Nuclear DFT electromagnetic moments in heavy deformed open-shell odd nuclei

Jacek Dobaczewski, University of York & University of Warsaw

In collaboration with B.C.T. Backes, M. Bender, J. Bonnard, G. Danneaux, R.F. Garcia Ruiz, R.P. de Groote, M. Kortelainen, D. Muir, A. Nagpal, W. Nazarewicz, A. Sánchez-Fernández, P.L. Sassarini, W. Satuła, X. Sun, J. Wood, H. Wibowo

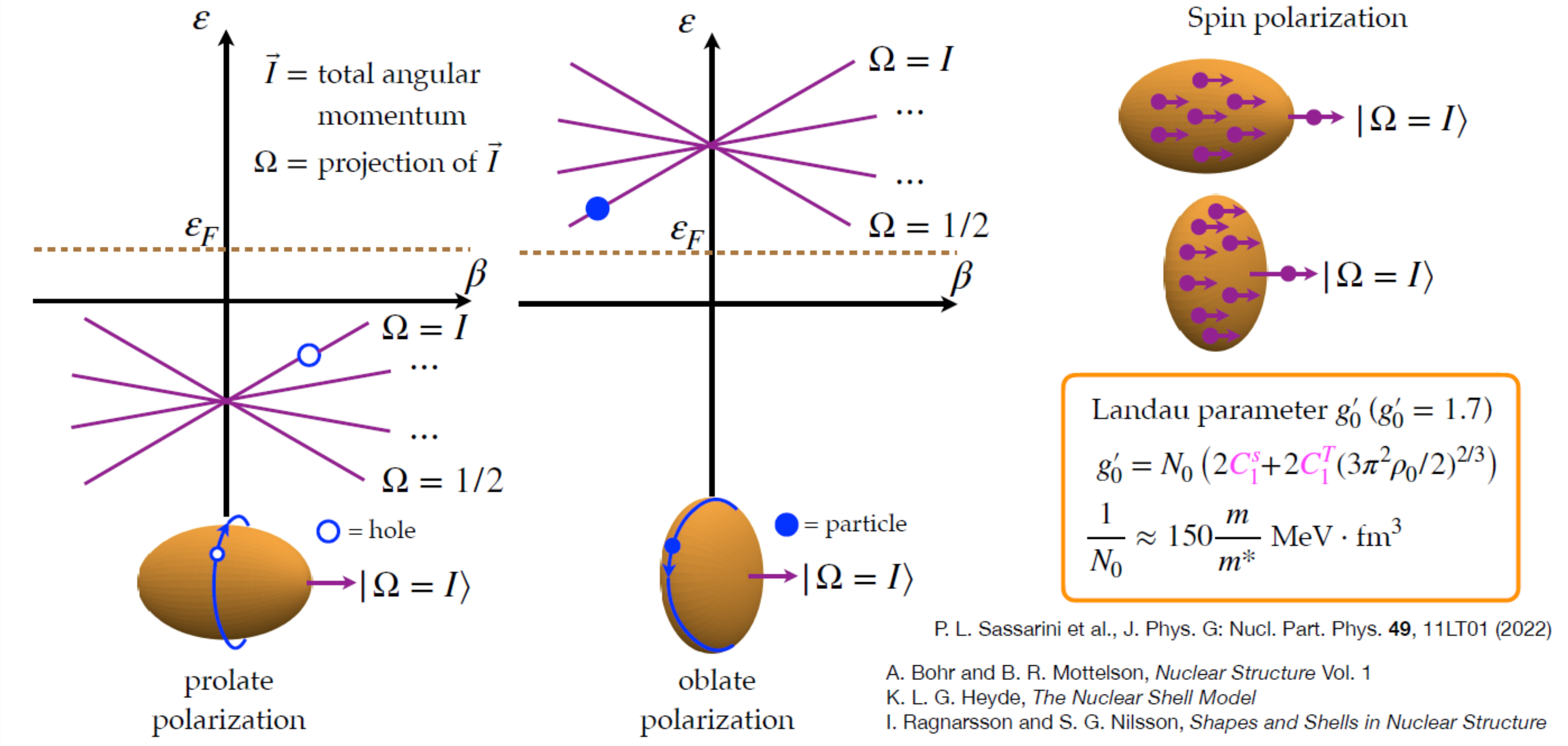
ISOLDE Workshop and Users meeting 2023
29 November to 1 December 2023 at CERN, Geneva, Switzerland

Outline

1. Methodology*
2. Gd-Pb*
3. Dy
4. Sn-Gd
5. In*
6. Ag*
7. Sn*
8. Sb
9. What next?

*published

Shape and spin polarization



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

A. Bohr and B. R. Mottelson, *Nuclear Structure* Vol. 1
K. L. G. Heyde, *The Nuclear Shell Model*
I. Ragnarsson and S. G. Nilsson, *Shapes and Shells in Nuclear Structure*

Picture: courtesy H. Wibowo

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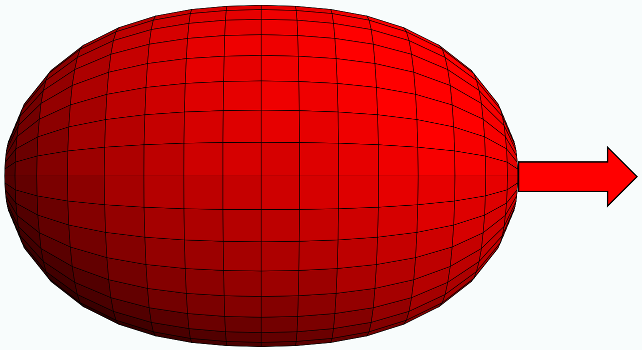
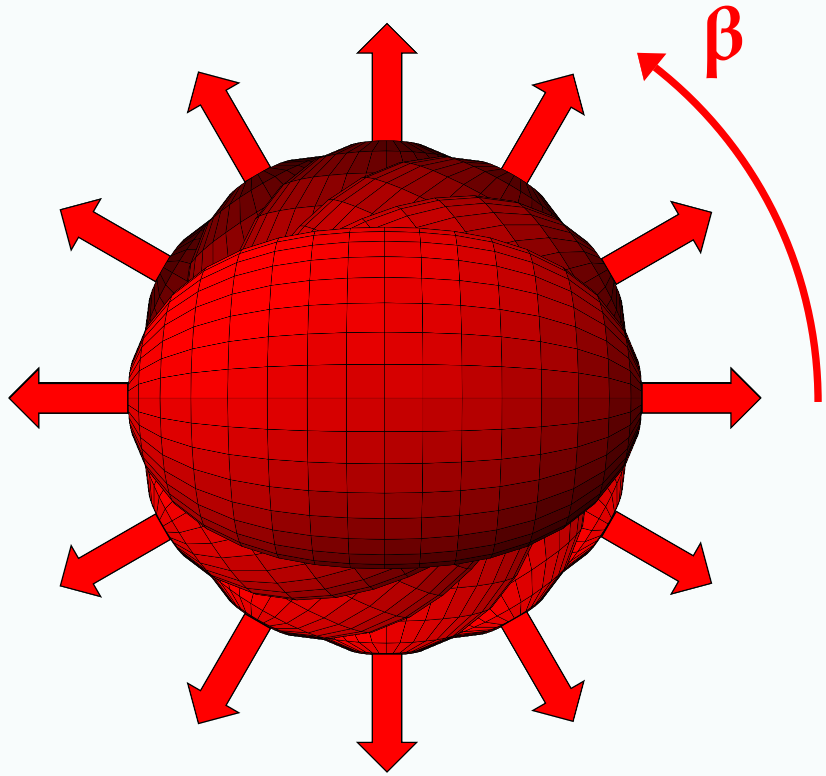
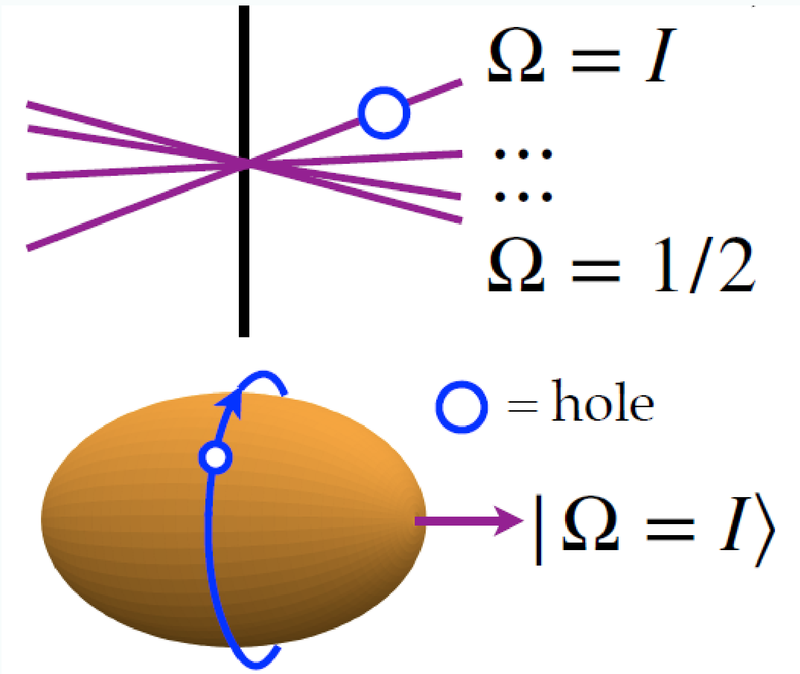
Time-odd spin alignment & symmetry restoration

"Intrinsic"
Symmetry broken







"Laboratory"
Symmetry restored

$$|IM\rangle = \mathcal{N}_I \int_{\beta=0}^{\pi} \mathrm{d}\beta \, d^I_{M\Omega}(\beta) |\Omega, \beta\rangle$$

J. A. Sheikh et al., J. Phys. G48, 123001 (2021)

Nuclear quadrupole & dipole moments

Spectroscopic electric quadrupole Q and magnetic dipole μ moments are :

$$Q = \sqrt{\frac{16\pi}{5}} \langle II \,|\, \hat{Q}_{20} \,|\, II \rangle \quad \text{and} \quad \mu = \sqrt{\frac{4\pi}{3}} \langle II \,|\, \hat{M}_{10} \,|\, II \rangle \,.$$

P. Ring and P. Schuck, *The Nuclear Many-Body Problem*

$$\hat{Q}_{20} = \sqrt{\frac{5}{16\pi}} e \sum_{i=1}^{A} \left(\frac{1}{2} - t_3^{(i)}\right) \left\{3z_i^2 - r_i^2\right\}; \quad \hat{M}_{10} = \sqrt{\frac{3}{4\pi}} \mu_N \sum_{i=1}^{A} \left\{ g_s^{(i)} s_{zi} + g_\ell^{(i)} \ell_{zi} \right\};$$

$$g_s^{(i)} = g_p(g_n) = 5.59(-3.83)$$

$$g_\ell^{(i)} = 1(0)$$

Intrinsic moments = moments of the symmetry-broken state
Spectroscopic moments = moments of the symmetry-restored state

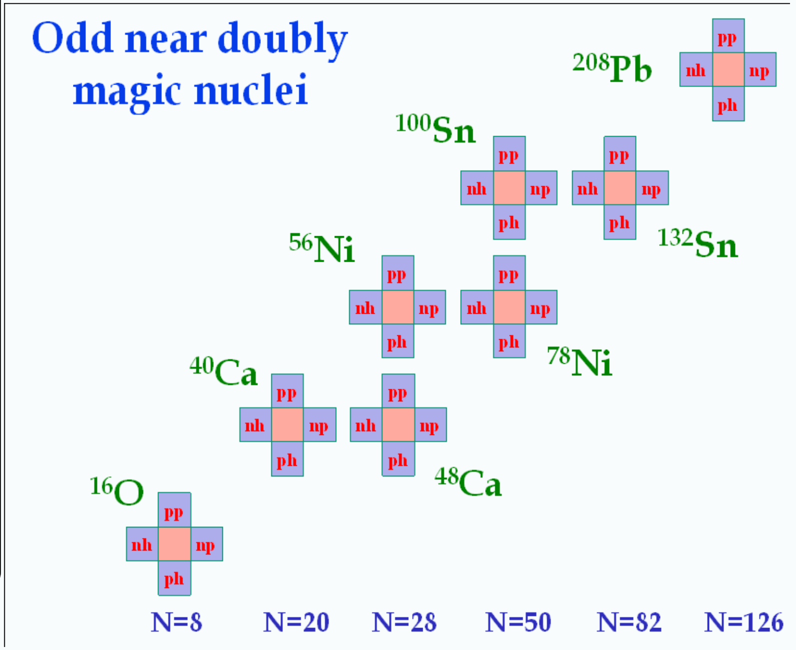
Spectroscopic moments = moments measured experimentally

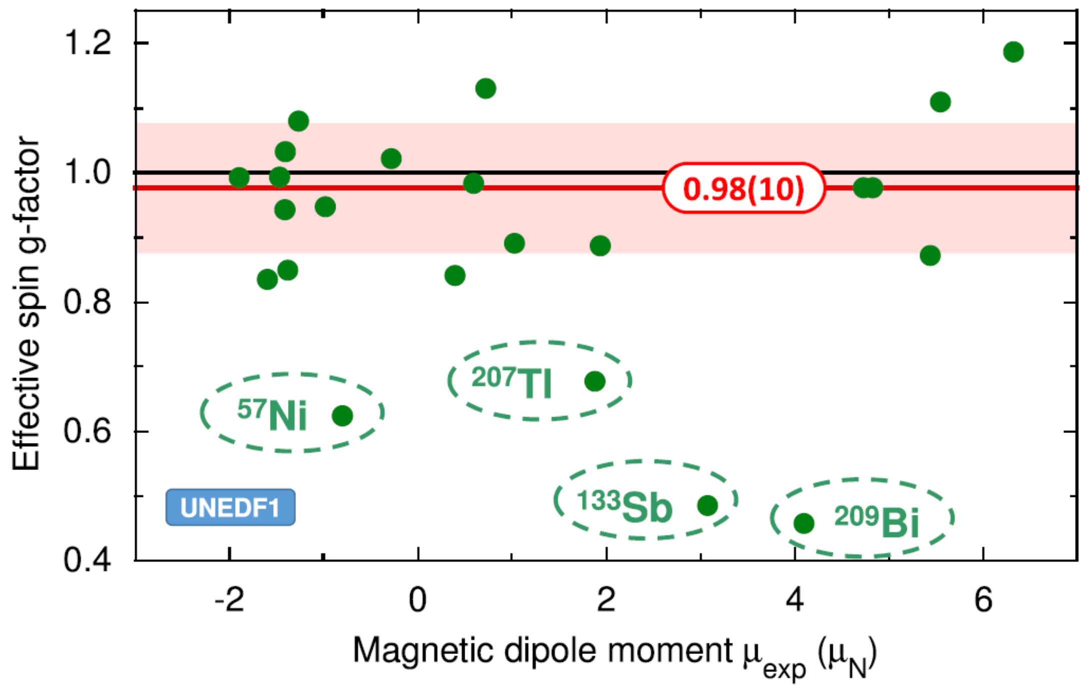
Effective spin g-factor? Who ordered that?

