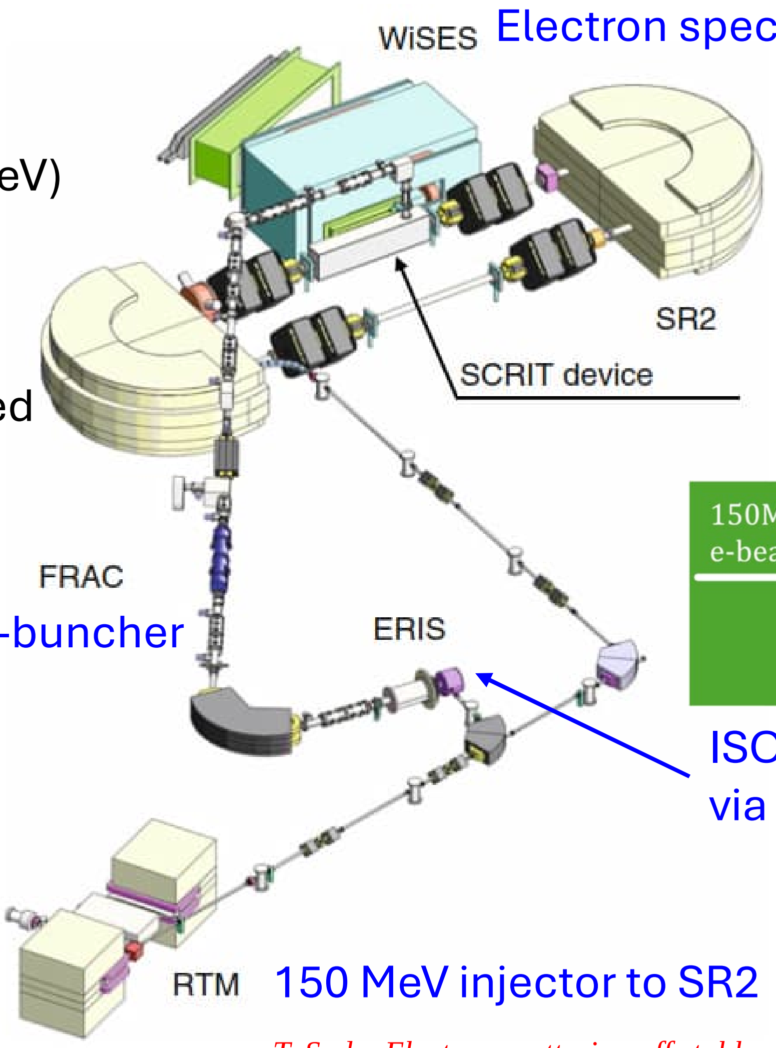
Phys. Rev. Lett. **131**, 092502 (2023) – Published 30 August 2023

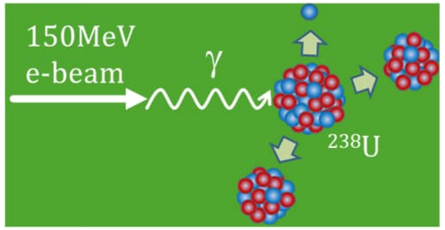
Physics Viewpoint: What Do Unstable Atomic Nuclei Look Like?



The first electron-scattering experiment off unstable radioisotopes marks a milestone for understanding the shape of exotic atomic nuclei.

Show Abstract +





T. Suda, Electron scattering off stable and unstable nuclei, Handbook of Nuclear Physics (2023)

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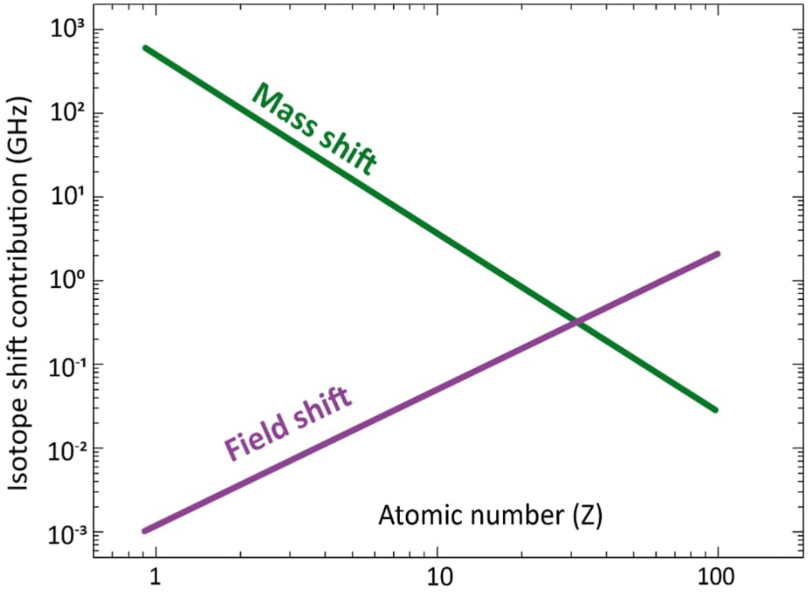
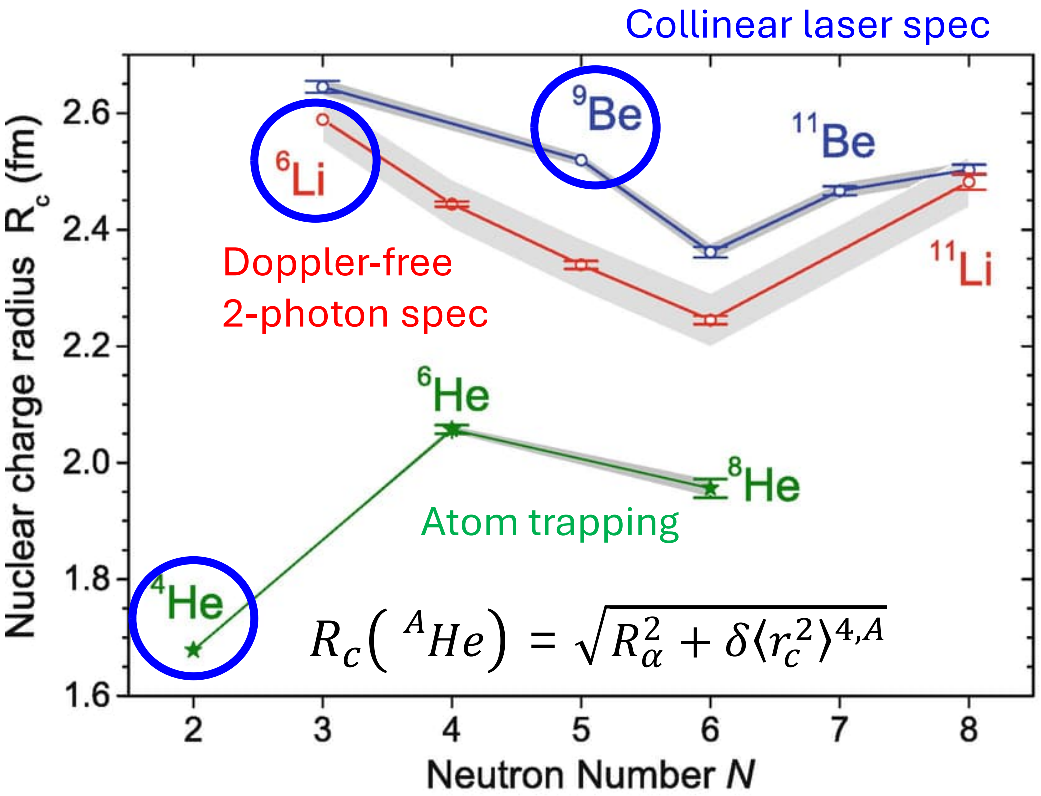
Nuclear charge radii of exotic nuclei

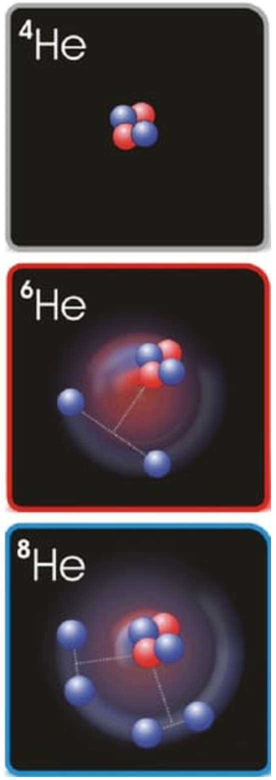
Nuclear charge radii of the lightest nuclei

Reminder: $\delta\nu_i^{A,A'} = K_i \dfrac{m_{A'} - m_A}{m_A\, m_{A'}} + F_i \boxed{\delta\langle r^2\rangle^{A,A'}}$

$\delta\langle r^2\rangle^{A,A'} = \langle r^2\rangle^{A} - \langle r^2\rangle^{A'}$



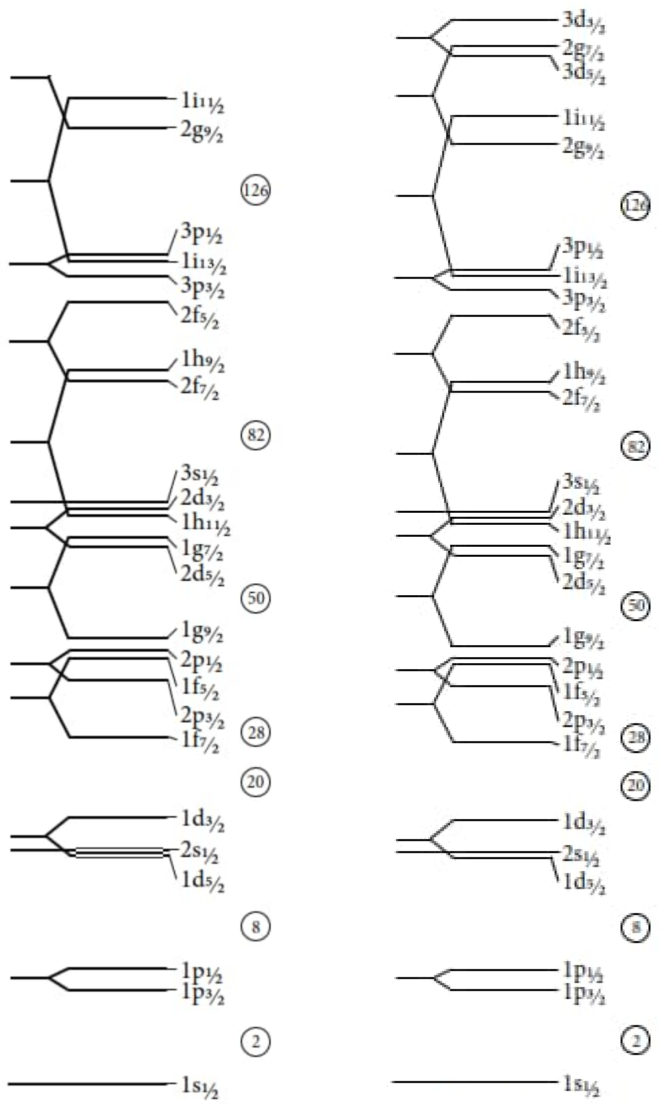


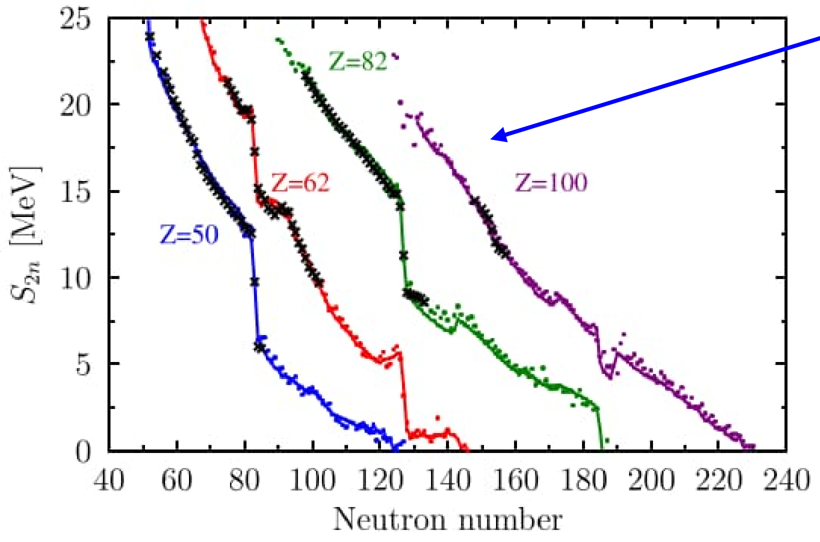


- Cornerstones for *ab inito* calculations due to a small number of nucleons
- Intriguing features – clustering; halos of nuclear matter extending to very large radii.
- State-of-the-art experiments and precise atomic mass-shift calculations needed

Nörtershäuser and Moore, Nuclear Charge Radii, Handbook of Nuclear Physics (2023)

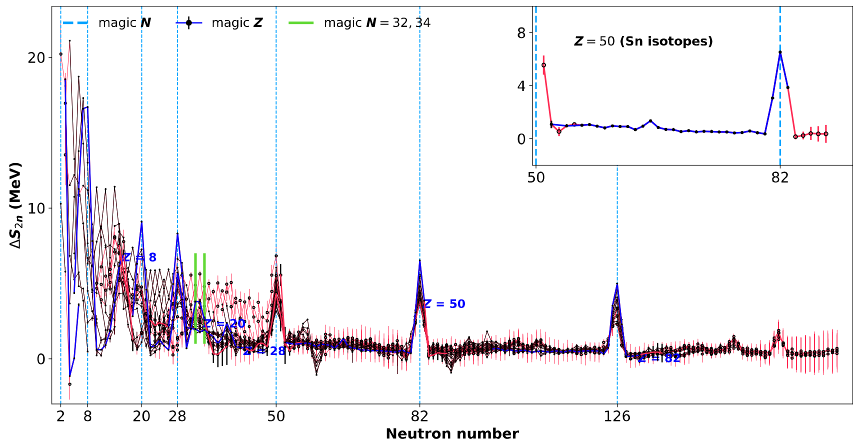
Reminder: the nuclear shell model



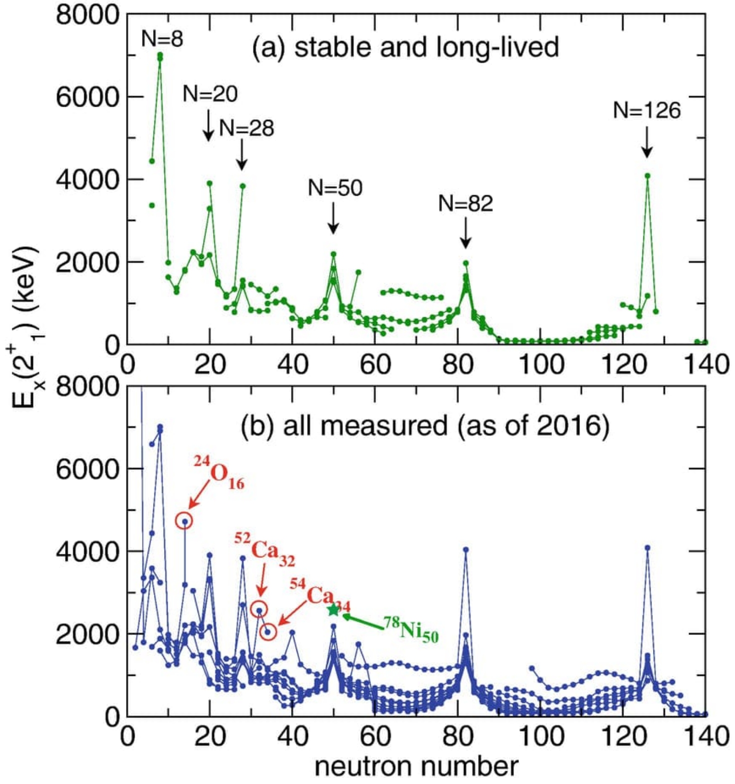


G. Scamps et al., Eur. Phys. J A 57 (2021) 333.

- AME2020 (black crosses)
- HFB-21 (dots)
- BSkG1 (lines)

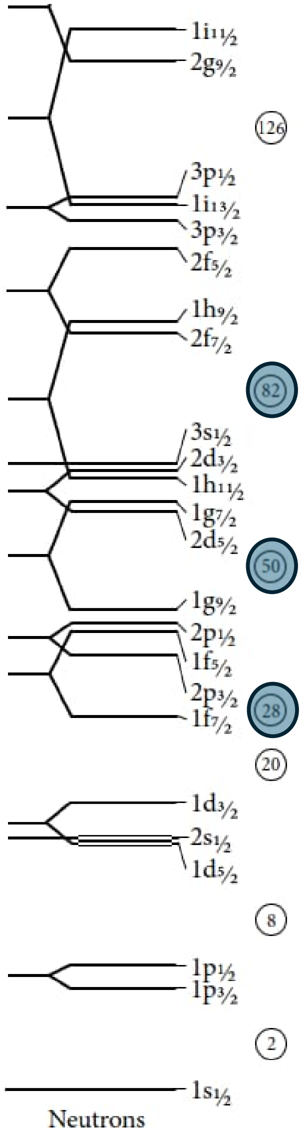


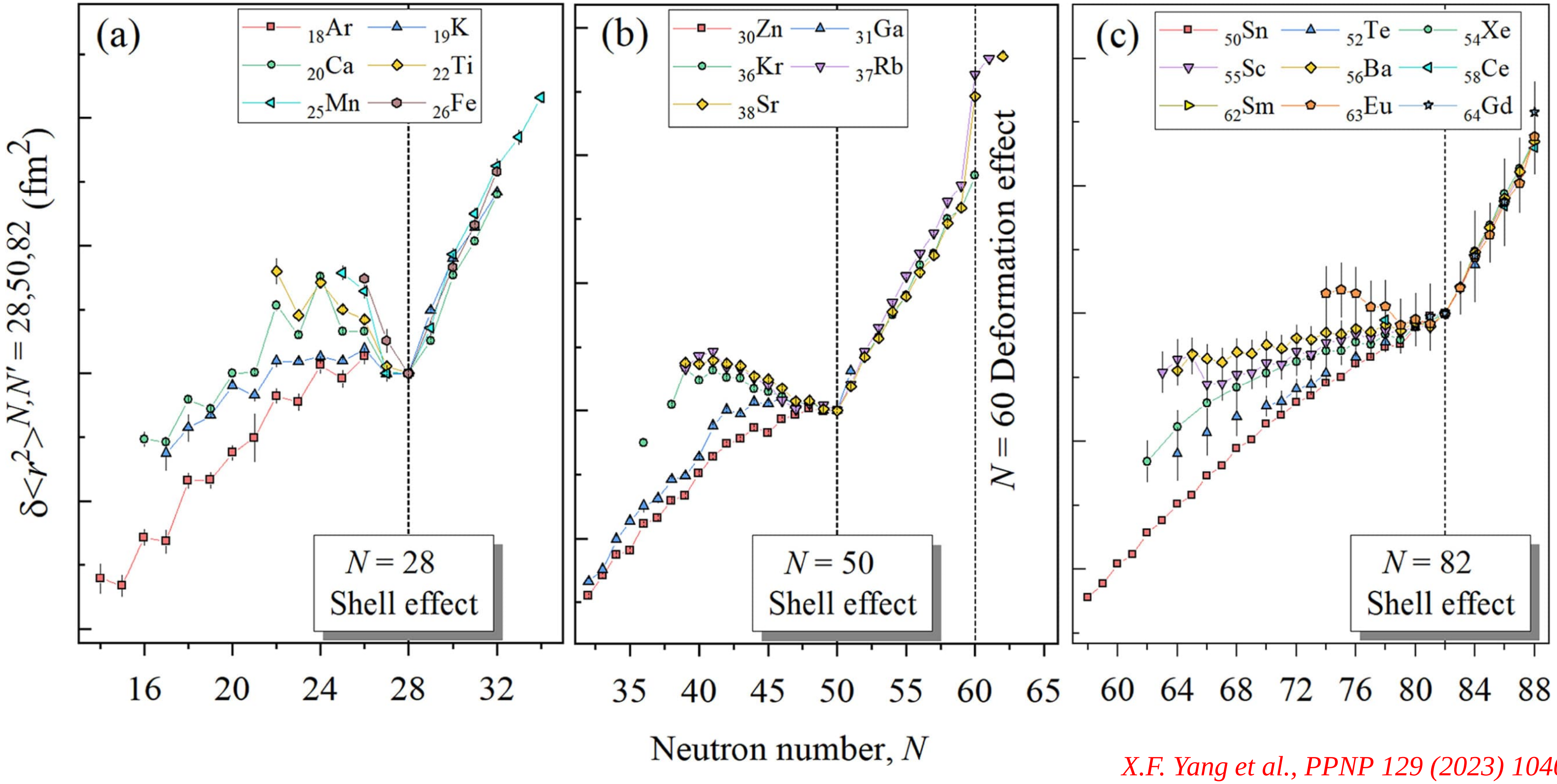
$\Delta S_{2n}(N,Z)$ shell gap energies



Otsuka et al., Rev. Mod. Phys. 92 (2020) 015002

Nuclear shell effects - ``kinky´´ trends!





X.F. Yang et al., PPNP 129 (2023) 104005

- The effect of all neutron shell closures for N≥28 is visible as a kink in the charge radii
- Much theoretical effort employed, including *ab initio* and DFT approaches
- Odd-even staggering effects are probed via isotope shift measurements.

