Abrupt change in nuclear moments of indium isotopes at magic number 82 explained by nuclear theory

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On behalf of the CRIS collaboration

Massachusetts Institute of Technology

ISOLDE workshop 2022, December 1st

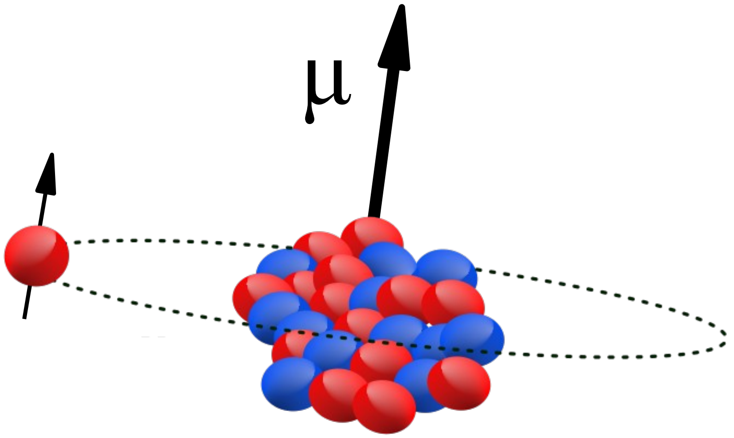
Overview

- Nuclear Magnetic Dipole Moments – the free single-particle limit and signatures of nuclear shell structure
- Indium isotopes (Z = 49) – a proton hole in magic Z = 50
- Laser Spectroscopy to reach N = 82
- Comparing results with recently developed ab-initio nuclear theory and density-functional theory calculations

Nuclear Magnetic Dipole Moments

Single-particle limit

- In the single-particle limit, the nuclear magnetic dipole, μ, is a combination contribution generated by nuclear spin, $\mathbf{g_s}$, and orbital motion $\mathbf{g_L}$



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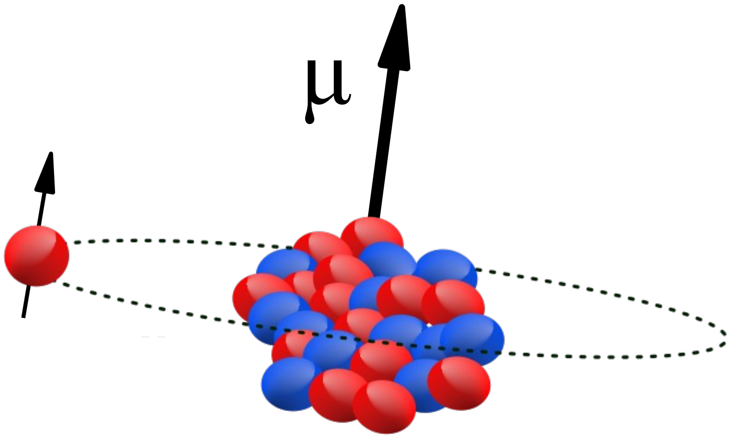

- Schmidt[1] values

$$\mu(I)_{s.p.} = I\left[\frac{1}{2}(g_L + g_S) + \frac{1}{2}(g_L - g_S)\frac{L(L+1) - \frac{3}{4}}{I(I+1)}\right] \qquad I = L \pm \frac{1}{2}$$

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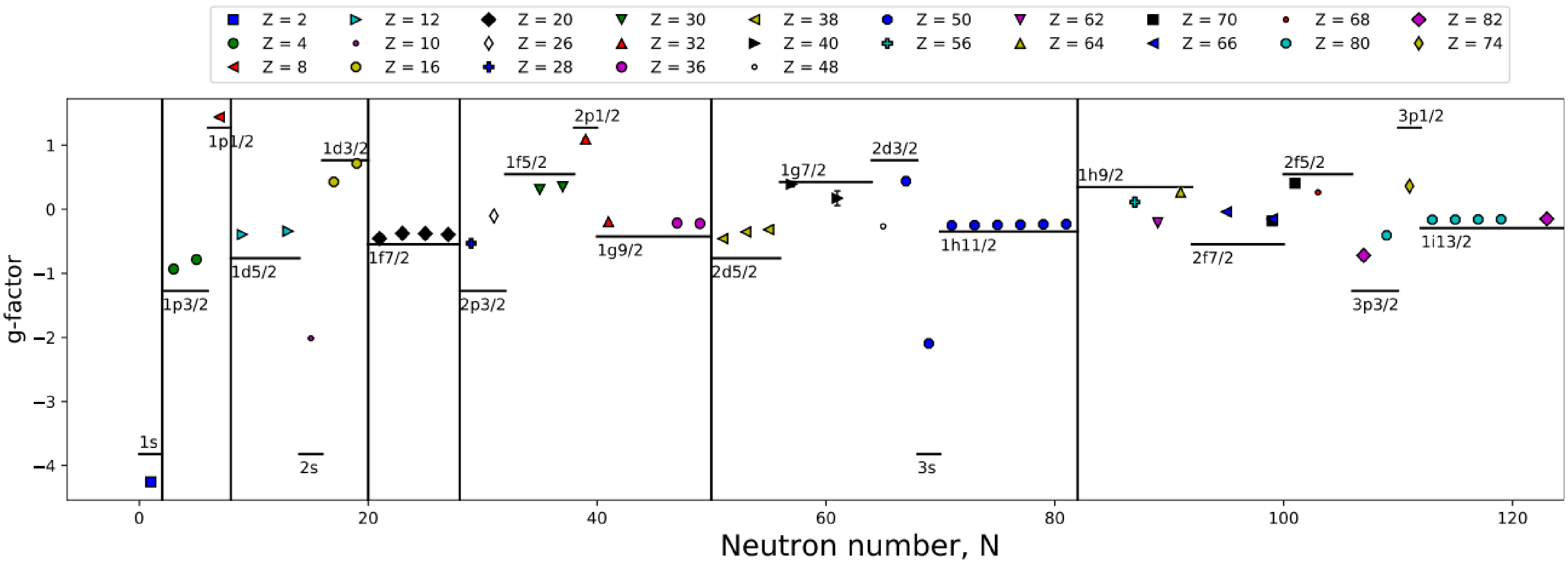
[1] T. Schmidt, May 1937, doi: 10.1007/BF01338744.