P. Sassarini *et al.*, J. Phys. G49 (2022) 11LT01

$$g_s^{(i)} = g_p(g_n) = 5.59(-3.83) \times g^{\text{eff}}\ ???$$

$$g_\ell^{(i)} = 1(0)$$



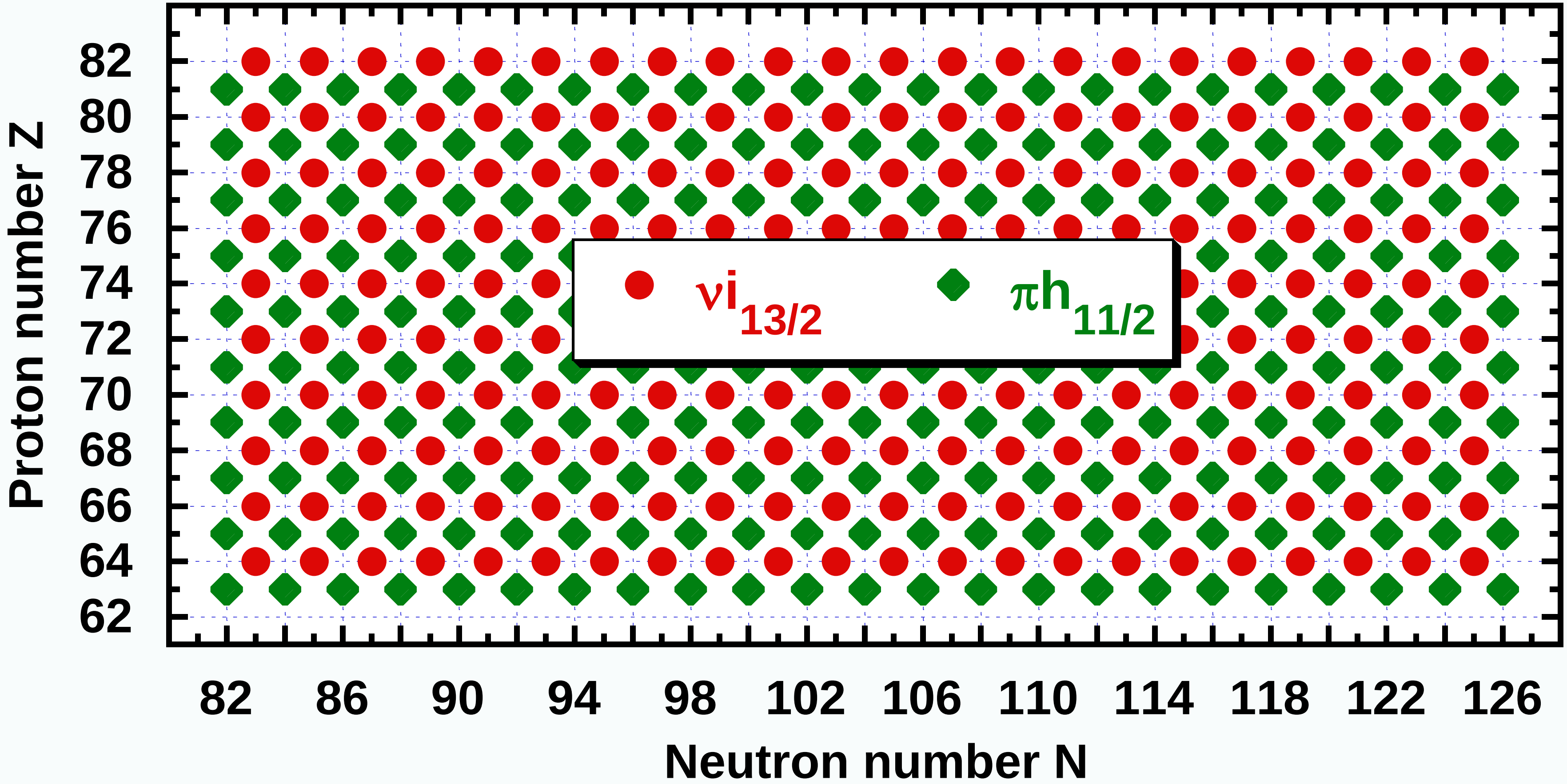


The bottom line

The nuclear electromagnetic moments of odd nuclei are all about:

1. **Polarization**
2. **Self-consistency**
3. **Symmetry restoration**

The first systematic nuclear-DFT analysis of the electromagnetic moments in heavy deformed open-shell odd nuclei



J. Bonnard *et al.*, Phys. Lett. B 843 (2023) 138014

Blocked quasiparticles were tagged by the neutron $i_{13/2}$ (Ω=+13/2) or proton $h_{11/2}$ (Ω=+11/2) single-particle orbitals

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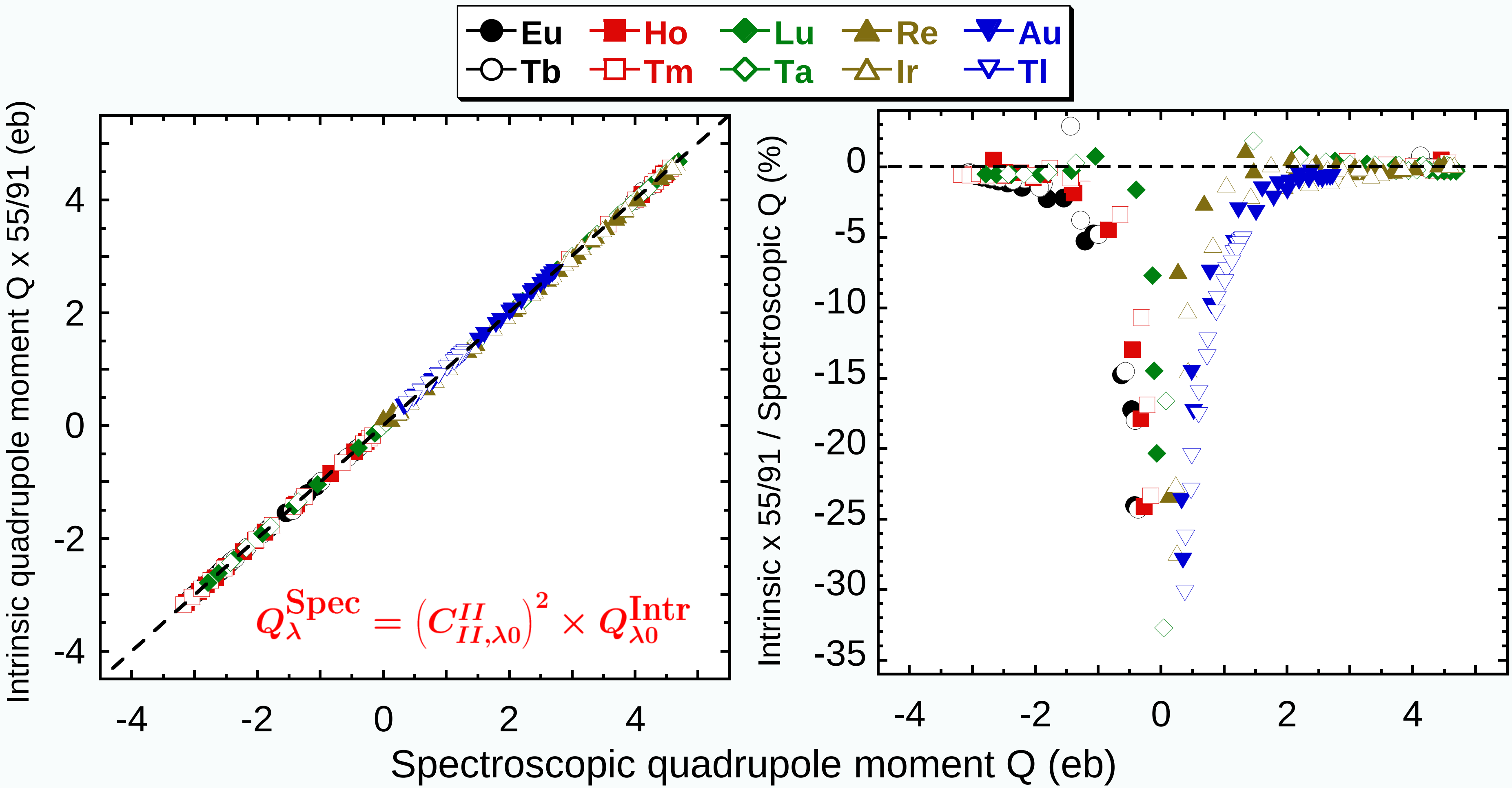
Heavy deformed π11/2⁻ odd-Z nuclei

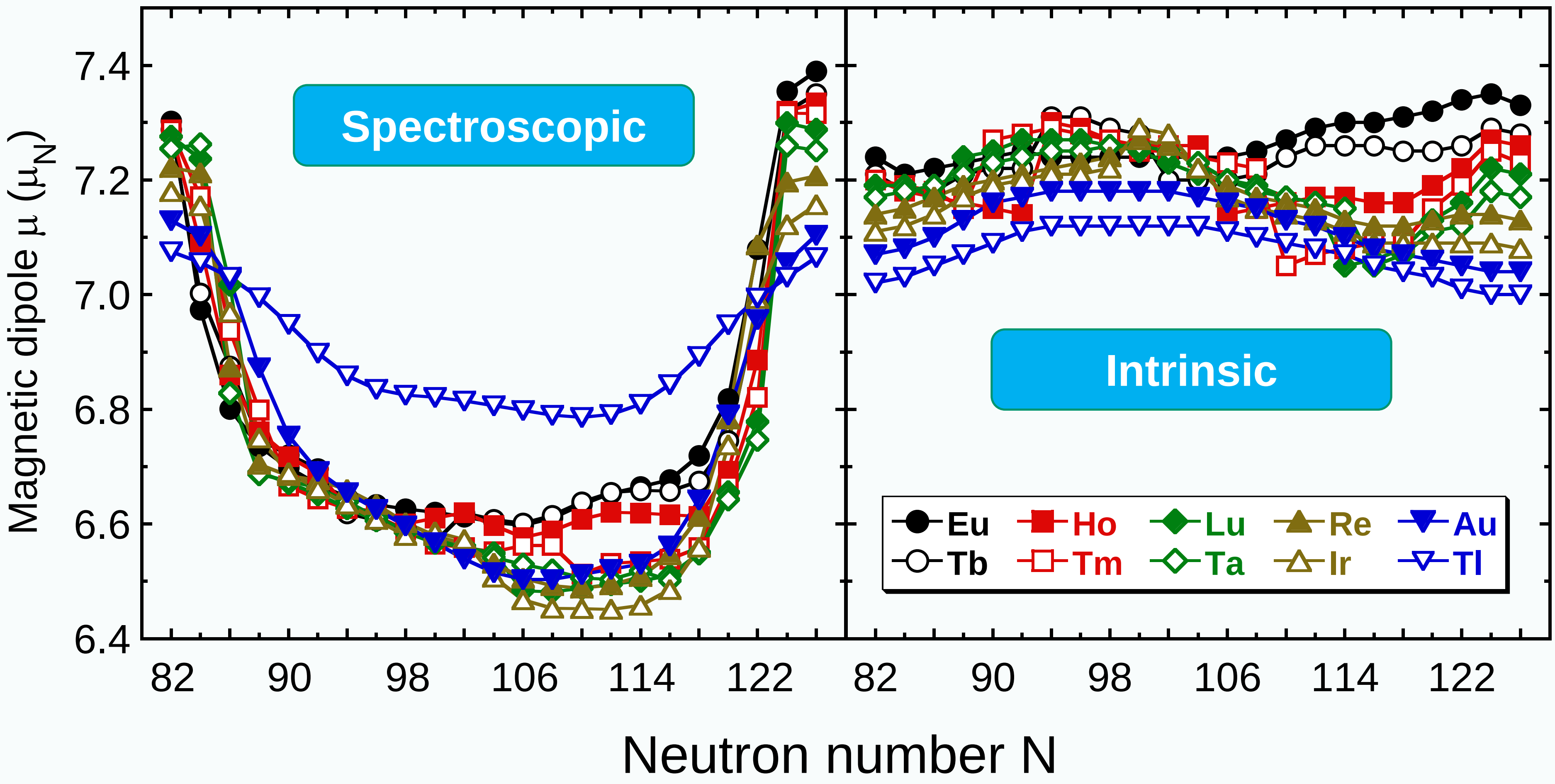


J. Bonnard *et al.*, Phys. Lett. B 843 (2023) 138014

Conclusion:

Spectroscopic electric quadrupole moments can be inferred from the intrinsic ones at ~5% precision only at |Q|>1b)

Heavy deformed π11/2⁻ odd-Z nuclei



J. Bonnard *et al.*, Phys. Lett. B 843 (2023) 138014

Conclusion:

