KU LEUVEN

Ground and isomeric state properties of Ag isotopes

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NUSTAR Week September 2025

CRIS

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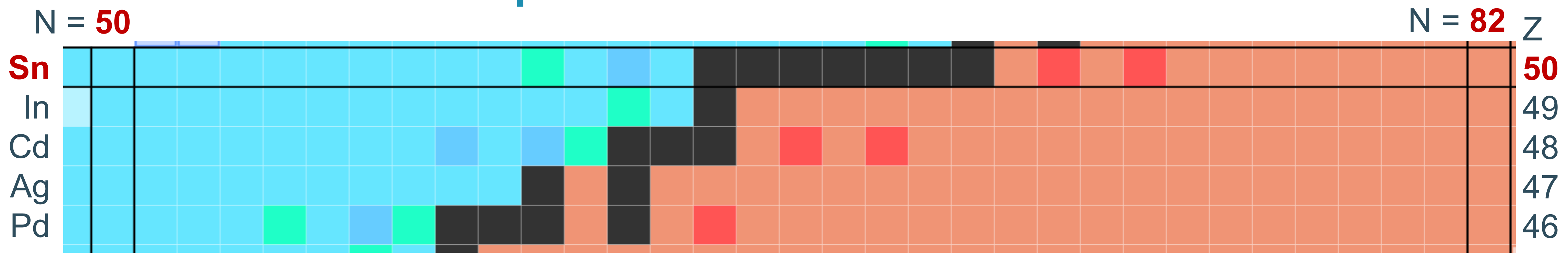
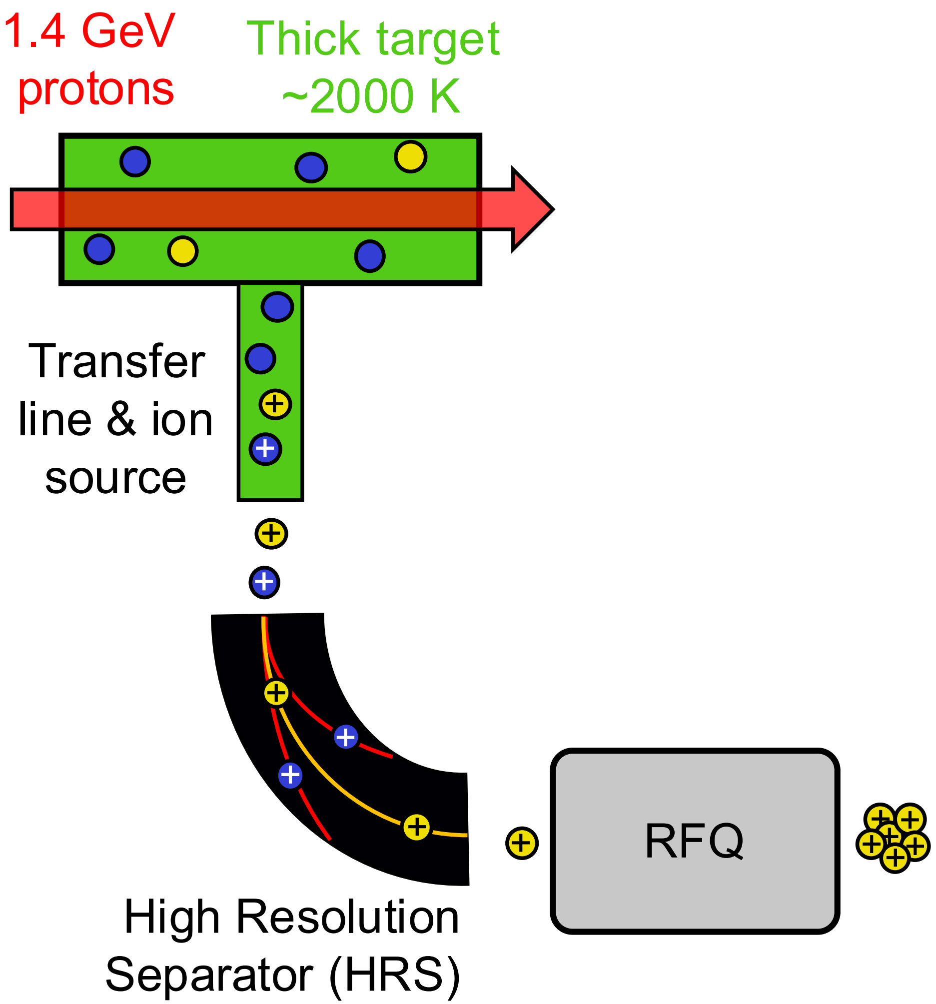
Nuclear landscape below $Z = 50$



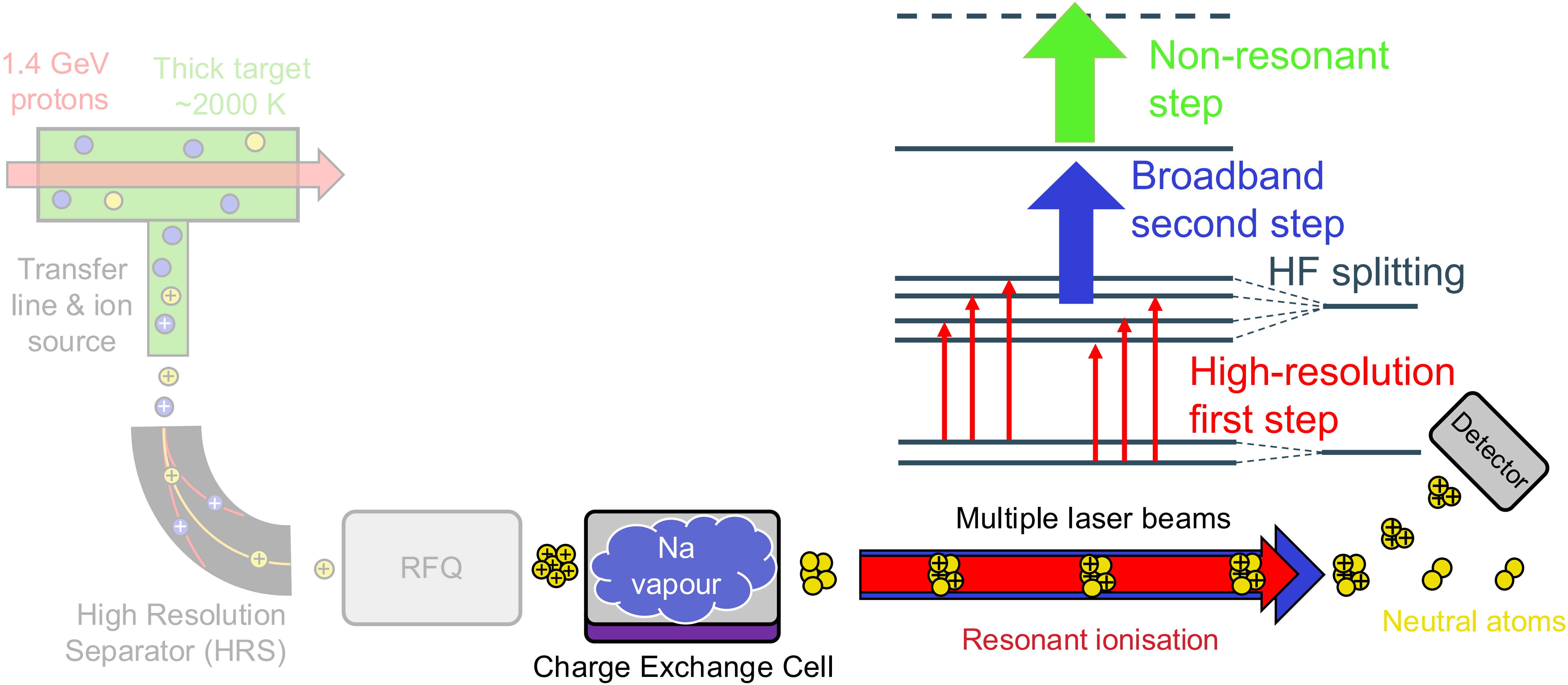
- Closed shell Sn ($Z = 50$) transitioning to well-deformed Pd region ($Z \leq 46$)
- Probe single particle behaviour of proton holes moving away from $Z = 50$
- Probe collectivity from $N = 50$ to $N = 82$ magic shell closures
- Many long-lived states accessible to laser spectroscopy

Significant Bohr-Weisskopf effect in silver

ISOLDE beam generation and manipulation



Collinear Resonance Ionisation Spectroscopy (CRIS)