Nuclear Magnetic Dipole Moments

Fingerprint of the shell model

- Critical evidence for the shell structure of nuclei[1,2]



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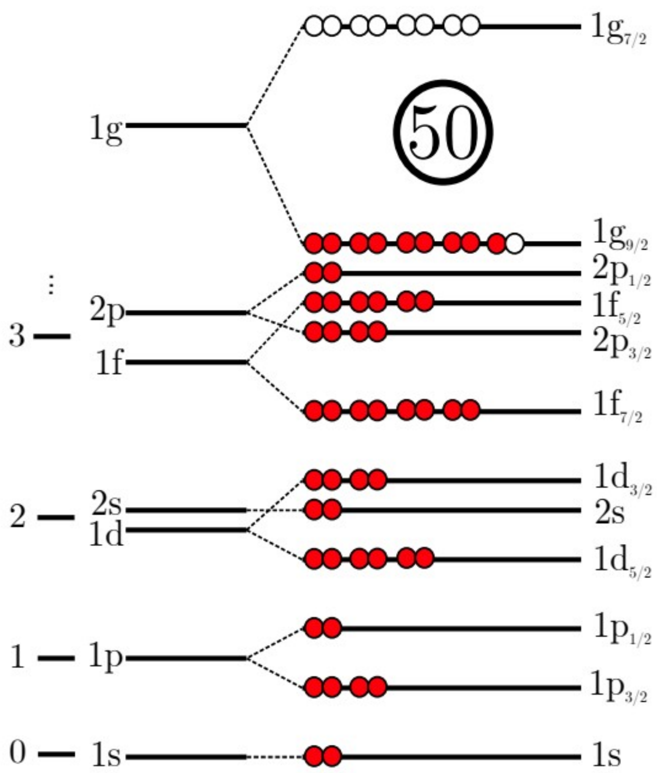
[1] - O. Haxel, J. H. D. Jensen, and H. E. Suess, “On the ‘magic numbers’ in nuclear structure,” 1949, doi: 10.1103/PhysRev.75.1766.2
[2] - M. G. Mayer, “On Closed Shells in Nuclei. II,” 1949, doi: 10.1103/PhysRev.75.1969. Data from: N. J. Stone, 2005, doi: 10.1016/j.adt.2005.04.001.

Nuclear Magnetic Dipole Moments

Fingerprint of the shell model



The experimental results:

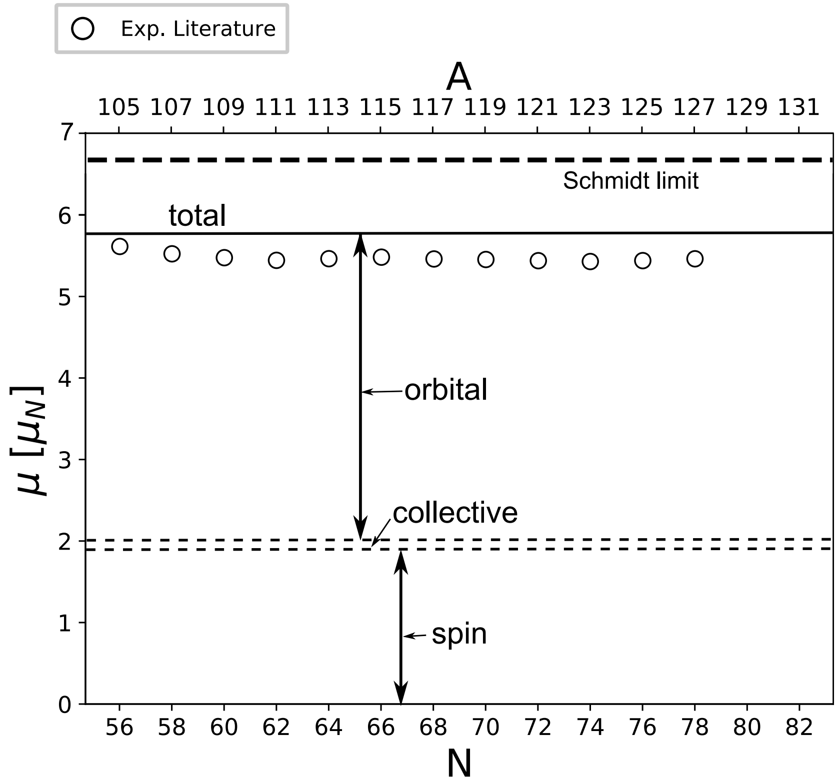
- Laser spectroscopy of the magnetic dipole moments, μ, (mainly) and electric quadrupole moments, Q_s, of $^{113\text{-}131}$In ($Z = 49$)
- N = 64 → N = 82

Focus on even-N, odd-A:

- Z = 49: Unpaired proton in $\pi g_{9/2}$ orbital with changing number of neutron pairs

Nuclear Magnetic Dipole Moments

πg9/2 proton hole of In (Z = 49)



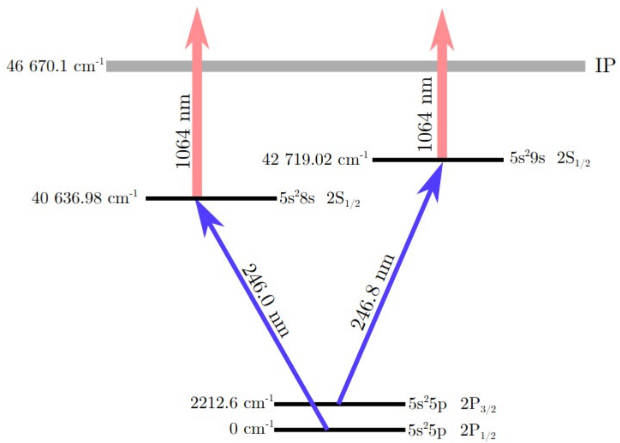
- $\pi g_{9/2}$ proton hole of In ($Z = 49$) was an archetypal example[1] of single-particle behaviour
- Remarkable constancy of μ: <5% variation over 22 neutrons
- Deviations from Schmidt limit were historically explained using 'effective g-factors' to account for the nuclear medium

$$g_s^{eff} = 0.7 g_s^{free}$$

[1] Heyde, K. The Nuclear Shell Model. Springer Series in Nuclear and Particle Physics (Springer Berlin Heidelberg, Berlin, Heidelberg, 1990).