Spectroscopic magnetic dipole moments cannot be inferred from the intrinsic ones

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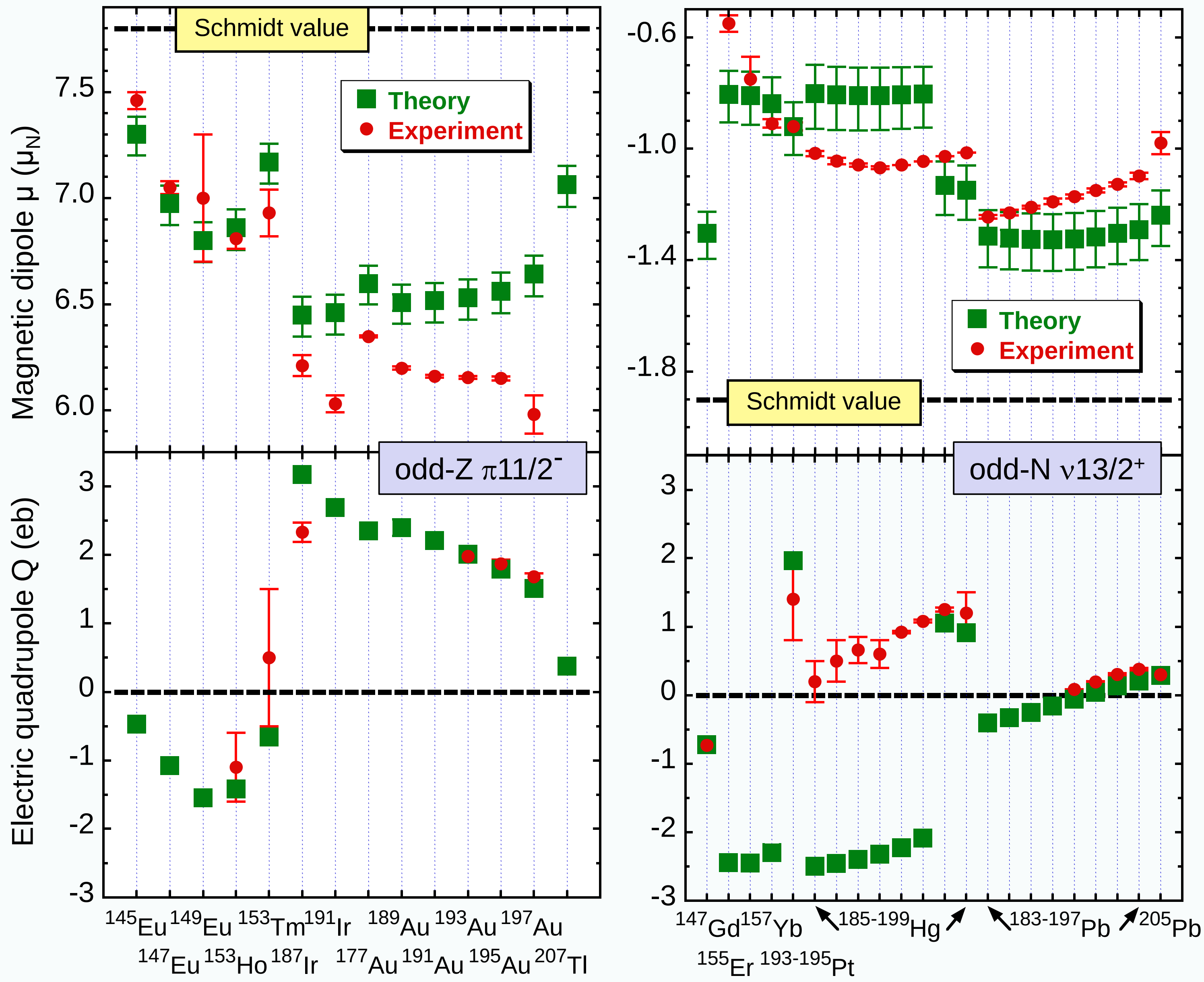
Spectroscopic moments: theory vs. experiment



J. Bonnard *et al.*, Phys. Lett. B 843 (2023) 138014

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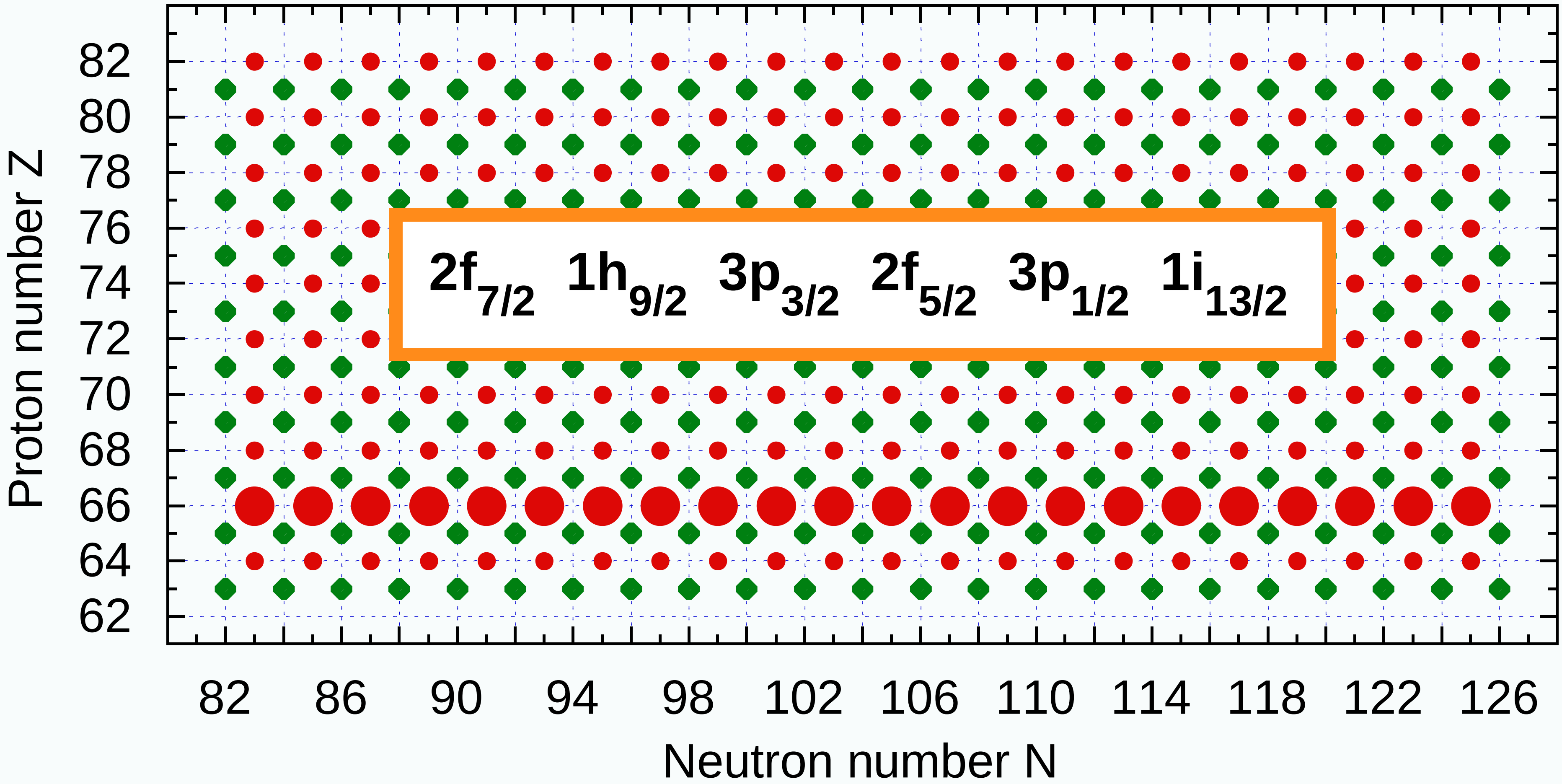
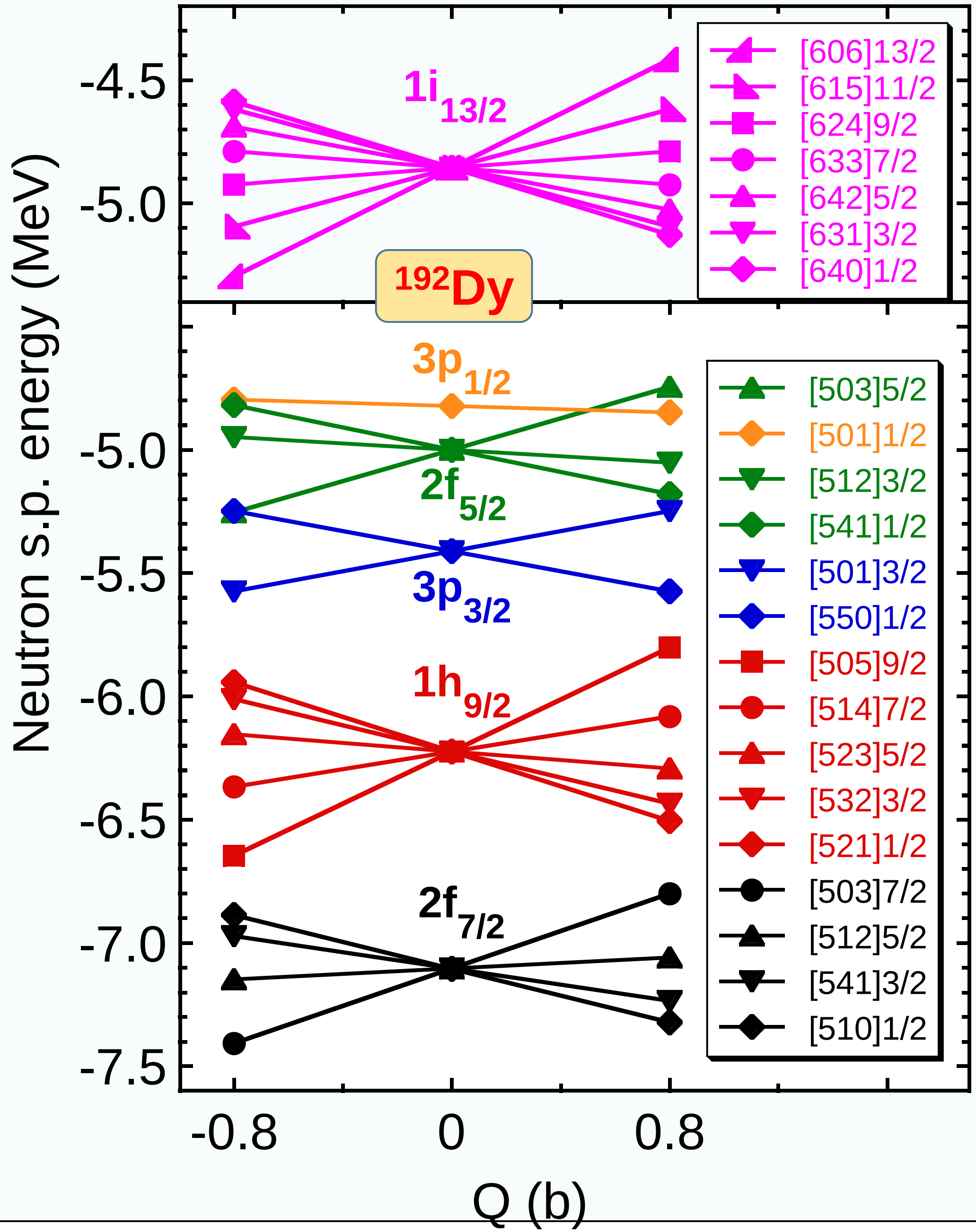
The first systematic nuclear-DFT analysis of the electromagnetic moments in excited quasiparticle states



J. Dobaczewski *et al.*, to be published

How to calculate odd nuclei in nuclear DFT?



without pairing

A even, $p > A$, $h \leq A$

$$|\Psi\rangle^{\text{even}}_{\text{HF}} = a^+_A \ldots a^+_2 a^+_1 |0\rangle$$

$$|\Psi\rangle^{\text{odd}}_{\text{HF}} = \begin{cases} a^+_p |\Psi\rangle^{\text{even}}_{\text{HF}} \\ a_h |\Psi\rangle^{\text{even}}_{\text{HF}} \end{cases}$$

with pairing

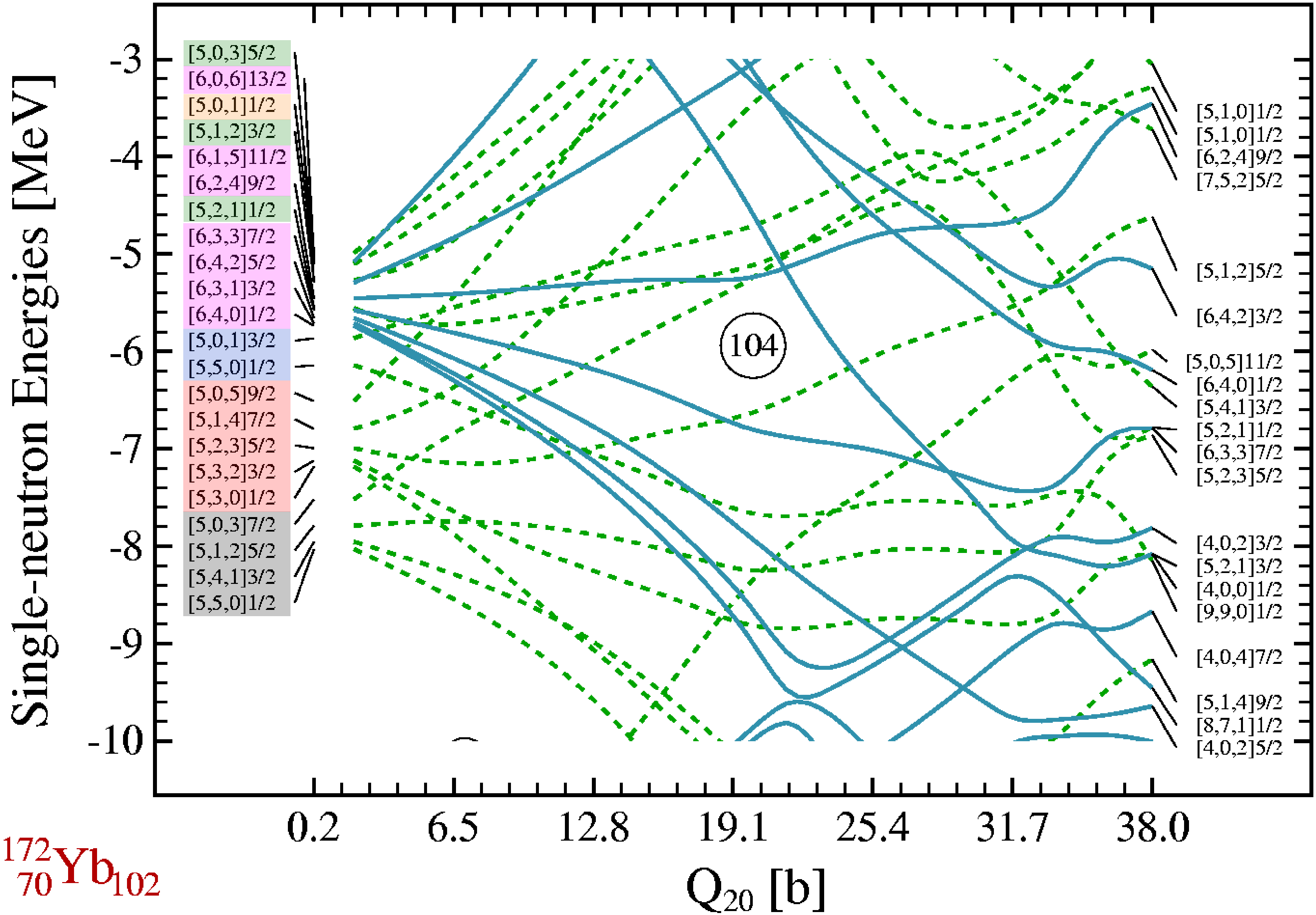
$$|\Psi\rangle^{\text{even}}_{\text{HFB}} = \prod_{\mu>0} \left(u_\mu + v_\mu a^+_{\bar{\mu}} a^+_\mu\right) |0\rangle$$

$$|\Psi\rangle^{\text{odd}}_{\text{HFB}} = \beta^+_\nu |\Psi\rangle^{\text{even}}_{\text{HFB}}$$

$$= a^+_\nu \prod_{\nu\neq\mu>0} \left(u_\mu + v_\mu a^+_{\bar{\mu}} a^+_\mu\right) |0\rangle$$

tagging quasiparticle states

$$\max_\mu \left\{ \langle \varphi_\nu | \phi^{\text{upper}}_\mu \rangle, \langle \varphi_\nu | \phi^{\text{lower}}_\mu \rangle \right\}$$