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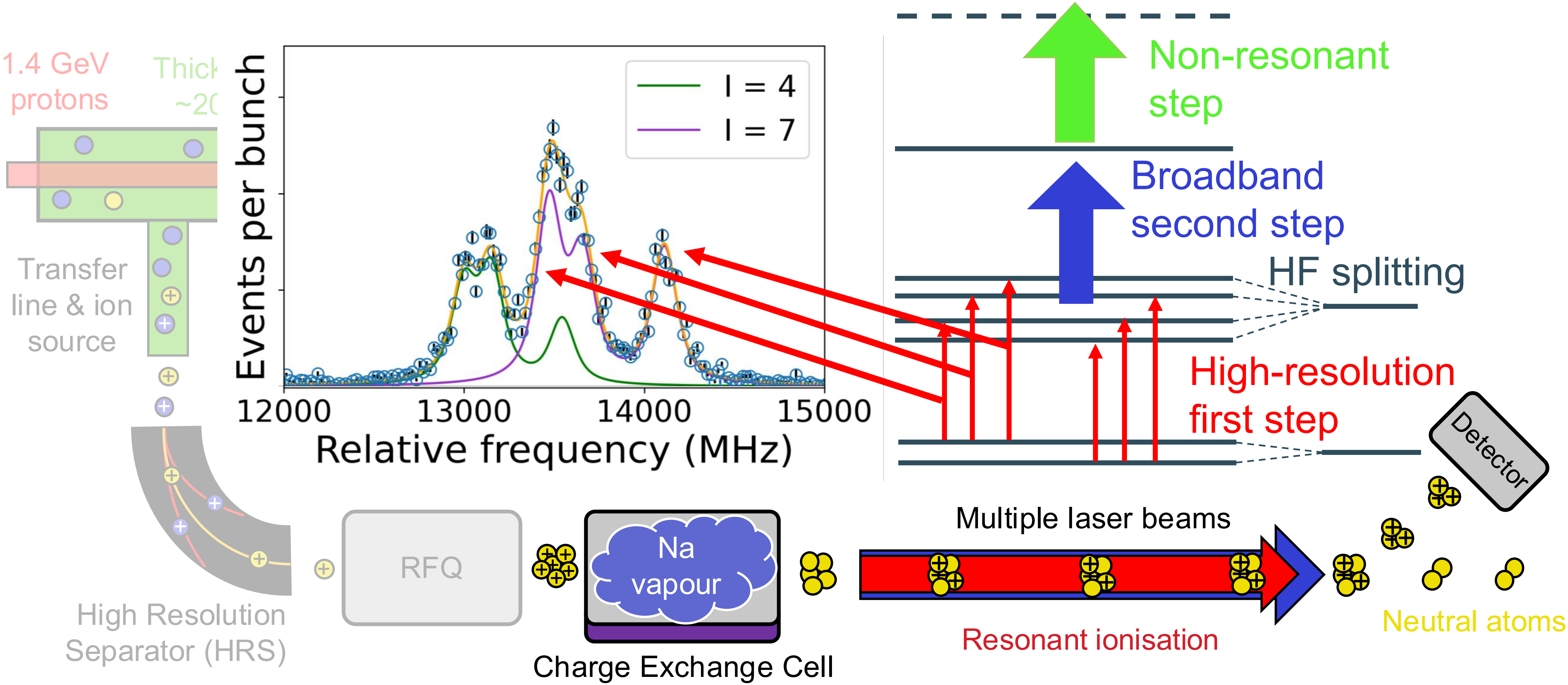
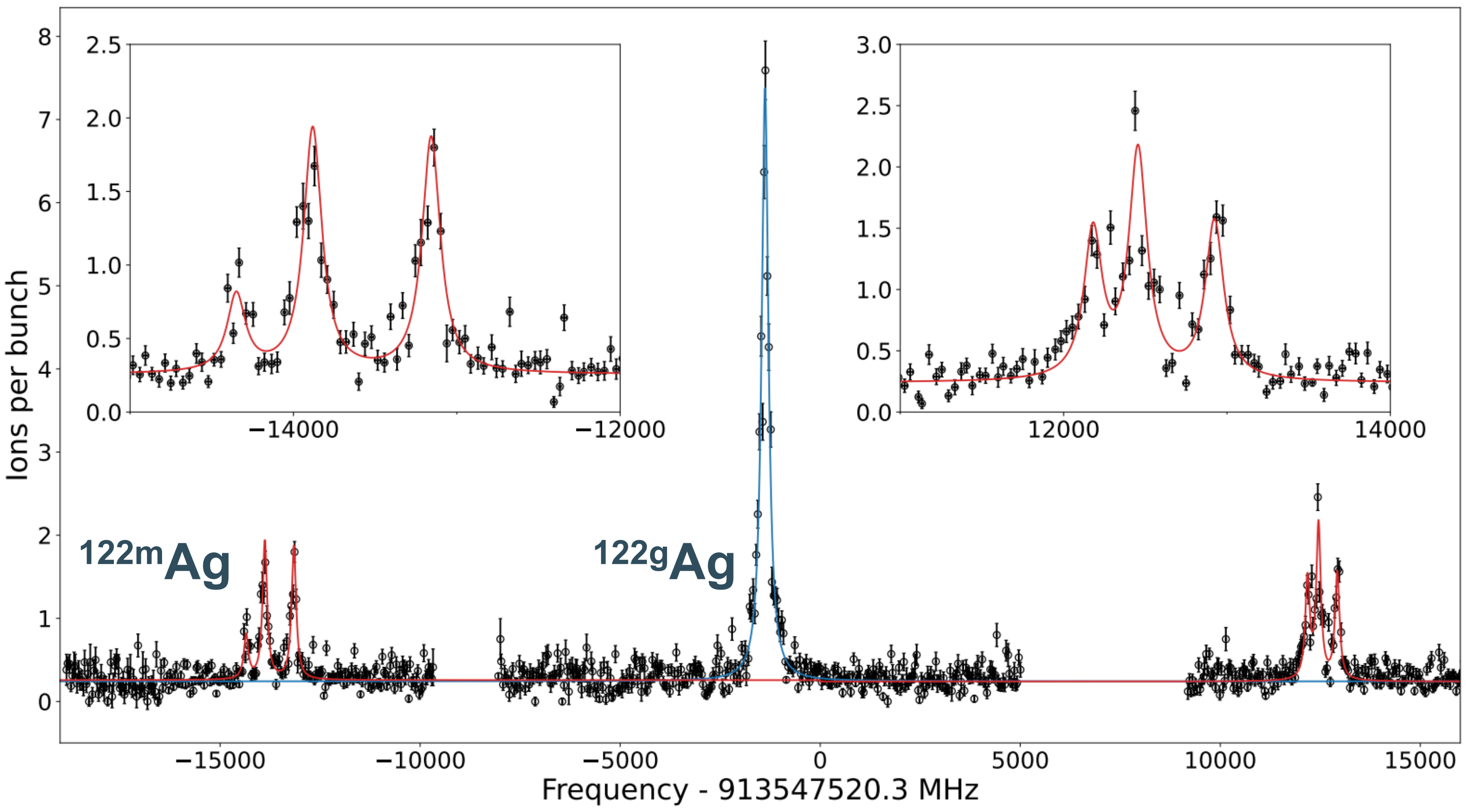
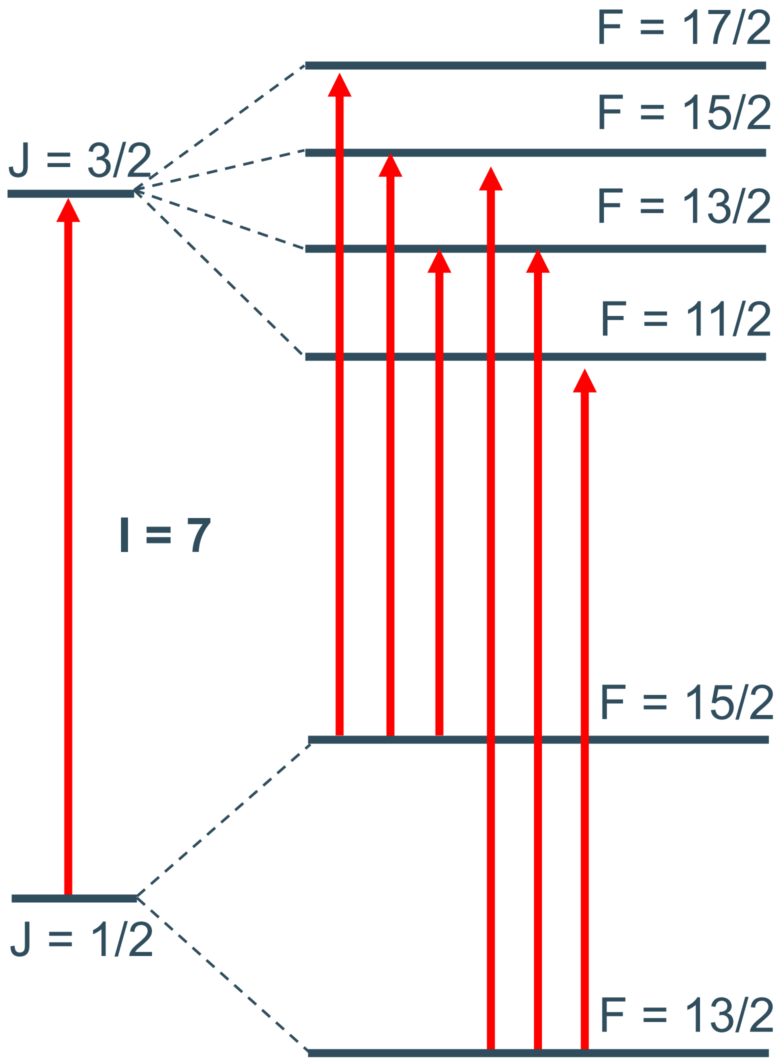


Nuclear structure from hyperfine spectra

- Hyperfine interaction **shifts/splits** atomic states

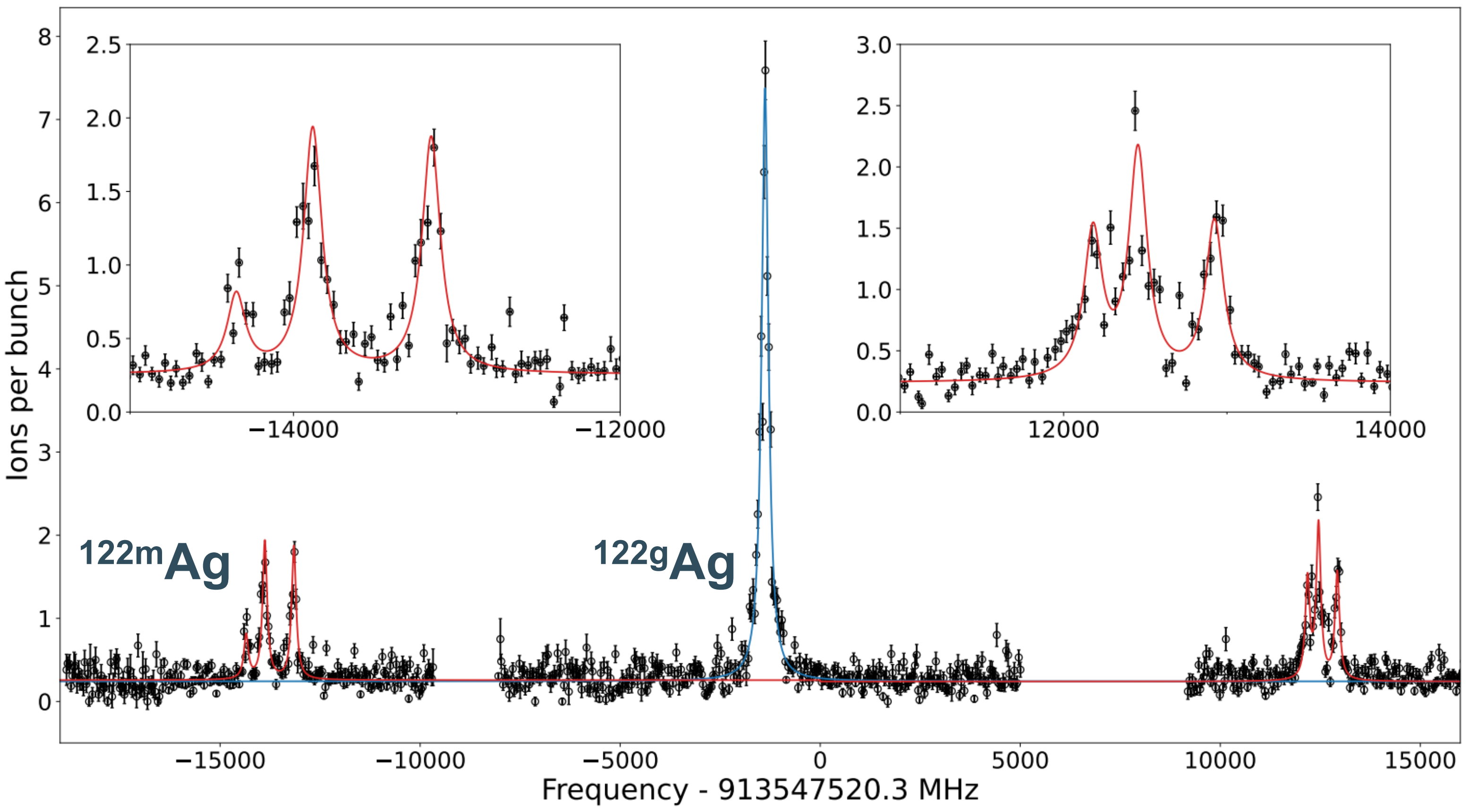


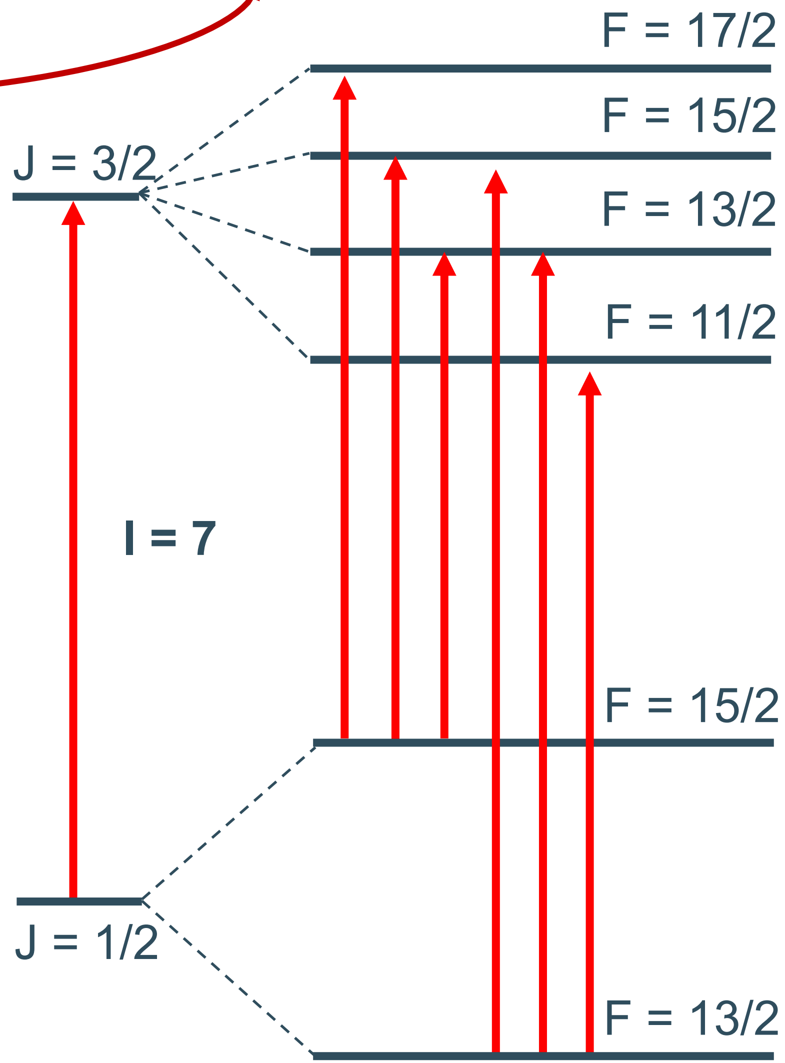


Nuclear structure from hyperfine

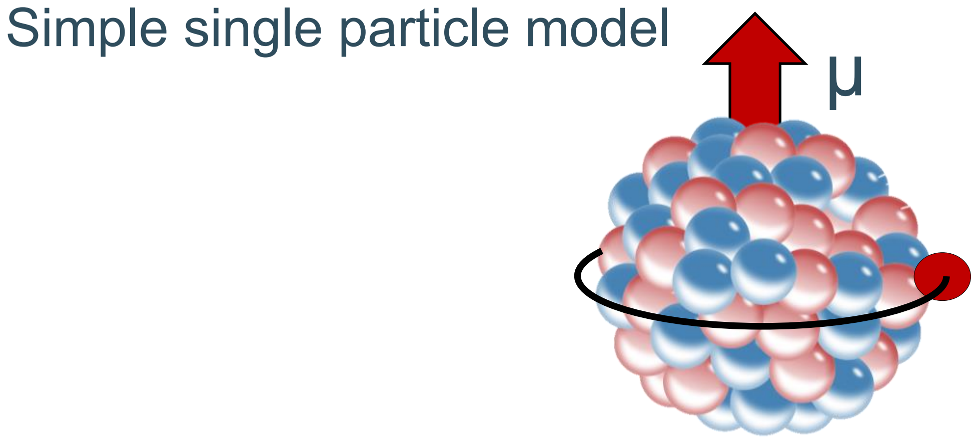
Charge radius, dipole and quadrupole moment