Collinear Resonance Ionization Spectroscopy (CRIS)

- Implemented at ISOLDE, CERN at the CRIS setup[1]- takes advantage of bunched ions and pulsed lasers for efficient ionization and ion detection
- Selectivity enhanced by linewidth and number of resonant steps to reach IP (~10^7 per step):

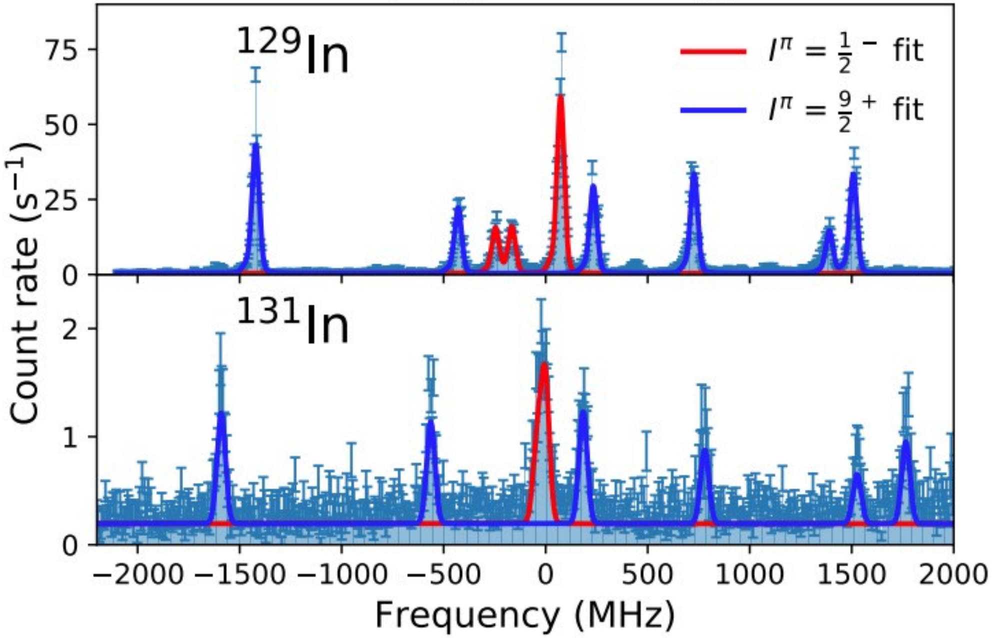


- Allowed hyperfine structure measurements (~20 MHz linewidth) in atomic systems in some of the lowest production rate isotopes to date at ISOLDE (<20 ions/s) [2]

[1] A. R. Vernon et al., Sci. Rep. 2020, doi: 10.1038/s41598-020-68218-5
[2] R. P. de Groote et al., Nature Phys 2020, doi: 10.1038/s41567-020-0868-y

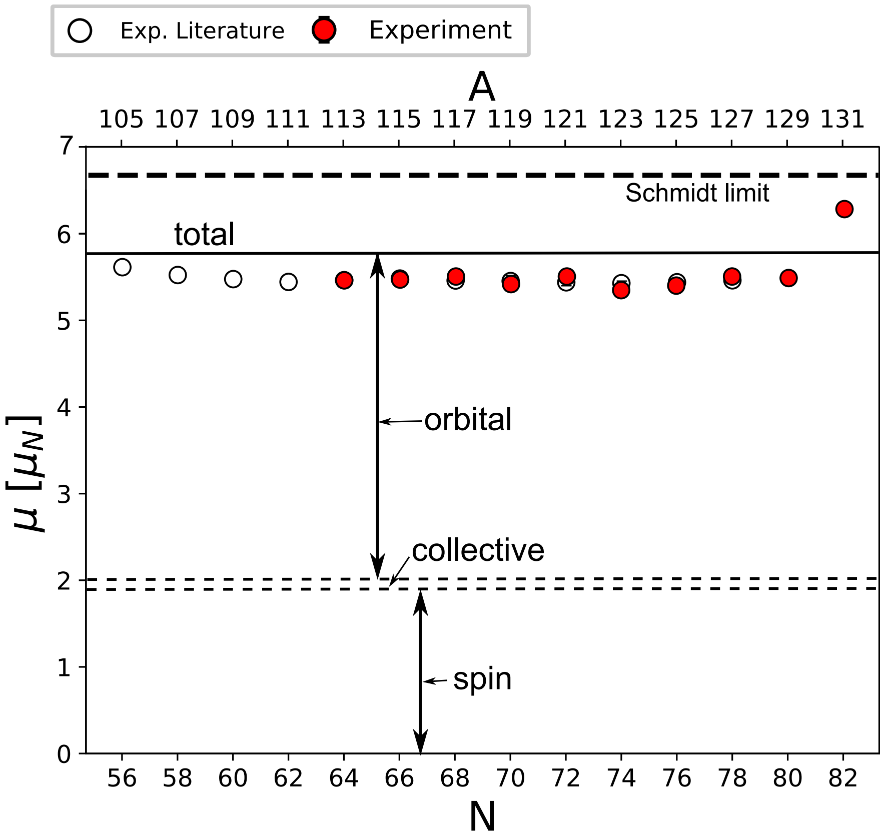
Collinear Resonance Ionization Spectroscopy