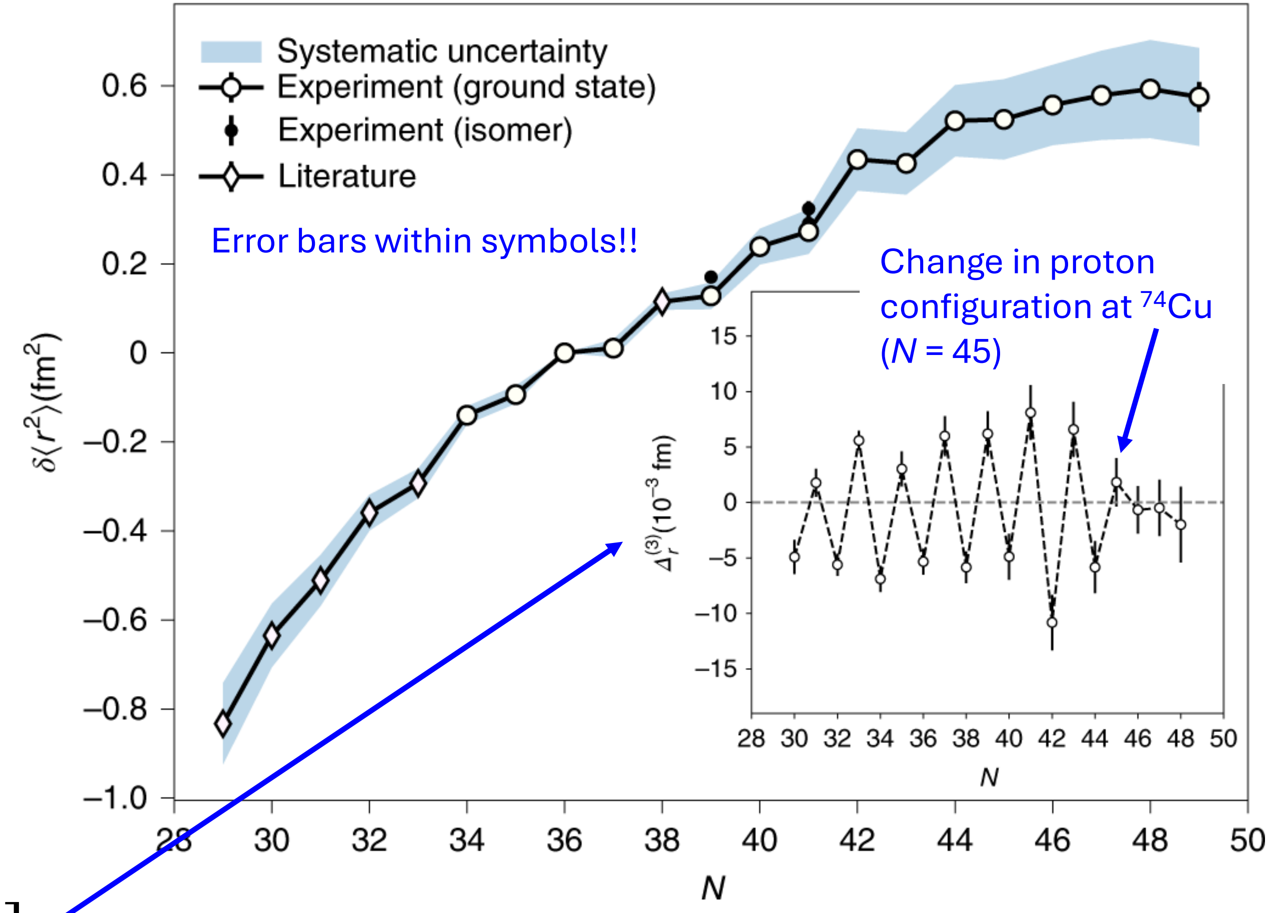
Odd-even staggering in the radii

- Odd-even staggering in charge radii is seen throughout the nuclear landscape. Generally it is very small in comparison to the total radius, however we are sensitive to this in laser spectroscopy.
- Typically, an isotope with an odd neutron number is slightly smaller than the average of the two neighboring even-N isotopes.
- An explanation may point towards a reduction of pairing correlations due to the unpaired neutron….

It may be quantified via a so-called 3-point difference formula:

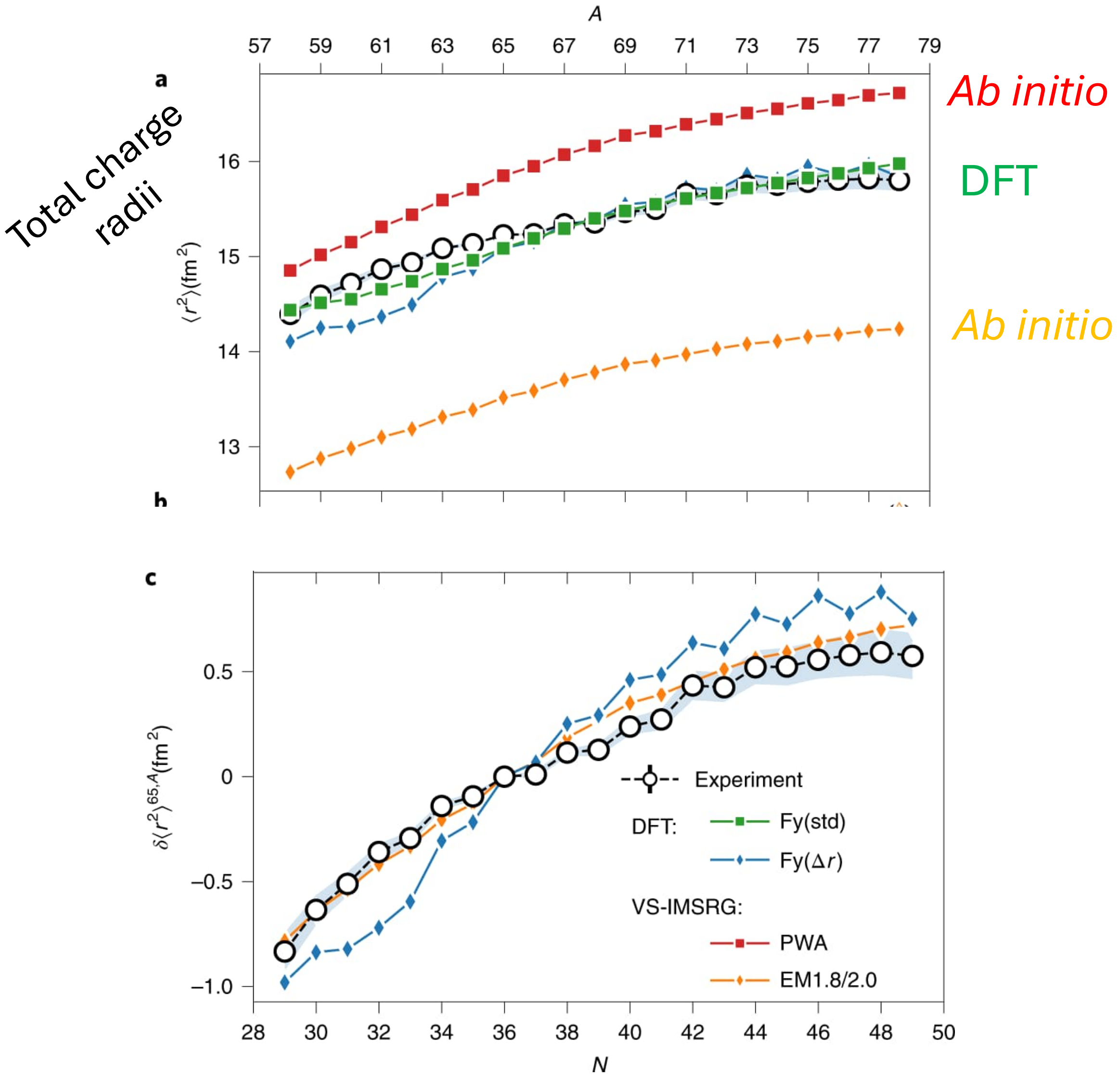
$$\Delta^{(3)}r = \frac{1}{2}[r(N+1) - 2r(N) + r(N-1)]$$

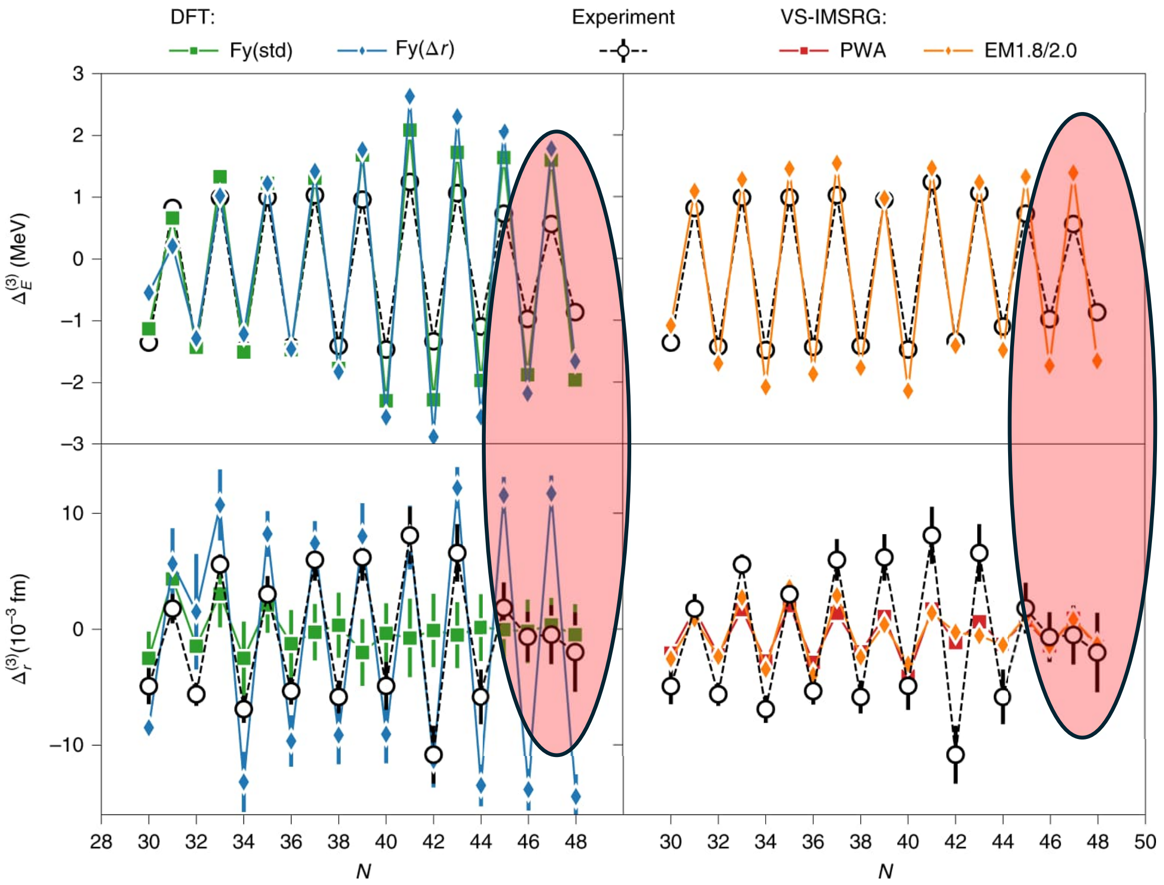
Copper isotope chain



R.P. de Groote et al., Nature Physics 16 (2020) 602

Benchmarking state-of-the-art theory





- Top panel are three-point mass differences
  - well reproduced by VS-IMSRG calcs; overestimated by DFT

R.P. de Groote et al., Nature Physics 16 (2020) 602

Nuclear charge radii and deformation

Nuclear charge radii offer a means to probe nuclear deformation, even for isotopes with nuclear spin I = 0, ½, that do not possess a spectroscopic quadrupole moment!

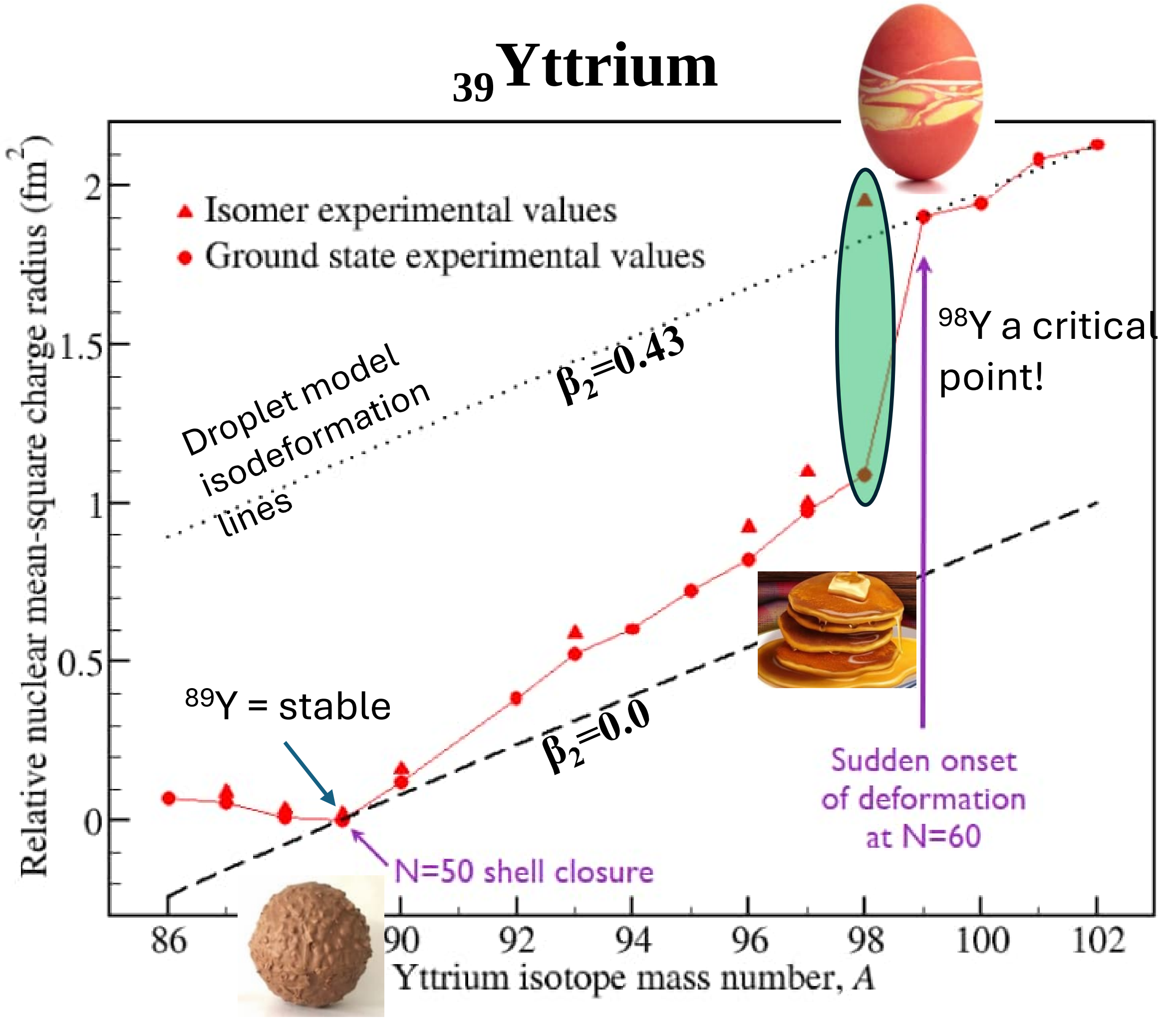
From a simple liquid droplet model approach – we can expand a deformed charge distribution in terms of spherical harmonics.

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

Quadrupole deformation parameter (shape)

$$\langle r^2 \rangle = \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \left(\langle \beta_2^2 \rangle + \langle \beta_3^2 \rangle + \ldots \right) \right)$$

Radius of spherical nucleus of the same volume



Note: charge radius is probing the deformation of ALL isotopes/states!

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

Identifying the trends in the raw data

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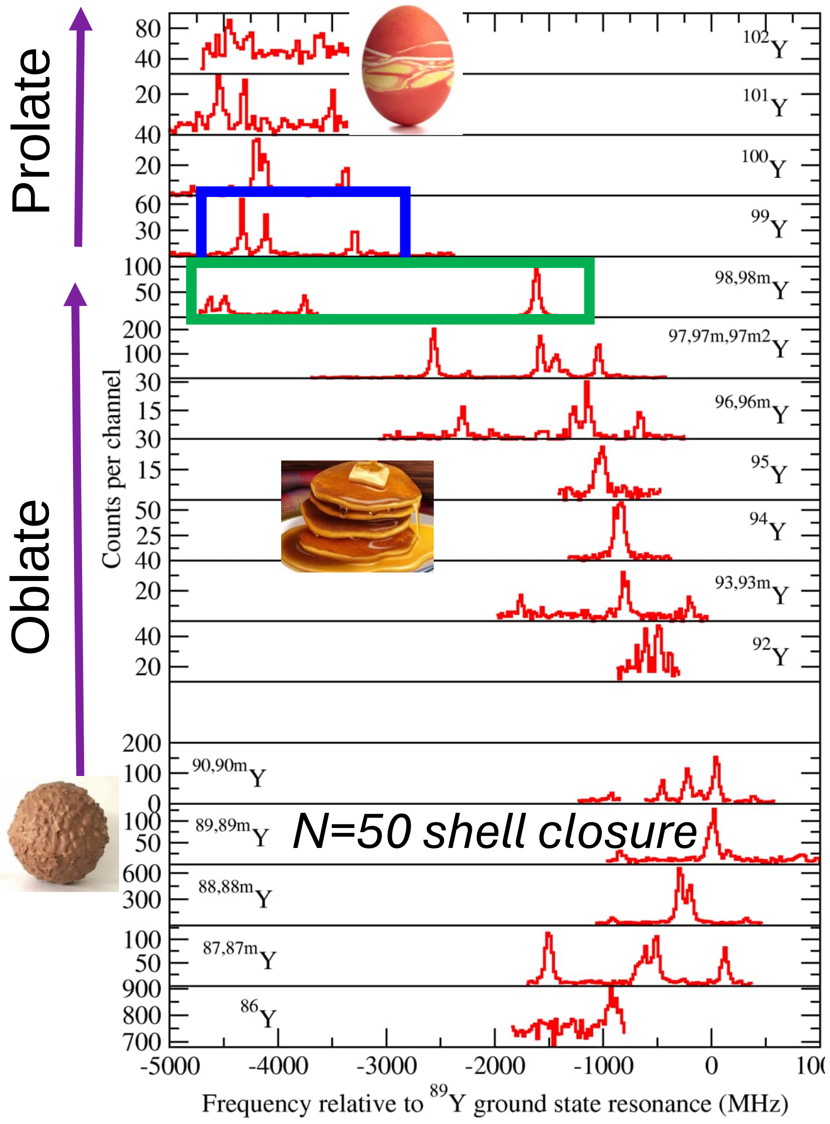
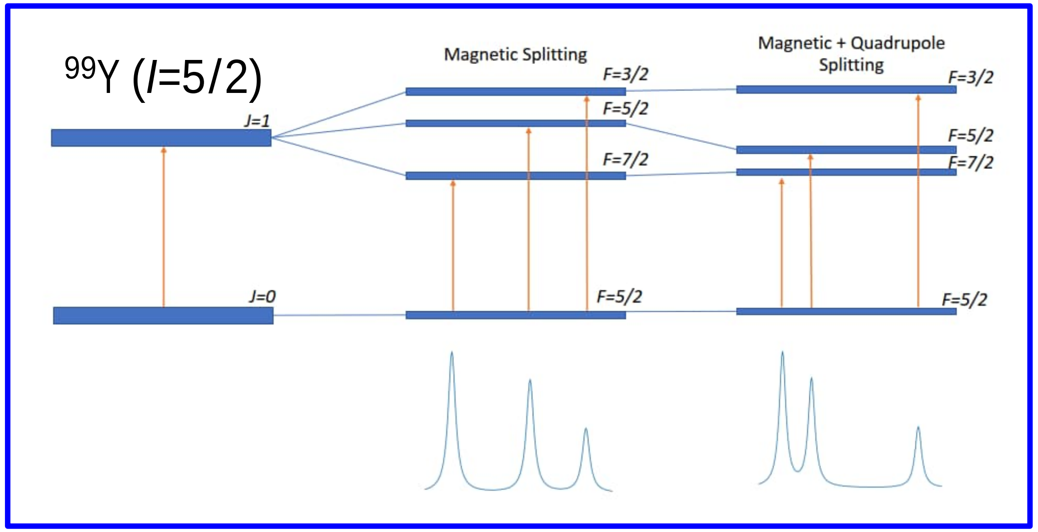
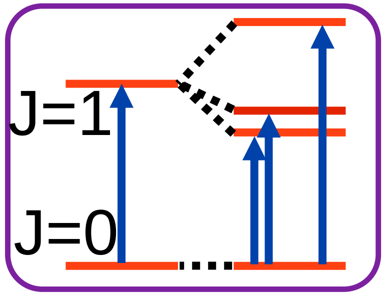
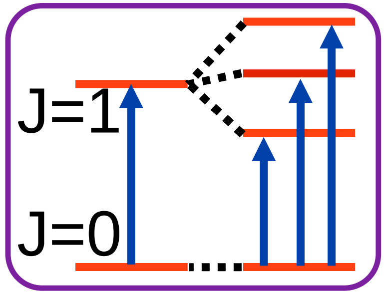


Yttrium contains many isomeric (long-lived) nuclear states





Prolate



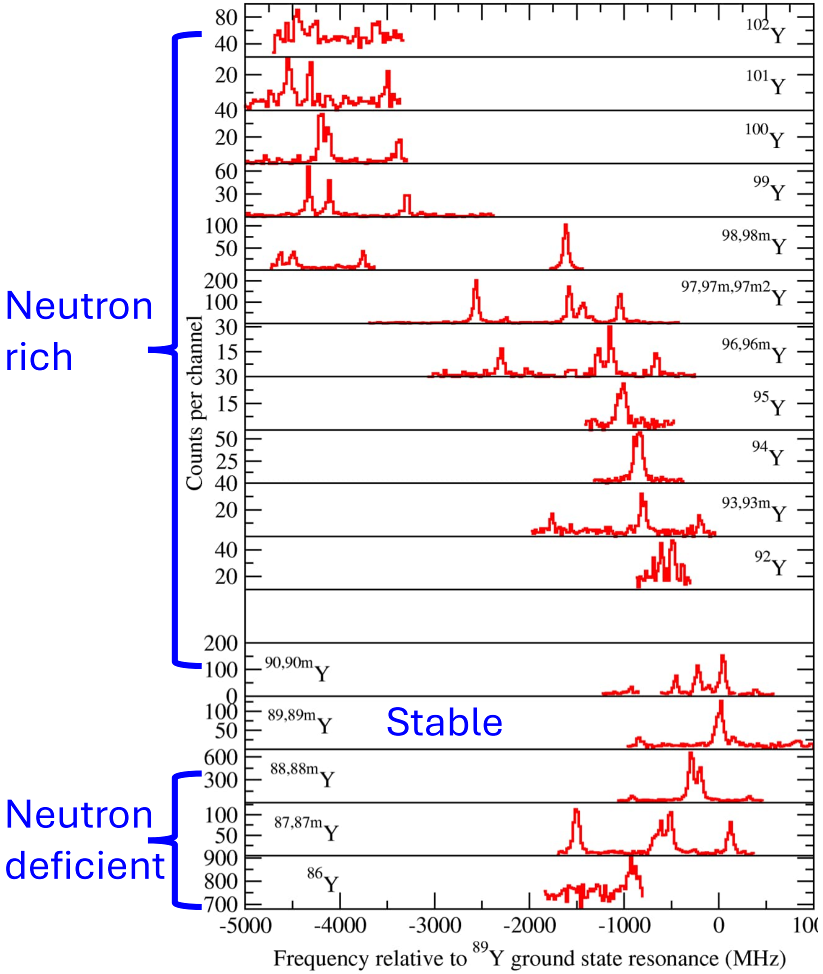
Oblate

- ^{98}Y is at a ``critical point´´ whereby the ground state exhibits a weakly oblate shape; the isomer a rigid prolate shape – a ``coexistence of shapes´´ in one nucleus