Single-neutron Energies [MeV]
-3
-4
-5
-6
-7
-8
-9
-10
[5,0,3]5/2
[6,0,6]13/2
[5,0,1]1/2
[5,1,2]3/2
[6,1,5]11/2
[6,2,4]9/2
[5,2,1]1/2
[6,3,3]7/2
[6,4,2]5/2
[6,3,1]3/2
[6,4,0]1/2
[5,0,1]3/2
[5,5,0]1/2
[5,0,5]9/2
[5,1,4]7/2
[5,2,3]5/2
[5,3,2]3/2
[5,3,0]1/2
[5,0,3]7/2
[5,1,2]5/2
[5,4,1]3/2
[5,5,0]1/2
104
[5,1,0]1/2
[5,1,0]1/2
[6,2,4]9/2
[7,5,2]5/2
[5,1,2]5/2
[6,4,2]3/2
[5,0,5]11/2
[6,4,0]1/2
[5,4,1]3/2
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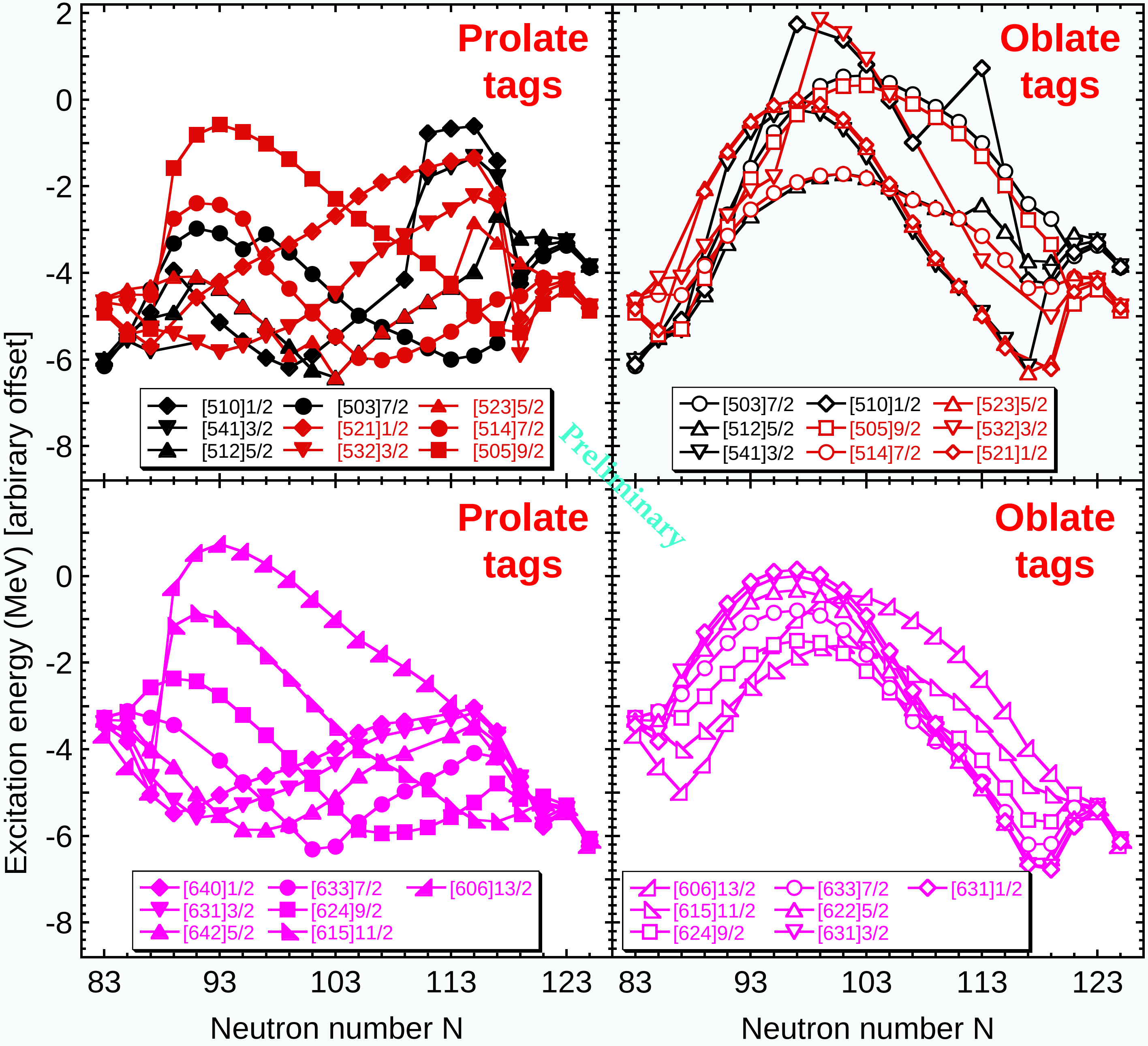
[6,3,3]7/2
[5,2,3]5/2
[4,0,2]3/2
[5,2,1]3/2
[4,0,0]1/2
[9,9,0]1/2
[4,0,4]7/2
[5,1,4]9/2
[8,7,1]1/2
[4,0,2]5/2
0.2
6.5
12.8
19.1
25.4
31.7
38.0
Q20 [b]
172 70 Yb 102

Excitation energies of odd dysprosium isotopes



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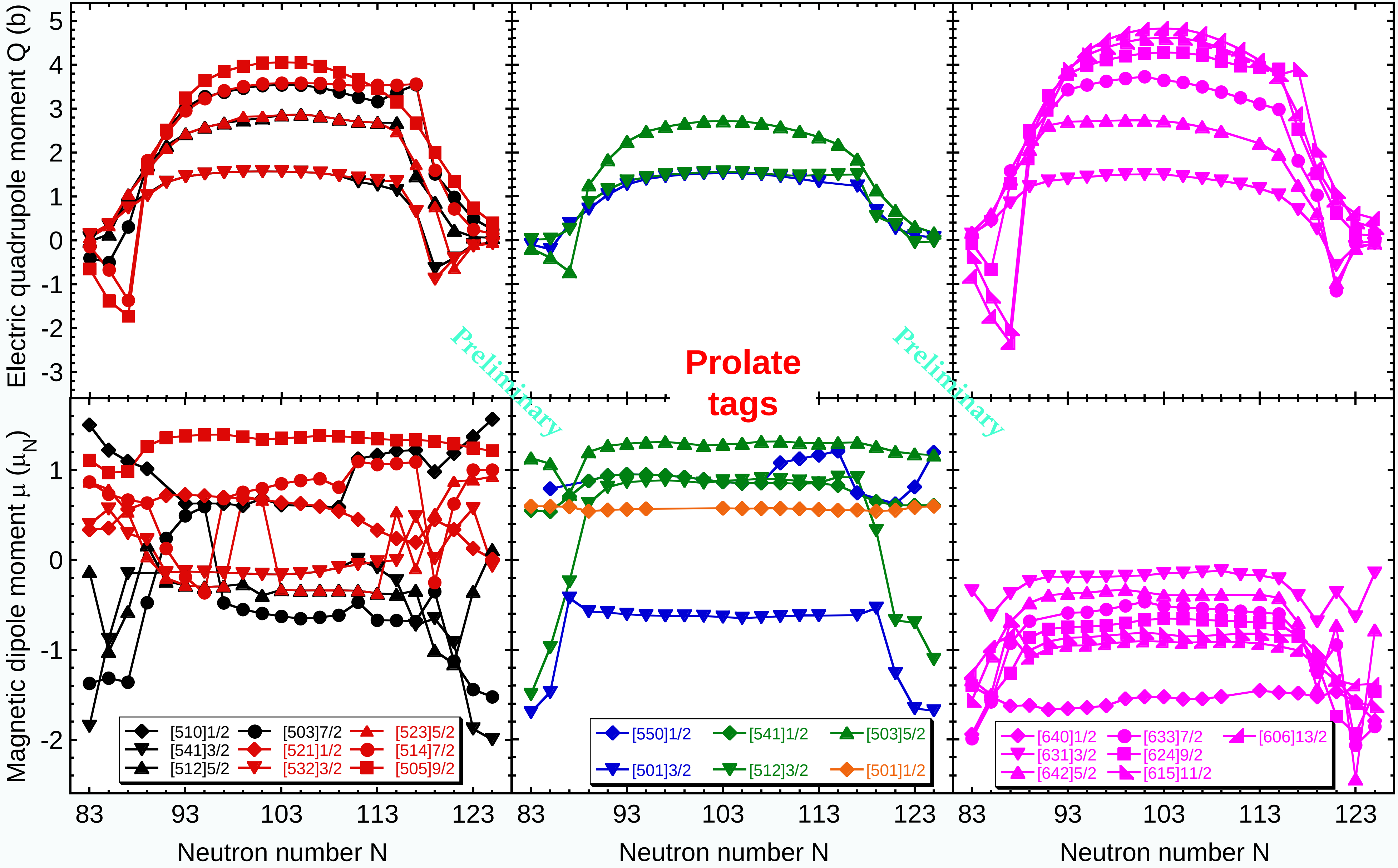
Electromagnetic moments of odd dysprosium isotopes



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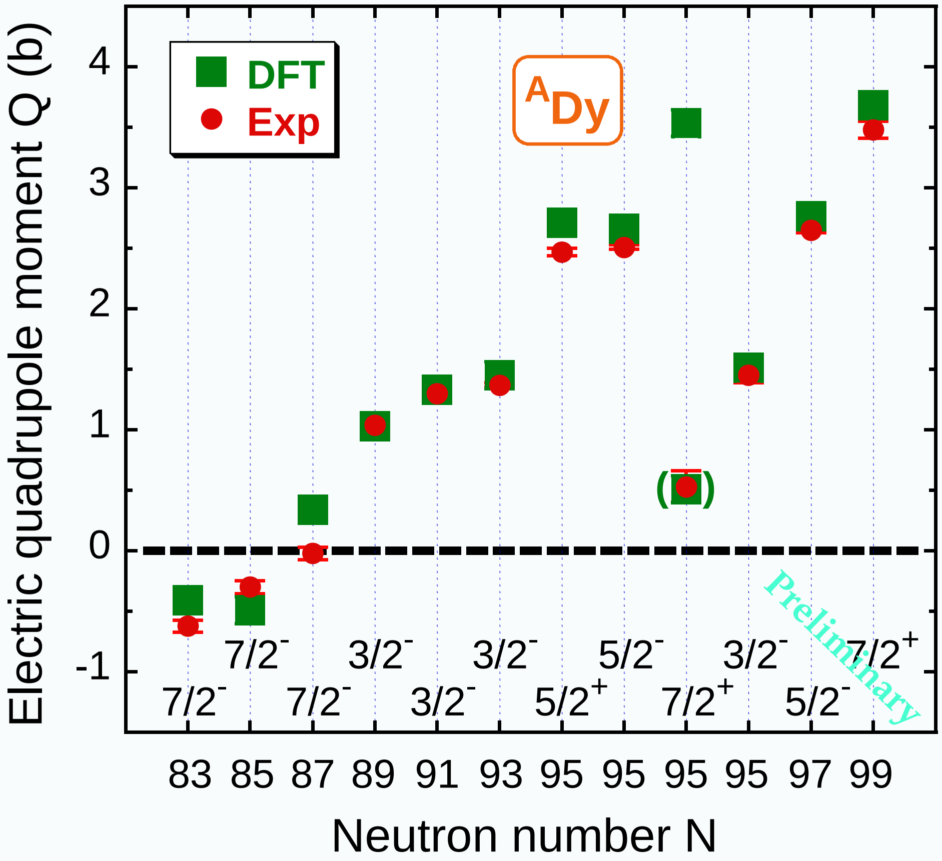
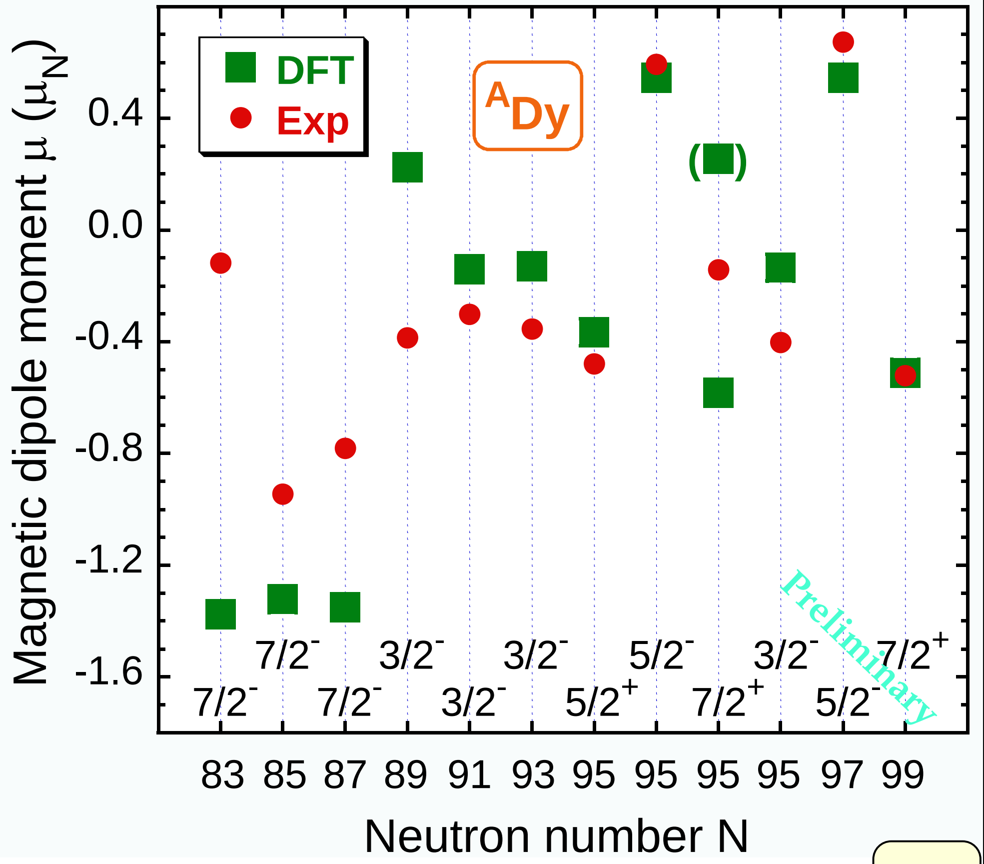
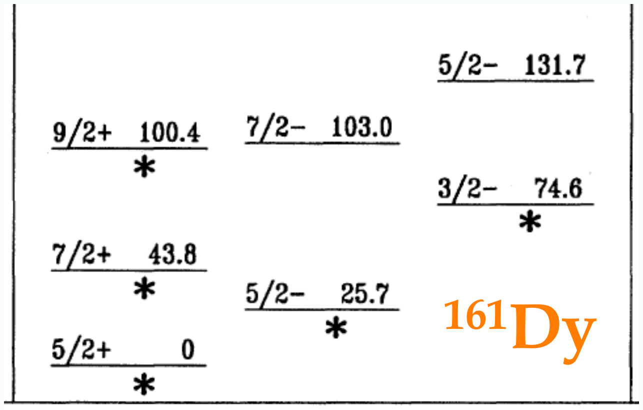
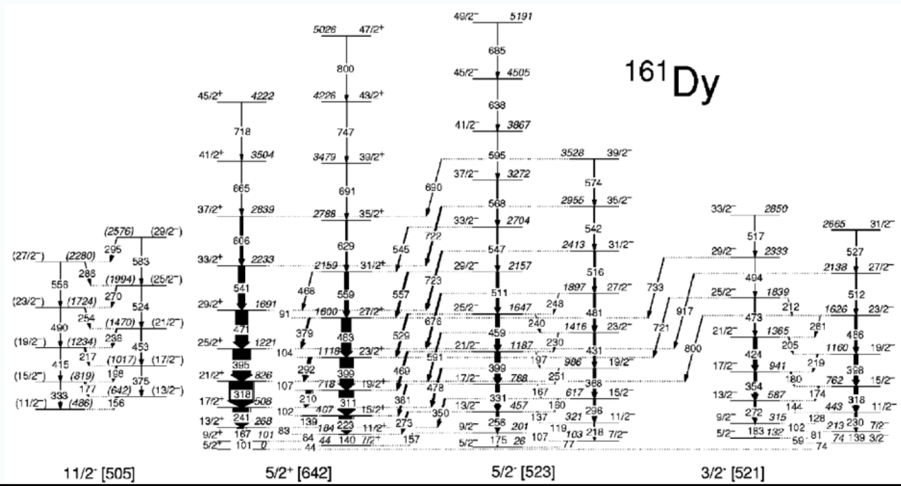
Electromagnetic moments of odd dysprosium isotopes