$5s^2 5p\ ^2P_{3/2}^{\circ} \rightarrow 5s^2 9s\ ^2S_{1/2}$



Nuclear Magnetic Dipole Moments

πg9/2 proton hole of In (Z = 49)



- Sudden uptick observed towards Schmidt limit at $N = 82$ (^{131}In).
- 93% of the free-particle value!
- In contrast with $g_s^{eff} = 0.7 g_s^{free}$ for Sn region

‘Ab-initio’ Valence Space In-Medium Similarity Renormalisation Group (VS-IMSRG) results

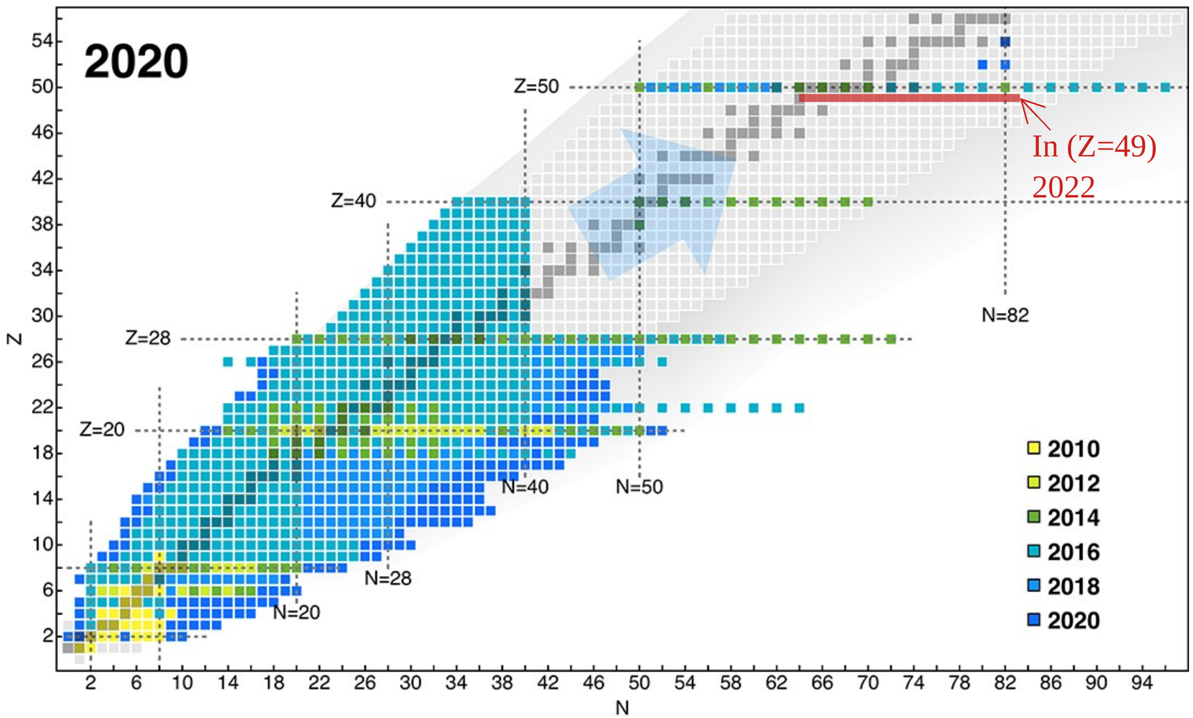


Figure Ref. : H. Hergert, “A Guided Tour of ab initio Nuclear Many-Body Theory,” Front. Phys., vol. 8, 2020, doi: 10.3389/fphy.2020.00379.

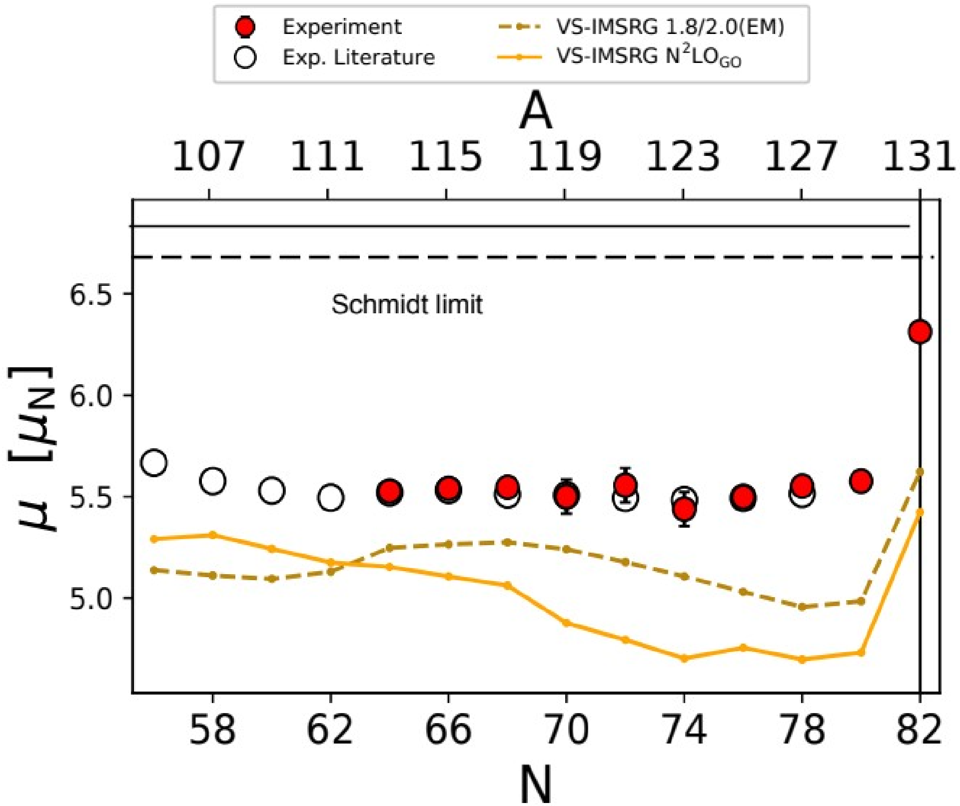
VS-IMSRG: **J. Holt, T. Miyagi, S.R. Stroberg – TRIUMF**