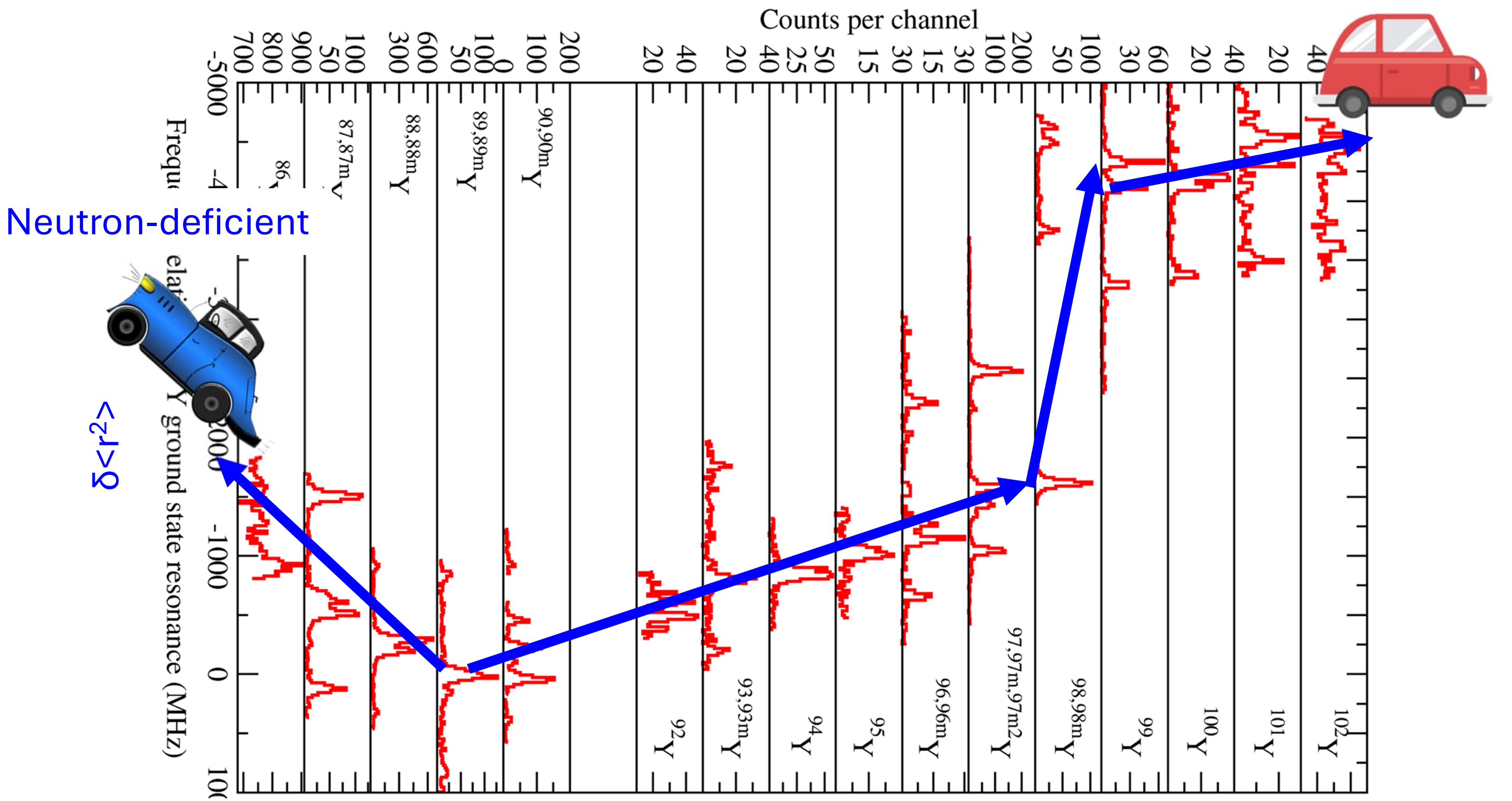
B. Cheal et al., Phys. Lett. B 645 (2007) 133

Isotope shifts to charge radii – a ``simple´´ way

1. Take raw data: e.g., optical spectra of Y isotopes



2. Rotate raw data by 90 degrees
3. Add lines to guide the eye (and cars)
4. Modify axis labels



Deformation from the quadrupole moments

- If the nuclear spin has been assigned, *e.g.*, via laser spectroscopy or non-optical measurements (γ-ray spec), the intrinsic quadrupole moment can be calculated:

$$Q_s = Q_0 \frac{3K^2 - I(I+1)}{(I+1)(2I+3)}$$

- We then extract the quadrupole deformation parameter, β_2, from:

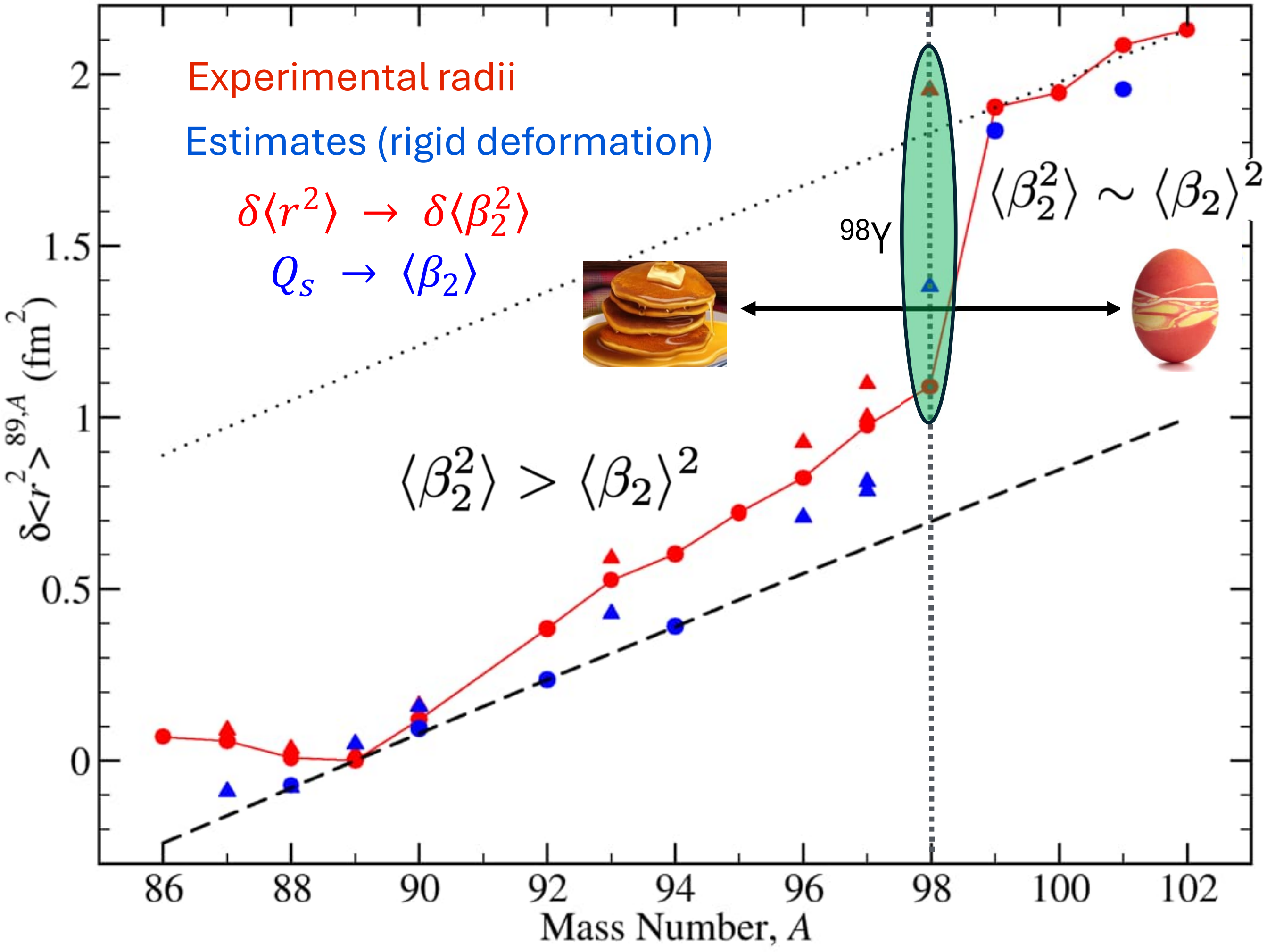
$$Q_0 \approx \frac{5Z\langle r^2\rangle_{\mathrm{sph}}}{\sqrt{5\pi}}\langle\beta_2\rangle(1+0.36\langle\beta_2\rangle)$$

- The mean-square quadrupole deformation parameter, $\langle\beta_2^2\rangle$, is extracted from our mean-square charge radius:

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

- Compare $\langle\beta_2^2\rangle$ with $\langle\beta_2\rangle^2$

Yttrium isotopes (Z=39)



^{98}Y - Shape coexistence at the critical point

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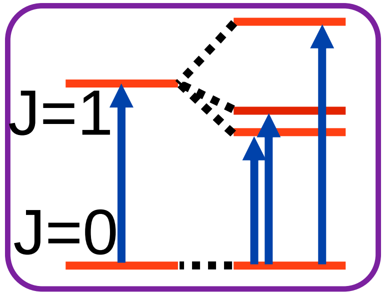
In our original spectroscopy, we used the ionic ground-state transition $5s^2\ ^1S_0 \rightarrow 4d5p\ ^1P_1$ (363 nm) for all Y isotopes*.

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

The problem of J = 0 → J = 1 lines – each nuclear spin fits equally well.



Prolate

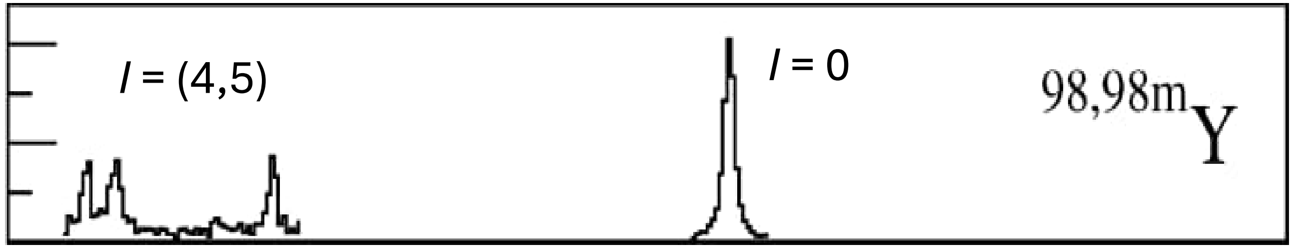
3 peaks maximum for each nuclear state

A	I^π	A (MHz)	B (MHz)	$\delta\nu$ (MHz)
98m	(4)	−88.3(0.6)	+324.7(4.2)	−2746(3)
98m	(5)	−73.7(0.4)	+339.1(4.2)	−2735(3)

A	I^π	μ (μ_N)	Q_s (b)	$\delta\langle r^2\rangle$ (fm^2)
98m	(4)	+2.98(2)	+1.73(19)	+0.863
98m	(5)	+3.11(2)	+1.80(20)	+0.860

- Three peaks tells us 3 unknowns (only)

- The nuclear spin was assumed to be either I = 4 or I = 5

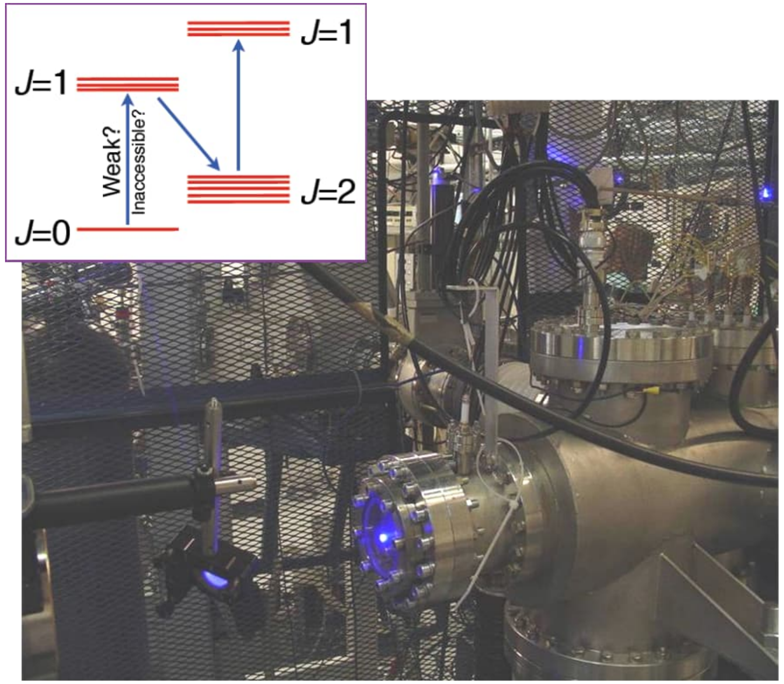


**GAMMASPHERE gamma-ray spectroscopy following β decay of ^{98m}Y indicated the spin was likely to be $I = (6,7)^+$

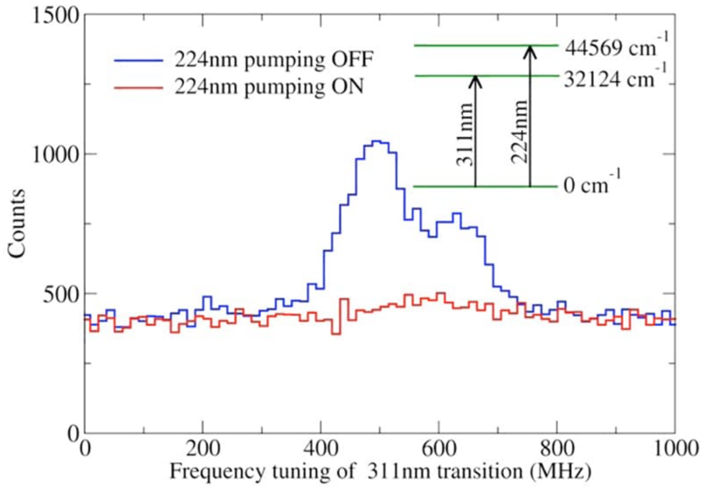
***W. Urban et al., PRC 96 (2017) 044333*

Optical manipulation in an RF cooler-buncher

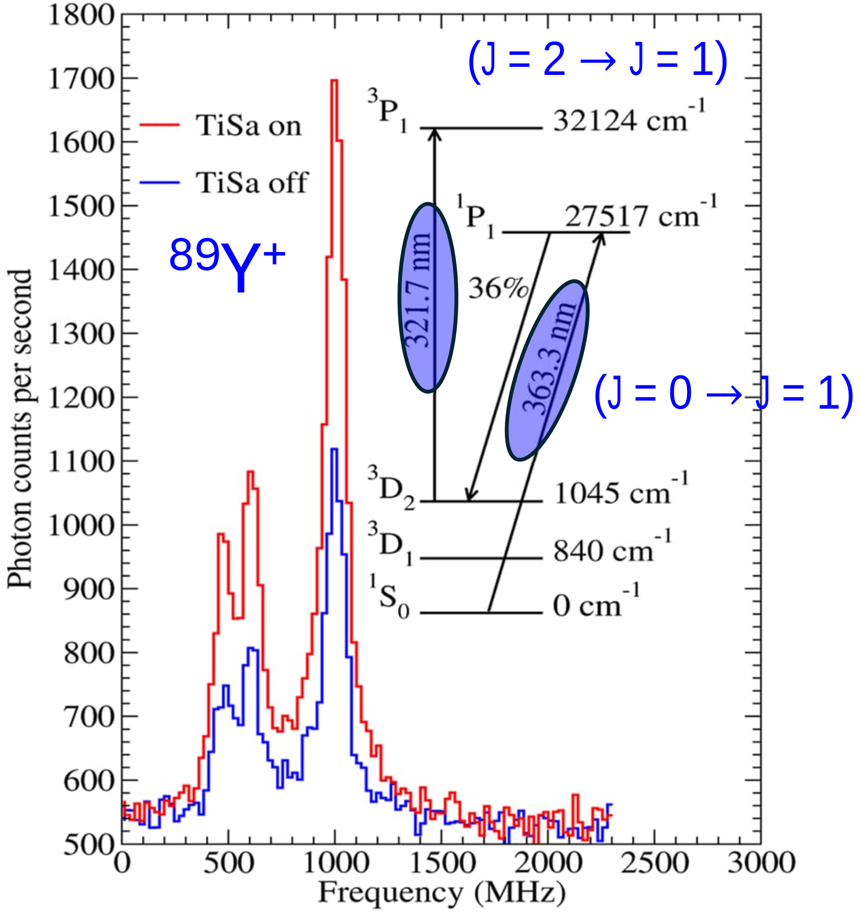
- Ions are excited with laser light introduced along the cooler axis
- De-excitation may occur to a metstable state.
- Useful if the ground state transition is J = 0 → 1 (e.g., Y)
- Useful if the ground state transition is weak/inaccessible (e.g., Nb)



B Cheal…IM, et al., Phys. Rev. Lett. 102 (2009) 222501



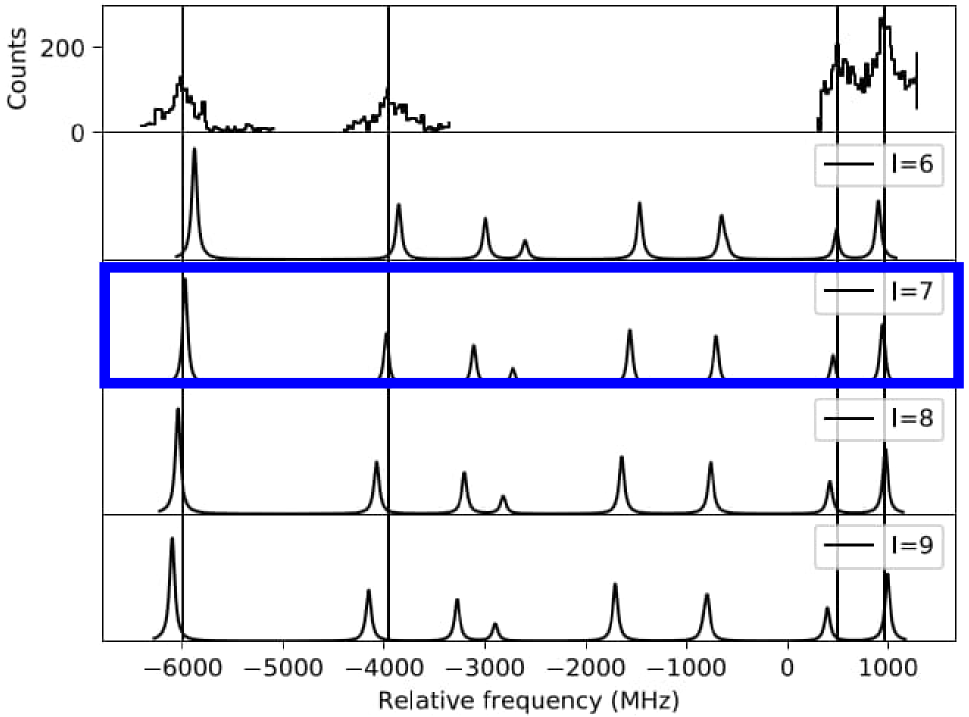
- Collinear: 311-nm transition
- Few mW of 224 nm light completely depopulates the ground state.

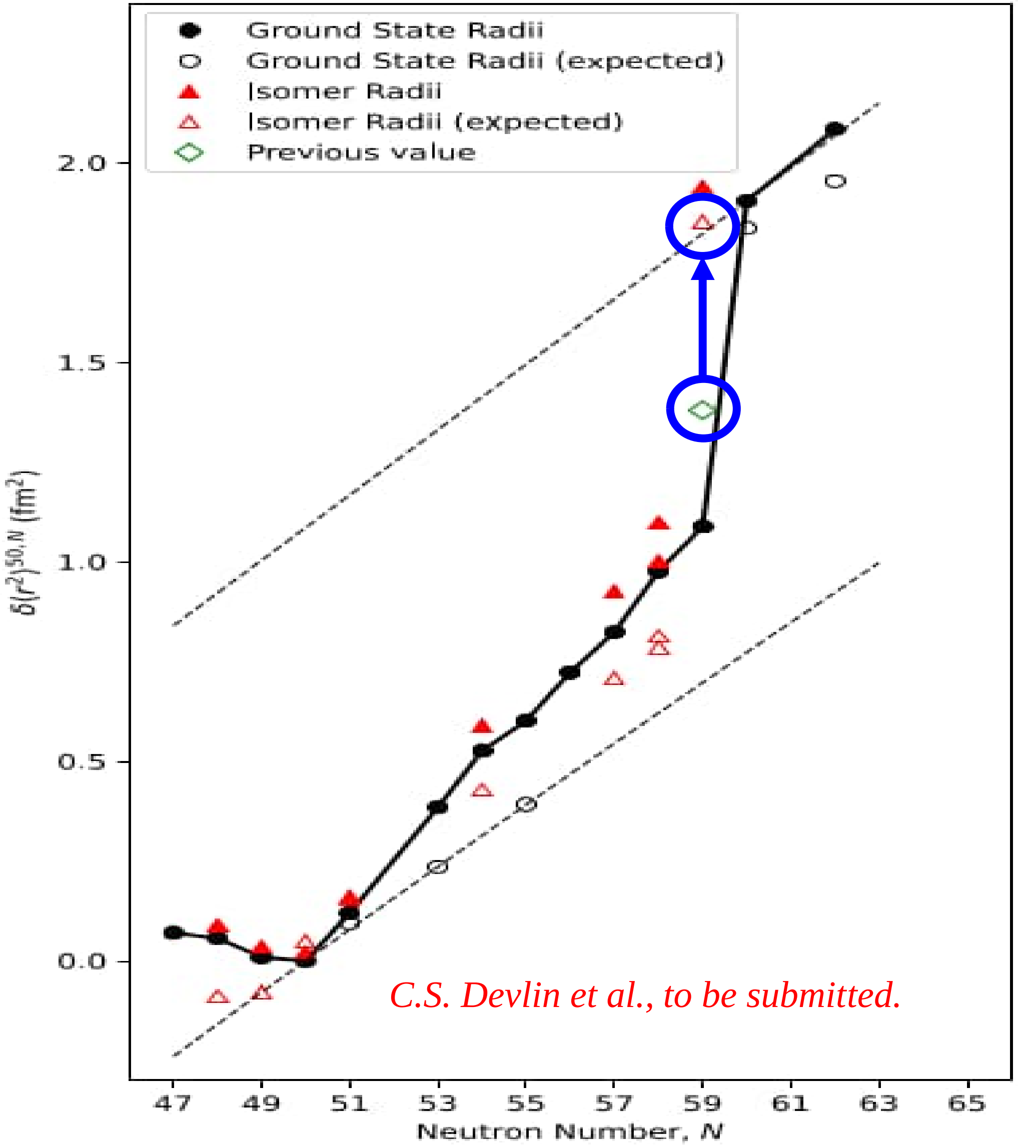


K. Baczynska et al., J. Phys. G 37 (2010) 105103

Illustrating the sensitivity to the nuclear spin *I*

Perform laser spectroscopy on a transition with higher J values (J = 2 to J = 1). Note we don't need to measure all expected peaks!