- Hyperfine interaction **shifts/splits** atomic states

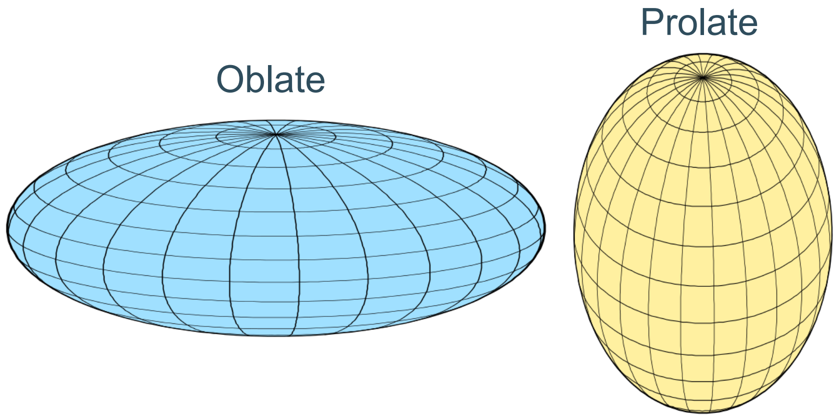




Nuclear properties

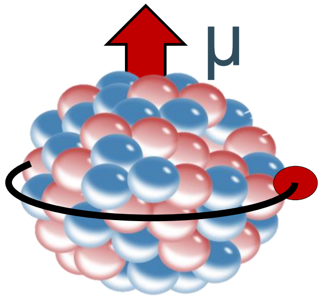


- Mean squared charge radius $\langle r^2 \rangle$:
  - Collective property
  - Size of the distribution of protons
- Magnetic dipole moment μ:
  - Induced by orbiting charged particles + intrinsic spin of nucleons
  - Configuration of the nucleus
  - g-factor: $g = \frac{\mu}{I}$
- Electric quadrupole moment Q:
  - Distribution of protons
  - Deformation of the nucleus

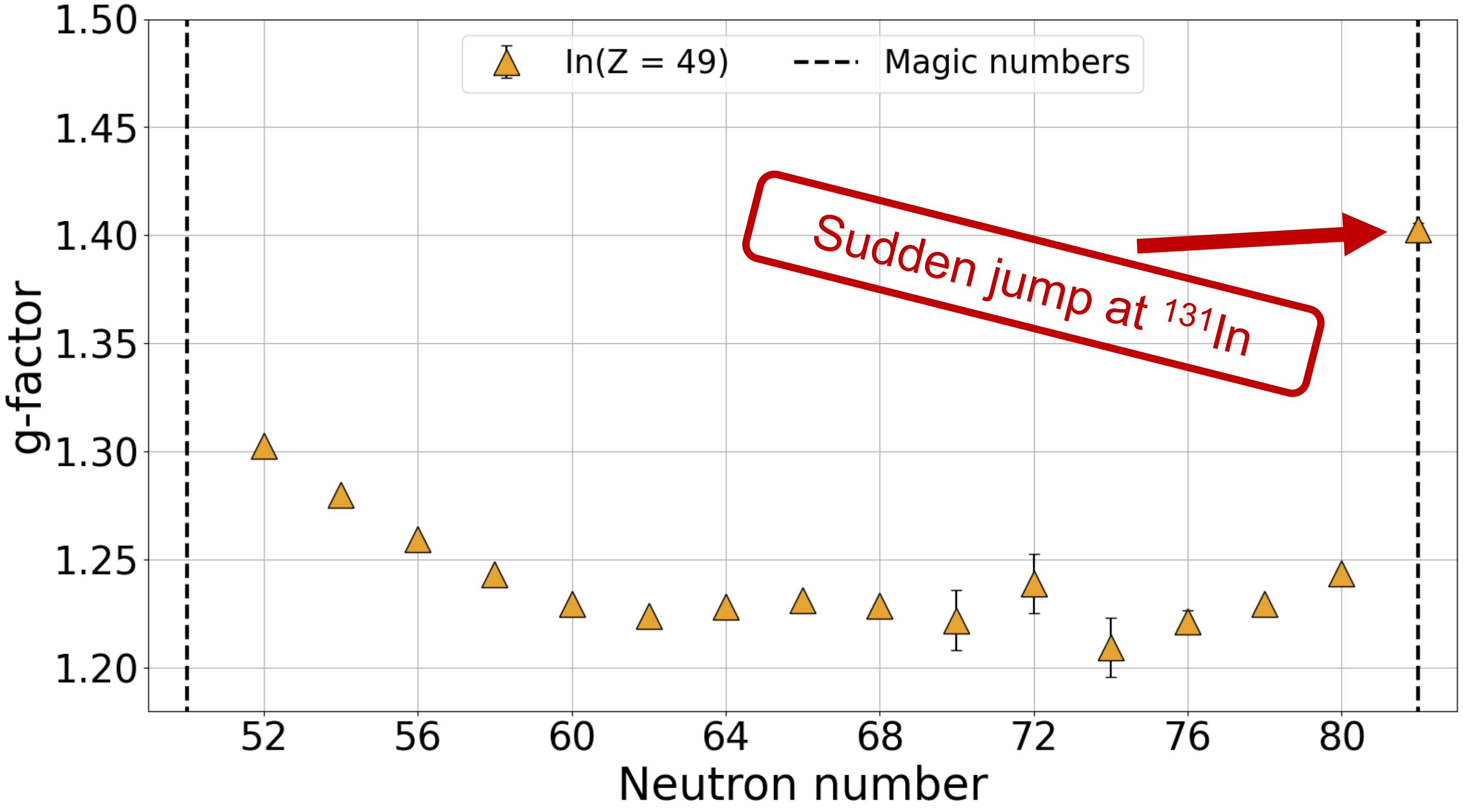


Single particle behaviour in Z = 49 indium

- Single proton hole indium
  - Simple configuration?



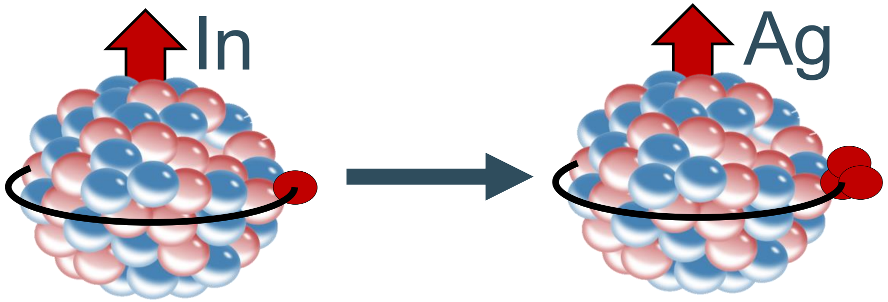
- Textbook example for single particle behaviour[1]
- Interpretation **challenged** by ^{131}In[2]



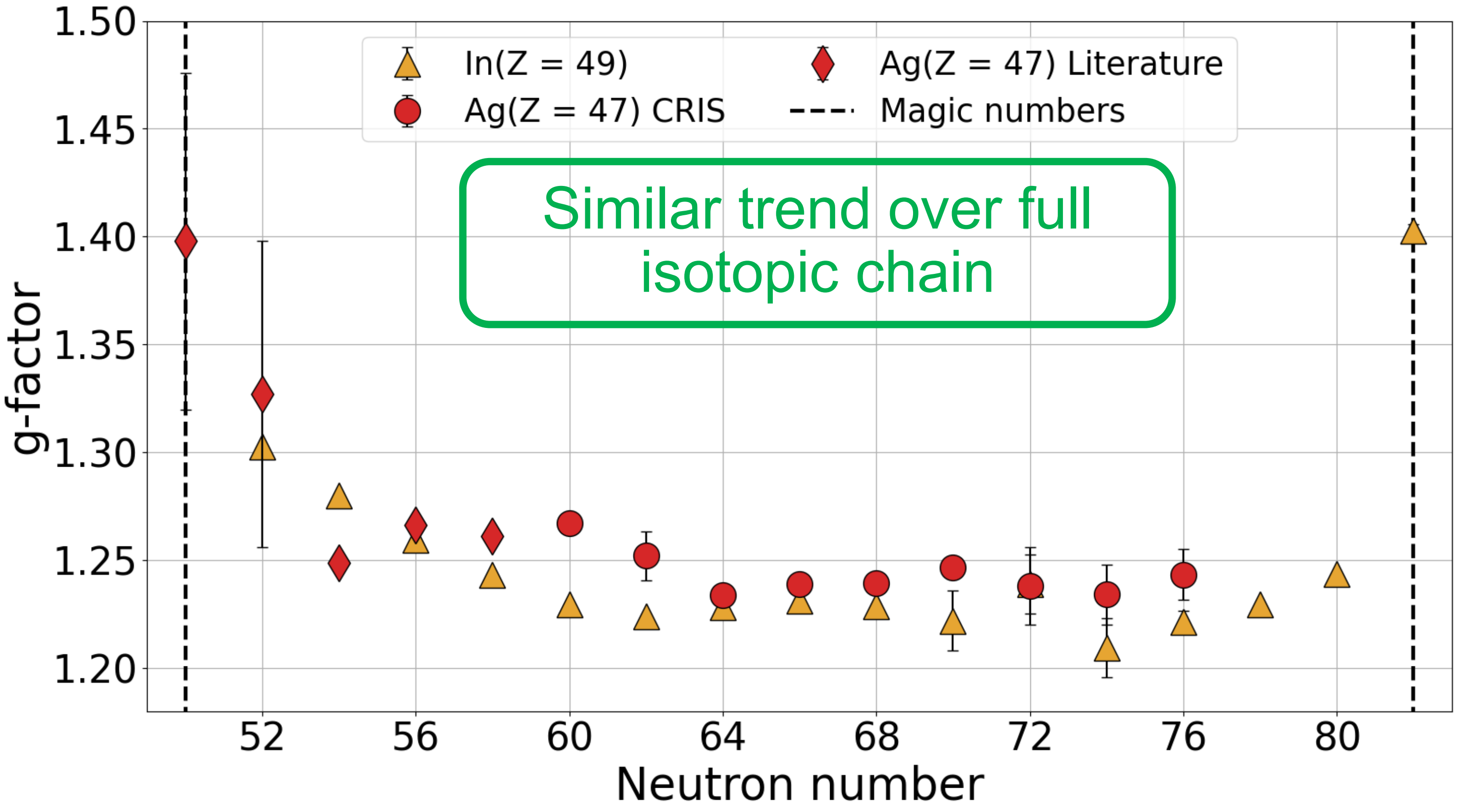
[1] K. L. G. Heyde, *et al.*, Springer Series in Nuclear and Particle Physics (1990).
[2] A.R. Vernon, *et al.*, Nature **607**, 260–265 (2022).
[3] J. Karthein, *et al.*, Nat. Phys. **20**, 1719–1725 (2024).

What about silver?

- Three proton hole silver
  - Similar configuration?



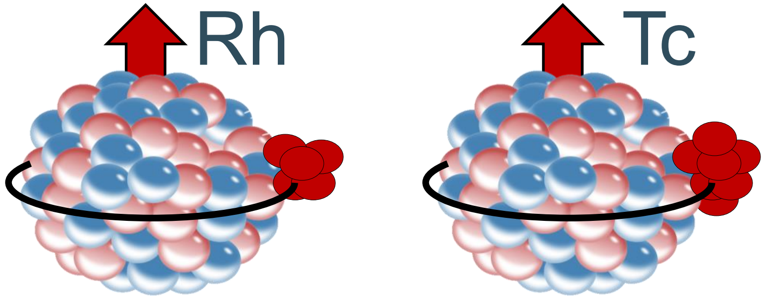
Removing protons has no effect on the g-factor for these states