- An ‘ab-initio’ method which starts from nucleon-nucleon interactions constrained by chiral effective field theory[1]
- Recent advances[2] have allowed calculations of nuclear moments of the heaviest to date using this ‘ab-initio’ method

[1] S. R. Stroberg, 2019, doi: 10.1146/annurev-nucl-101917-021120
[2] T. Miyagi, S. R. Stroberg, P. Navrátil, K. Hebeler, and J. D. Holt, “Converged ab initio calculations of heavy nuclei,” 2022. https://arxiv.org/abs/2104.04688v1.

Nuclear Magnetic Dipole Moments

VS-IMSRG 'ab-initio'

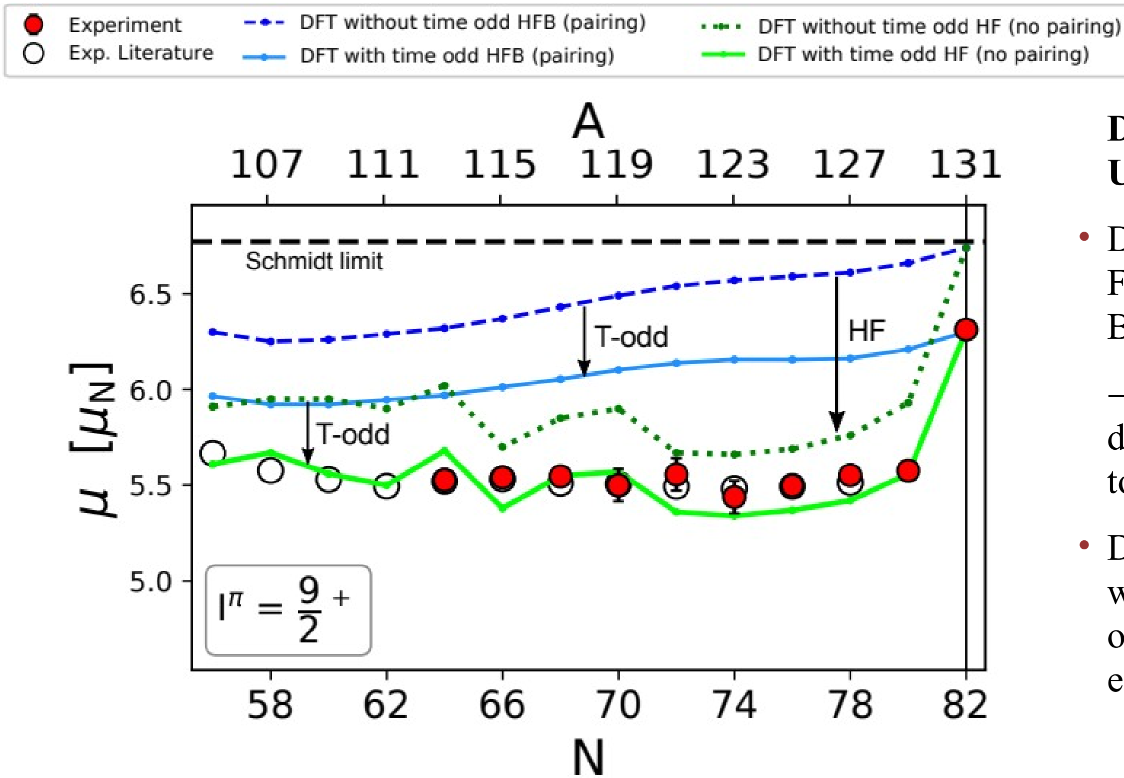


- Abrupt uptick captured by VS-IMSRG calculations
- Local variations usually well captured by method
- Shift in magnitude: meson-exchange currents, or three-body forces known to already be important at A<10 would shift overall magnitude

[1] - S. Pastore et al, 2013, https://doi.org/10.1103/PhysRevC.87.035503

Nuclear Magnetic Dipole Moments

Density Functional Theory



DFT: J. Dobazewski, J. Bonnard – University of York

- DFT calculations performed with Hartree-Fock (‘no pairing’) and Hartree-Fock-Bogoliubov (‘pairing’)

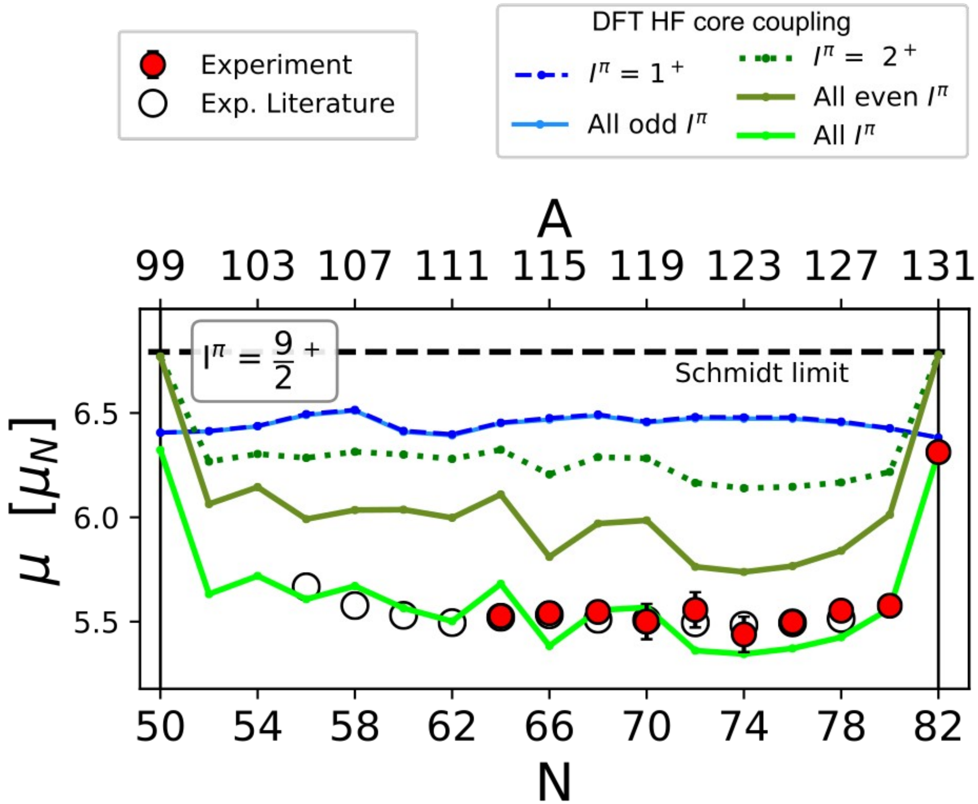
  → highlight importance of single-particle description (single-reference HFB unable to reproduce jump)