- Firm spin assignment, I = 7, allowing for revised hyperfine *A* and *B* parameters, thus nuclear moments.
- The isomer has a much higher quadrupole moment than previously thought – a strong (prolate) deformation that is very rigid.

Charge radii systematics (shape change region)

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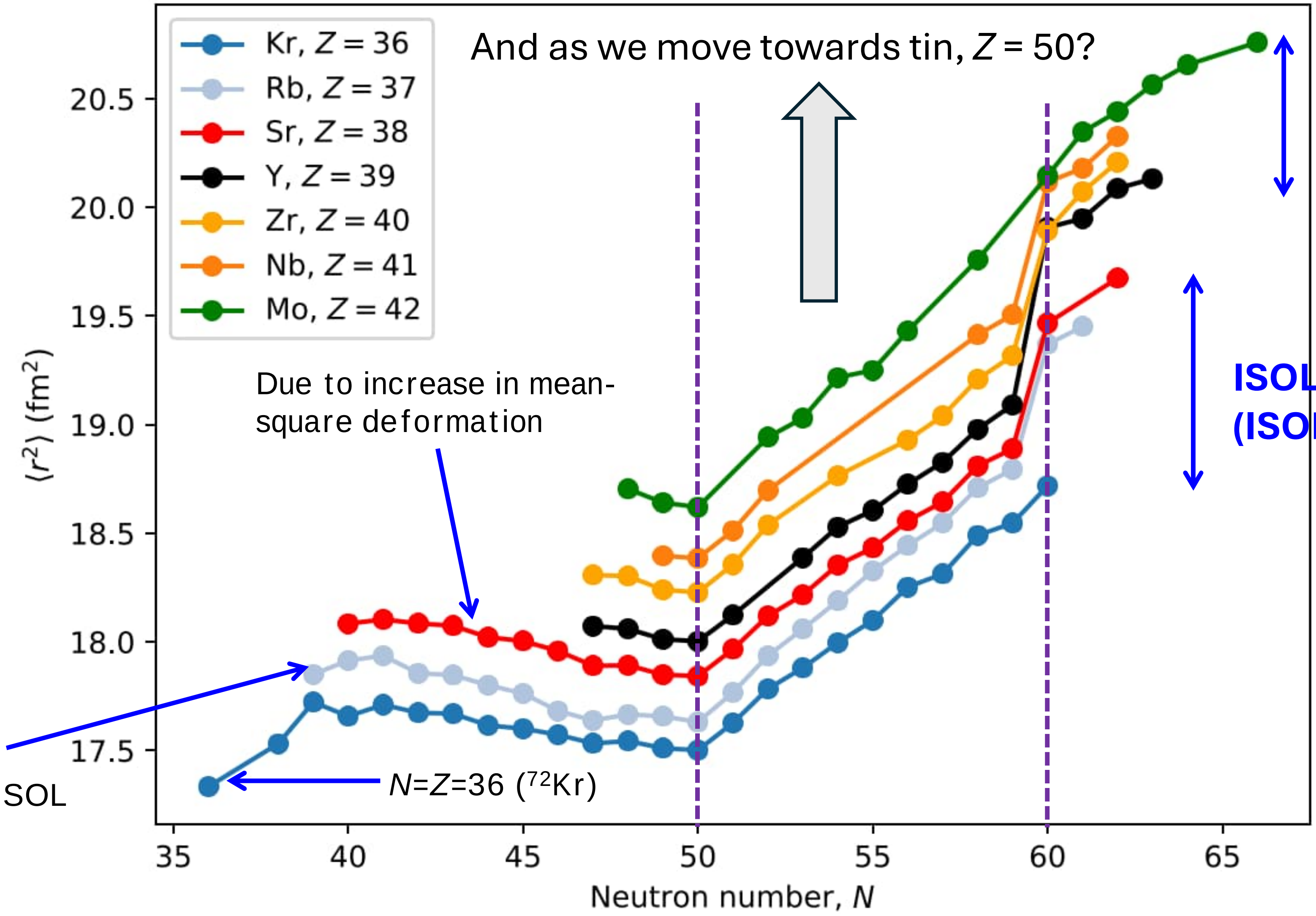

N=Z=^{74}Rb; (TRIUMF – ISOL technique)

JYFL (gas cell production of refractory elements)

ISOLDE (ISOL production)

Overview figure: Nörtershäuser & Moore, Handbook of Nuclear Physics (2023)

Charge radii systematics in the tin region

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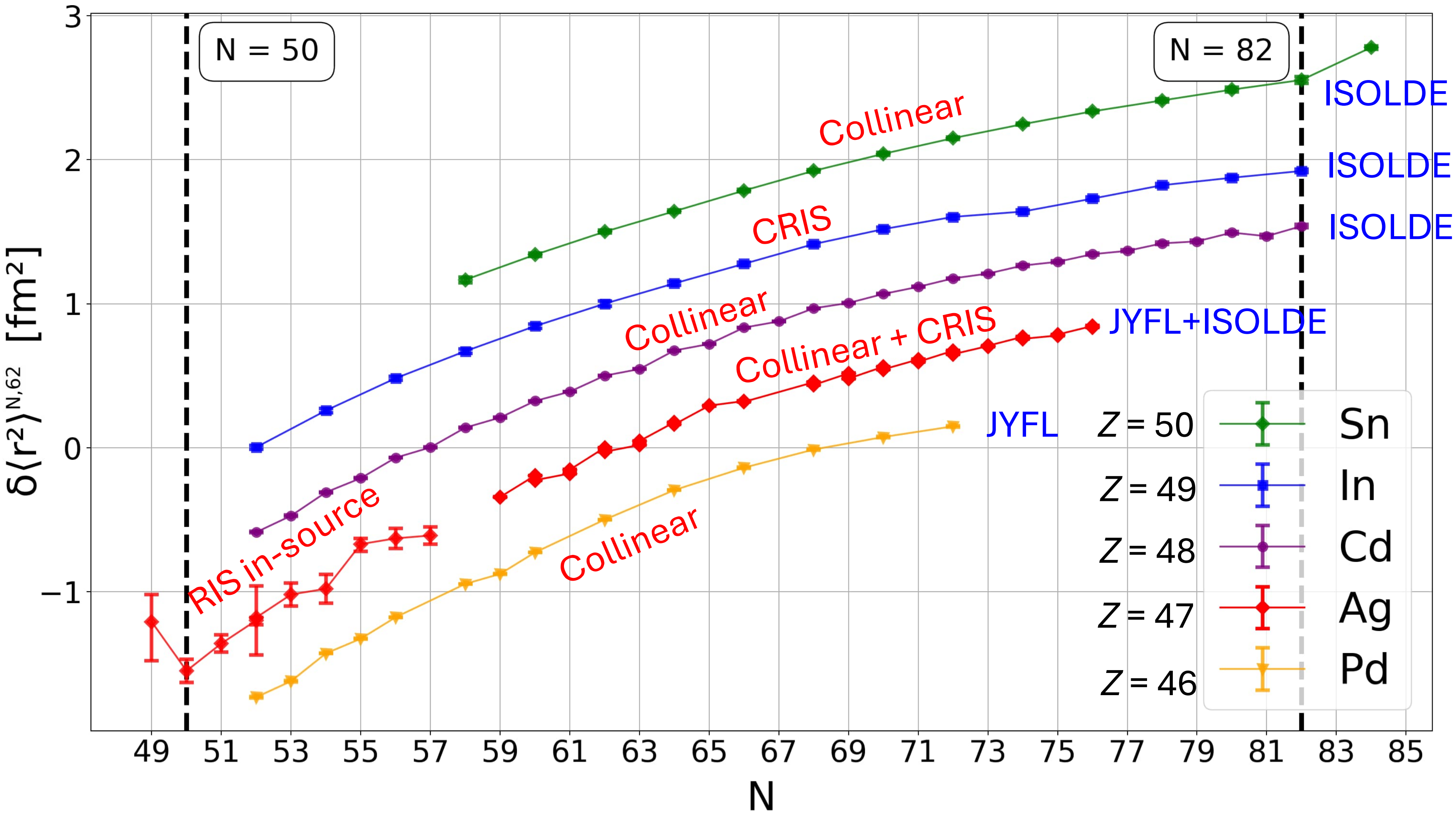

Sn: *C. Gorges et al., PRL 122 (2019) 192502*

In: *J. Karthein et al., Nat. Phys. 20 (2024 1719)*

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

Ag: *M. Reponen et al., Nat. Comm. 12 (2021) 4596 & to be submitted*

Pd: *S. Geldhof et al, PRL 128 (2022) 152501*

+ Ru (Z=44), N = 62 – 70 @Argonne!

- Fingerprints of triaxiality!!
- arXiv:2503.07841

- Accepted proposal for Rh (Z = 45) at JYFL (April 2025).

Complementarity with the nuclear mass surface

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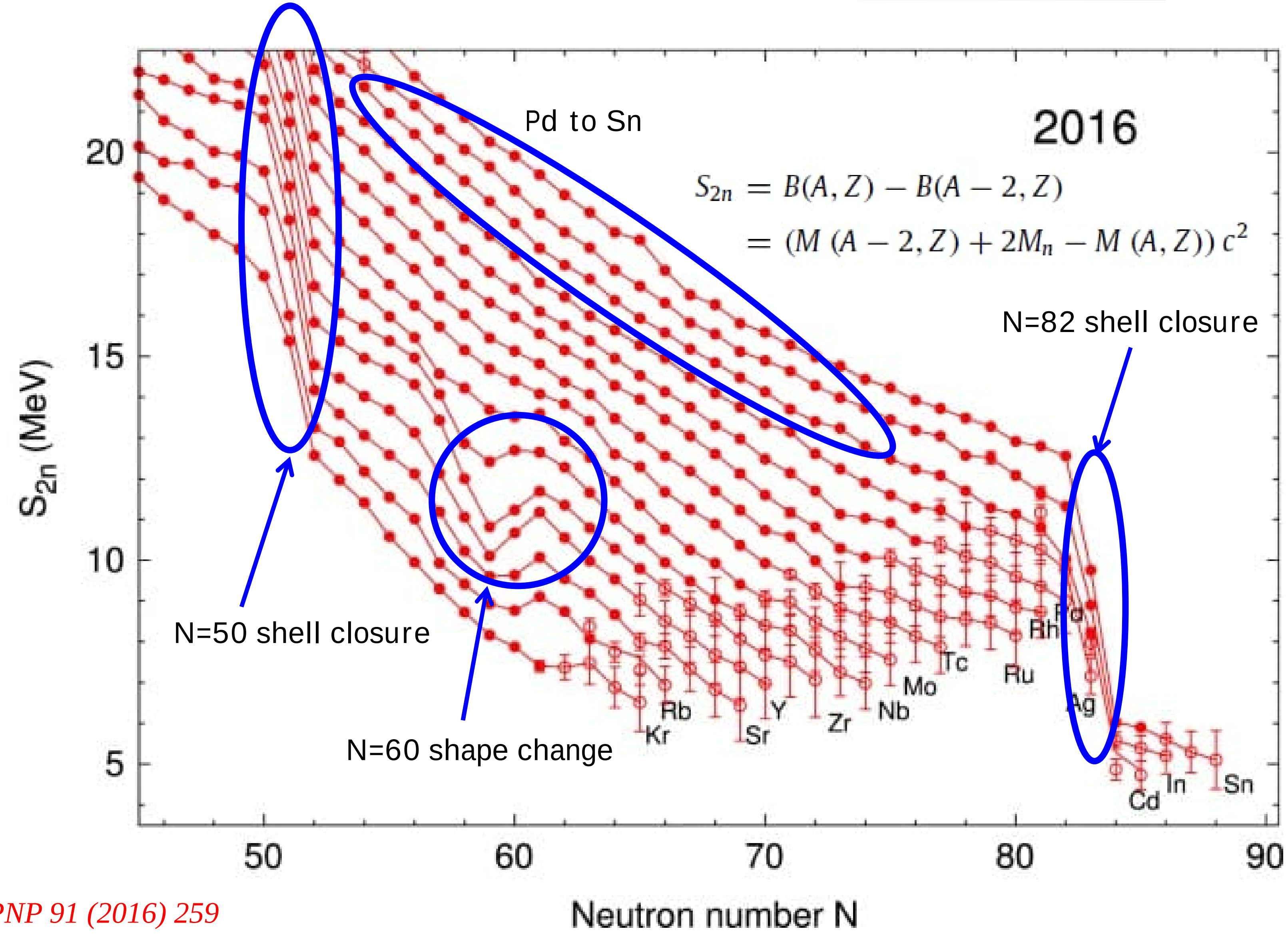
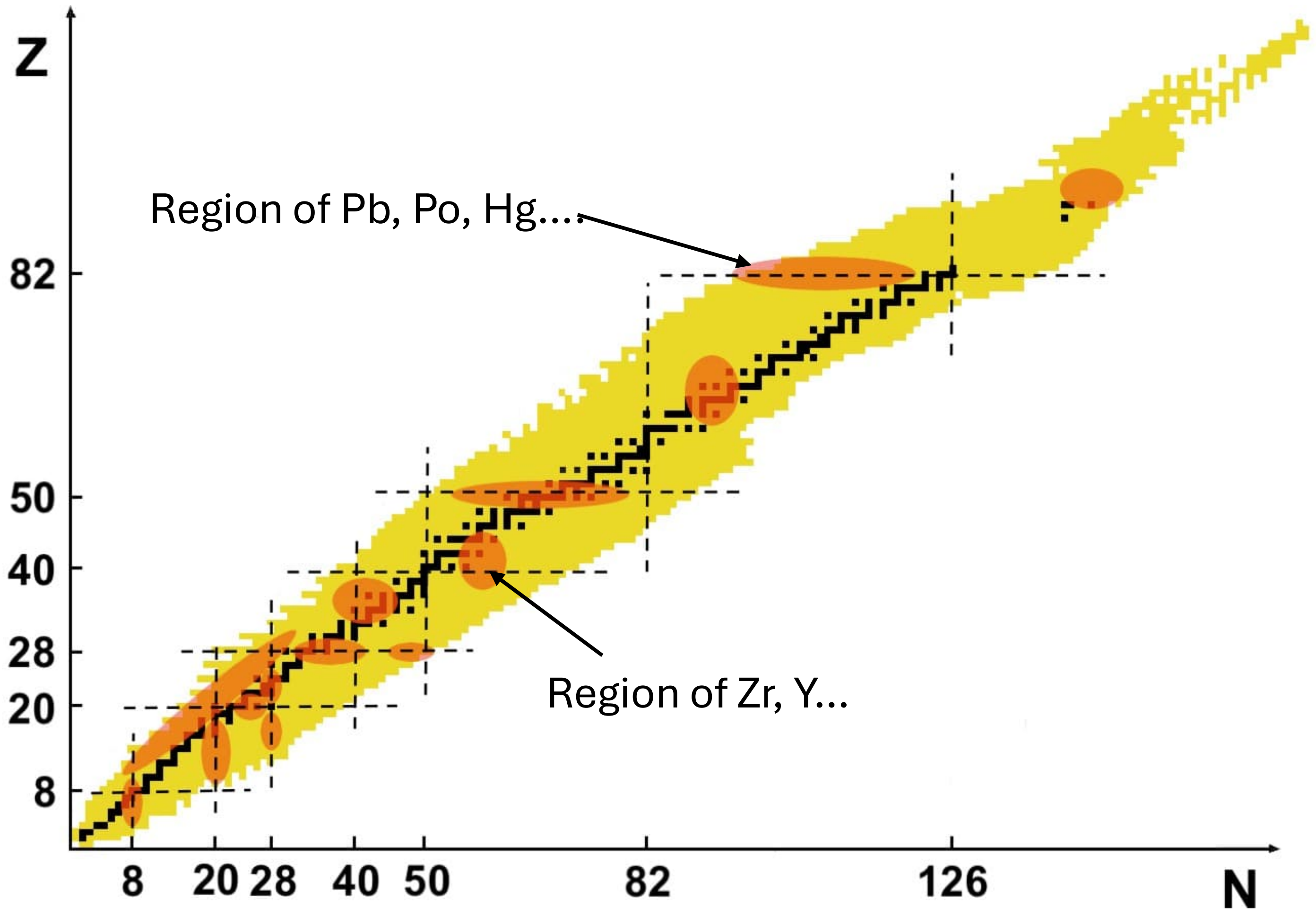


T. Eronen et al., PPNP 91 (2016) 259

Let’s dive a little more into shape coexistence



Landscape figure courtesy of M. Zielinska

- Shape coexistence appears to be unique in the realm of finite many-body quantum systems.
- An appearance of states characterized by different ``shapes´´ coexist at similar excitation energies.
- A widespread phenomenon in areas close to proton and neutron shell closures.
- Difficult to establish experimentally as the nuclear shape is not an observable!

For reviews on the subject:

K. Heyde and J.L. Wood, Rev. Mod. Phys. 83 (2011) 1467

P.E. Garret, M. Zielinska & E. Clement, PPNP 124 (2022) 103931

Proposed mechanism behind shape coexistence

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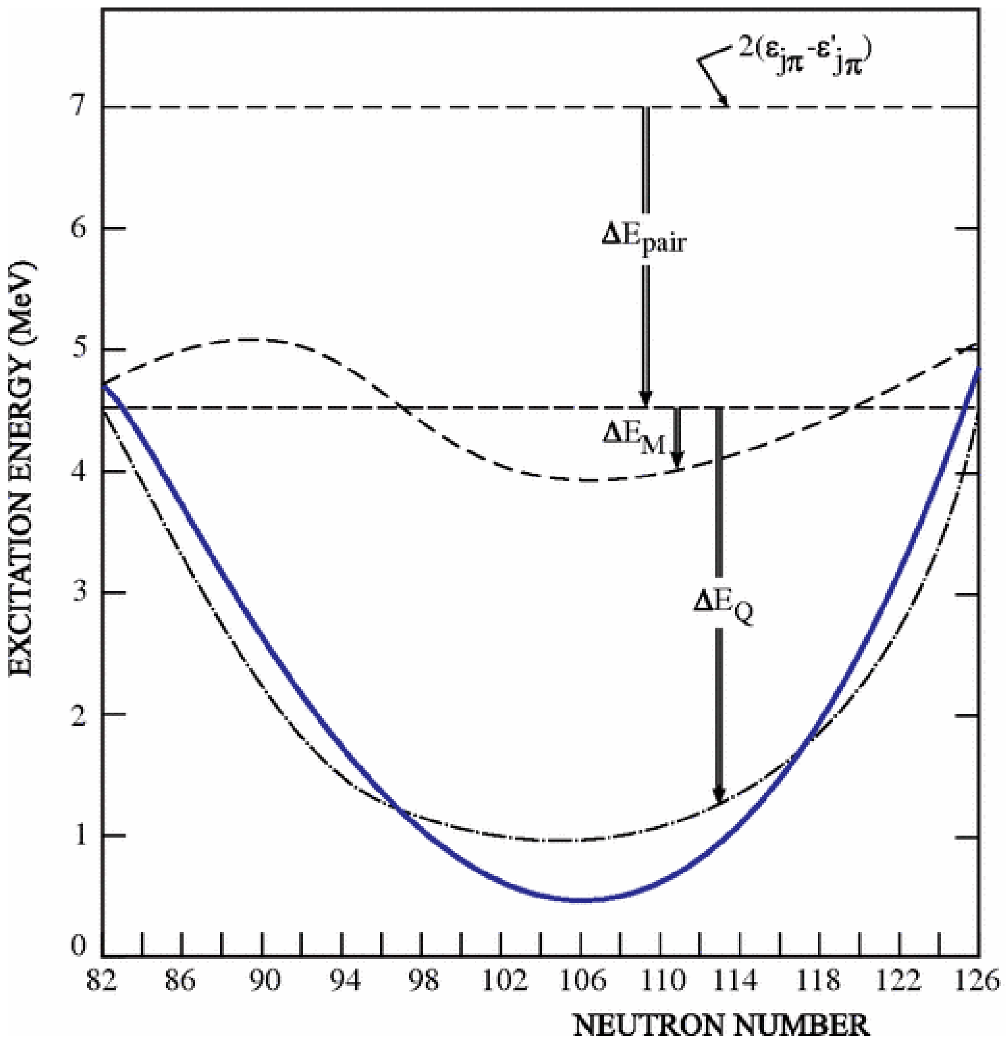
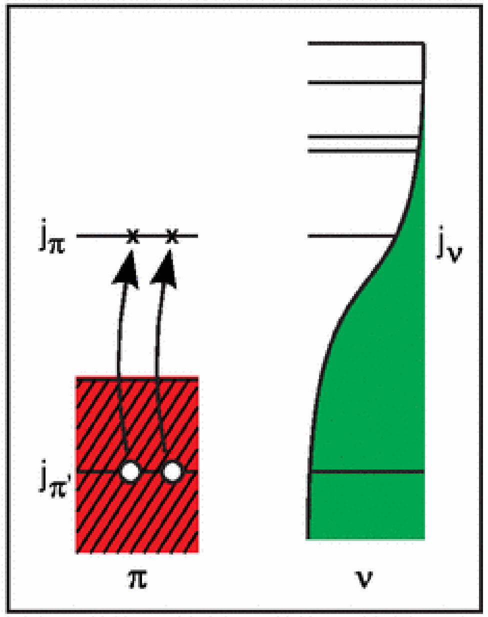
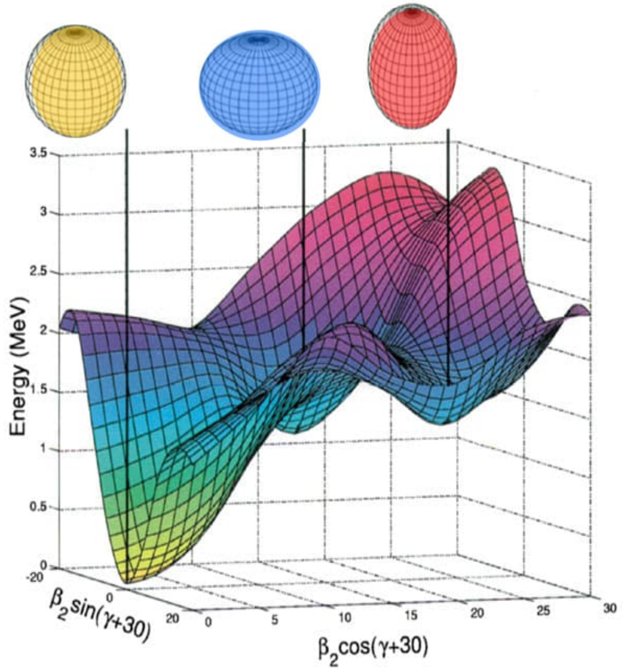


Figure from: Heyde and Wood, Rev. Mod. Phys. 83 (2011) 1467

- In a shell model picture: gain from correlations offsets the shell gap and multiparticle-multihole excitations go down in excitation energy
- Characteristic parabolic behaviour of intruder state energies.
- We also have the mean-field picture – competing configurations.