S. J. Margraf *et al.*, Phys. Rev. C52, 2429 (1995)



A. Jungclaus *et al.*, Phys. Rev. C67, 034302 (2003)

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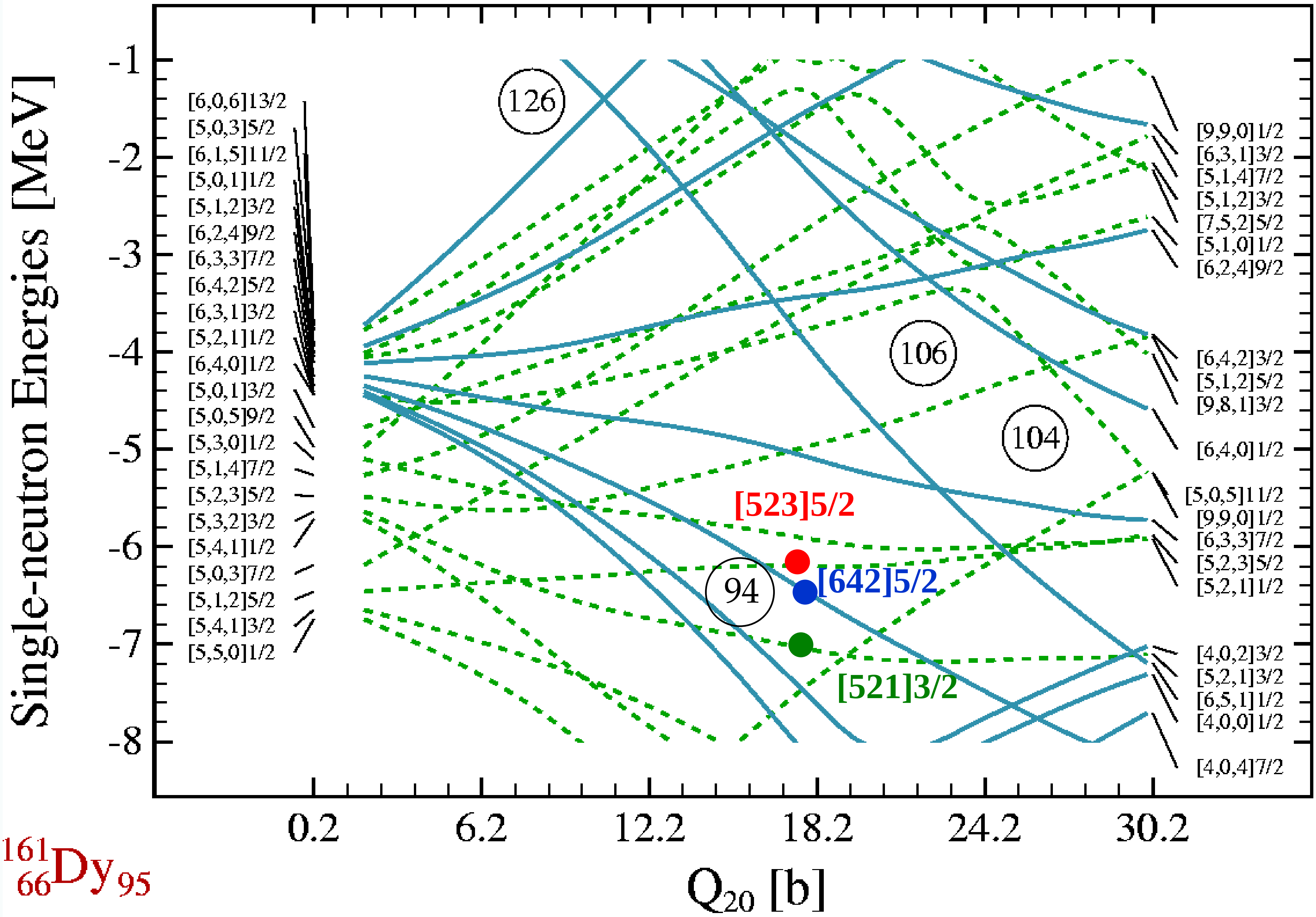

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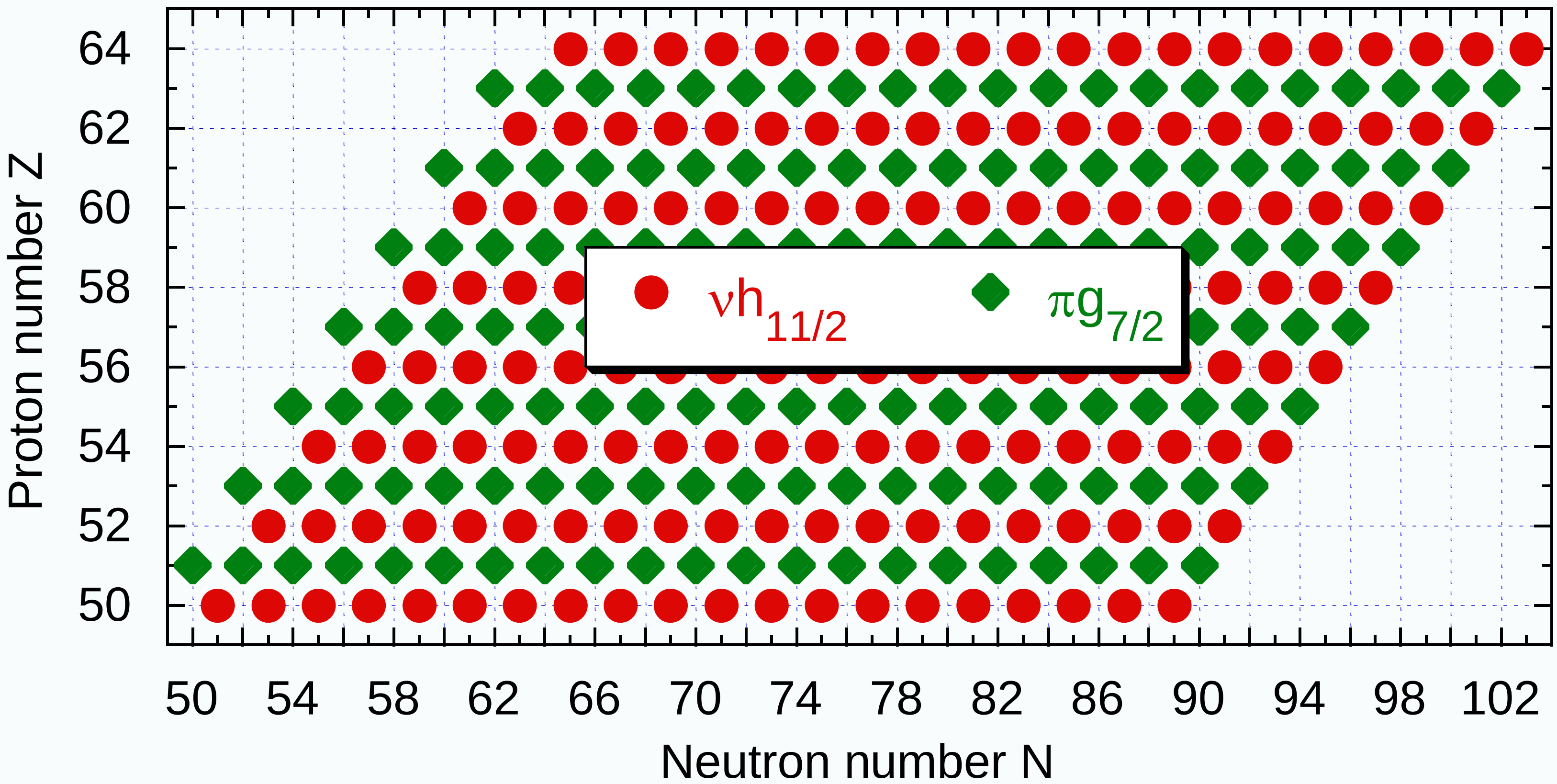
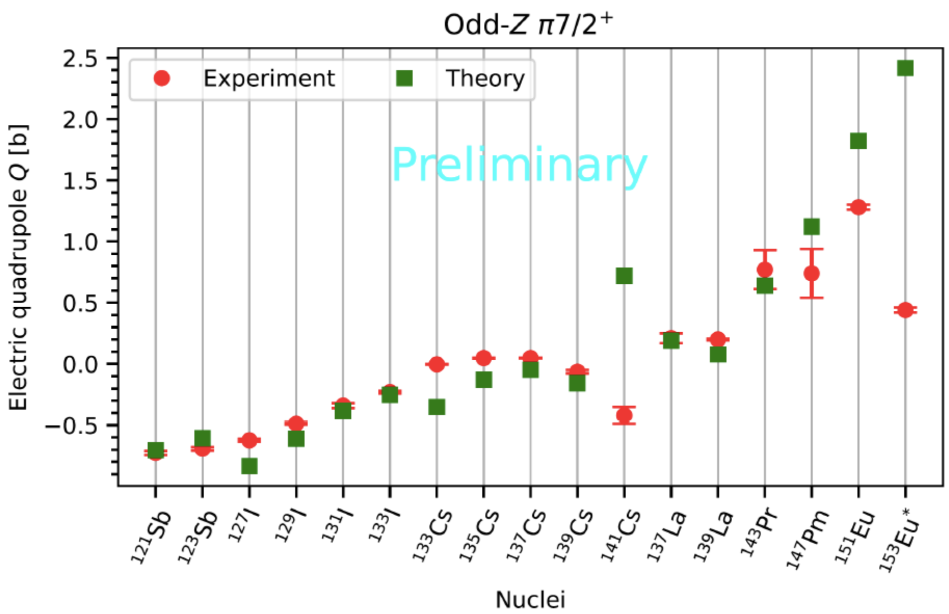
Nuclear-DFT analysis of electromagnetic moments between the Sn and Gd isotopes