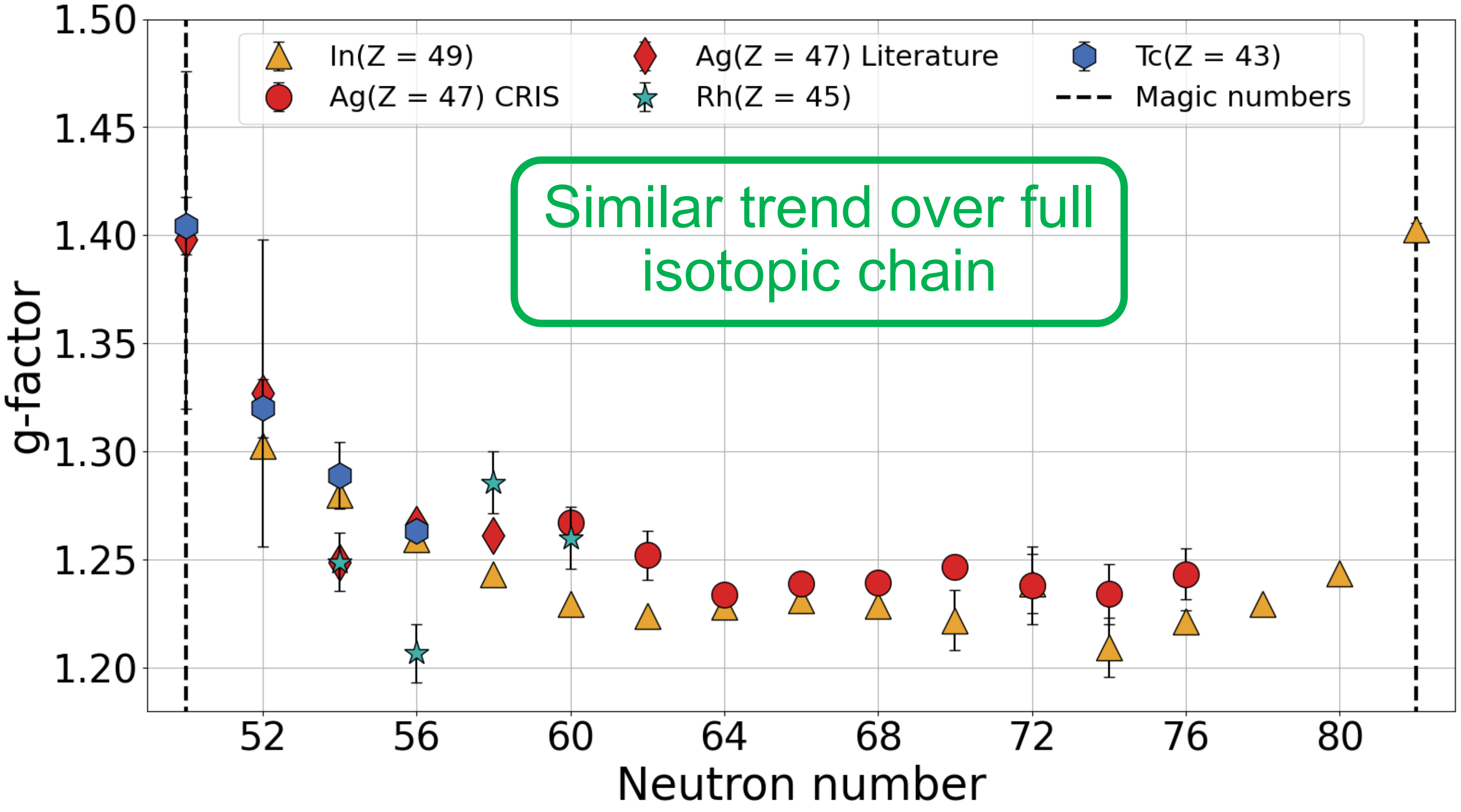
[1] R. Ferrer, *et al.*, Physics Letters B **728,** 191-197 (2014).
[2] U. Dinger, *et al.*, Nuclear Physics A **503.2,** 331-348 (1989).

Removing protons…

- Five proton hole Rh & seven proton hole Tc
  - Similar configuration?



Experimentally "similar" configuration

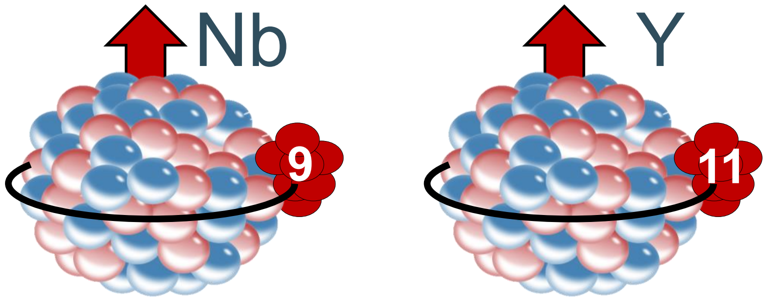


Similar trend over full isotopic chain

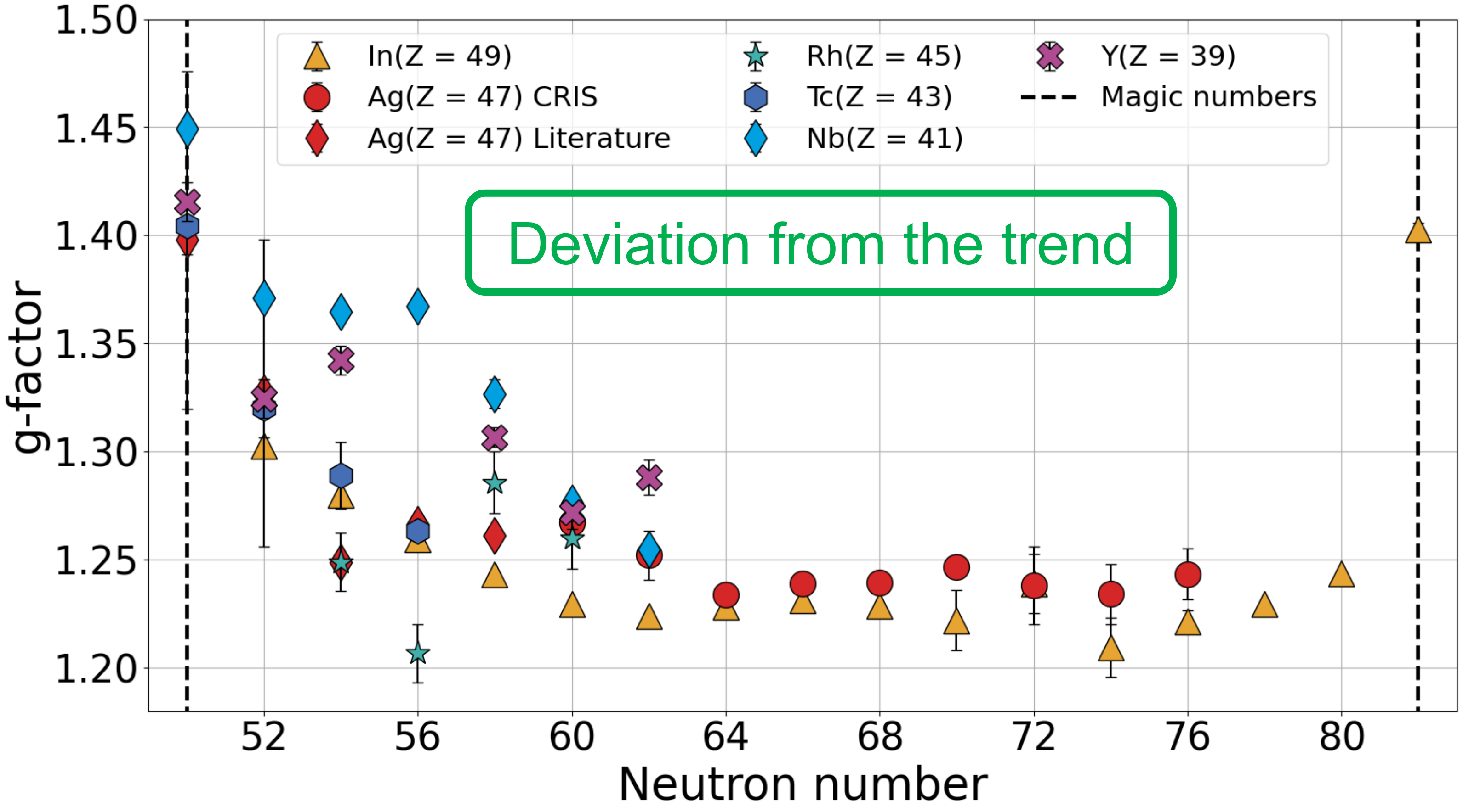
[1] G. Seewald, *et al.*, Phys, Rev. B **51.17**, 11484 (1995).
[2] B. Hinfurtner, *et al.*, Z. Physik A **350**, 311–318 (1995).
[3] H. Walchli, *et al.*, Phys. Rev. **85.3**, 479 (1952).

Removing *even more* protons…

- Nine proton hole Nb & eleven proton hole Y
  - Similar configuration?



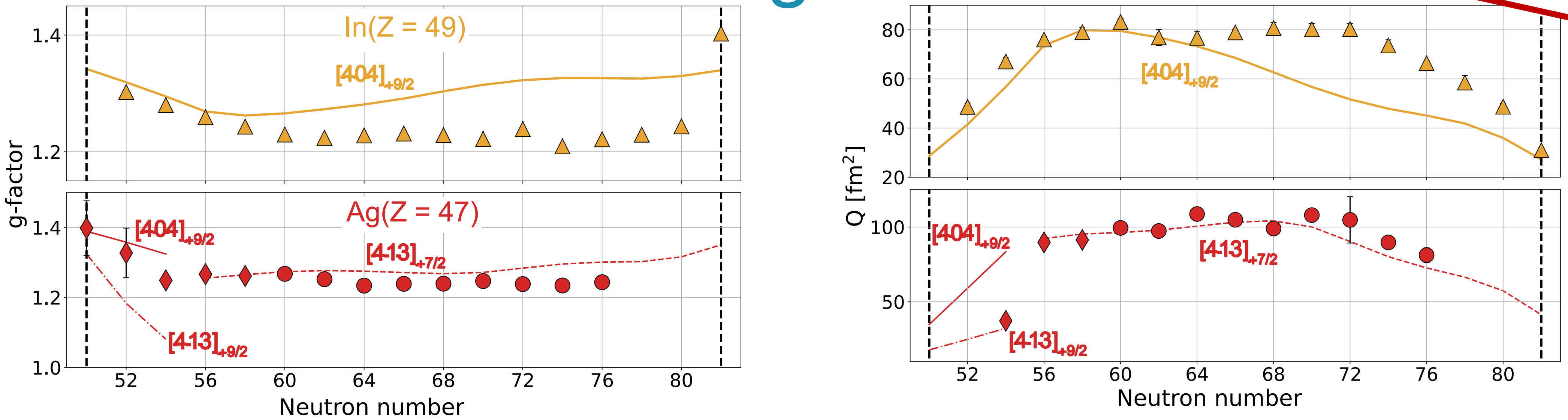
Can we predict this theoretically?



[1] B. Cheal, *et al.*, Phys. Rev. Lett. **102.22,** 222501 (2009).
[2] I. Berkes, *et al.*, Phys. Rev. C **44.1,** 104 (1991).
[3] R. Eder, *et al.*, Nuclear Physics A **451.1,** 46-60 (1986).
[4] B. Cheal, *et al.*, Phys. Lett. B **645.2-3,** 133-137 (2007).

DFT calculations using HFODD

Skyrme force parameter set from global analysis[1]



Good agreement for silver isotopes, **but** worse agreement for indium?

[1] P. L. Sassarini, *et al.*, J. Phys. G: Nucl. Part. Phys. **49**, 11LT01 (2022).