Famous example of triple shape coexistence in ^{186}Pb

A. Andreyev et al. Nature 405 (2000) 430

Shape staggering in the charge radii of Hg isotopes

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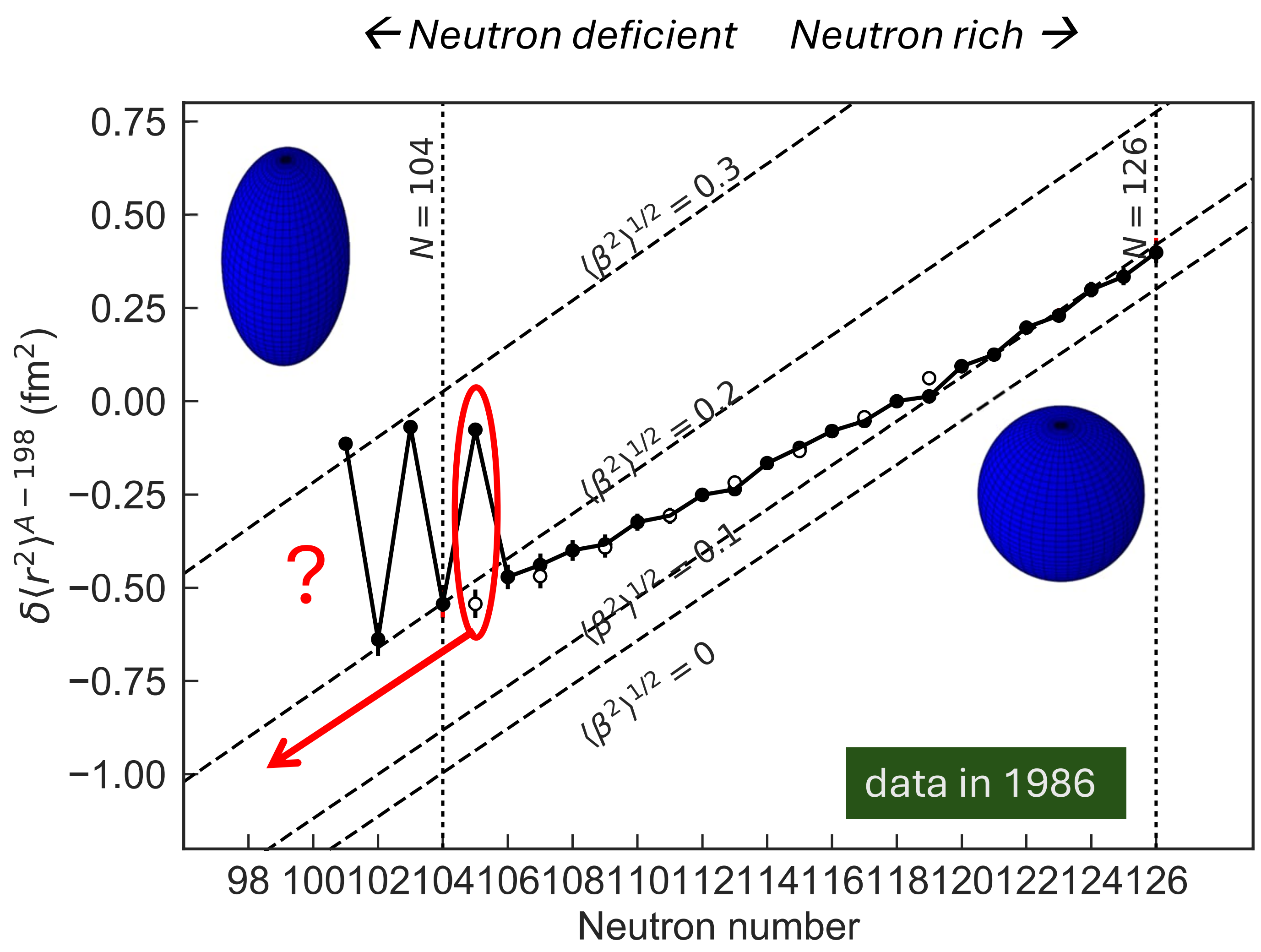
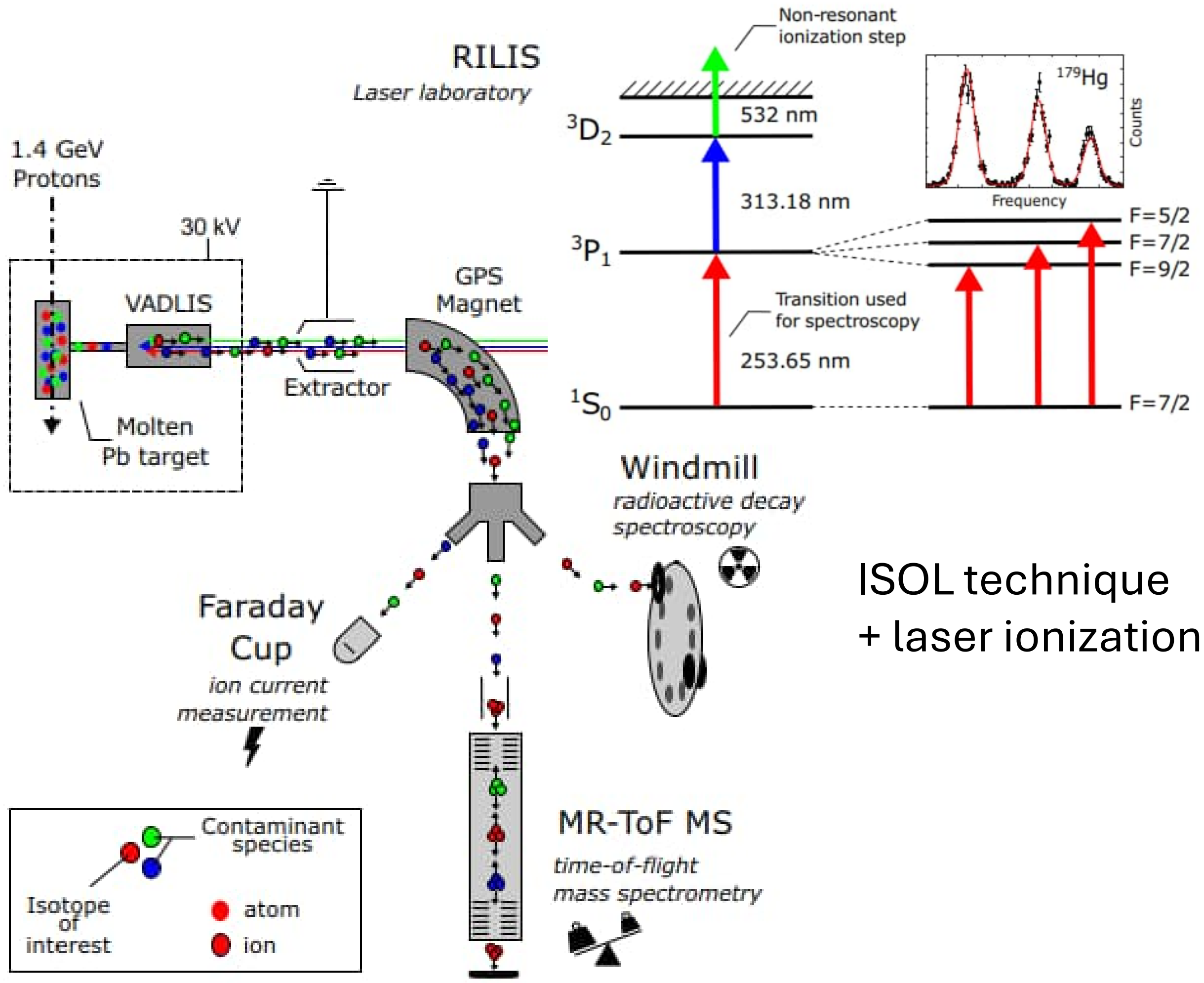


Huge increase in charge radius around the neutron mid-shell (N=104);

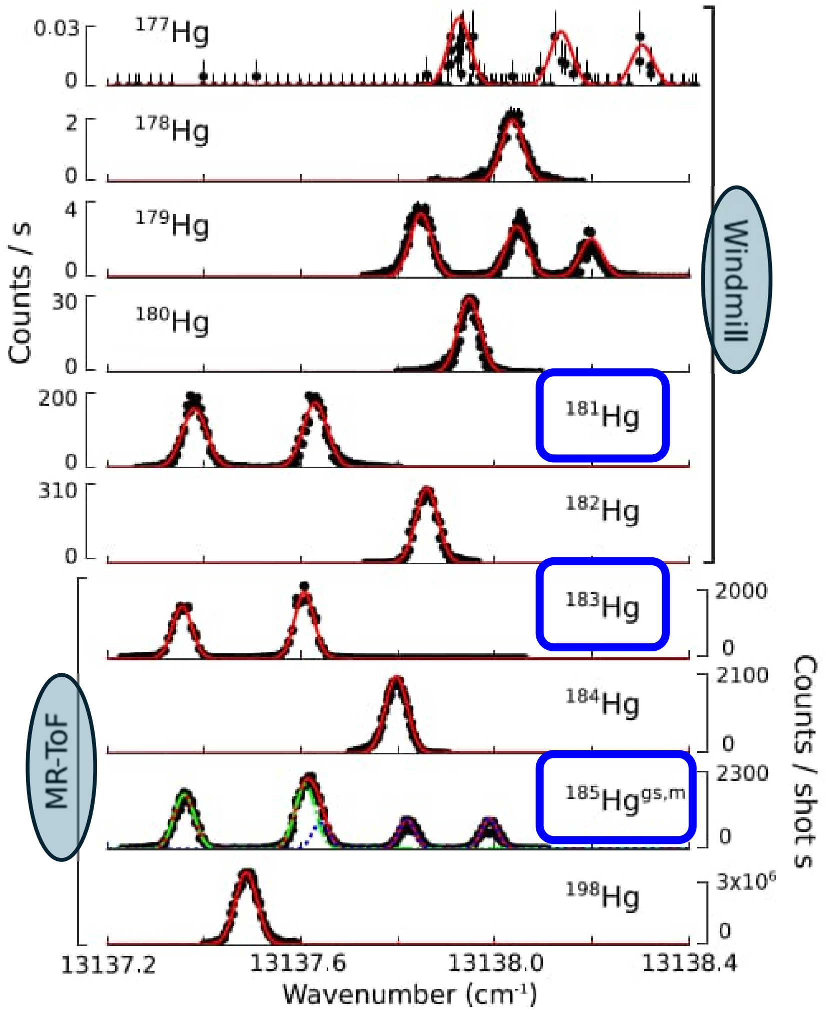
^{181,183,185}Hg (N=101,103,105)

Shape coexistence established in ^{185}Hg!

When does the staggering end?



ISOL technique
+ laser ionization



Combining detection in three different experimental stations

B. Marsh et al., Nature Phys. 14 (2018) 1163, S. Sels et al., Phys. Rev. C 99 (2019) 044306

After 30 years of developments...

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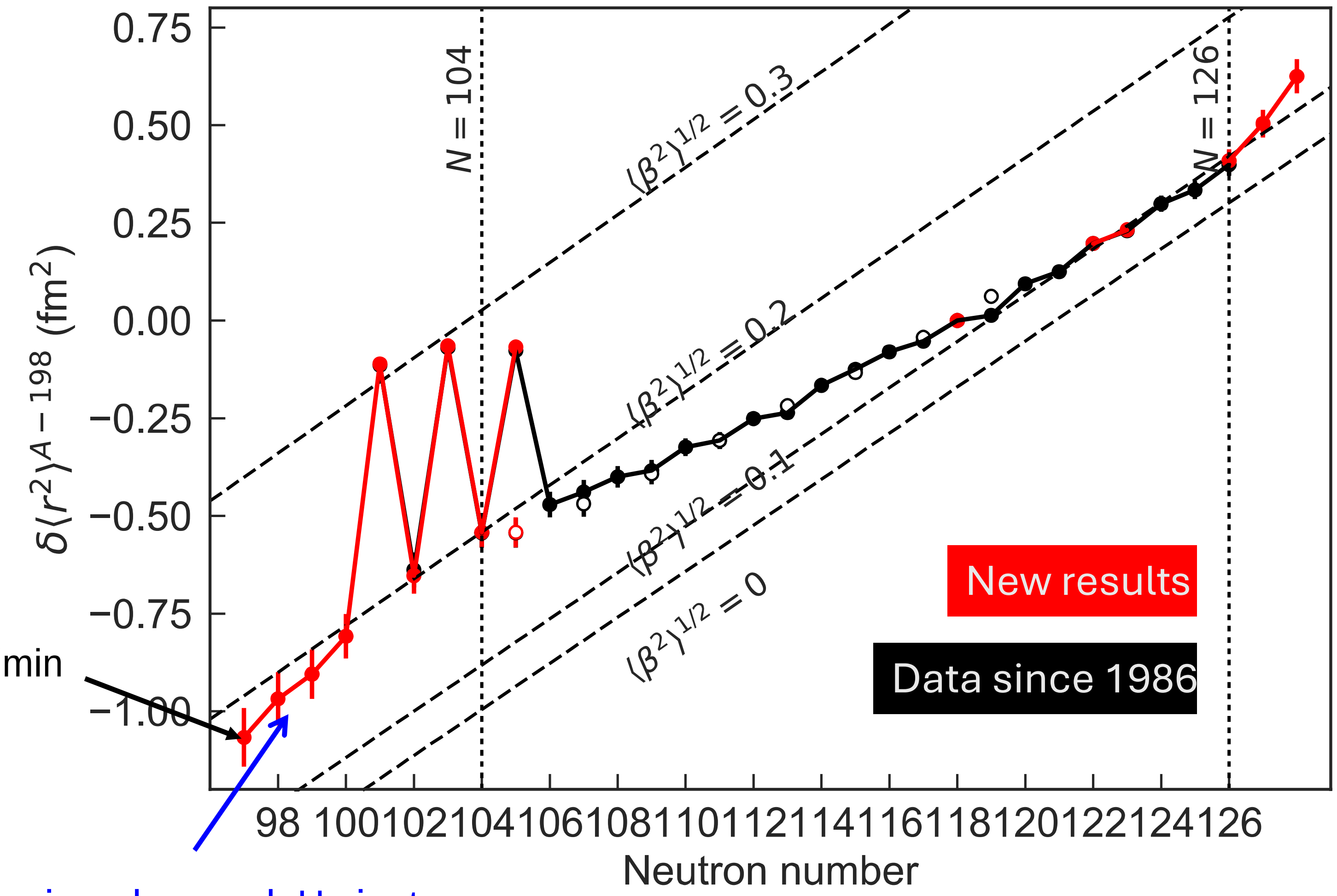

^{177}Hg (N=97)
Production few ions/min
$T_{1/2}$ = 127 ms.

End-point of staggering observed; Hg isotopes return to more spherically-shaped trend.

- Excellent agreement with older data.
- Combination of large-scale Monte Carlo shell-mode and DFT calculations performed.

B. Marsh et al., Nature Phys. 14 (2018) 1163, S. Sels et al., Phys. Rev. C 99 (2019) 044306

Staggering in the neighboring chains?

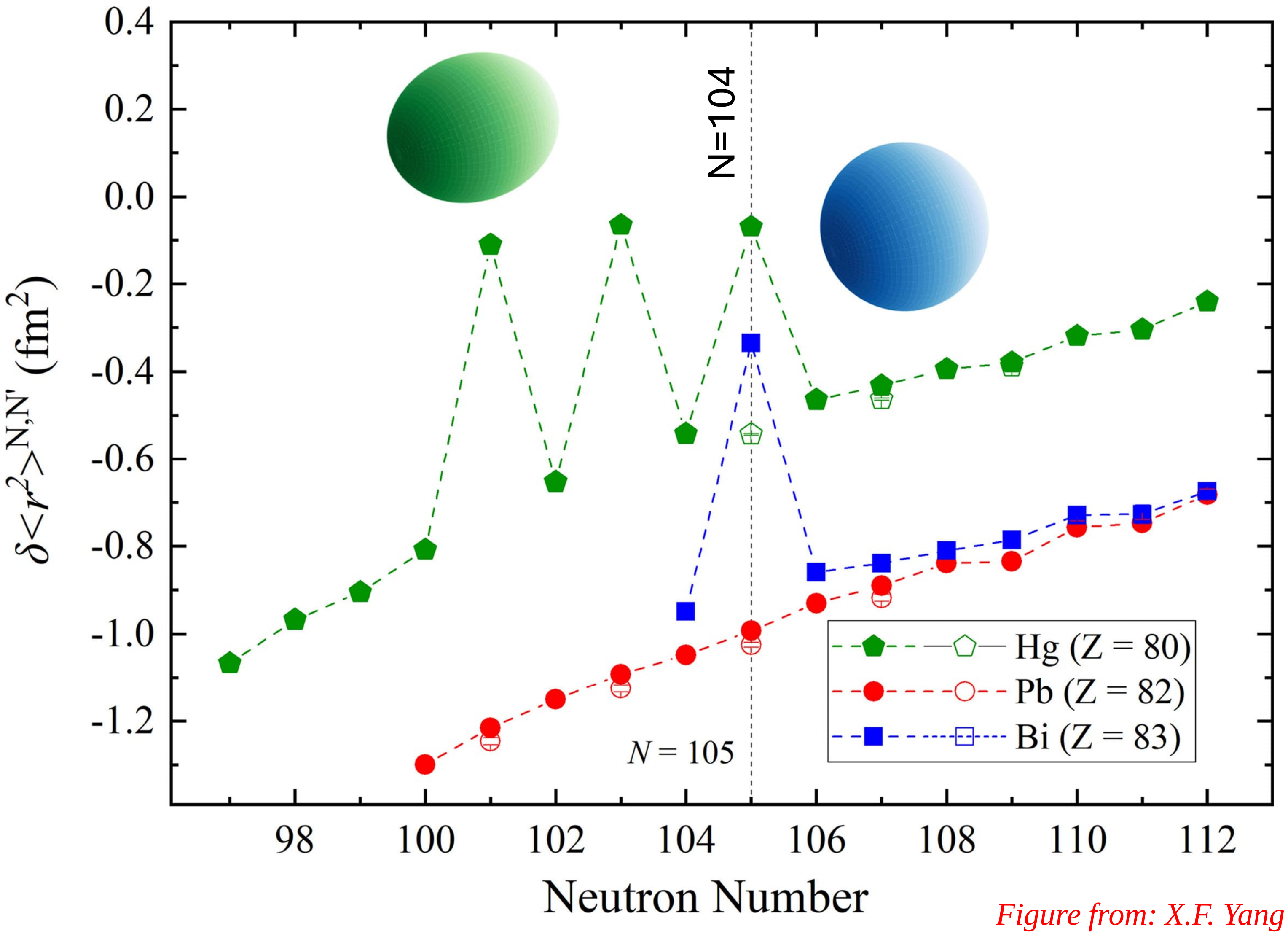

Figure from: X.F. Yang et al., PPNP 129 (2023) 104005.

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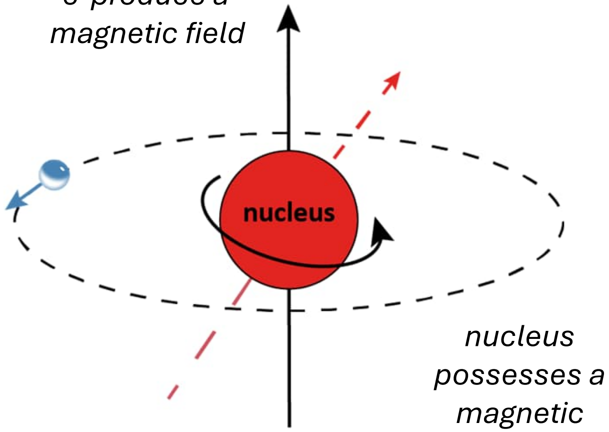
Magnetic dipole moments of exotic nuclei

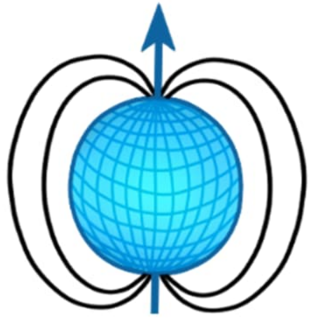
Magnetic moments – brief reminder

Let's start with a short reminder from Lecture 1 !

$$\hat{M}_1^0 = \sum_{j=1}^{A} \frac{\mu_N}{\hbar} \hat{e}_z \cdot \left(g_L^{(j)} \vec{L}_j + g_S^{(j)} \vec{S}_j \right)$$

We can see there are contributions from orbiting charge *L* and intrinsic spin *S*





Protons:	g_l = +1	g_s = +5.586
Neutrons:	g_l = 0	g_s = -3.826

(These are values for a *free* proton/neutron)

The magnetic dipole moment of a state of spin I = expectation value of the z-component of the dipole operator μ:

$$\mu = \langle I, I | \sum_{j=1}^{A} \frac{\mu_N}{\hbar} \hat{e}_z \cdot \left(g_L^{(j)} \vec{L}_j + g_S^{(j)} \vec{S}_j \right) | I, I \rangle = g I \mu_N .$$

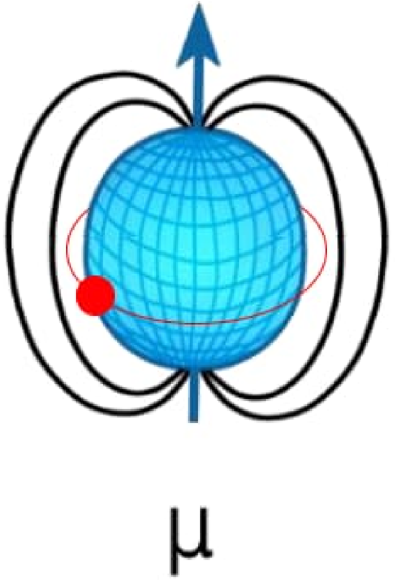
Single-particle magnetic moments

Without the need for any intensive computations to calculate the wave function of a nuclear state, we can gain insight very simply by comparing experimental g-factors with unpaired, single nucleons in a shell model orbital:

- Assume a single, unpaired nucleon outside of a core with which it does not interact with.
- All nucleons inside the nucleus nicely pair up to spin zero, contributing nothing to the magnetic moment.
- In this ”extreme” single-particle picture, we can write:

$$\mu_{\text{sp}}(j,l) = j\left(g_L + \frac{1}{2}\frac{g_S - g_L}{j}\right)\mu_N, \quad j = l + \frac{1}{2}$$

$$\mu_{\text{sp}}(j,l) = j\left(g_L - \frac{1}{2}\frac{g_S - g_L}{j+1}\right)\mu_N, \quad j = l - \frac{1}{2}$$



These expressions summarize the so-called Schmidt moments.