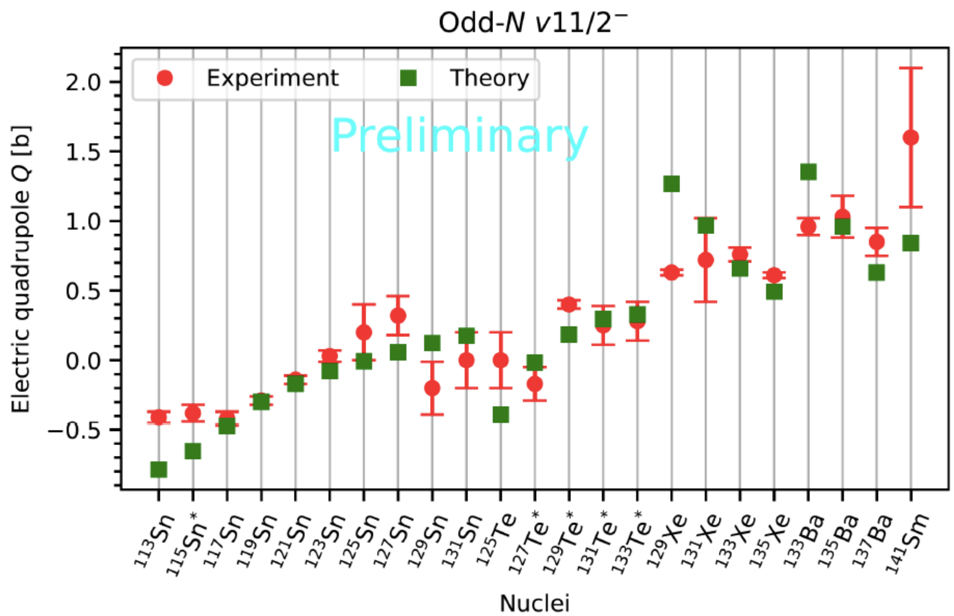
H. Wibowo *et al.*, to be published

Quadrupole moments: theory vs. experiment



N. J. Stone, *Table of nuclear magnetic dipole and electric quadrupole moments* (2014), INDC, report INDC(NDS)-0658

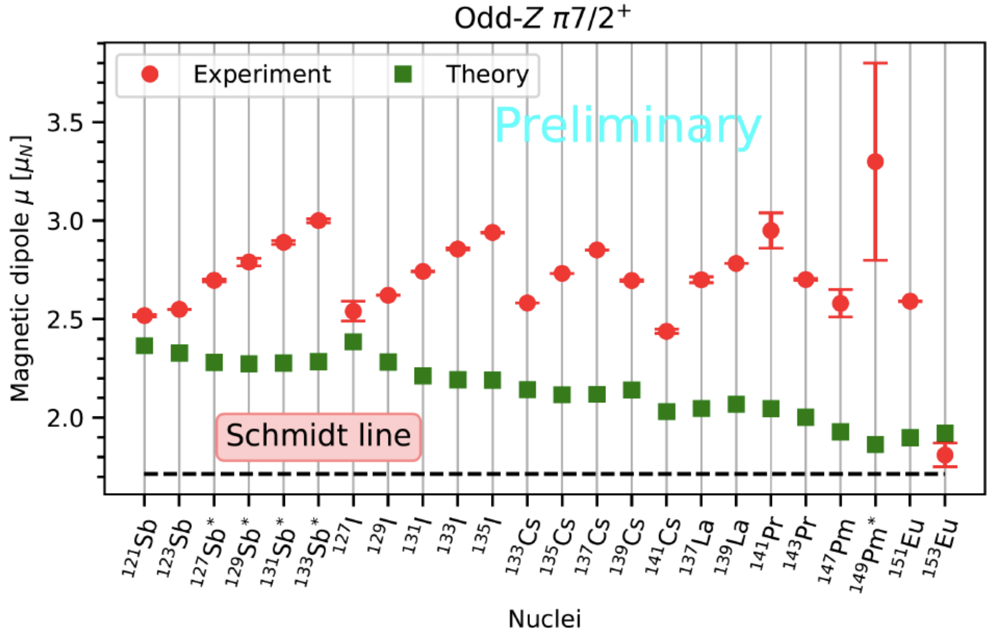
N. J. Stone, *Table of nuclear electric quadrupole moments, ADNDT 111-112*, 1 (2016)



Picture: courtesy H. Wibowo

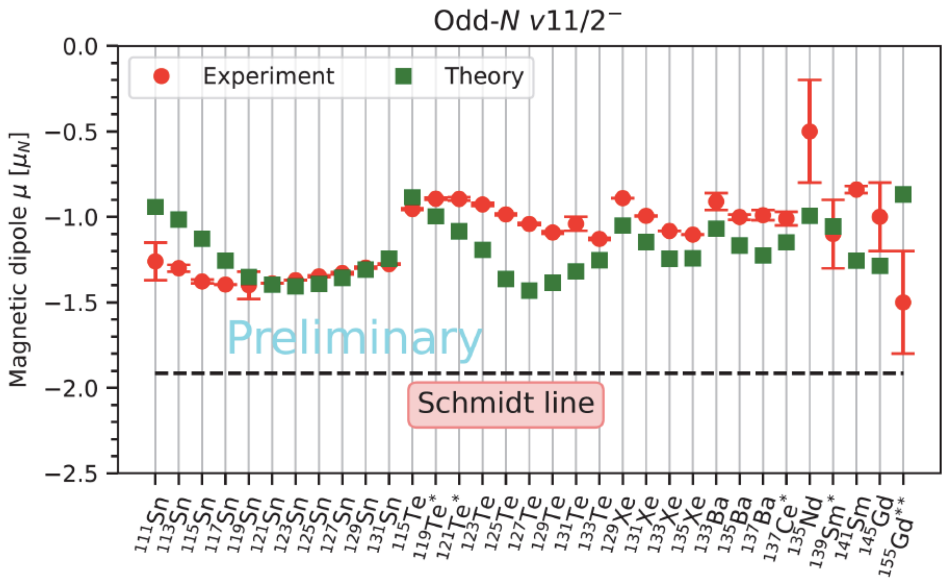
H. Wibowo *et al.*, to be published

Magnetic dipole moments: theory vs. experiment



N. J. Stone, *Table of nuclear magnetic dipole and electric quadrupole moments* (2014), INDC, report INDC(NDS)-0658

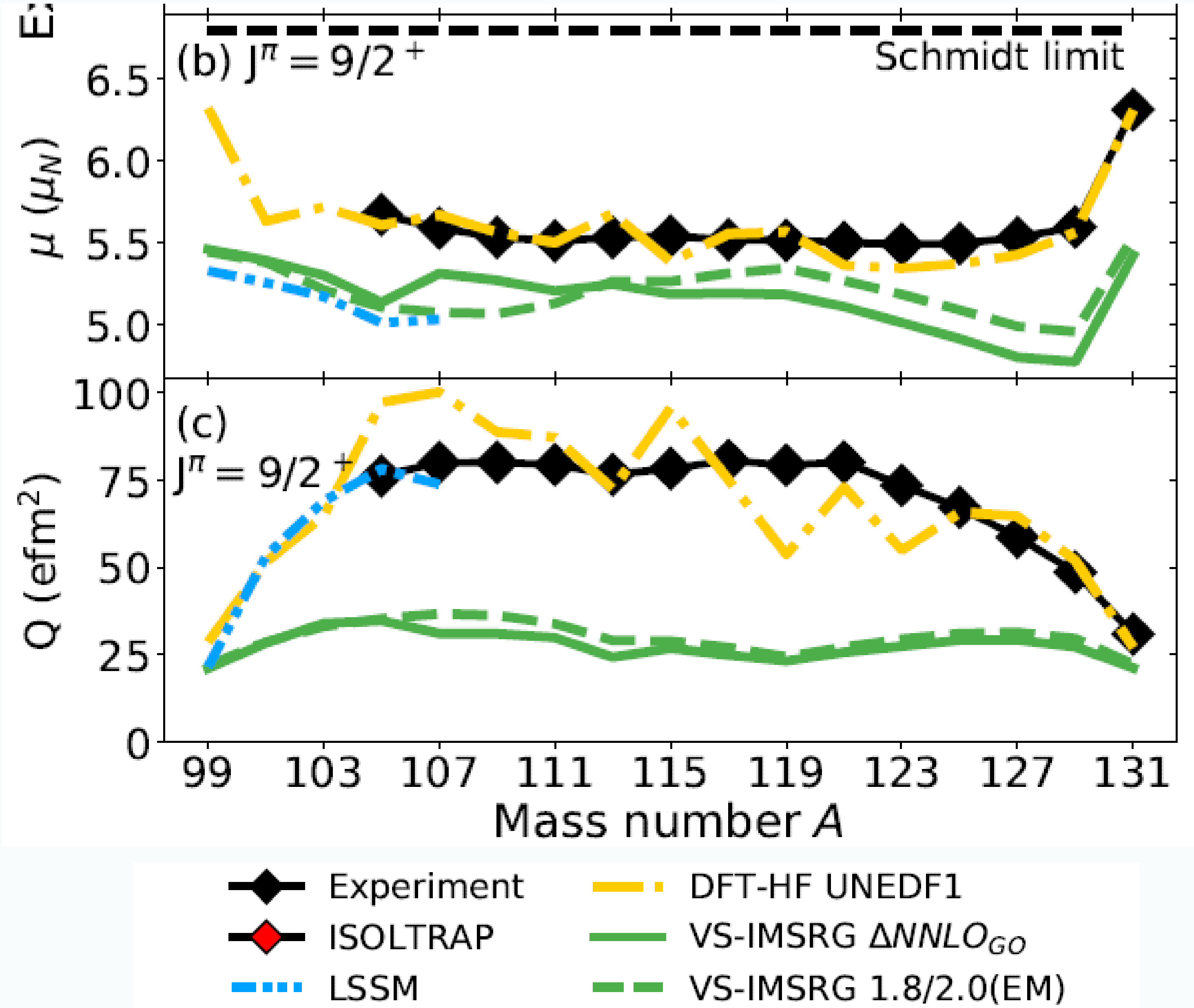
Schmidt lines represent the value of magnetic dipole moment of an odd-mass nucleus which is completely determined by the ℓ and j values of the unpaired nucleon (single-particle model).



Picture: courtesy H. Wibowo

H. Wibowo *et al.*, to be published

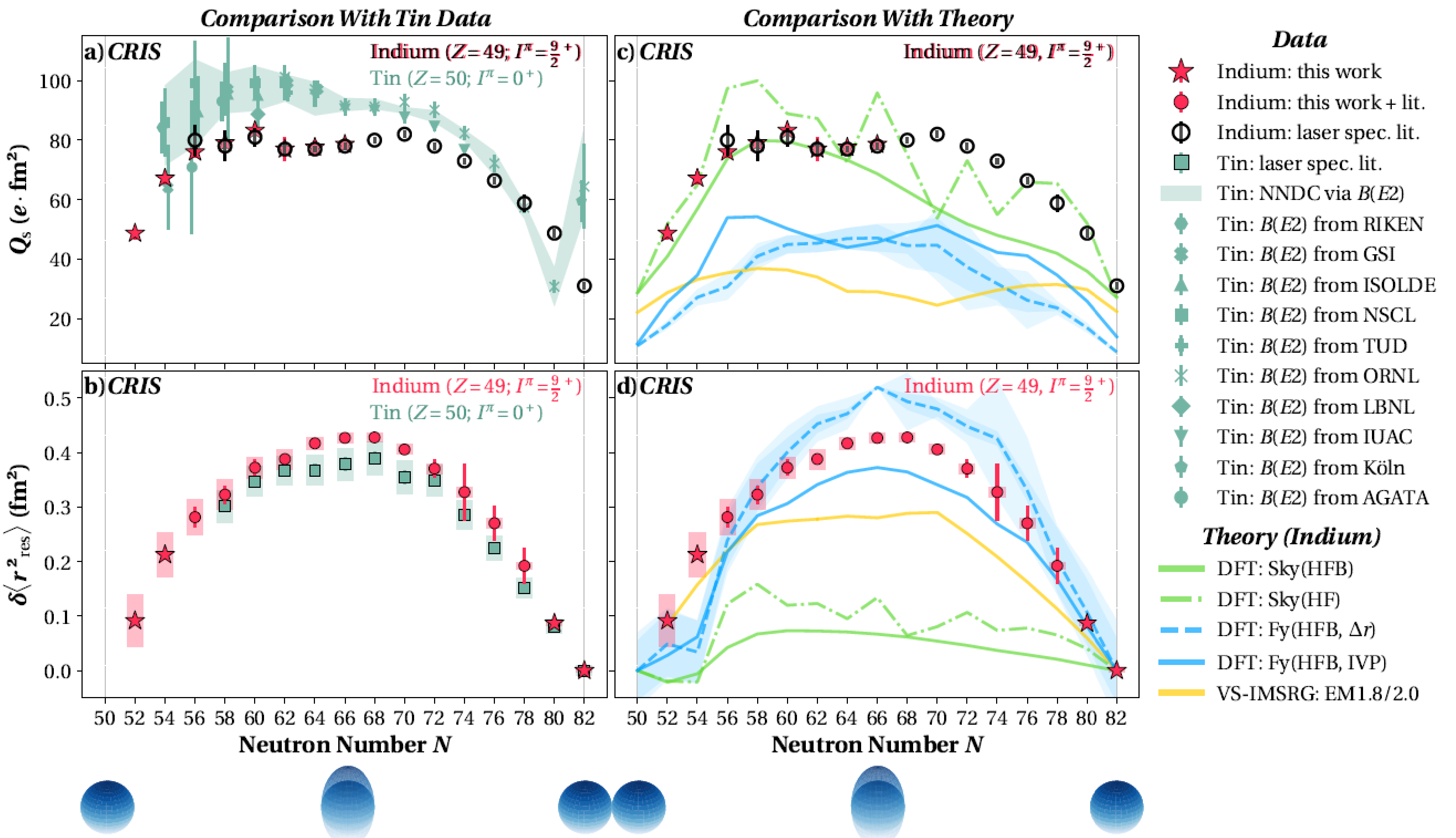
Moments of the 9/2 states in In



A.R. Vernon *et al.*, Nature 607, 260 (2022)