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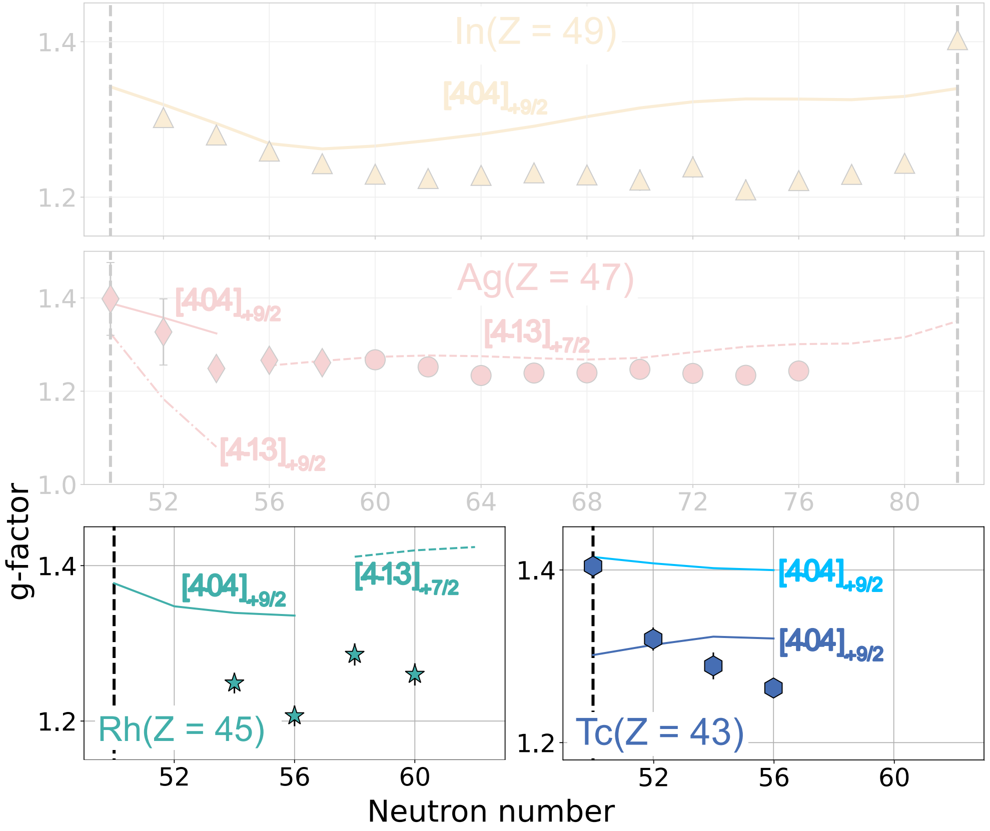
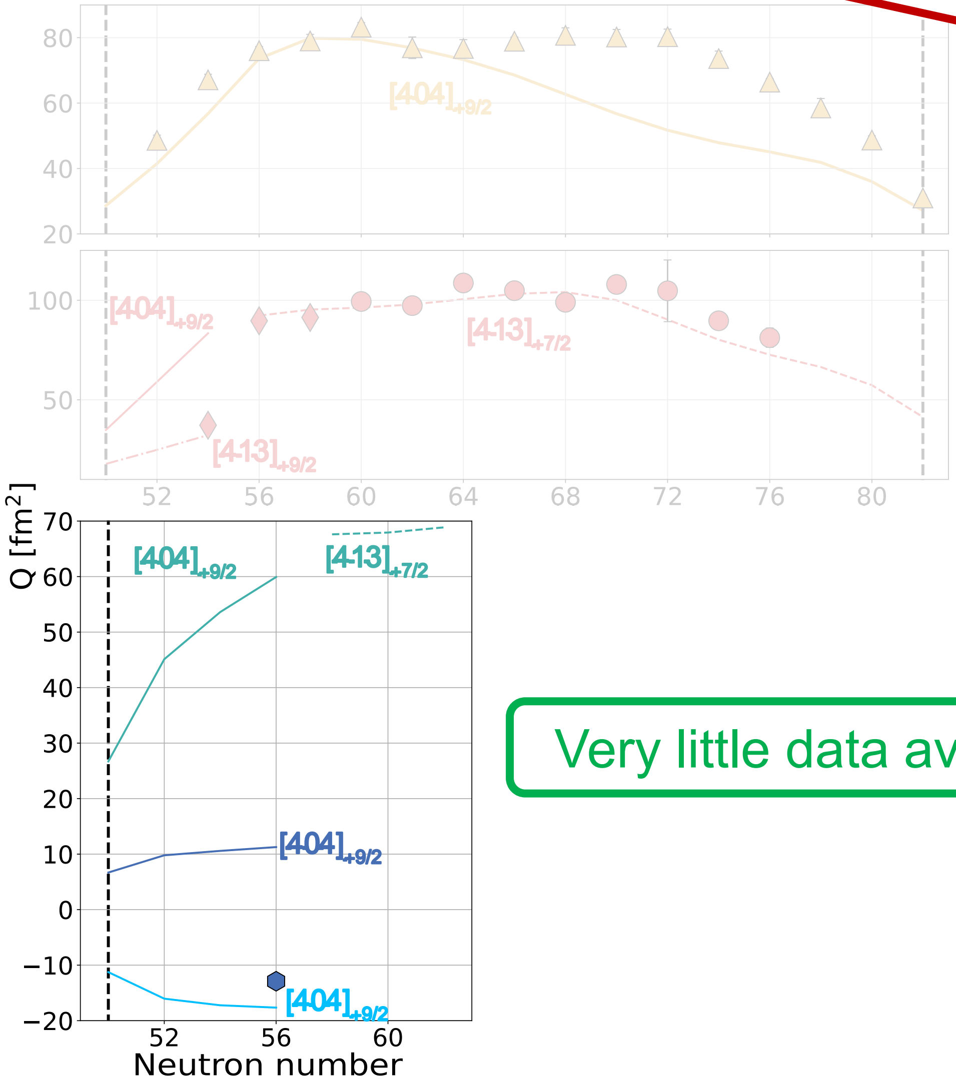


Reasonable agreement for Rh and Tc



Very little data available

[1] P. L. Sassarini, *et al.*, J. Phys. G: Nucl. Part. Phys. **49**, 11LT01 (2022).

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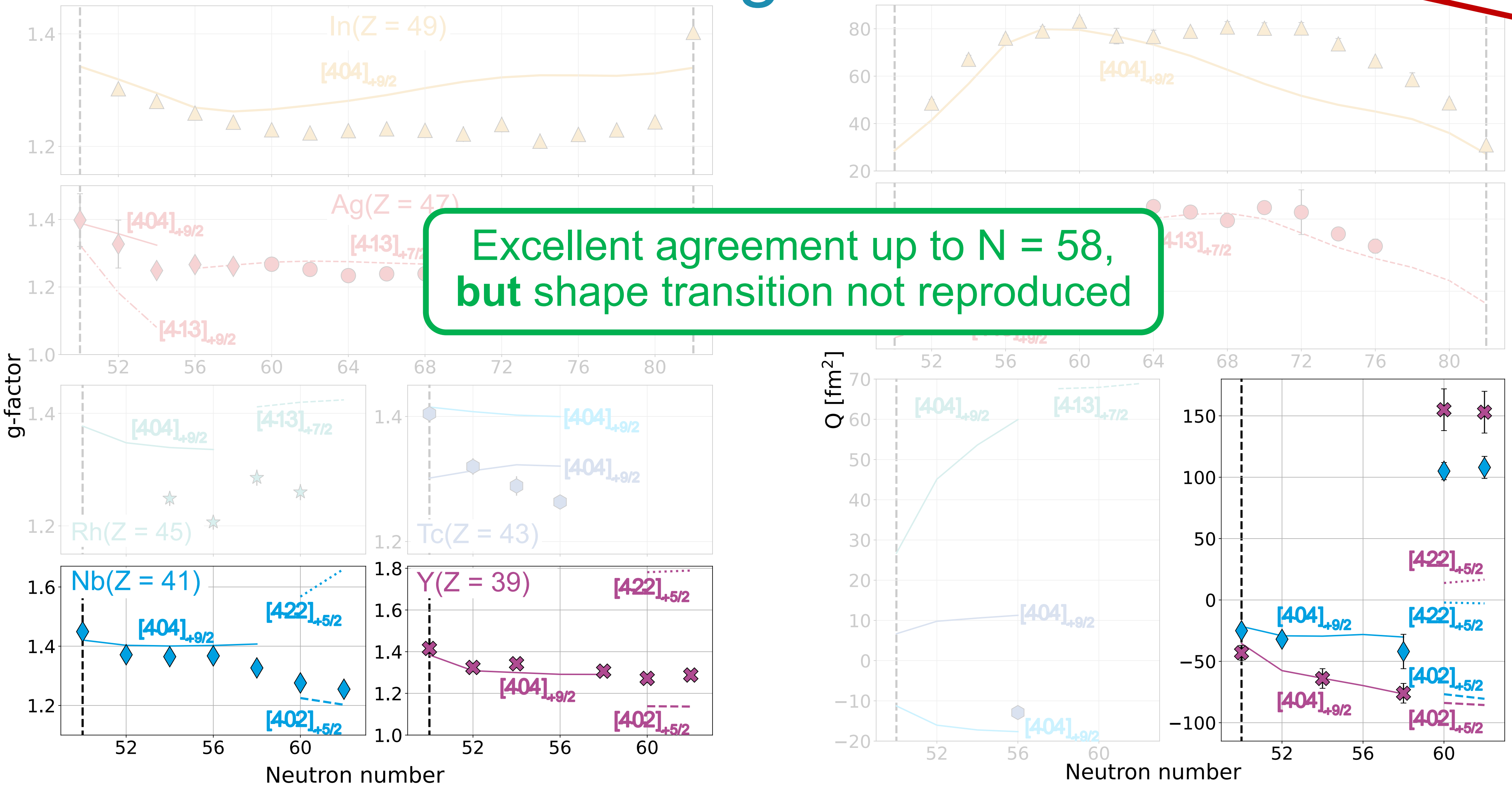


Excellent agreement up to N = 58, **but** shape transition not reproduced

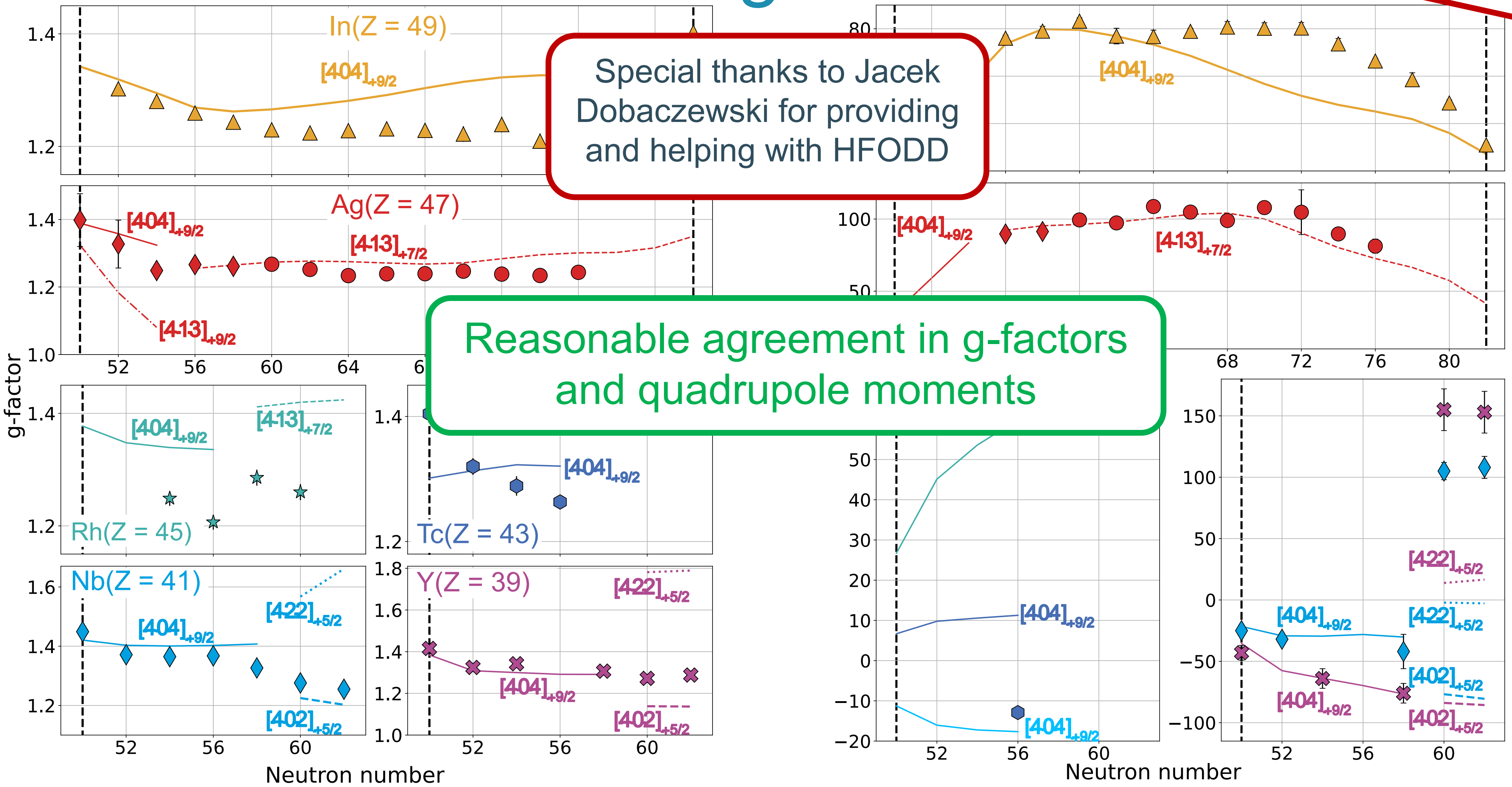
[1] P. L. Sassarini, *et al.*, J. Phys. G: Nucl. Part. Phys. **49**, 11LT01 (2022).