The Schmidt lines

For protons

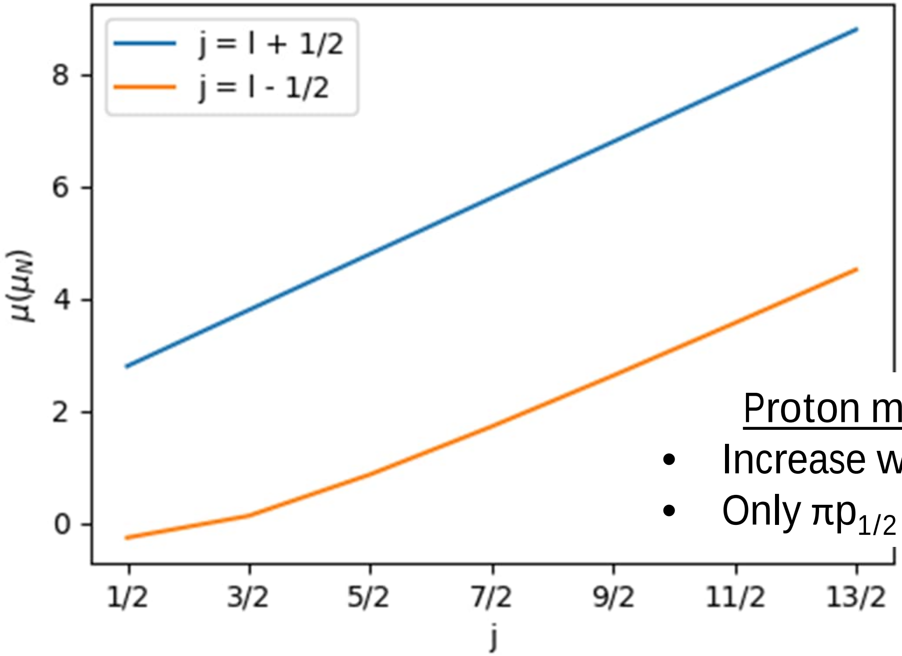
$$\mu = j - \frac{1}{2} + \frac{g_s^{\pi}}{2} \qquad \text{for } j = l + \frac{1}{2}$$

$$\mu = \frac{j}{j+1}\left(j + \frac{3}{2} - \frac{g_s^{\pi}}{2}\right) \qquad \text{for } j = l - \frac{1}{2}$$

For neutrons

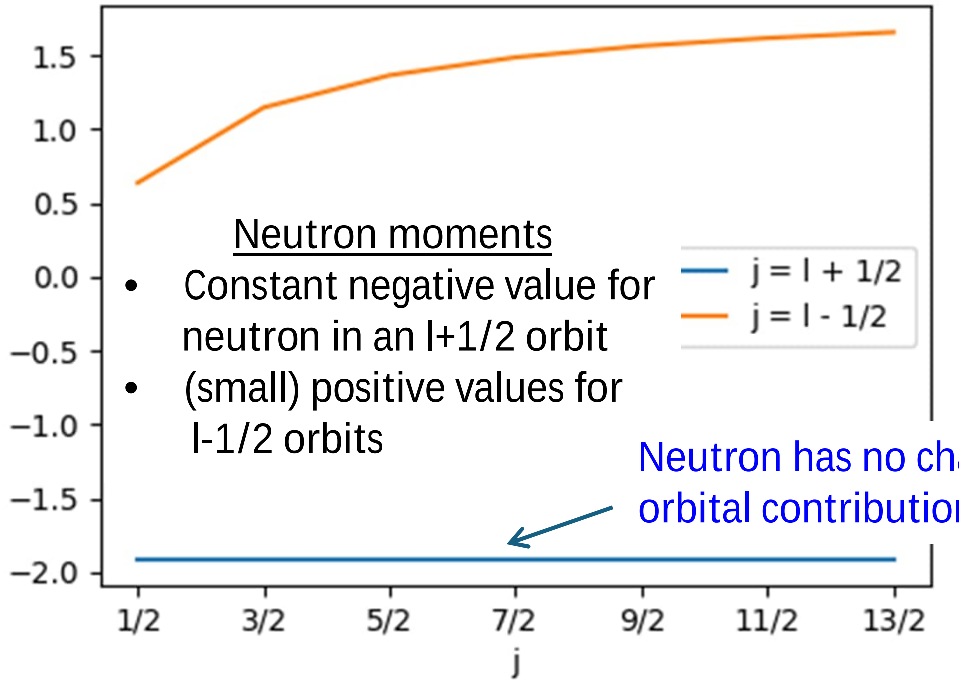
$$\mu = \frac{g_s^{\nu}}{2} = \text{-}1.913 \qquad \text{for } j = l + \frac{1}{2}$$

$$\mu = -\frac{j}{j+1}\frac{g_s^{\nu}}{2} \qquad \text{for } j = l - \frac{1}{2}$$



Proton moments

- Increase with j of orbit
- Only $\pi p_{1/2}$ is negative!



Neutron moments

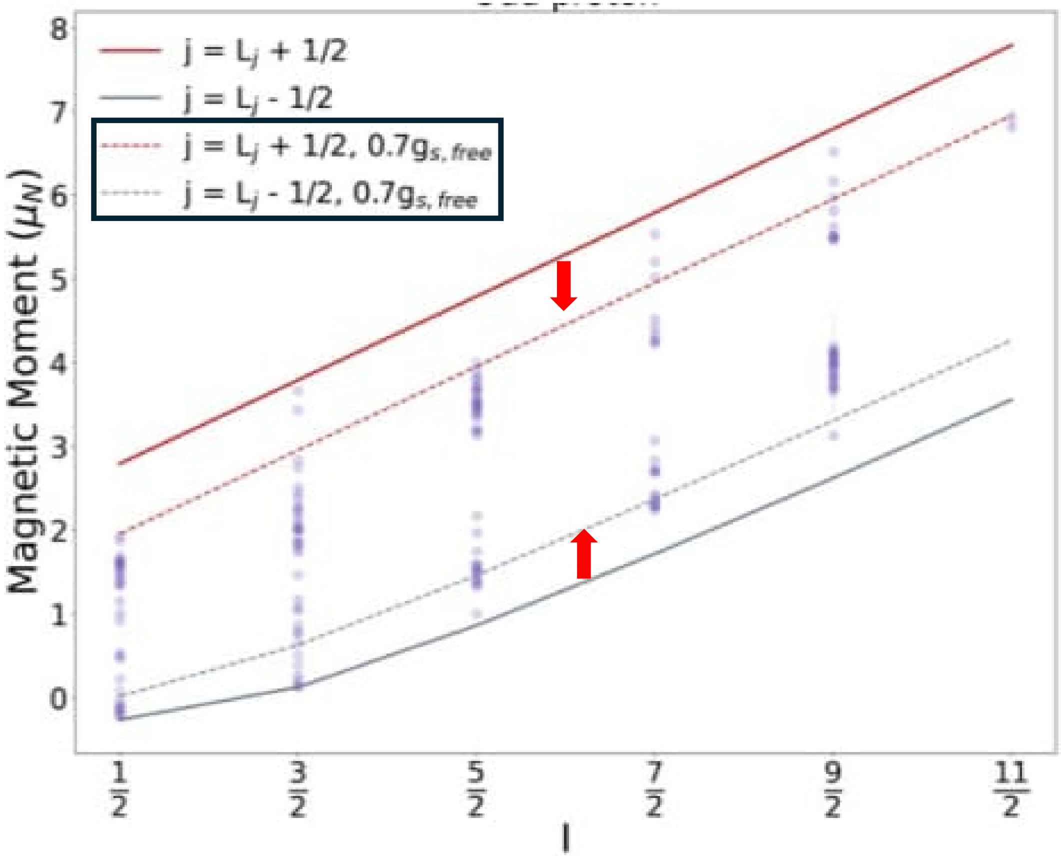
- Constant negative value for neutron in an l+1/2 orbit
- (small) positive values for l-1/2 orbits

Neutron has no charge, no orbital contribution

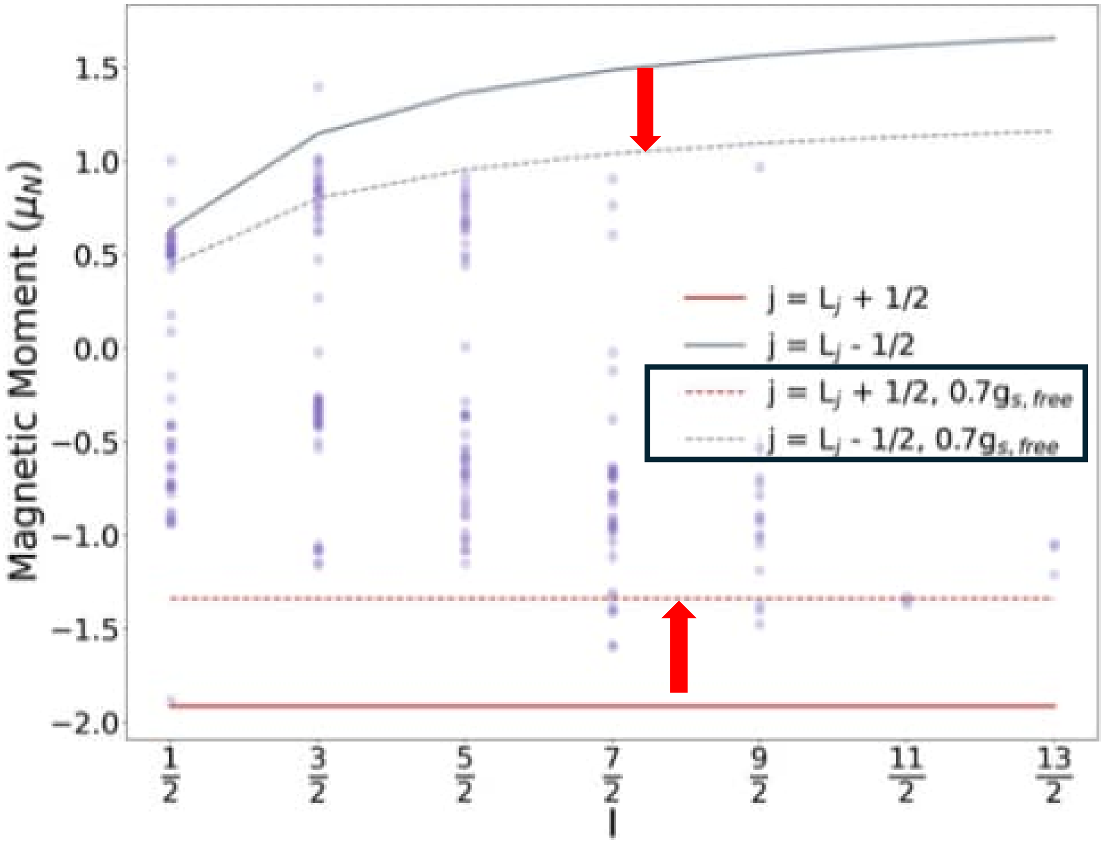
Comparison with experimental data

$g_s = 0.7\ g_{s,free}$

Odd proton



Odd neutron

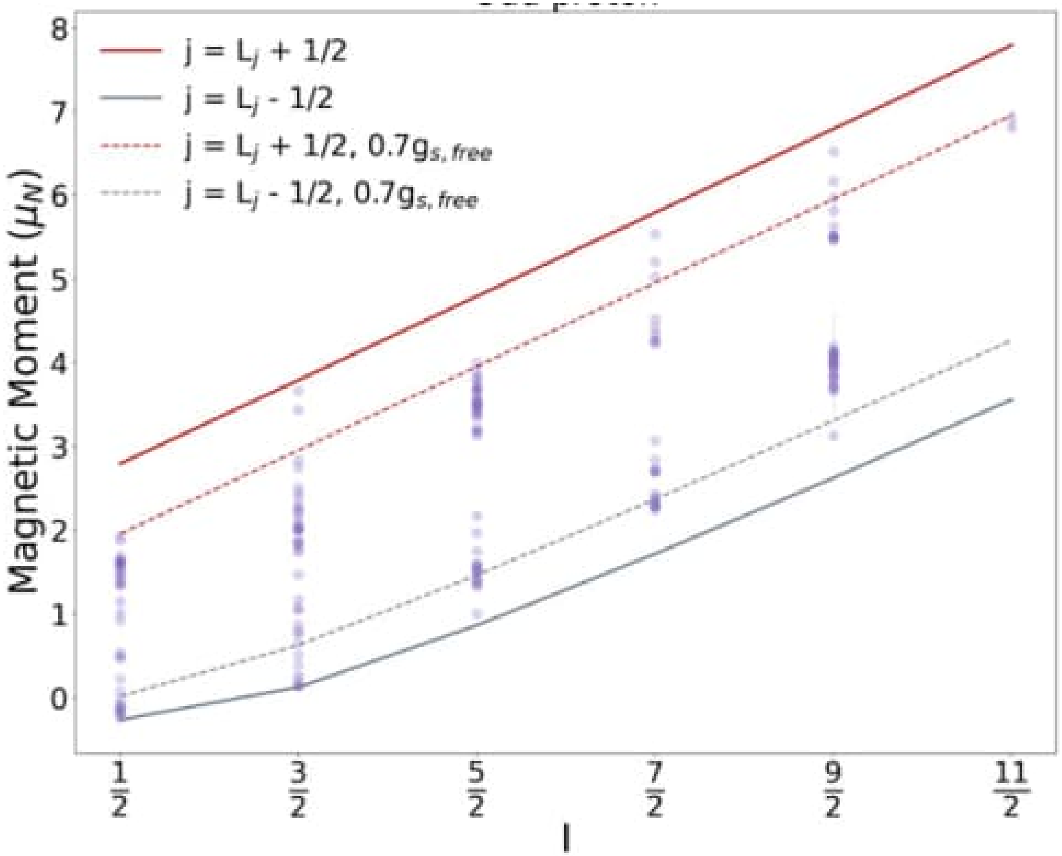


Data: Mertzimekis online database

Figure: de Groote & Neyens, Handbook of Nuclear Physics (2023)

Discussion pause…

Odd proton

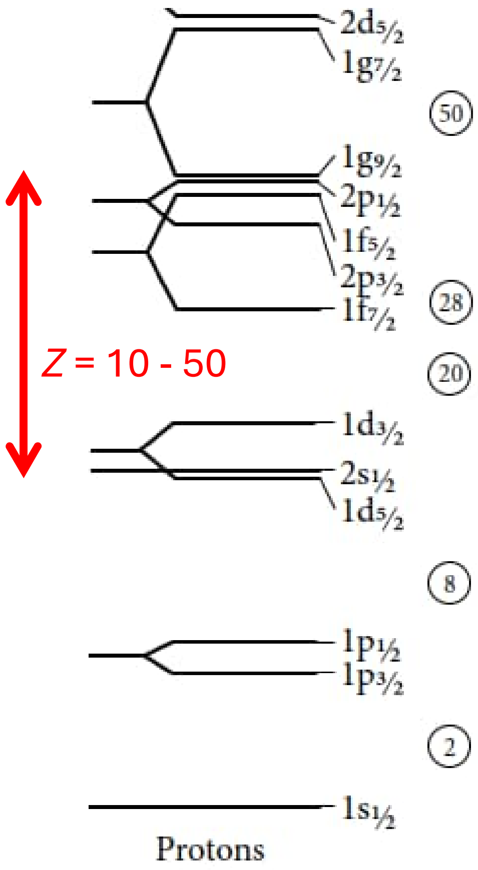


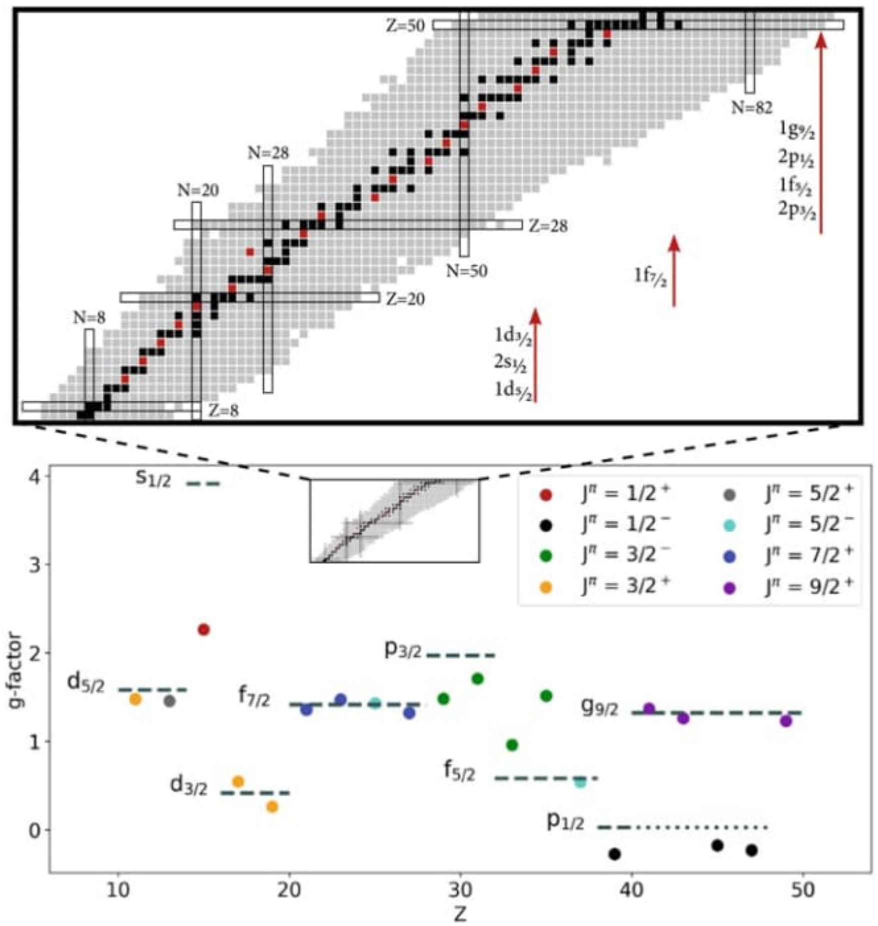
Why do you think there is a tendency to used ``quenched´´ g factors in the shell model?

Nucleons are not free but embedded in the nuclear medium; configuration mixing affects the assumption of perfect single-particle behavior.

Magnetic moments and the shell model

Magnetic moments have excellent sensitivity to the orbital occupied by the unpaired nucleon. With our experimental precision, magnetic moments (and g factors) have provided some of the most important evidence for the validity of the nuclear shell model!





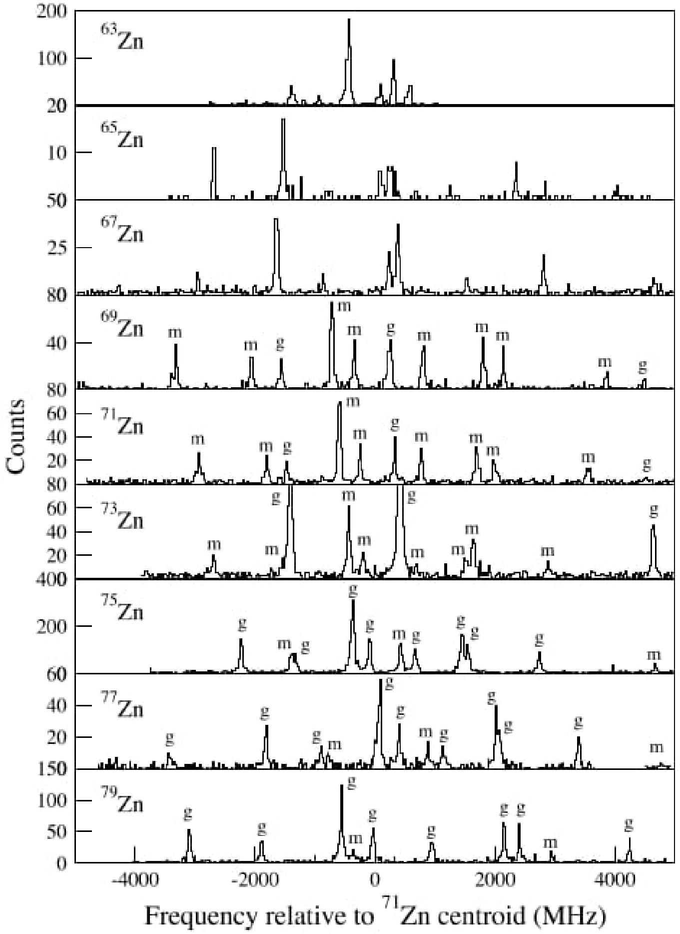
- g factors of the most abundant, stable odd-Z isotopes between Z = 11 and 49
- Many line up well with the quenched effective single-particle g-factors of specific single-particle orbits
- Gradual filling of the orbits as a function of Z, rather closely following the shell-model orbits
- Cases seen in which the g-factors indicate a not so pure wave function
- Caution…are we really "measuring" single-particle states? ☺ A model construct!!