- DFT calculations[1] performed with and without time-odd mean fields → time-odd components are essential to reproduce experimental magnetic dipole moments

[1] Sassarini, P. L. and Dobaczewski, J. , 2022, https://doi.org/10.48550/arxiv.2111.04675

Nuclear Magnetic Dipole Moments

Density Functional Theory

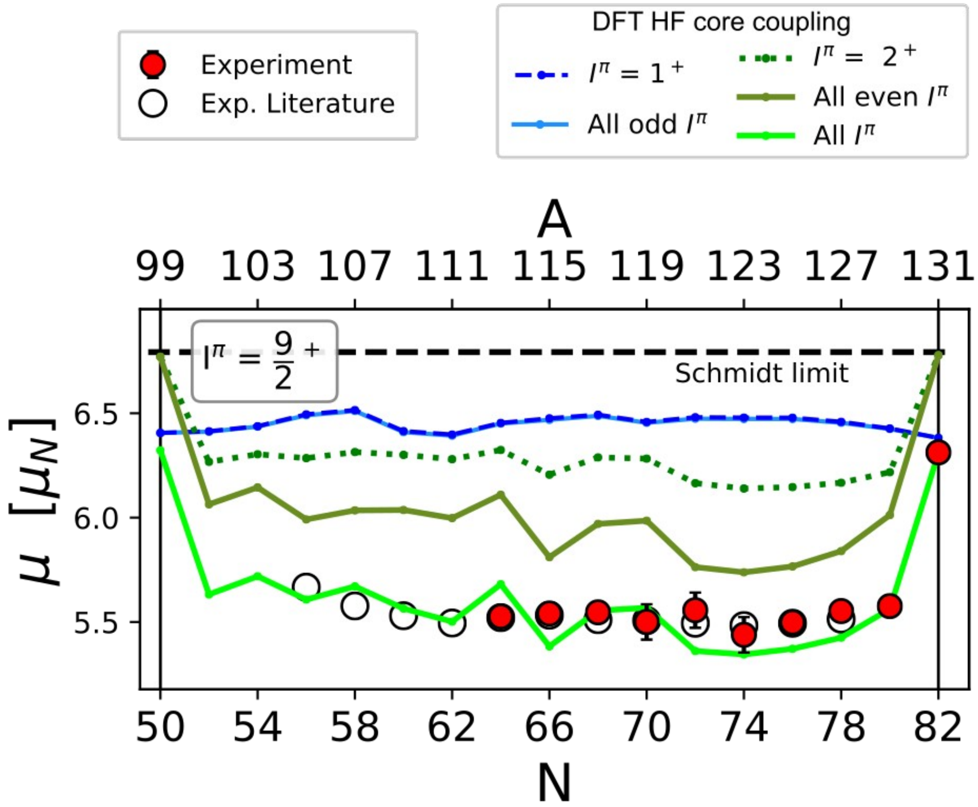


Further details:

- Effect of time-odd mean fields primarily acts through odd states (1^+, 3^+, ... 9^+)
- Single-hole experimental value reproduced almost entirely by the 1^+ state
- (0+ included in all, which gives the single-particle limit)