DFT calculations using HFODD

Skyrme force parameter set from global analysis[1]

Special thanks to Jacek Dobaczewski for providing and helping with HFODD

Reasonable agreement in g-factors and quadrupole moments



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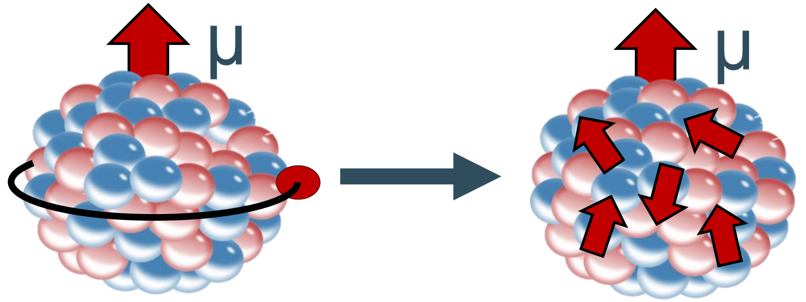
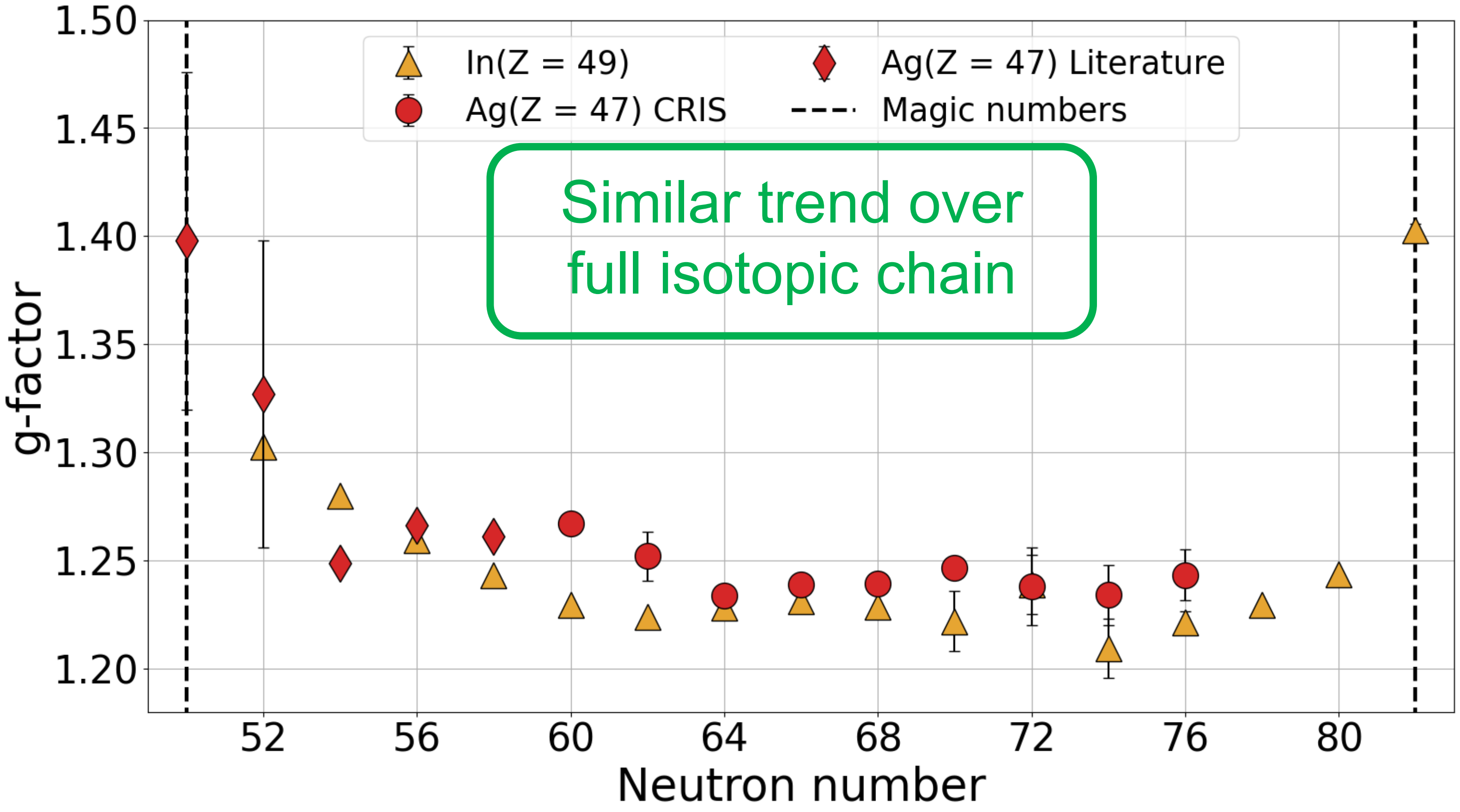
Bohr-Weisskopf effect in silver

Contribution to the hyperfine anomaly

BW insensitive atomic state

- Interaction between nuclear magnetisation and electrons
  - *Large* in J<1 atomic states, e.g. $S_{1/2}$





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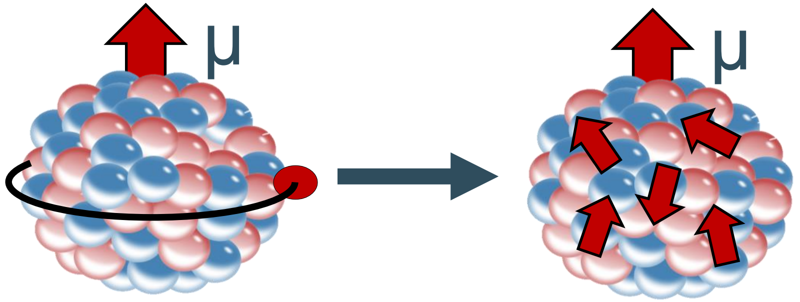
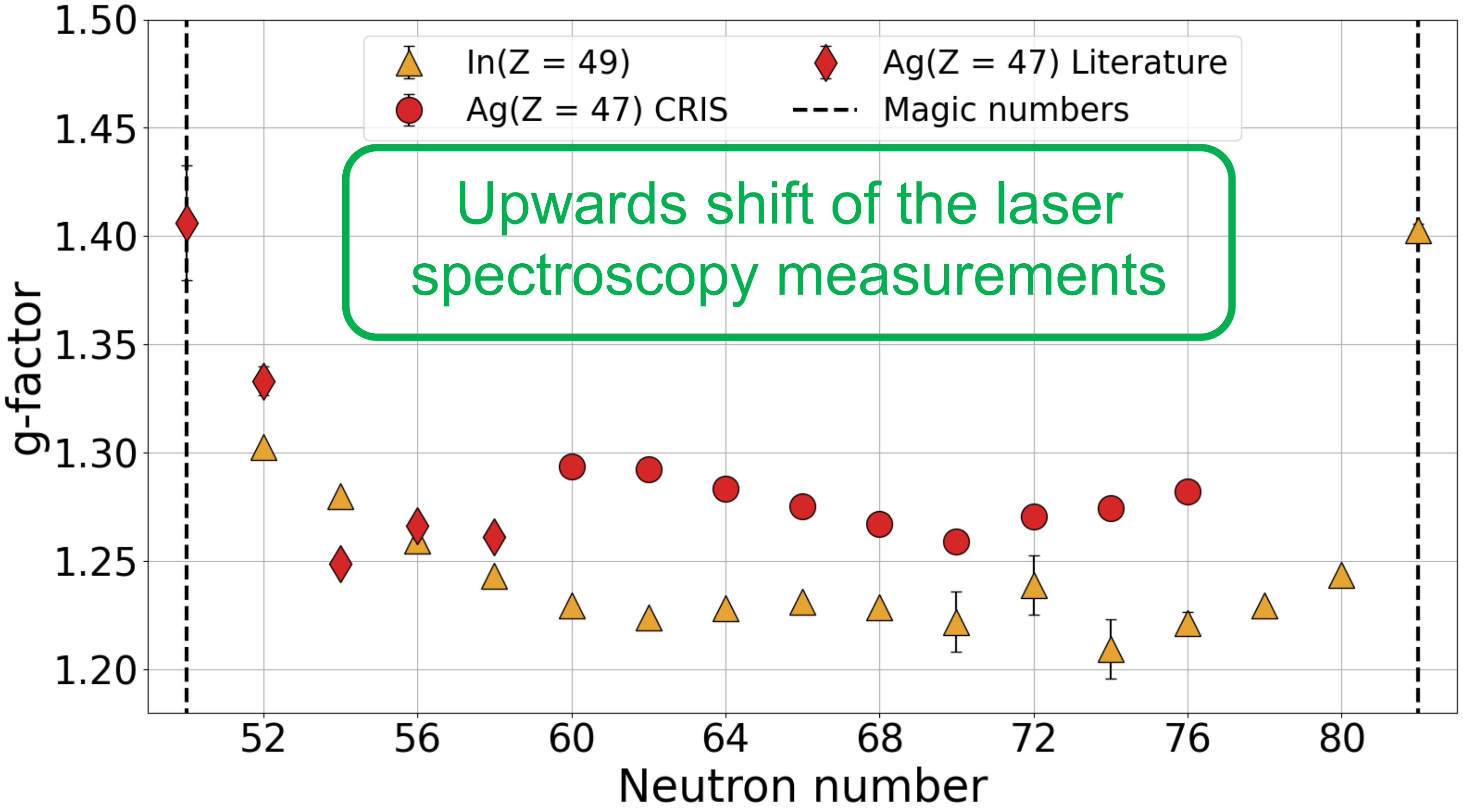


Can we probe the nuclear magnetisation distribution?



Upwards shift of the laser spectroscopy measurements

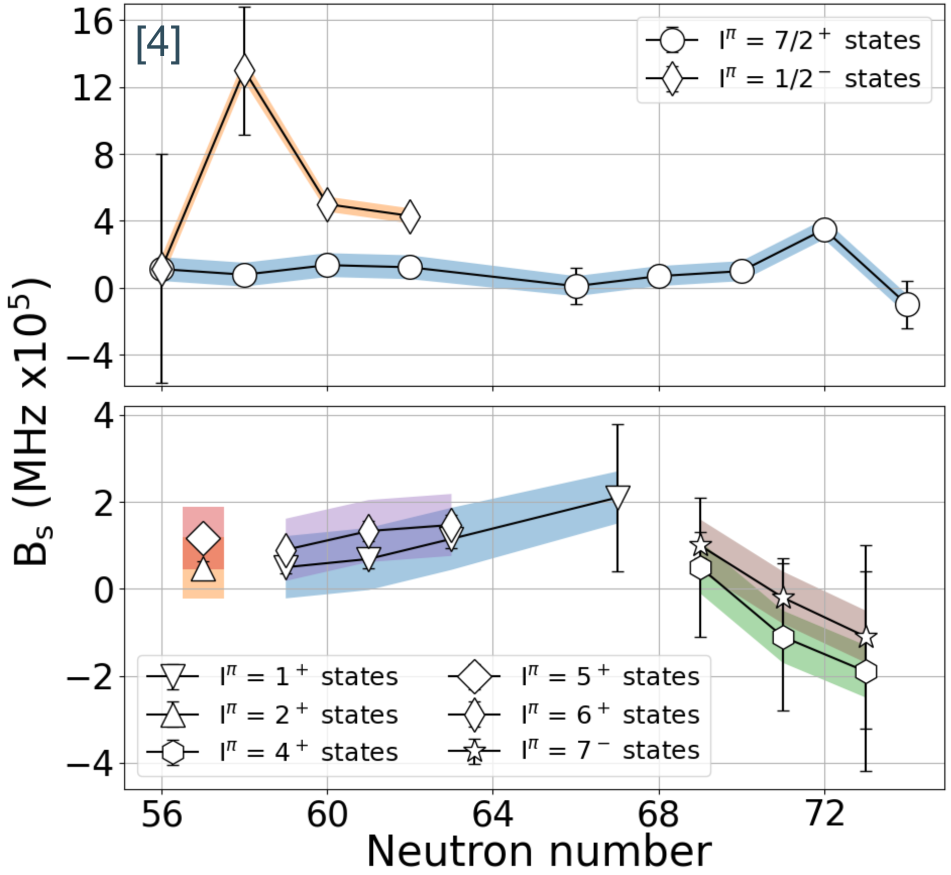
We can also extract BW contribution

Combine BW sensitive state, BW insensitive state & atomic calculations

→ **BW effect contribution**

Absolute BW parameter B_S

$$B_s = \frac{\tilde{A}_0 + \tilde{A}_{QED} - \frac{IJ}{\mu_{P3/2}} A_{S1/2}}{\bar{\bar{A}}_{BW,el}}$$



[1] Skripnikov, L. V, *et al.*, The Journal of Chemical Physics 153.11 (2020).
[2] Sanamyan, G., B. M. Roberts, and J. S. M. Ginges. Physical Review Letters 130.5, 053001 (2023).
[3] Skripnikov, L. V., *et al.*, (In preparation).
[4] Credit to Mualla Aytekin for data