Figure: de Groote & Neyens, Handbook of Nuclear Physics (2023)

Case example: zinc isotopes ($Z = 30$)

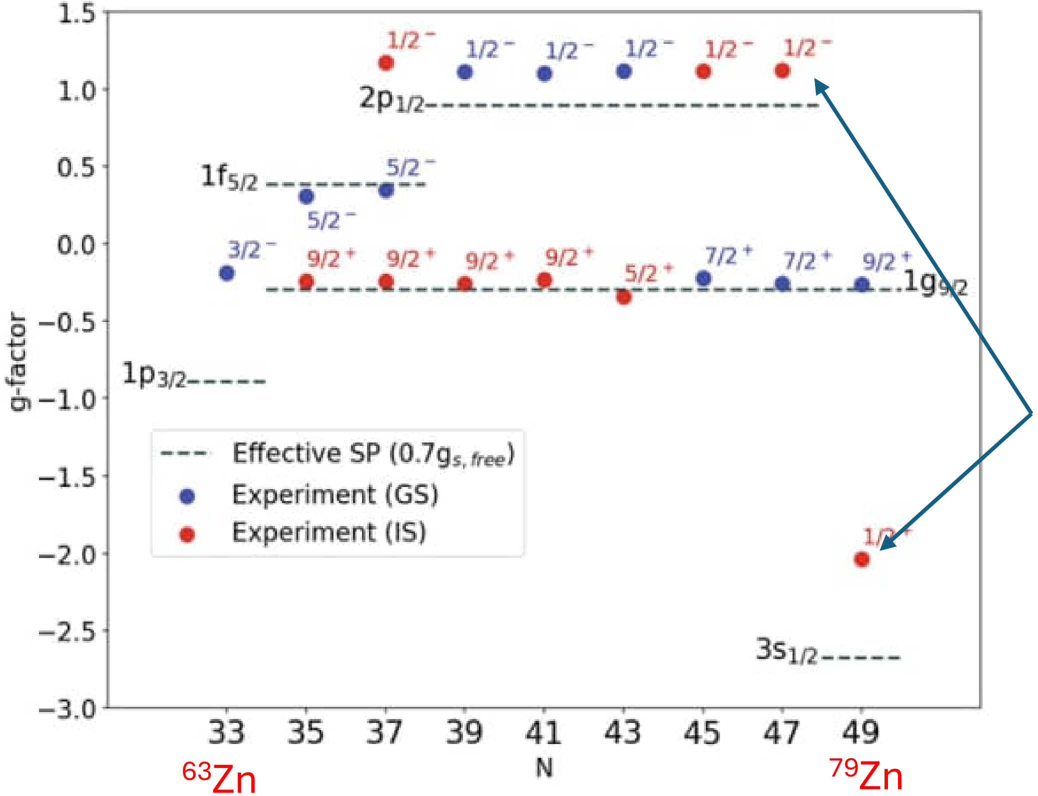
Data obtained via collinear laser spectroscopy at ISOLDE*

Discussion paper, Wraith et al.



4s4p $^3P_2 \rightarrow$ 4s5s $^3S_1$ transition (481 nm)

- $Z = 30$ (2 protons beyond the $Z = 28$ magic core)
- In nearly all isotopes, two long-lived states were found in the spectra
- Some g factors are positive, some negative – relative alignment of l and s.



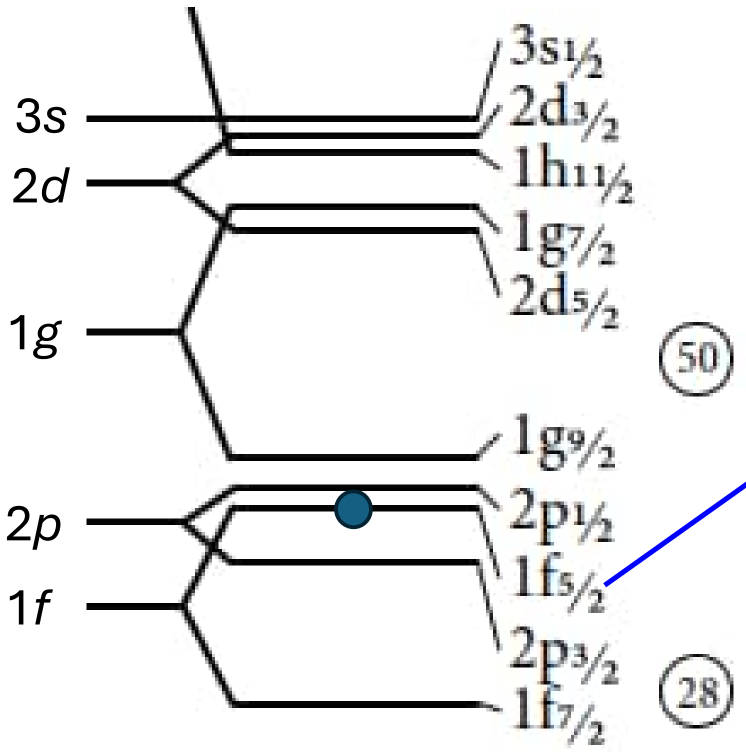
Two I = ½ states have different parities and a very different g-factor!

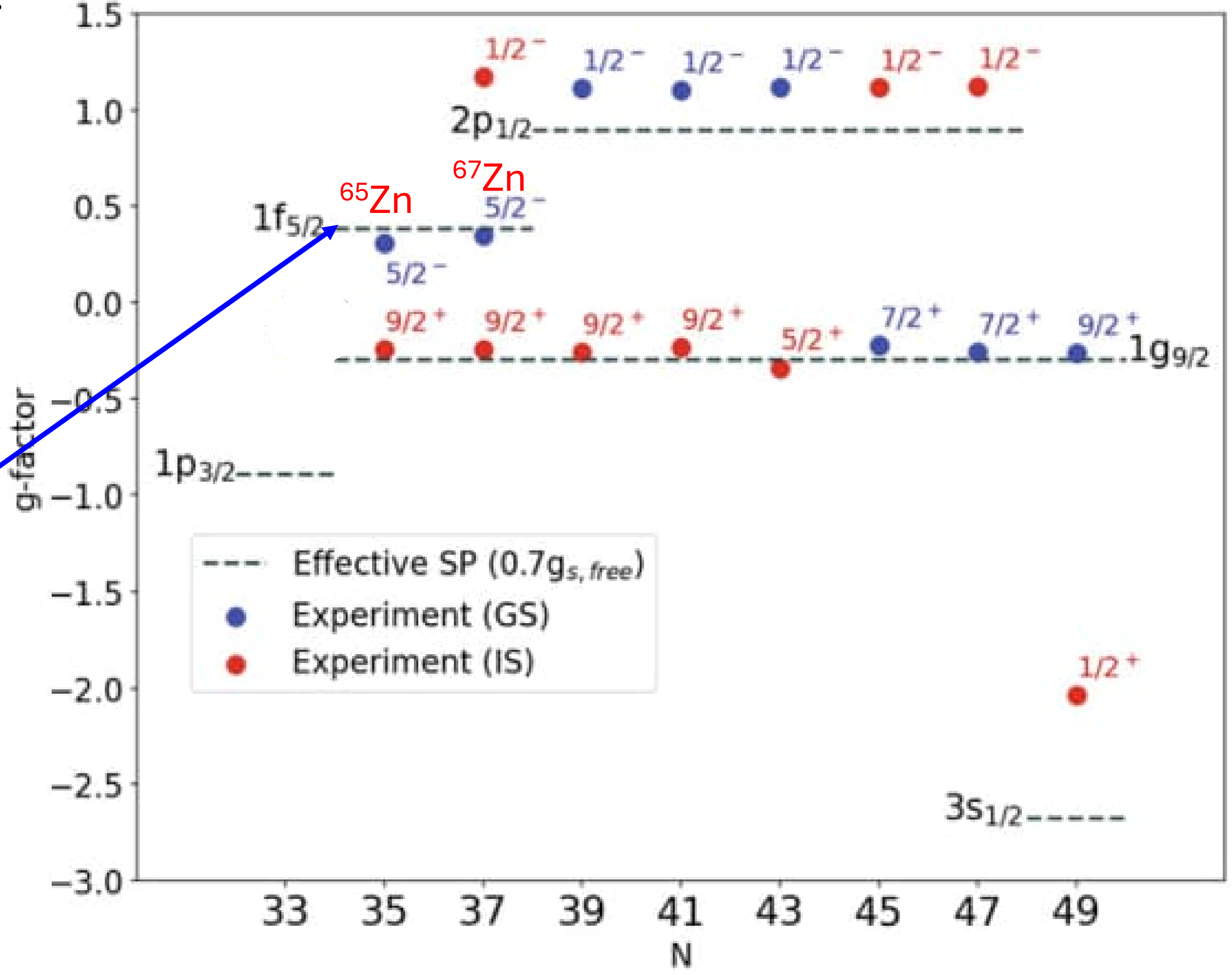
C. Wraith et al., Phys. Lett. B 771 (2017) 385

Example: zinc isotopes ($Z = 30$)

Gradual filling of orbits between neutron shell closures $N = 28$ and $N = 50$.

We can now suggest some configurations!





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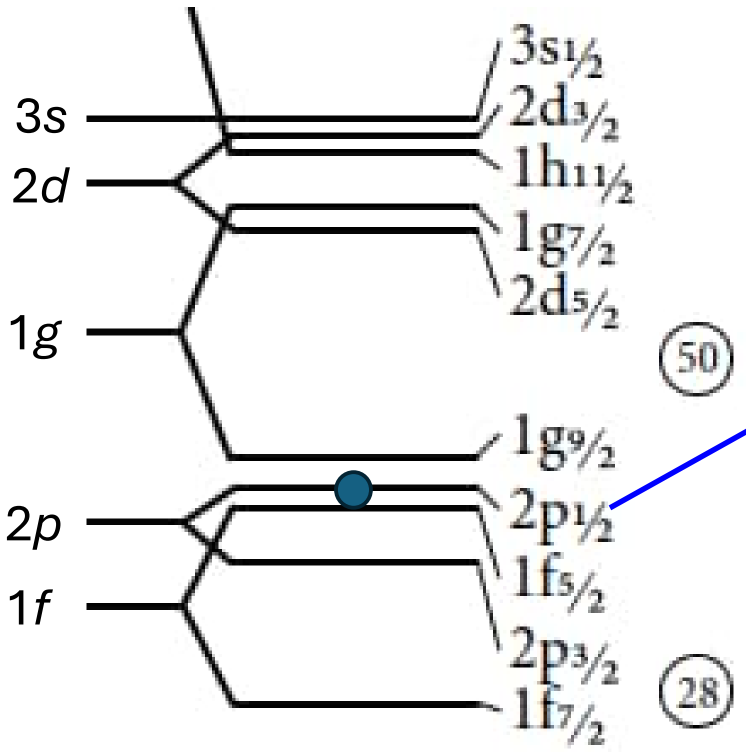

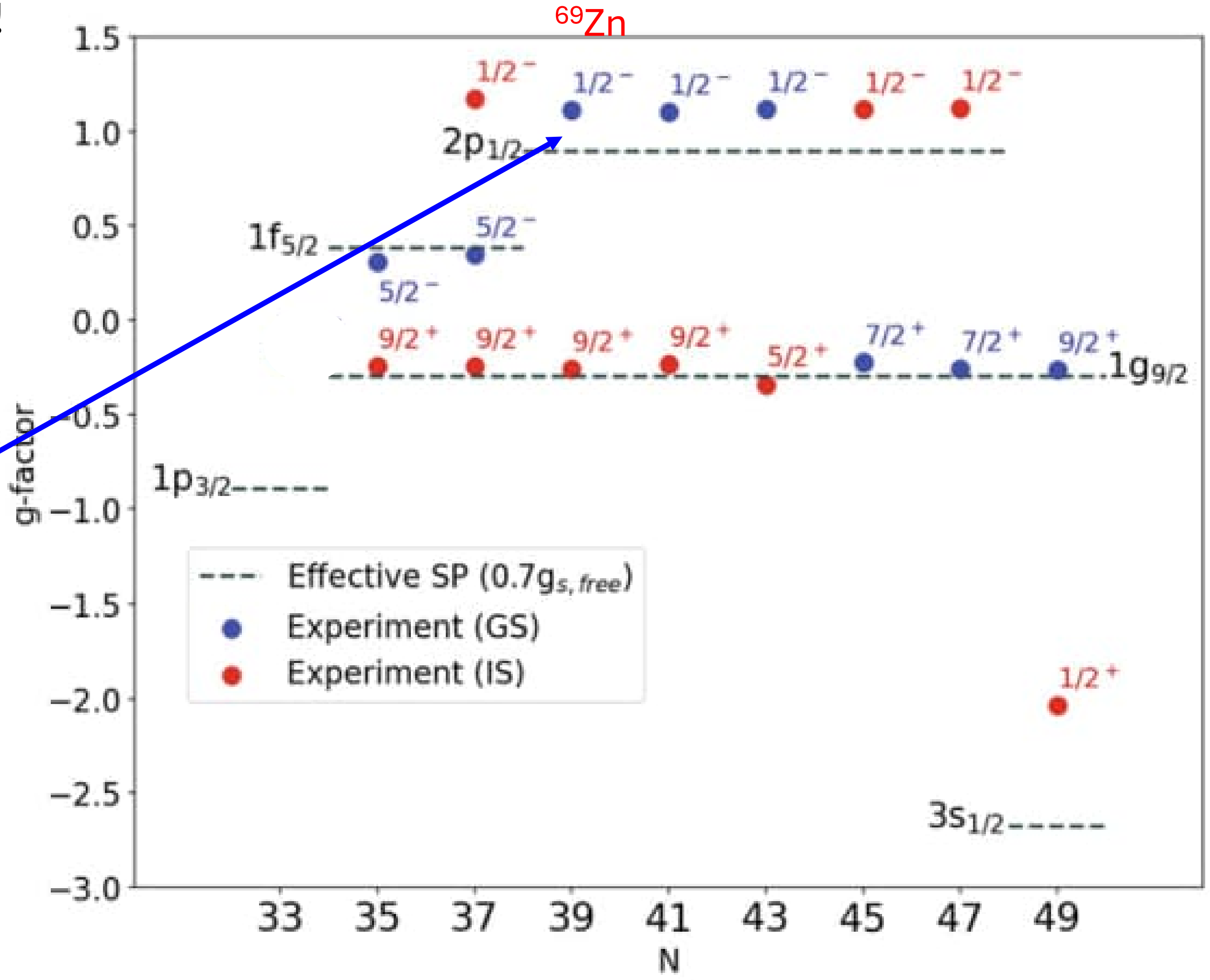

Example: zinc isotopes ($Z = 30$)

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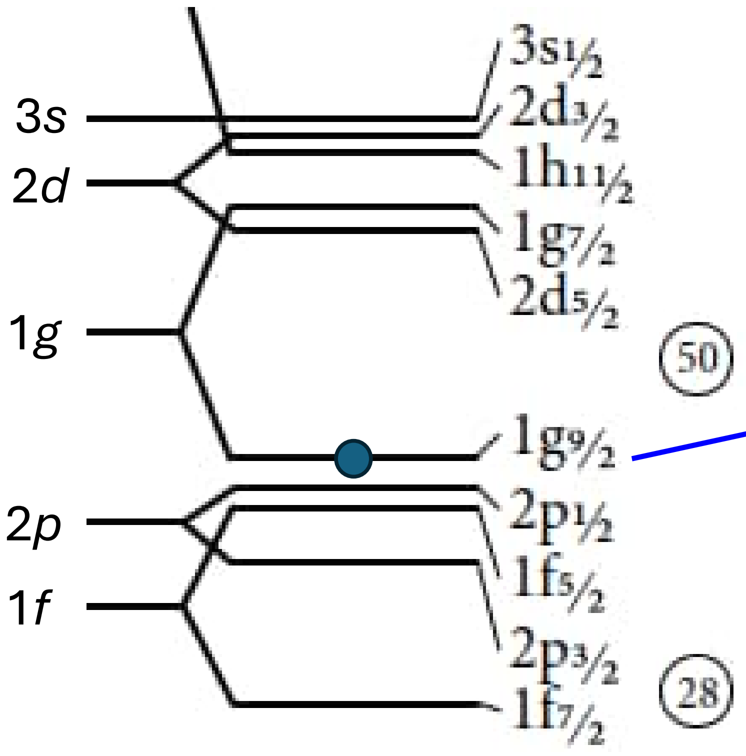
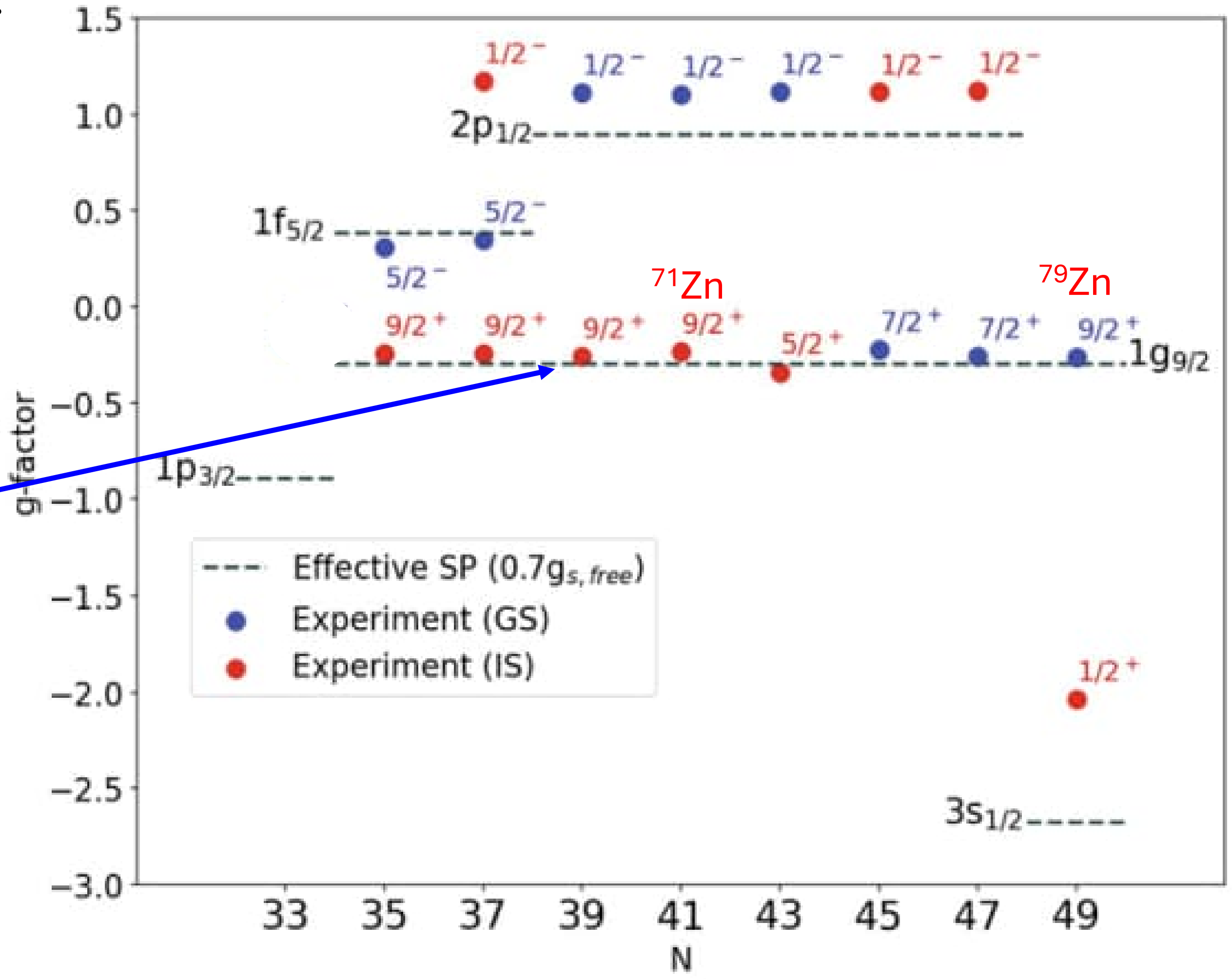
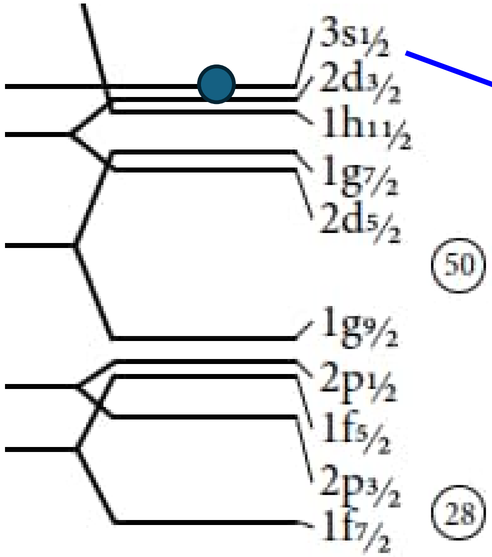
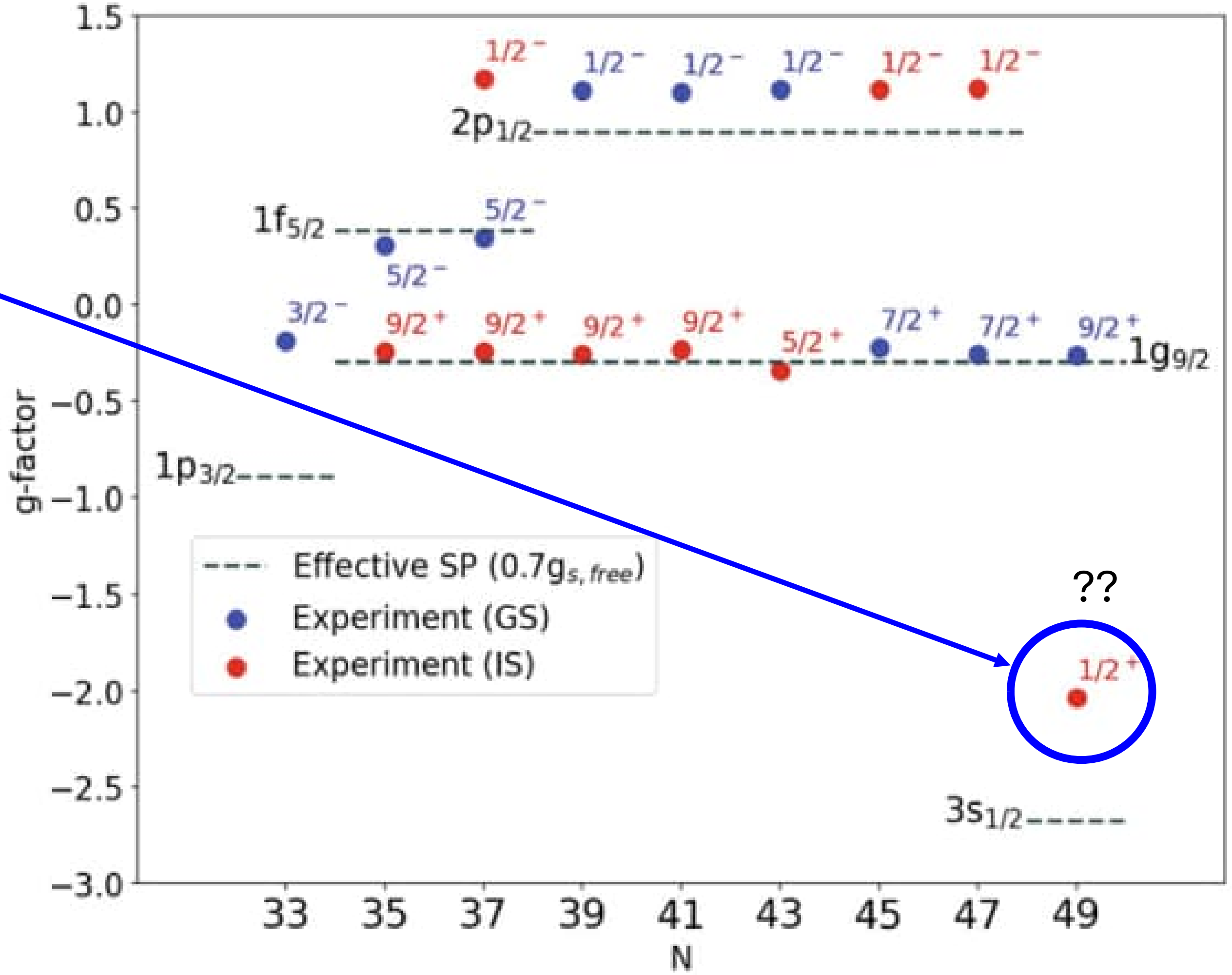