Nuclear Magnetic Dipole Moments

Density Functional Theory

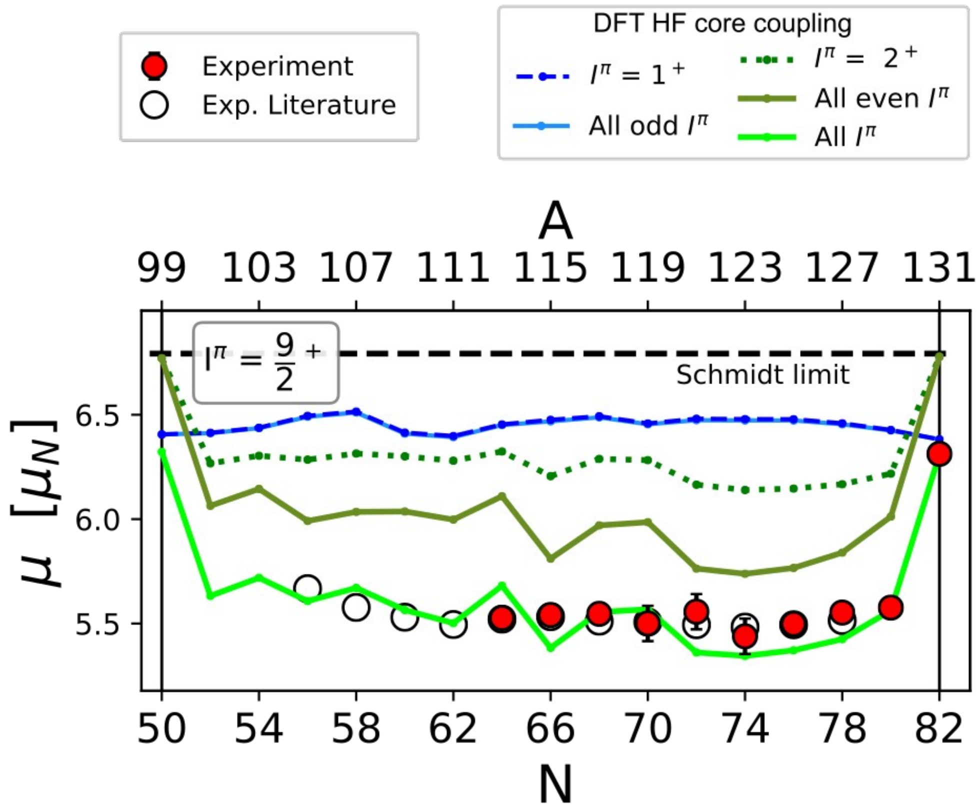


Further details:

- Coupling of unpaired proton to even states (mainly 2^+, 4^+, 6^+) create strong decrease of μ when neutron shell opens away from magic $N = 82$
- Same phenomena predicted for $N = 50$

Nuclear Magnetic Dipole Moments

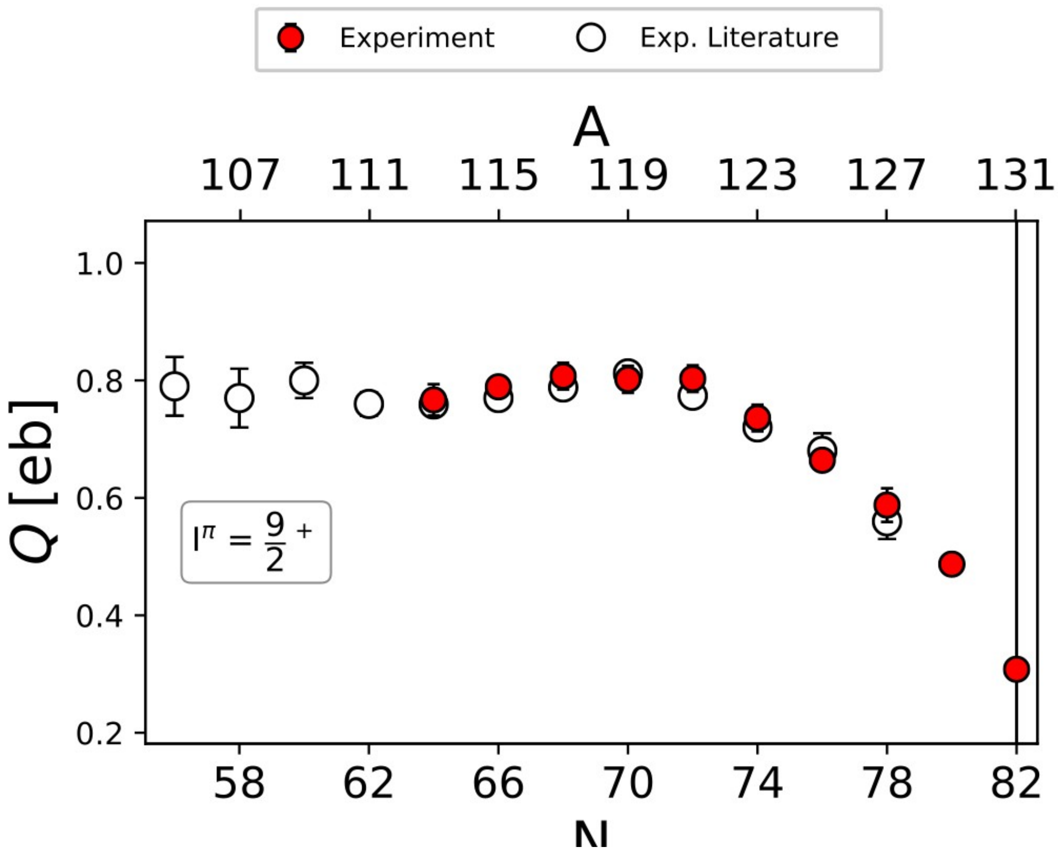
Density Functional Theory



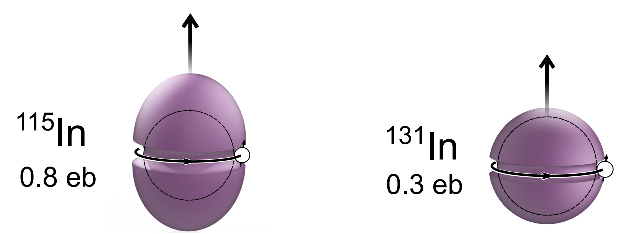
- Therefore, at $N = 82$ we observe an abrupt change from 'charge polarisation' to 'spin polarisation'

Nuclear Electric Quadrupole Moments

πg9/2 proton hole of In (Z = 49)