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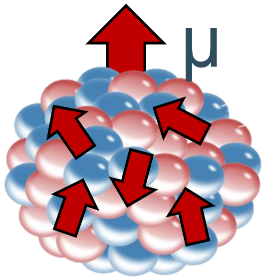
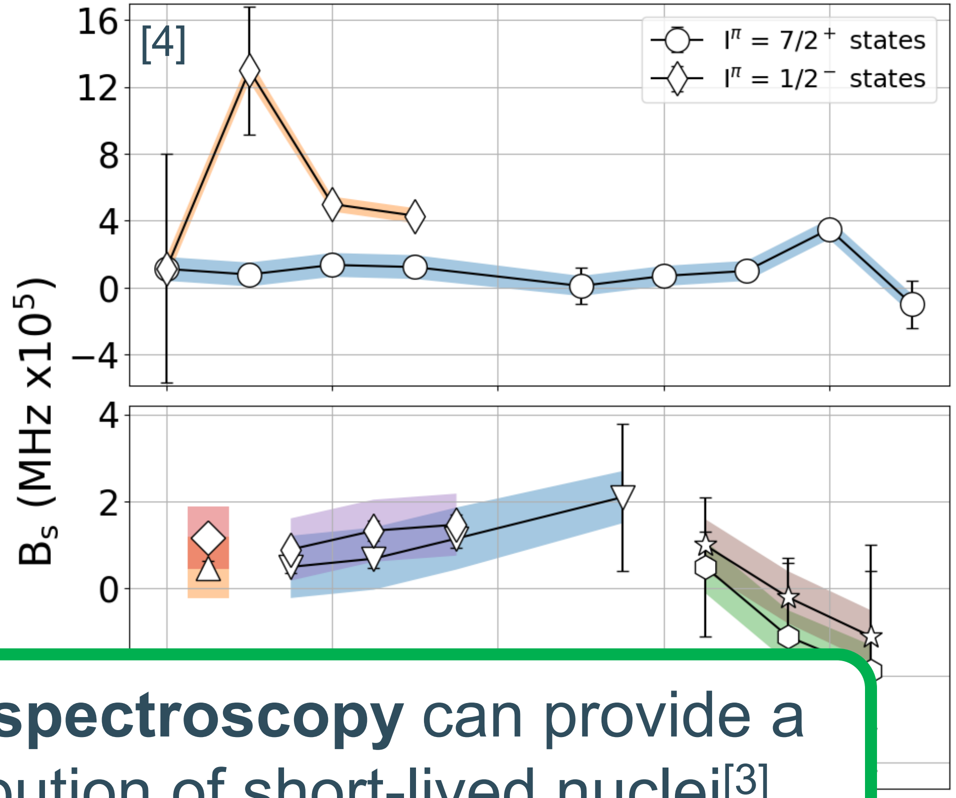


Absolute BW parameter B_S

$$B_s = \frac{\tilde{A}_0 + \tilde{A}_{QED} - \frac{IJ}{\mu_{P3/2}} A_{S1/2}}{\bar{\tilde{A}}_{BW,el}} \propto \int gf\big(1 - F(r)\big)dr^{[1]}$$

F(r) is unknown function of nuclear magnetisation distribution[2]



Combination of **atomic calculations and laser spectroscopy** can provide a benchmark for the nuclear magnetisation distribution of short-lived nuclei[3]

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Combine BW sensitive state, BW insensitive state & atomic calculations

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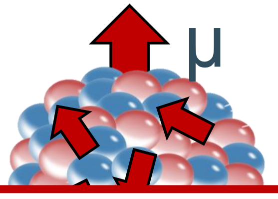
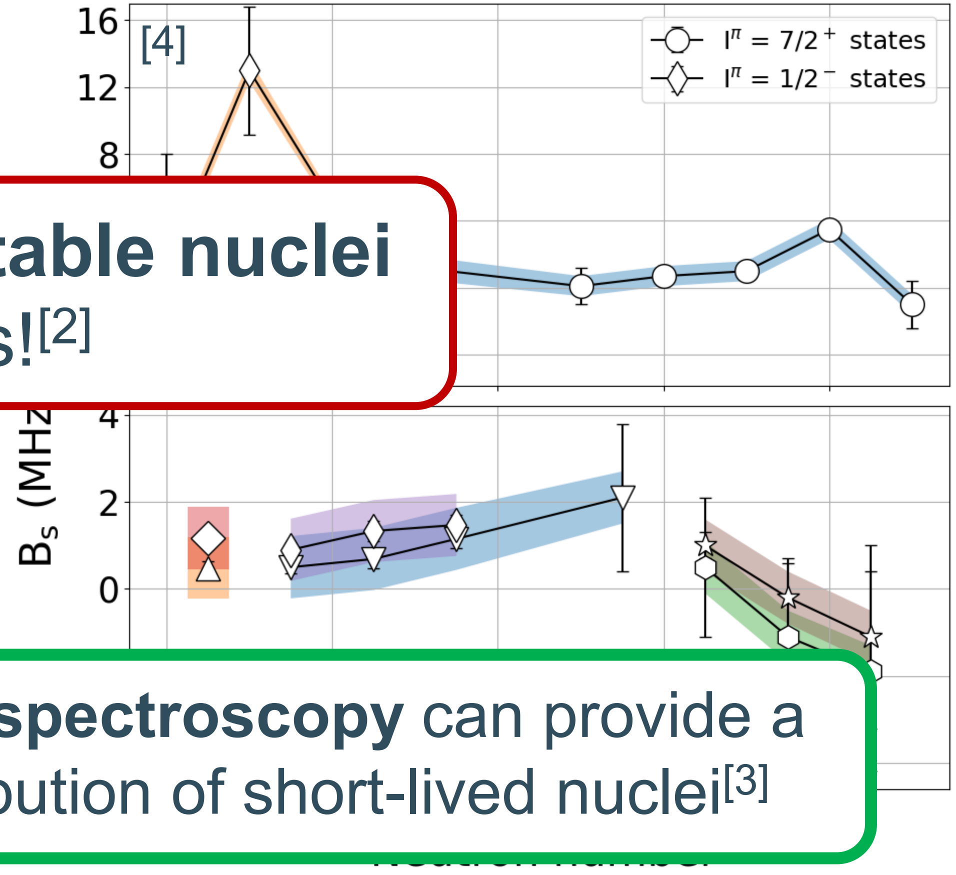


Absolute BW parameter B…

$$B_s = \frac{\tilde{A}_0 + \tilde{A}_{QED} - \ldots \mu \ldots}{\bar{\bar{A}}_{BW,\ldots}}$$

So far only performed on **stable nuclei** with muonic atoms![2]



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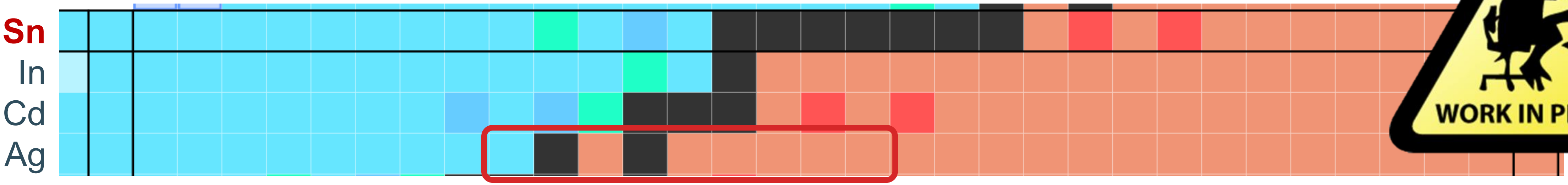
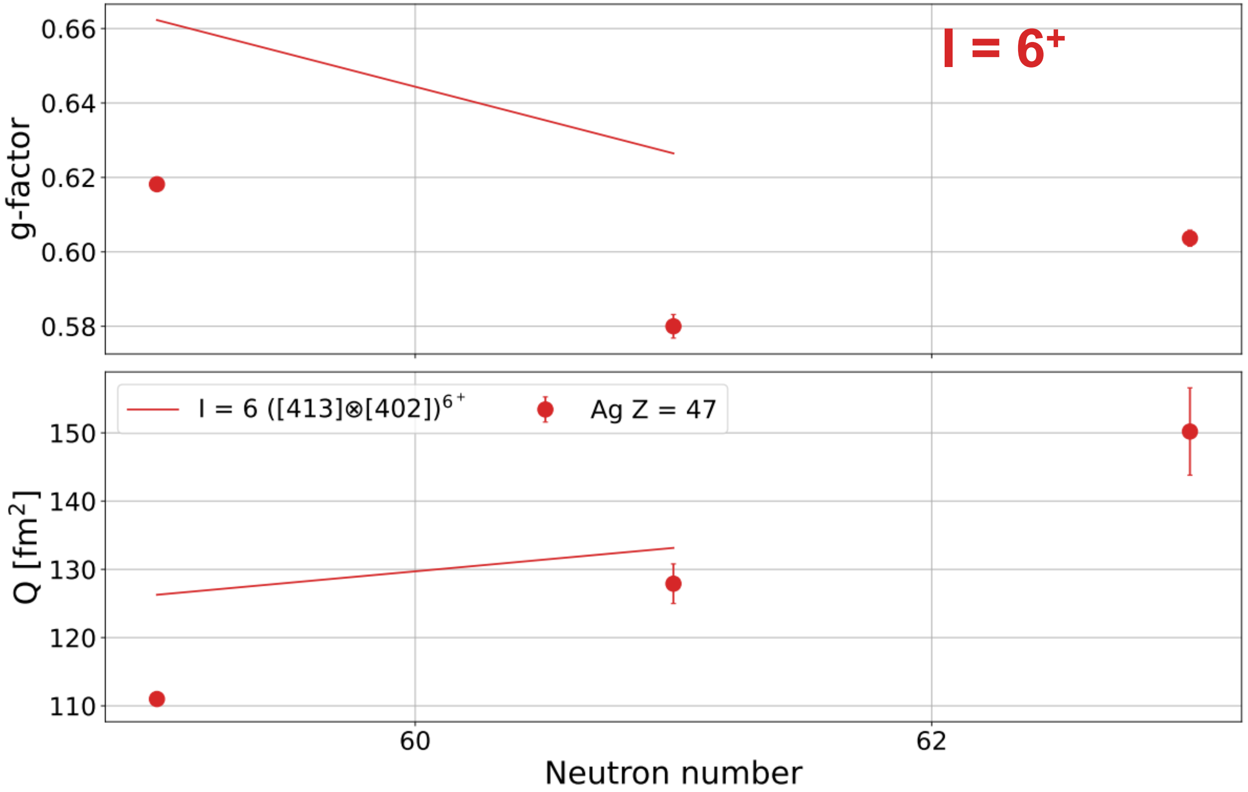
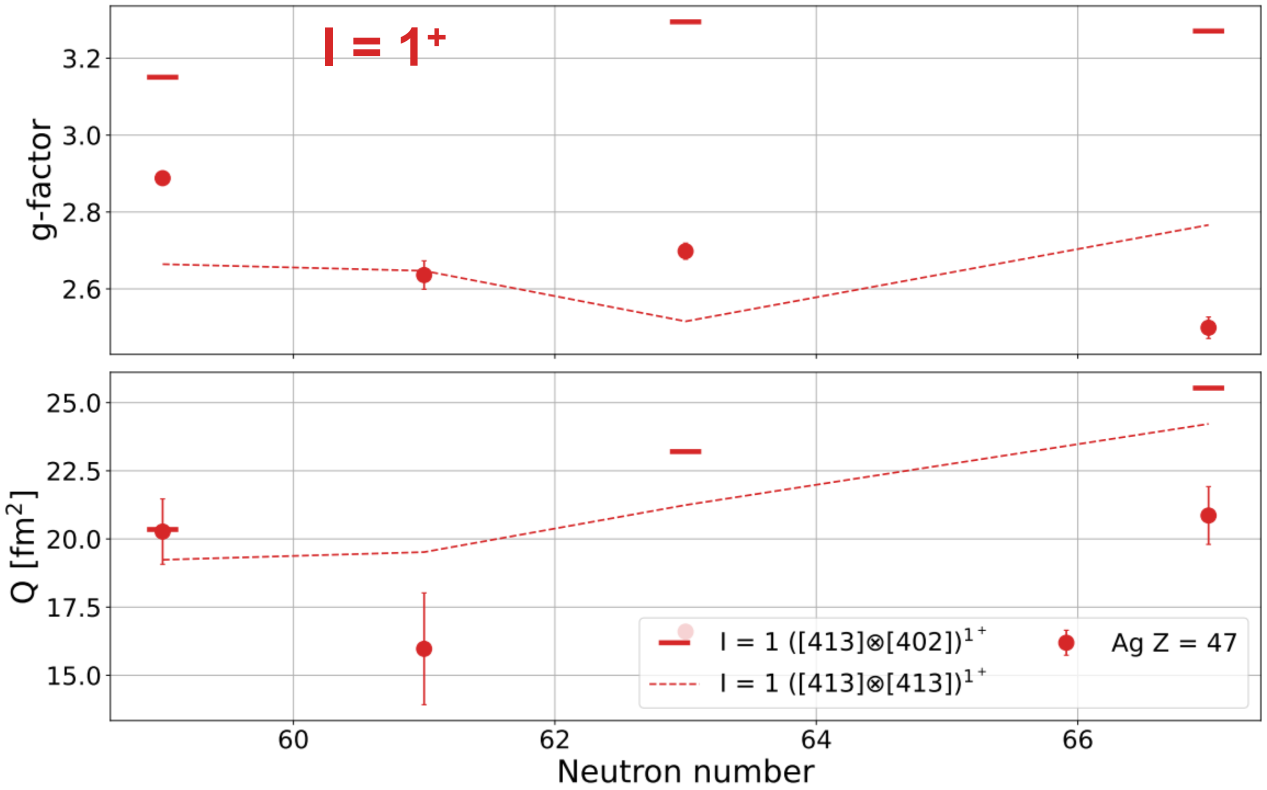
Odd-p odd-n mid-shell Ag