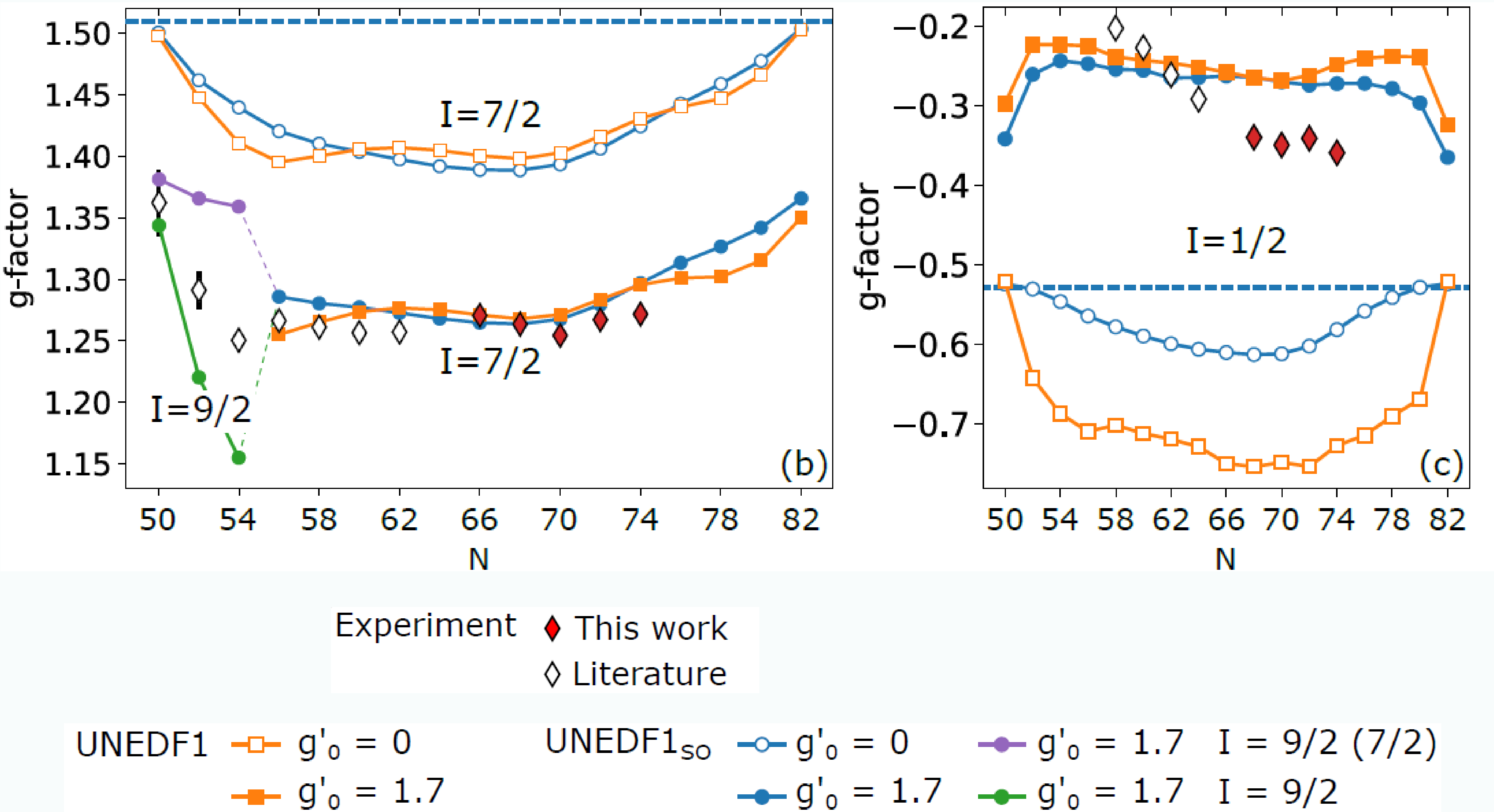
L. Nies *et al.*, Phys. Rev. Lett. 131, 022502 (2023)

Quadrupole moments and radii of In and Sn



J. Karthein *et al.*, arXiv:2310.15093

Moments of the 1/2, 7/2 & 9/2 states in Ag



R. P. de Groote *et al.*, Phys. Lett. B 848 (2024) 138352

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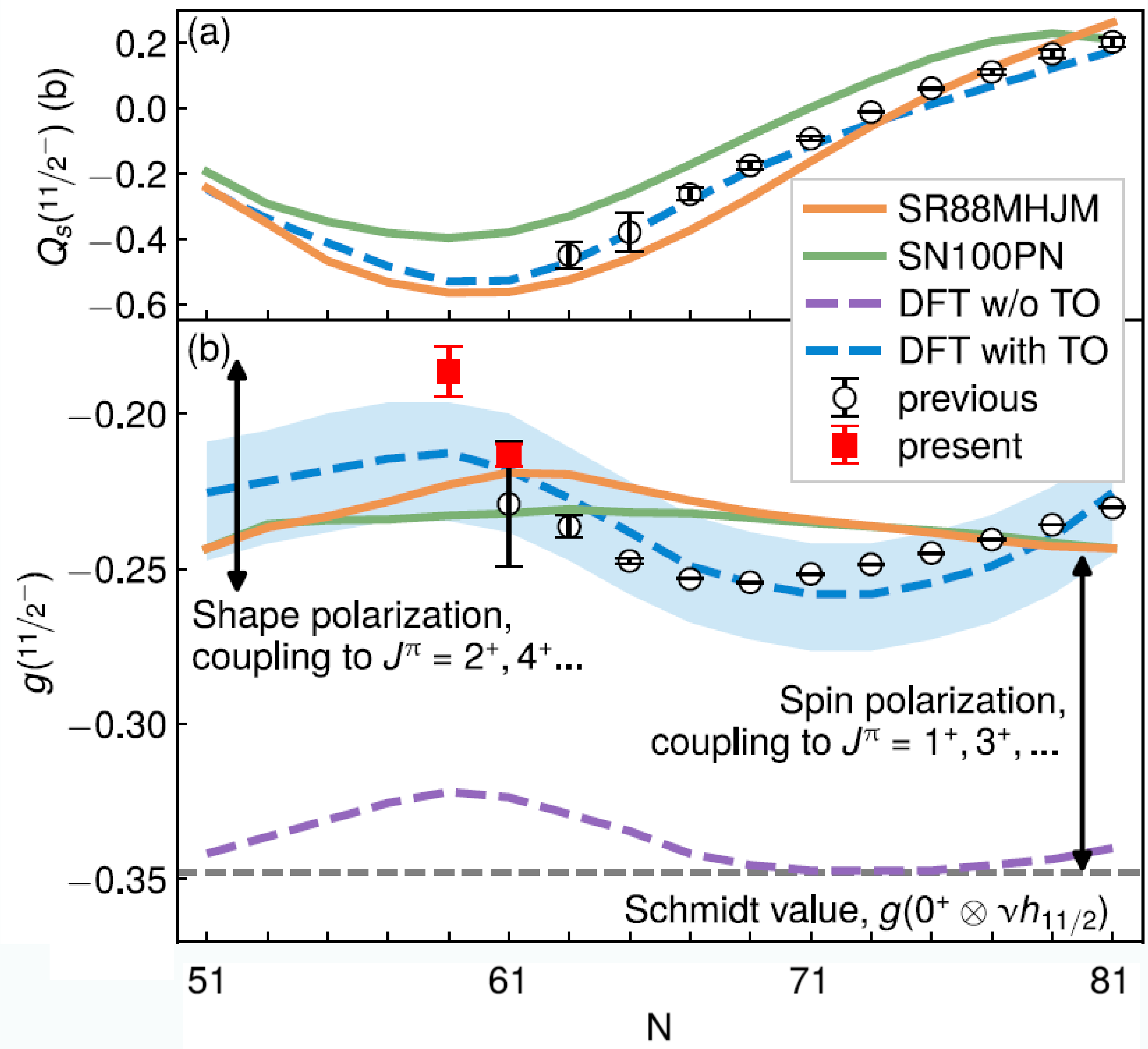
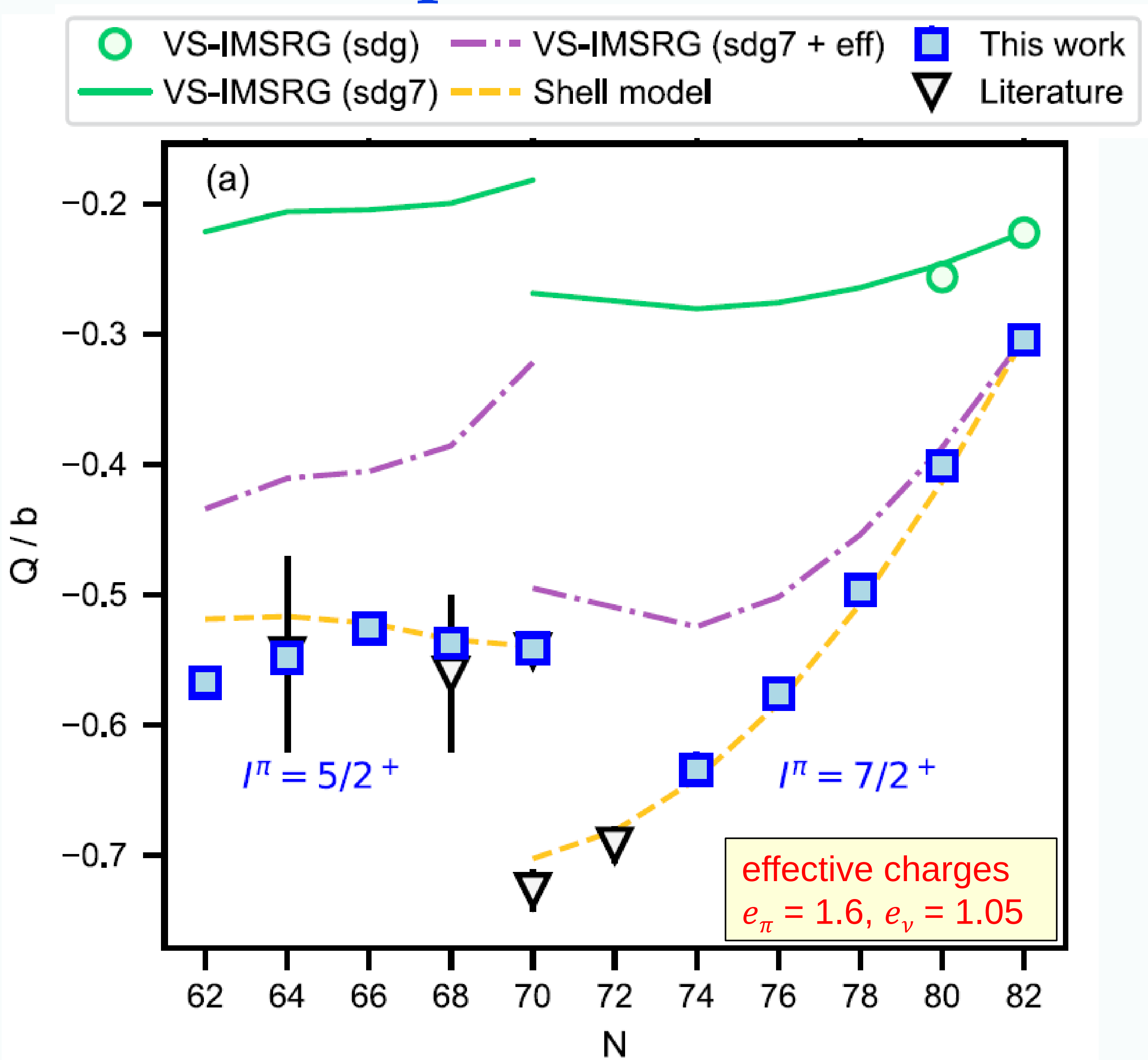
Moments of the $\nu h_{11/2}$ isomers in Sn

$g = \mu/I$



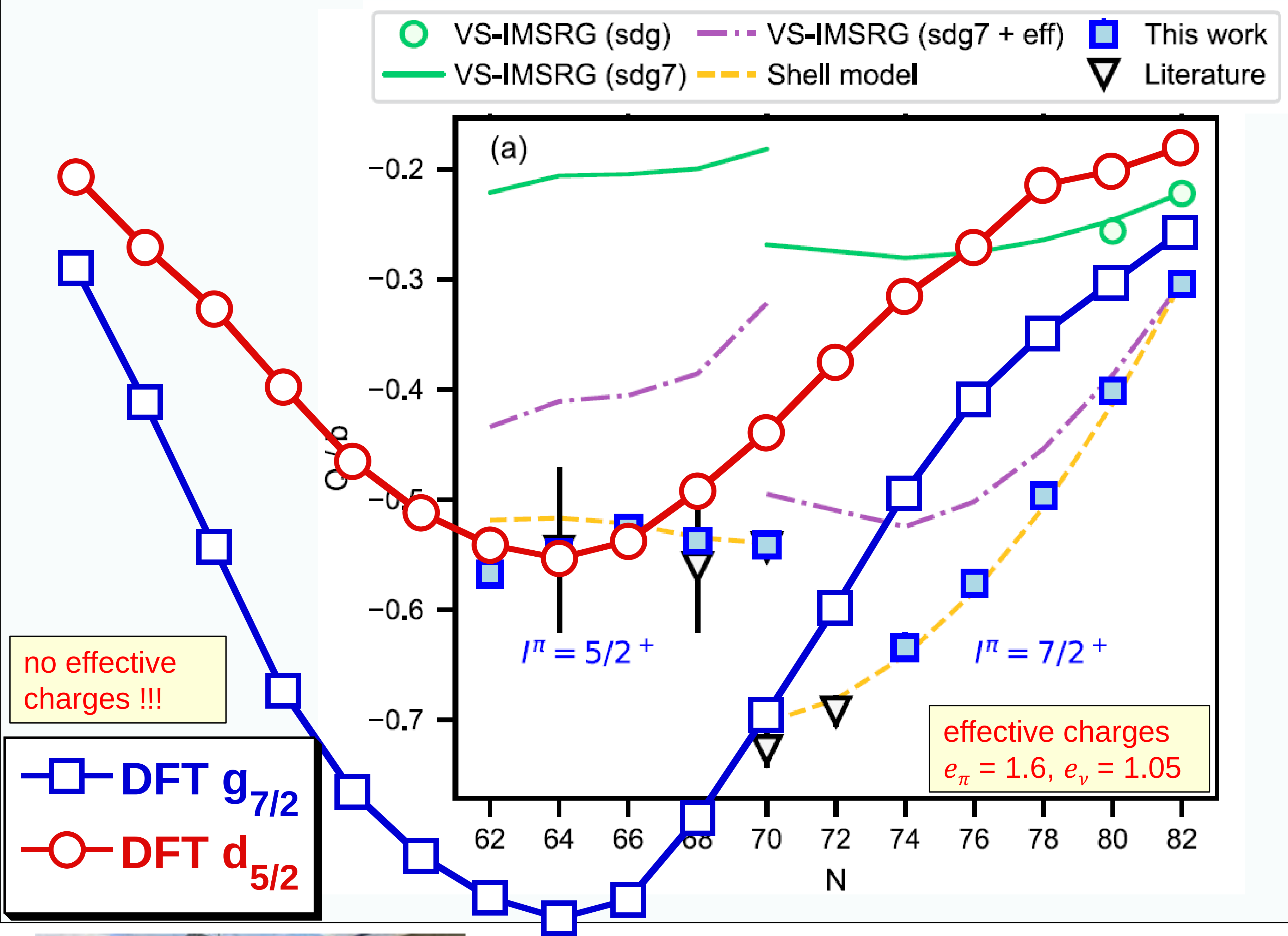
T.J. Gray *et al.*, Phys. Lett. B 847 (2023) 138268