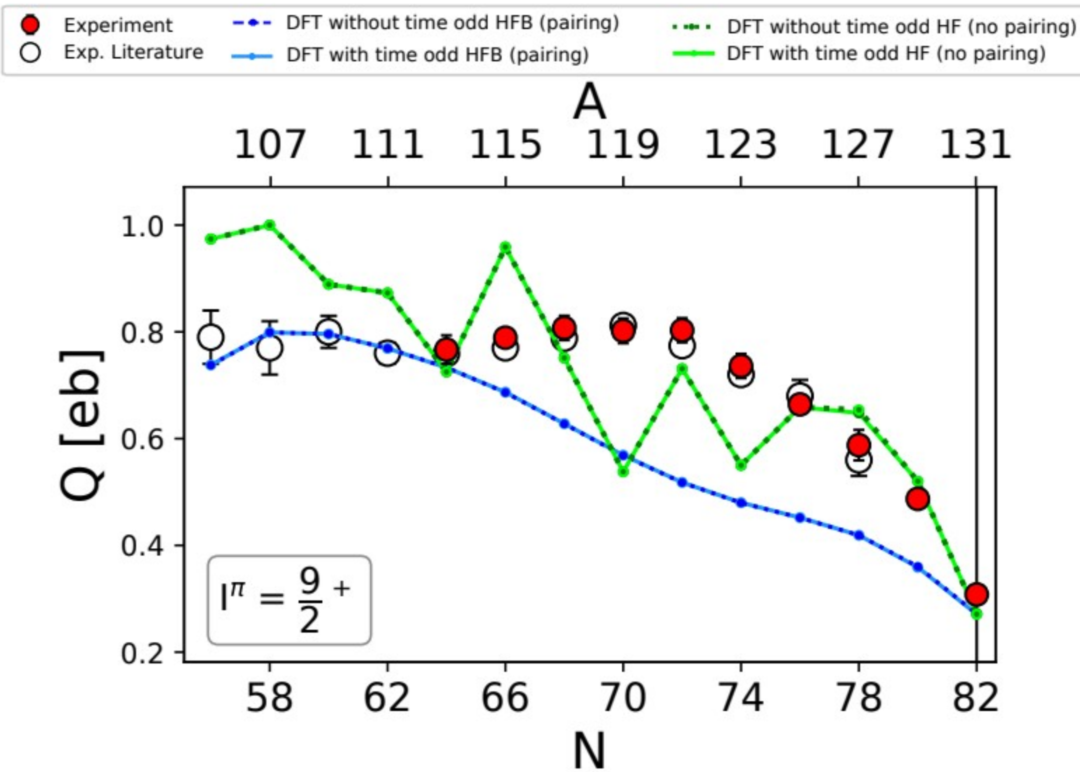


- Gradual decrease to ‘proton-hole’ value



Nuclear Electric Quadrupole Moments

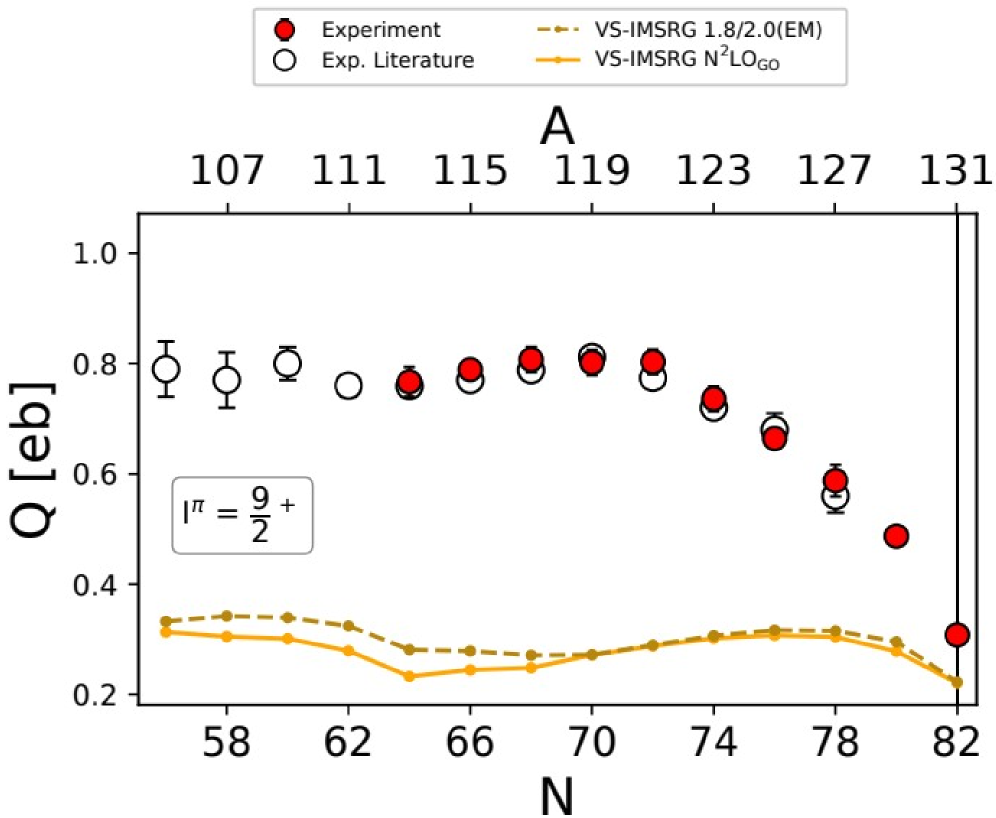
Density Functional Theory



- HF vs. HFB ('no pairing vs pairing') demonstrates that describing individual nucleon orbitals becomes important for the magnitude of Qs, but produces an inaccurate staggering.
- Developing a 'multi-reference' version of HFB is expected be needed

Nuclear Electric Quadrupole Moments

VS-IMSRG ‘ab-initio’



- VS-IMSRG reproduces local variations e.g. dip at $N = 64$
- Reproduction of magnitude a challenge for ‘ab-initio’ theory[1]- highly emergent property which requires inclusion of extensive many-body correlations

[1] - Henderson, J. et al. 2018 doi: 10.1016/j.physletb.2018.05.064

Conclusion

- Abrupt change in magnetic dipole moment at N=82, towards free single-particle value, shows single-particle picture not the complete for N<82 isotopes
- Ab-initio calculations now reaching heavier moments: change reproduced. Meson-exchange currents, three-body forces or higher-order many-body correlations need to be included for increased accuracy
- DFT calculations highlight a change from “charge polarisation” to “spin polarisation”
- Time-odd components of mean-field calculations essential to reproduce experiment
- Predictions demand measurements at N=50, and beyond N=82

Read more in the article here: A.R.Vernon et al. ***Nature*** 607, 260–265 (2022).

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Thanks for listening!