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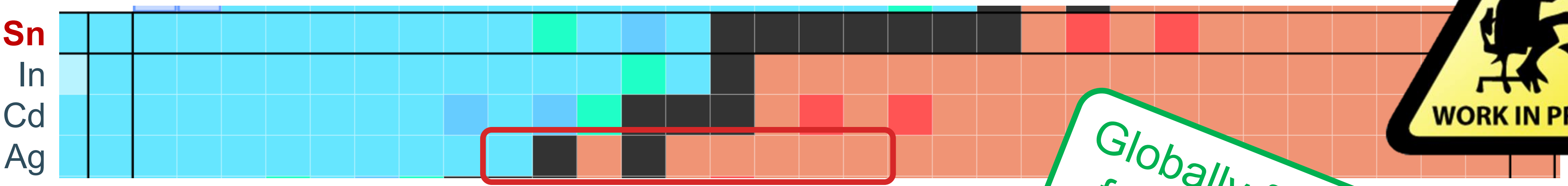
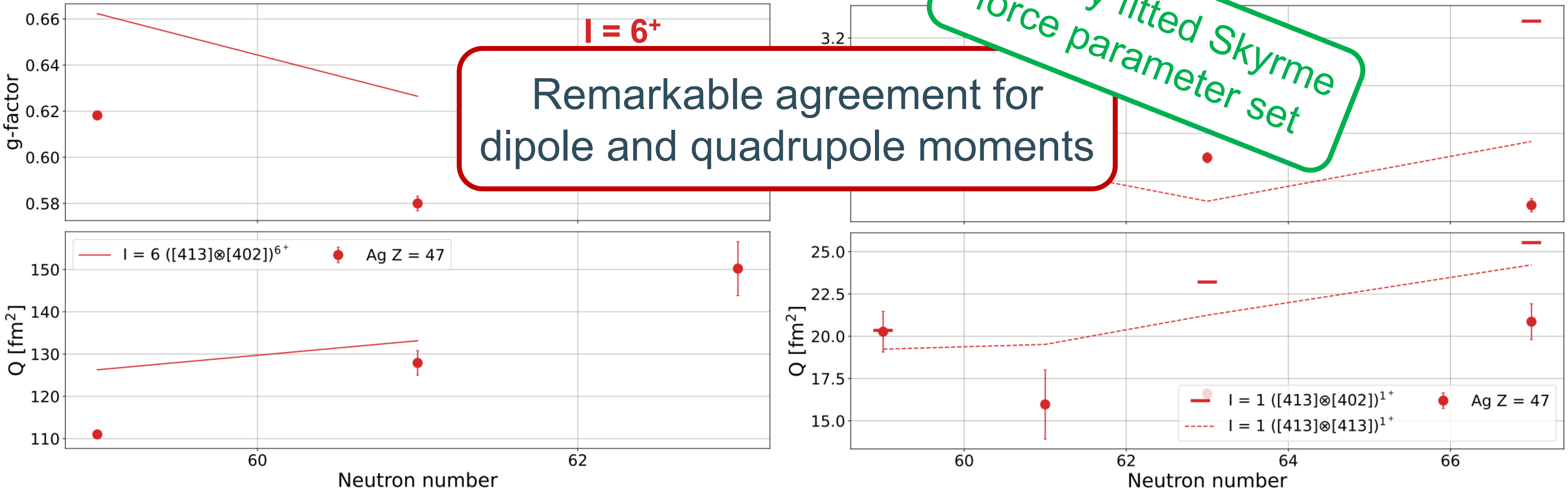
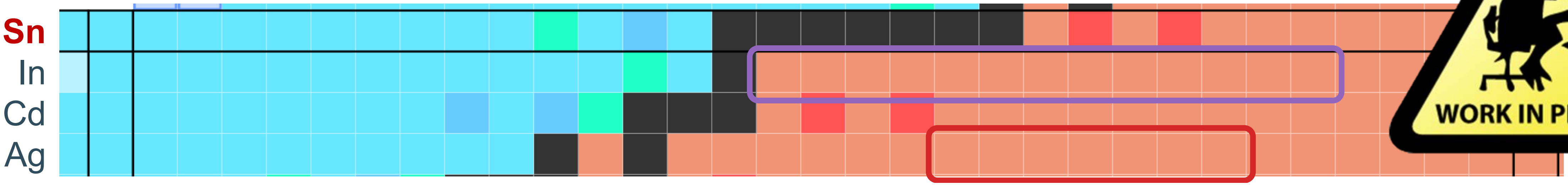


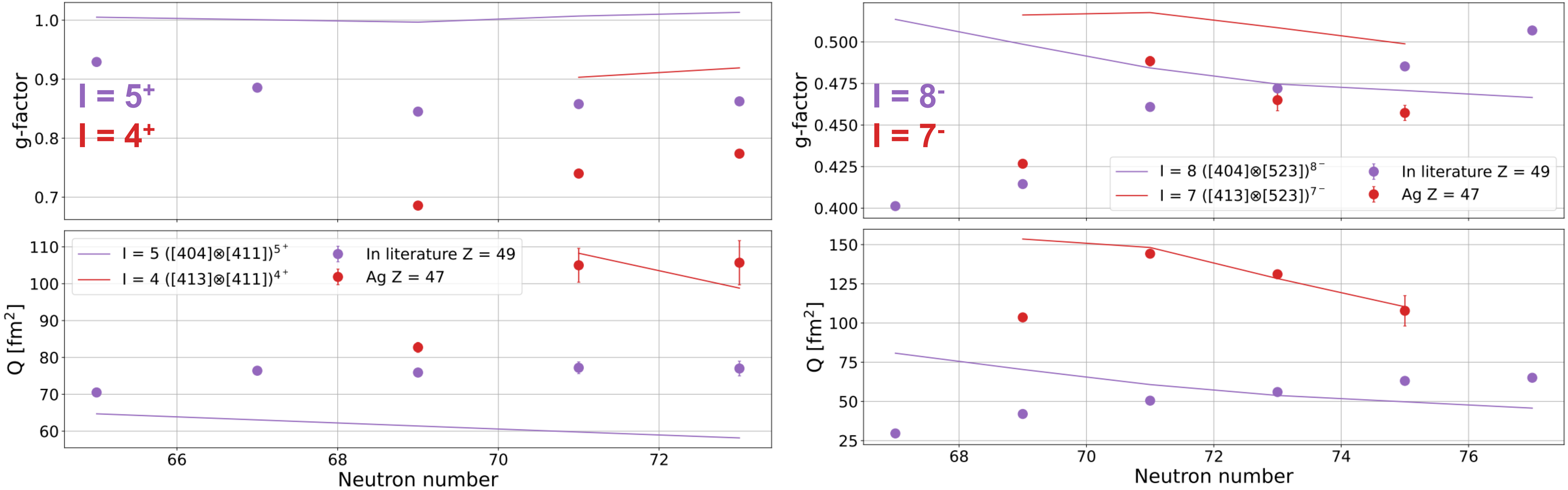
Globally fitted Skyrme force parameter set



Remarkable agreement for dipole and quadrupole moments

Odd-p odd-n neutron-rich Ag and In





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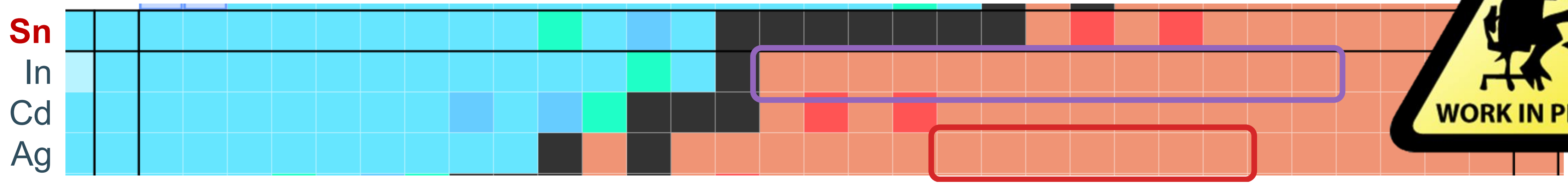

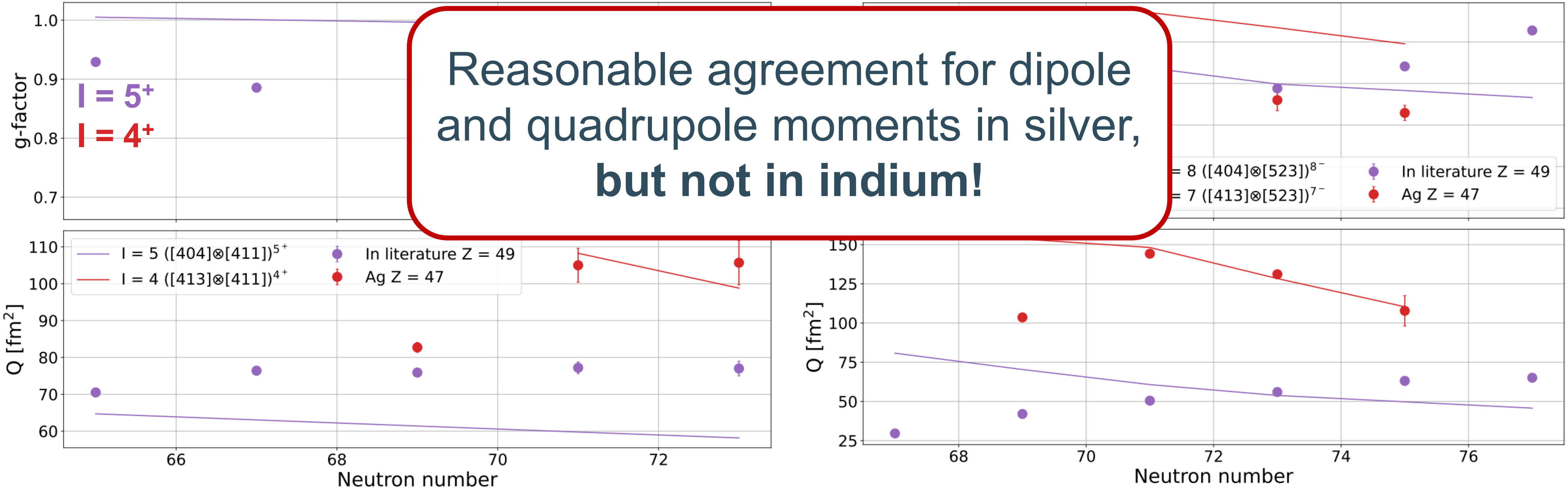

Reasonable agreement for dipole and quadrupole moments in silver, **but not in indium!**

Summary

- Odd-p even-n elements between Z = 39 & 49

→ **"Similar" configurations experimentally & can be predicted relatively well with DFT**

- Probe BW effect on **short-lived nuclei** via laser spectroscopy and atomic theory
  - Provide benchmark for nuclear magnetisation distribution

- Odd-p odd-n silver (& indium)

Good agreement with DFT

Disagreement in neutron-rich indium

Outlook

- Compare binding energies of odd-even Z = 39 to 49 elements to DFT results

Good agreement across multiple observables?

- Rh(Z = 45) experiment at IGISOL to expand nuclear structure data

Starting 14^{th} of October

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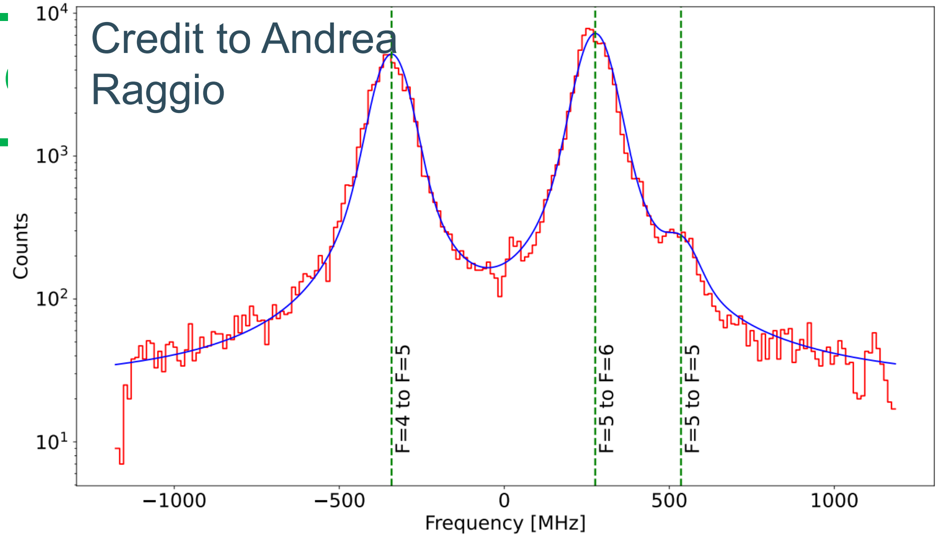
- Compare binding energies of odd-even Z = 39 to 49 elements to DFT results

Good agreement across multipl



- Rh(Z = 45) experiment at IGISOL to expand nuclear structure data

Starting 14th of October

- Continue DFT calculations on odd-odd and even-odd elements for Z = 39 to 49

Insight into the neutron configuration

Special thanks

Special thanks to **G. Neyens**, **R. de Groote, T. E. Cocolios** and the CRIS collaboration and M. Athanasakis-Kaklamanakis, L. V. Skripnikov and Jacek Dobaczewski