The case of the isomer in ^{79}Zn

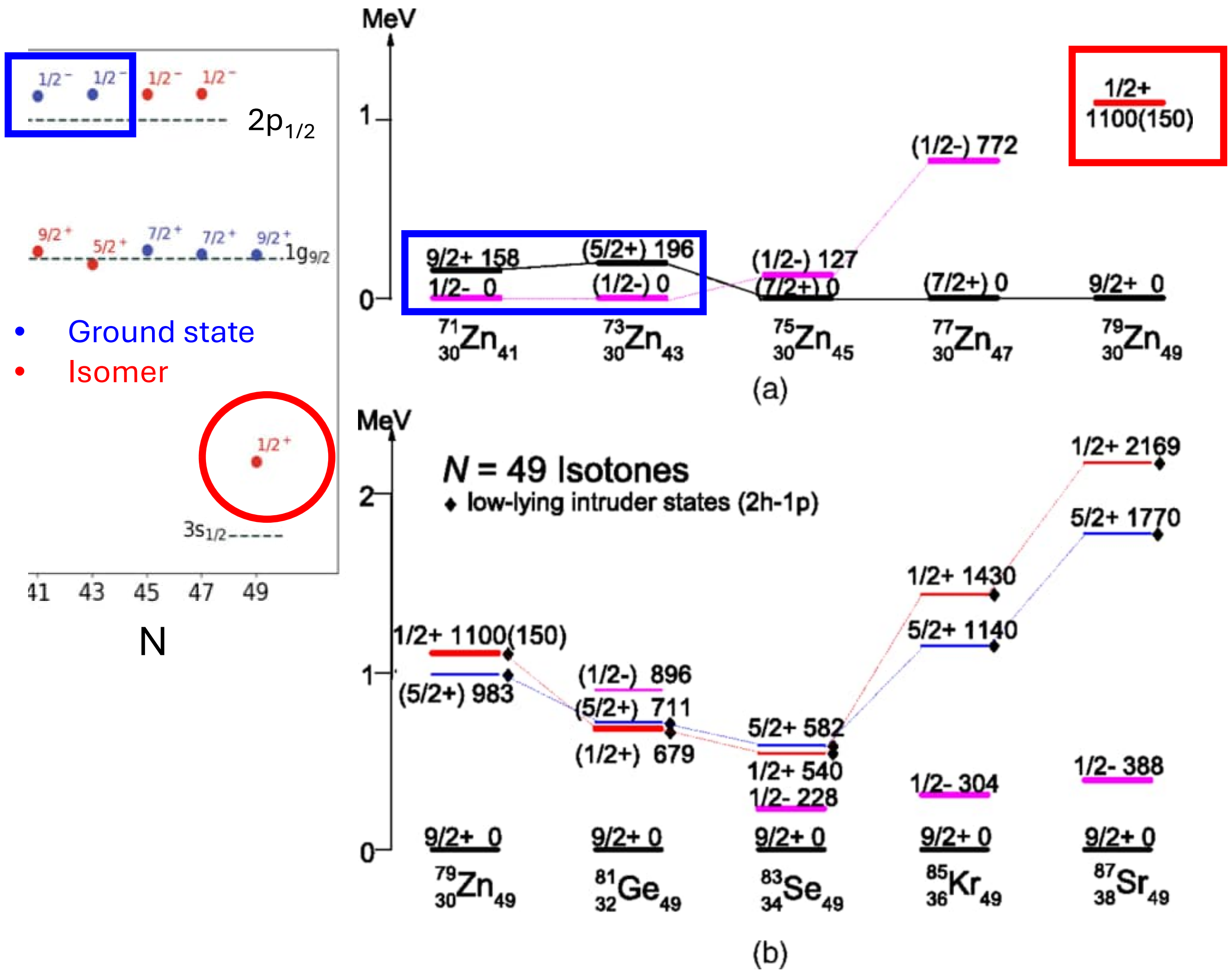
Gradual filling of shells between *N* = 28 and *N* = 50





- The g factor of the I = ½ isomer in ^{79}Zn shows a significant departure from the trend of the other I = ½ states
- The sign is different and the absolute value is larger – evidence for a different structure.
- We need a wave function with a large component with a neutron in the $s_{1/2}$ orbit – but in the spherical shell model this orbit lies above the *N* = 50 shell gap!

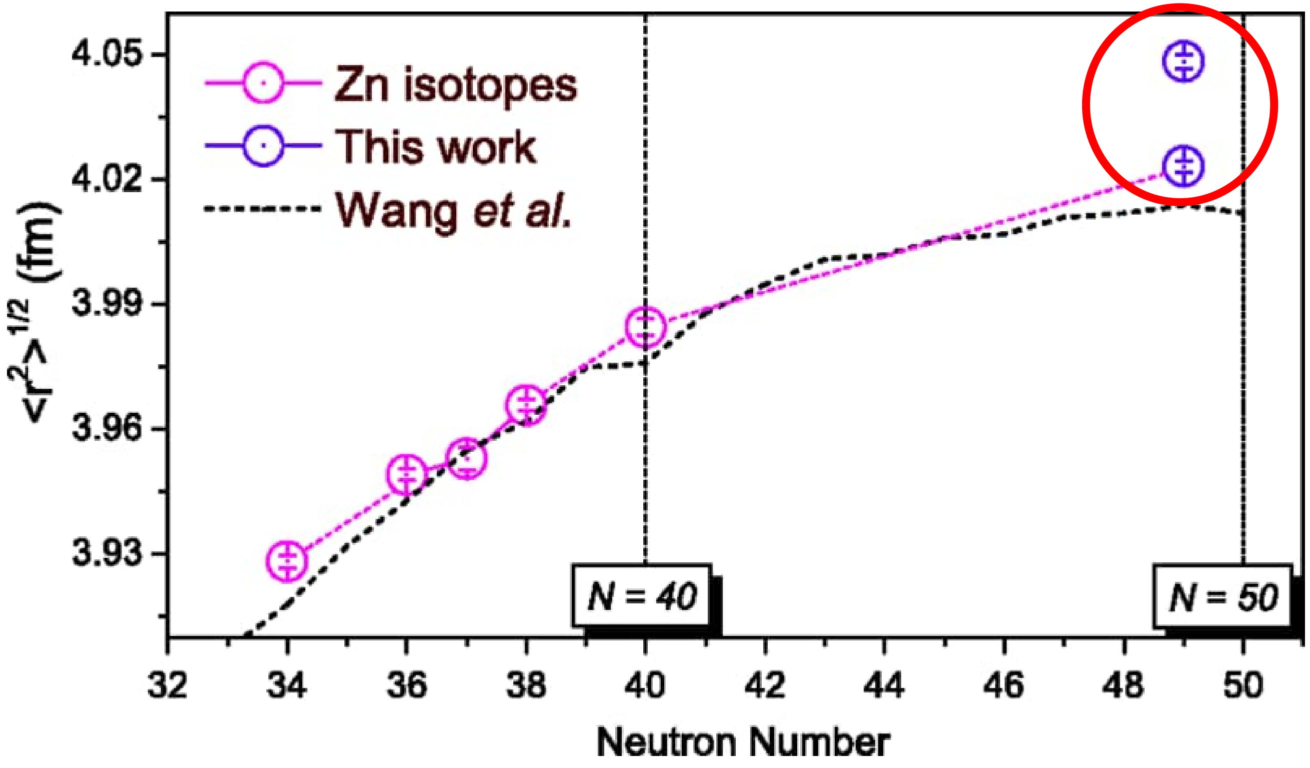
Trends in the neighboring *N* = 49 isotones



X.F. Yang et al., Phys. Rev. Lett. 116 (2016) 182502.

- (d,p) transfer reactions found evidence for intruder states in the region around *N* = 50, tentatively assiging a spin-parity ½$^+$ and excitation energy 1100(150) keV to ^{79m}Zn.
  - *R. Orlandi et al., Phys. Lett. B 740 (2015) 298.*
- This ½$^+$ state has a different parity assignment to the lighter mass ½$^-$ states, and a very different g factor (so different structure) – hence its an "intruder".
- Recent JYFLTRAP and ISOLTRAP mass measurements refined the excitation energy to 942(10) keV.
  - *L. Nies et al., Phys. Rev. Lett. 131 (2023) 222503.*

^{79}Zn – evidence of shape coexistence near ^{78}Ni



X.F. Yang et al., Phys. Rev. Lett. 116 (2016) 182502.

- Reminder: a nuclear spin of ½$^+$ has no observable quadrupole moment!
- A large isomer shift was seen for the ½$^+$, 1-MeV isomer in ^{79}Zn, pointing to a larger deformation.
- Larger deformation interpreted as due to the intruder nature of the isomeric state due to excitations across the N = 50 shell gap – additional holes in the neutron $g_{9/2}$ orbital (multi-particle – multi-hole excitations).

Aside: approaches to the shell model

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Choose your model space

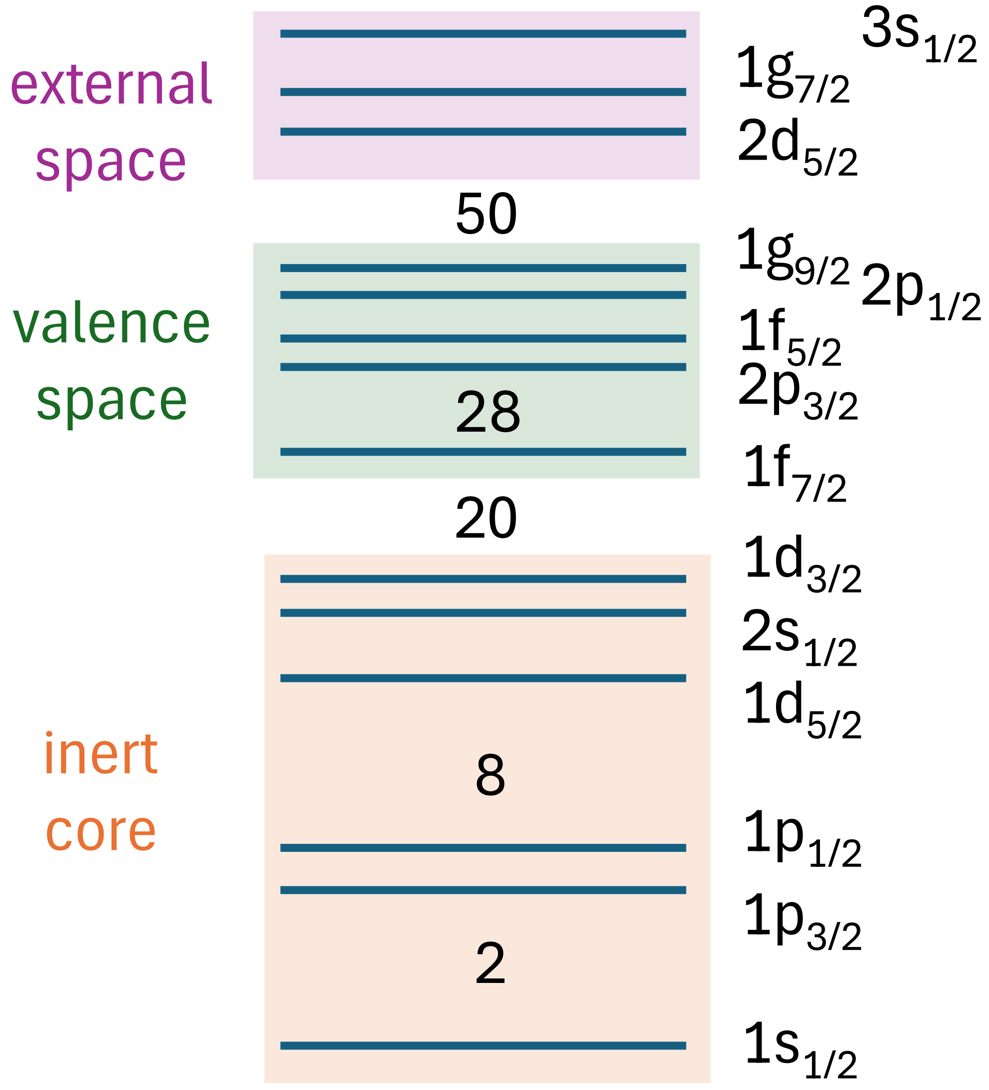
Create different configurations within that valence space, add residual interactions and deal them with using matrix diagonalisation.

Where do residual interactions come from?

Old days – purely empirical or schematic. Nowadays:
(i) take an N-N force (realistic) – modify within the nuclear medium (G-matrix, $V_{low\ k}$, etc)
(ii) tune against some experimental data in "simpler nuclei" – attempt to modify for effects of restricted model space

Choice of model space = degrees of freedom needed + size of calculation

Codes = ANTOINE, NuSHELL, KSHELL, OXBASH…etc
Interactions = Brown/Wildenthal USD, USDA, USDB, GXFP1, GXFP1A, Kuo/Brown, KB3, KB3G, FPD6, jj44b, JUN45, LNPS, A3DA-m, SDPF, … etc



Courtesy: Sean Freeman, UK nuclear physics summer school 2024

Benchmarking shell model interactions with Zn

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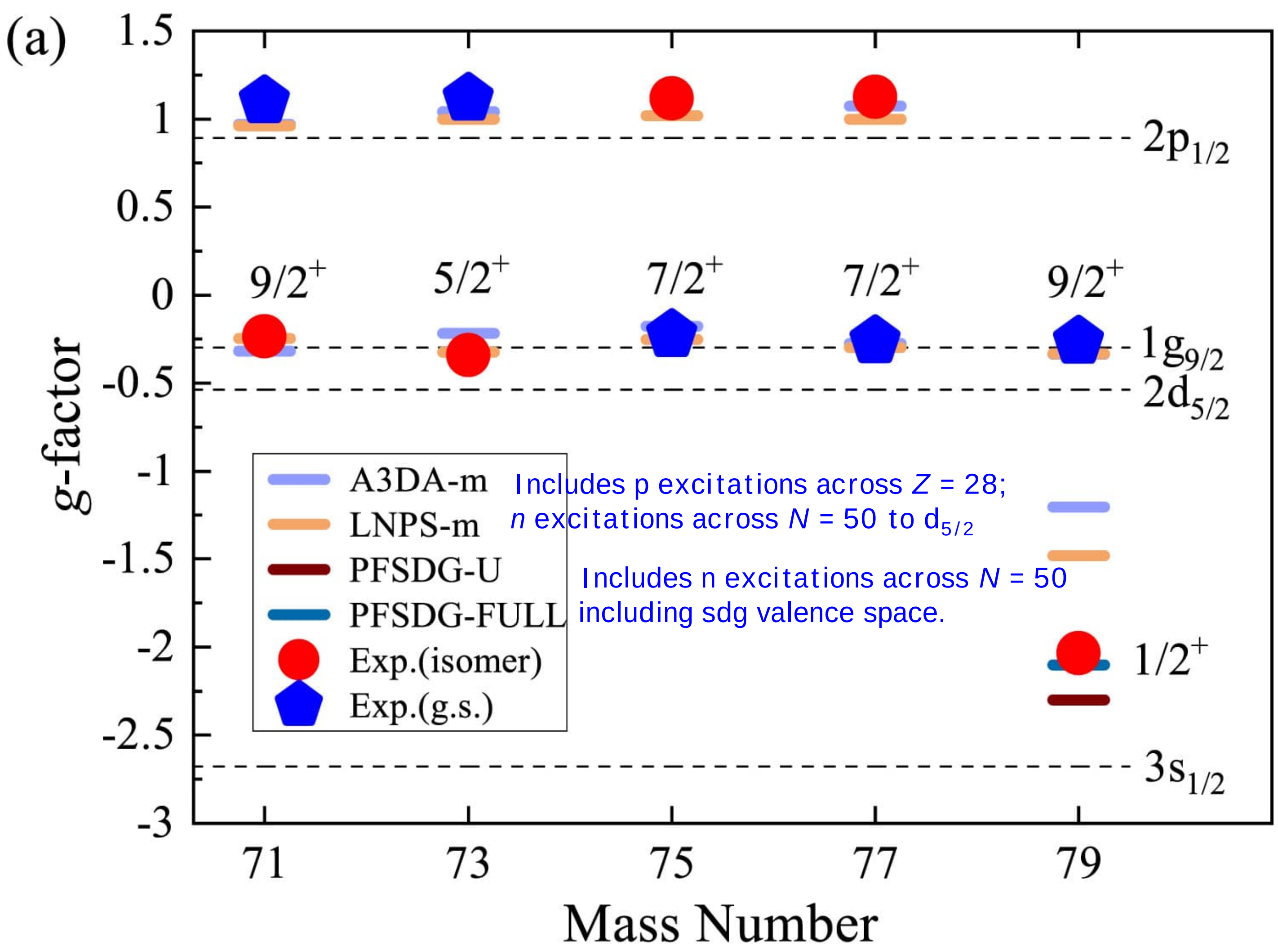

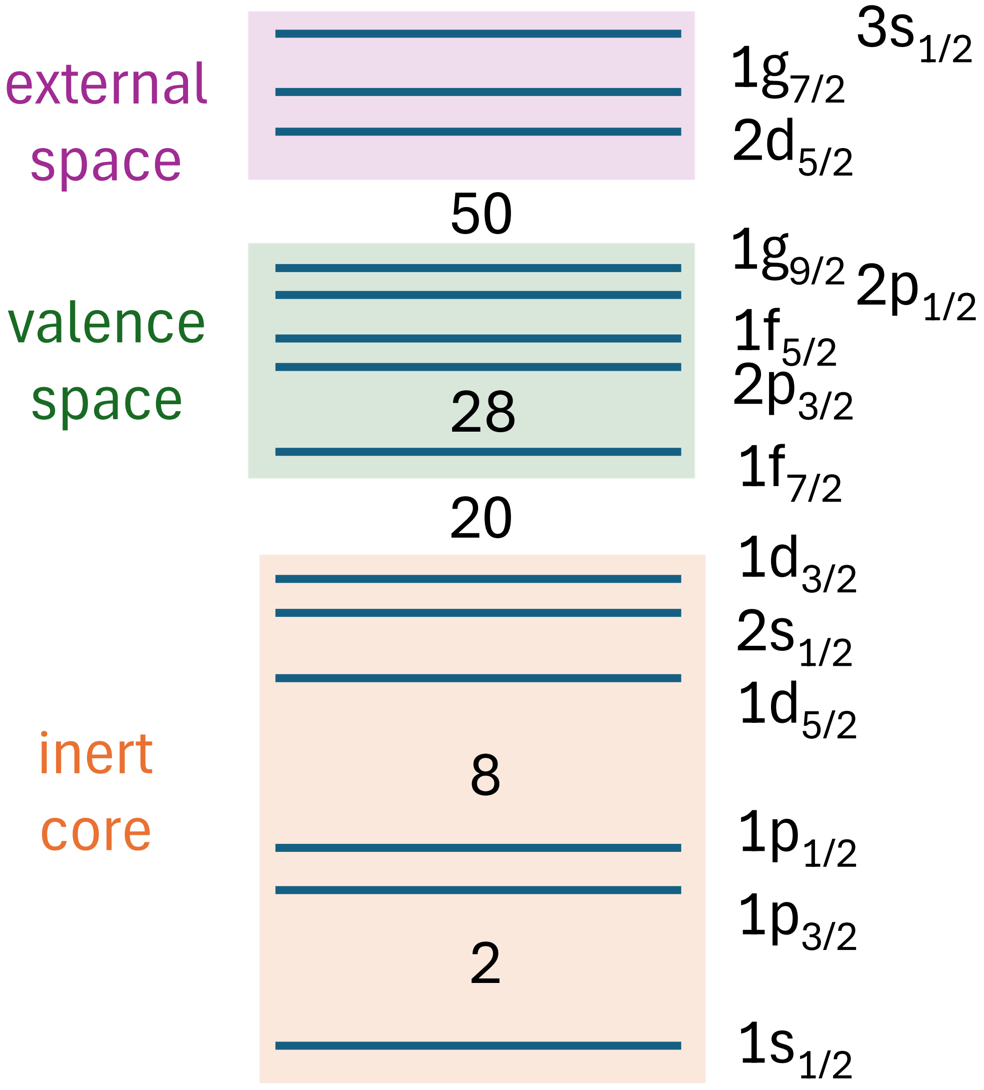

Data: C. Wraith et al., Phys. Lett. B 771 (2017) 385

Figure from: X.F. Yang et al., PPNP 129 (2023) 104005

Take home messages Lecture 4…

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- Non-optical methods of spectroscopy, for example electron scattering, muonic x-rays etc are important probes of absolute charge radii – however they are *mainly* limited to stable isotopes.

- Laser spectroscopy probes differential changes in charge radii, revealing subtle differences in nuclear charge radii – effects of clustering/halos in light nuclei, shell structure, nuclear deformation and indications for shape coexistence among others are revealed.

- Nowadays, we have a very fruitful and close interplay between experiment and theory, e.g., *ab initio* methods, energy density functionals.

- Magnetic moments are very sensitive to the configuration of unpaired nucleons – they can be used to identify ordering of single particle levels and via comparison with nuclear theory can benchmark shell model interactions and the role of collective excitations,…

- Decay spectroscopy is an important complementary tool which allows us to track the migration of (so-called) single-particle states and thus to predict if there would be a ground state spin inversion.