Quadrupole moments in Sb



S. Lechner *et al.*, Phys. Lett. B 847 (2023) 138278

Quadrupole moments in Sb



S. Lechner *et al.*, Phys. Lett. B 847 (2023) 138278

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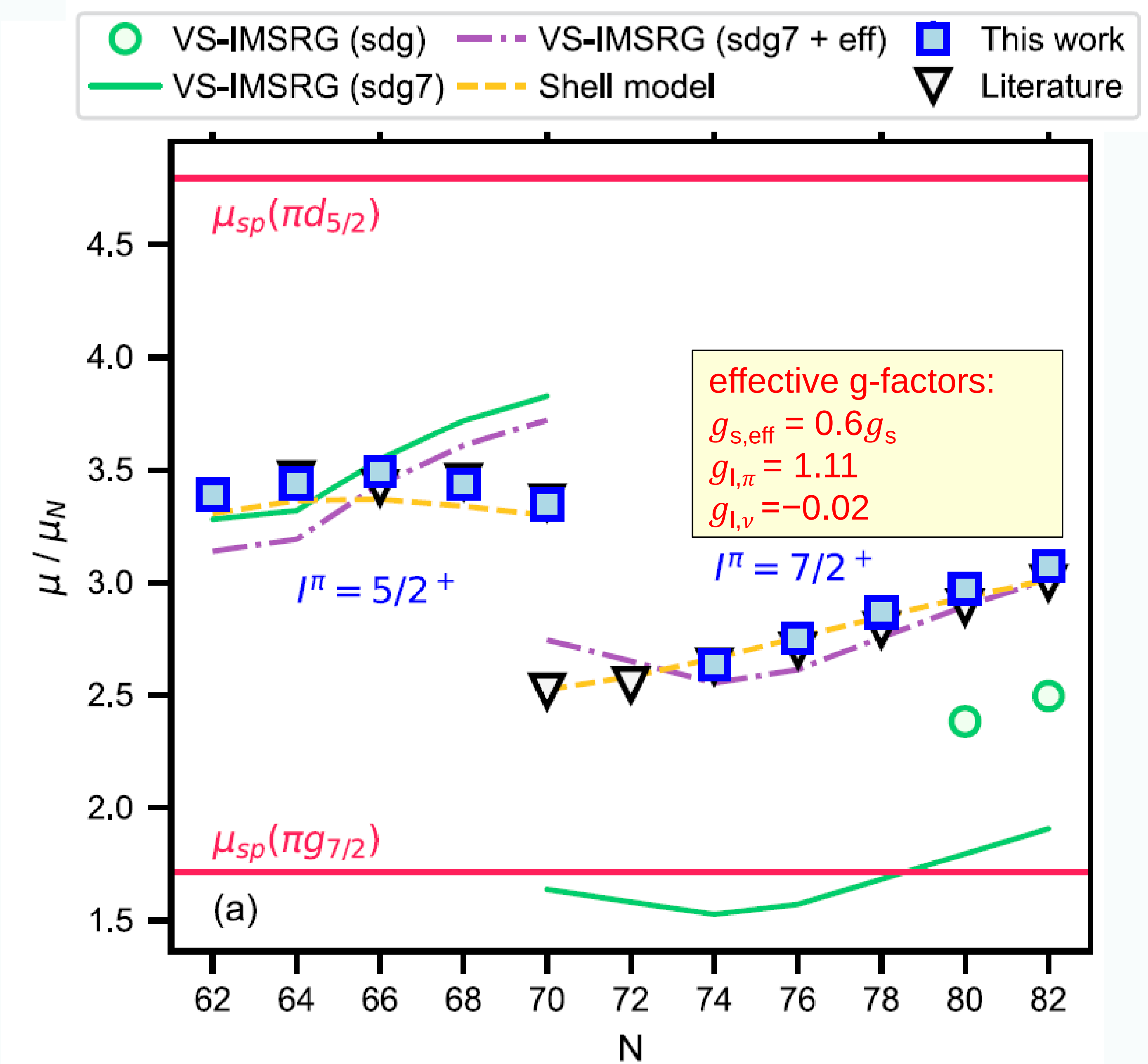
Magnetic dipole moments in Sb



S. Lechner *et al.*, Phys. Lett. B 847 (2023) 138278

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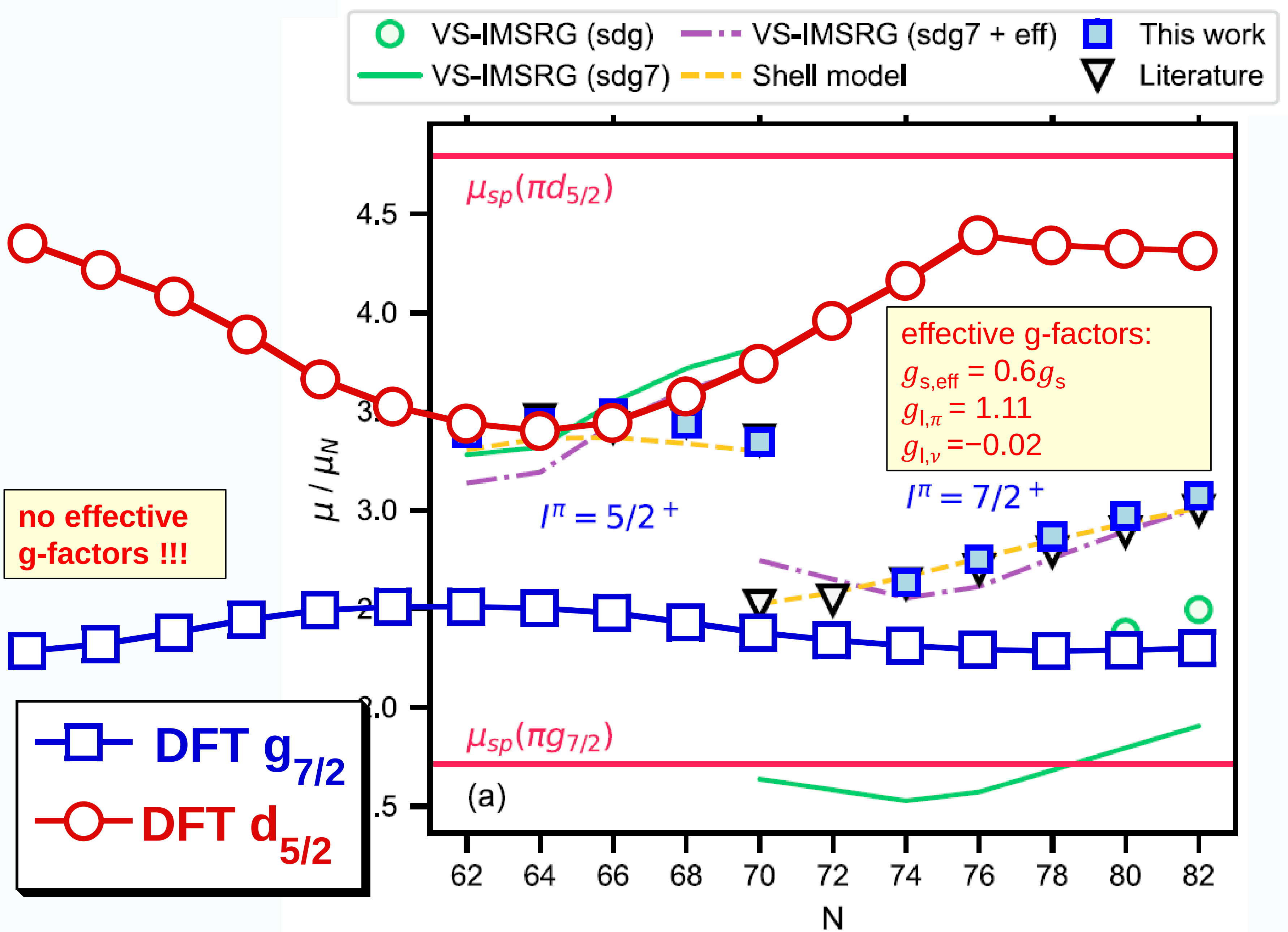
Magnetic dipole moments in Sb



S. Lechner *et al.*, Phys. Lett. B 847 (2023) 138278

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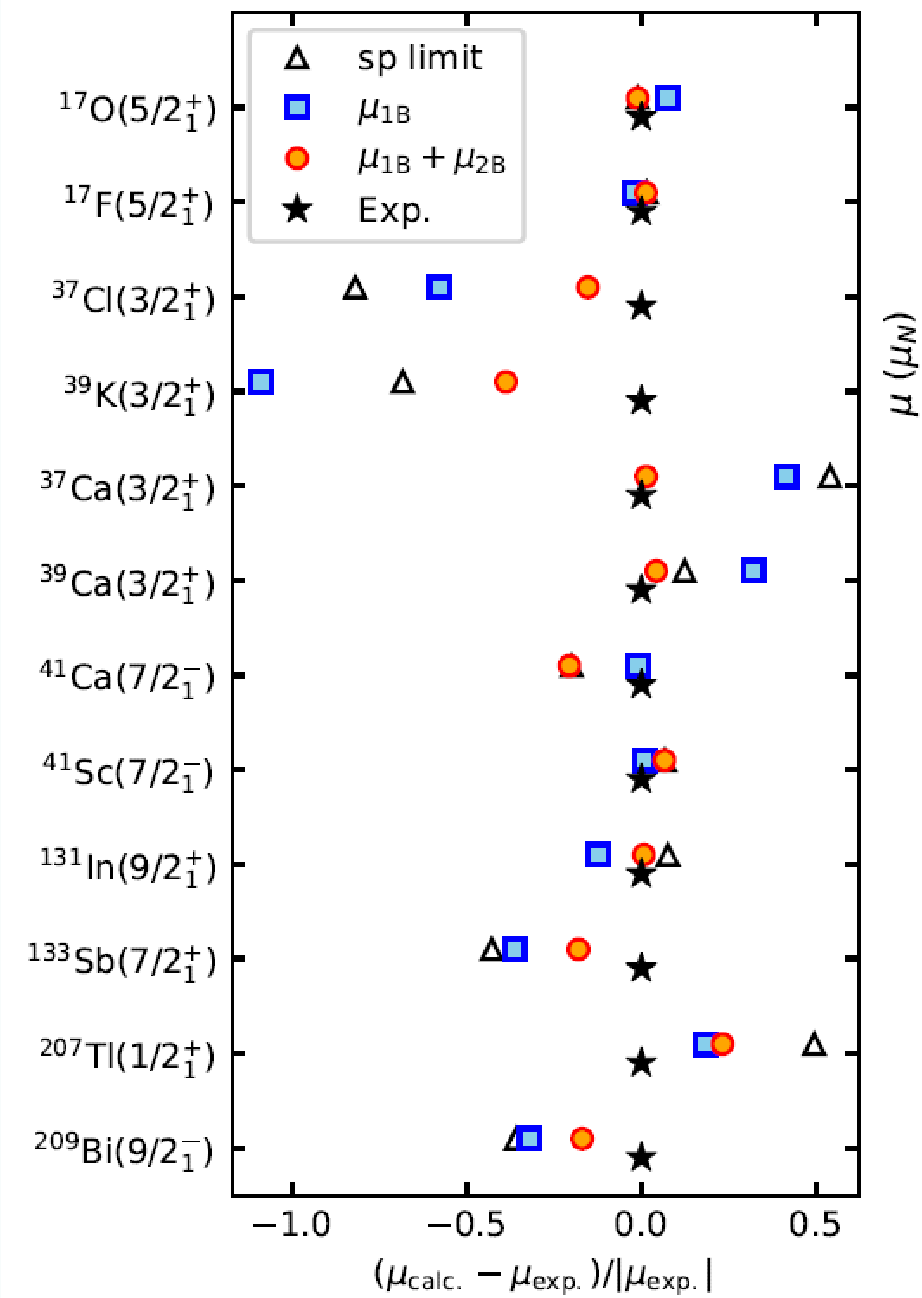
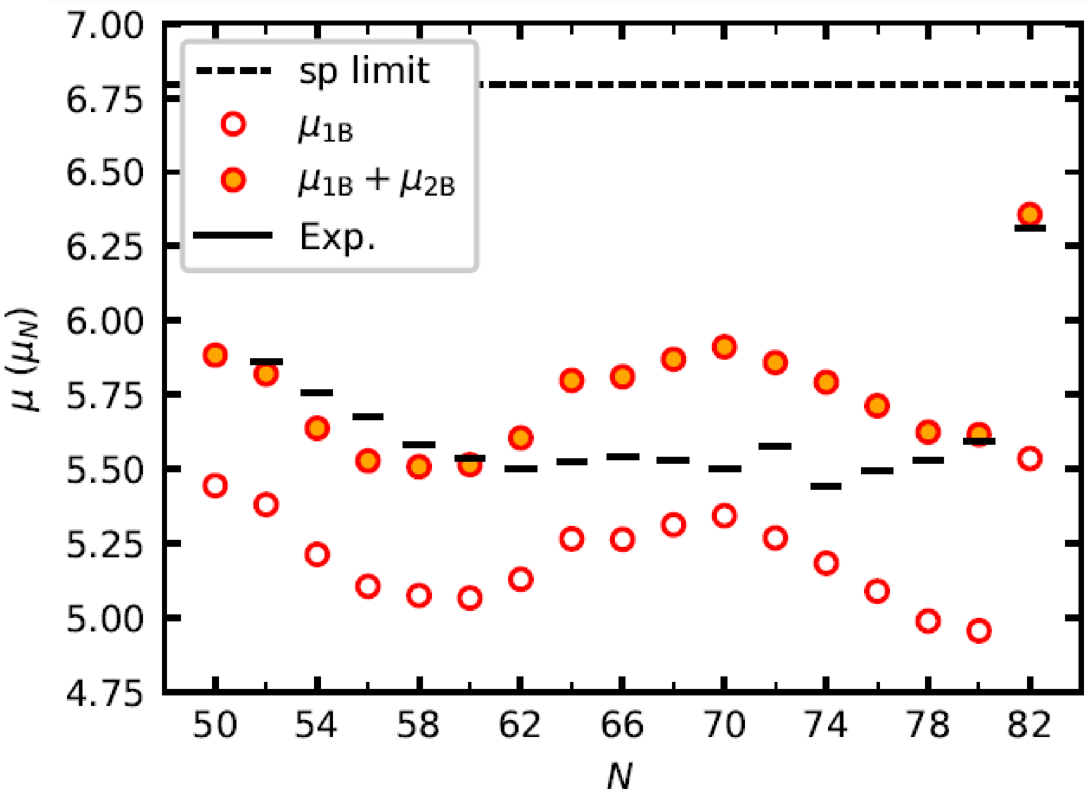
What’s next to consider	
Segré chart of electromagnetic moments	
Electromagnetic moments of odd-odd nuclei	★
More advanced functionals	★
Octupole deformation	
Triaxiality	★
Configuration interaction	
K-mixing	★★
Quadrupole/octupole collectivity	
Two-body meson-exchange currents	★★

Two-body-current corrections to magnetic moments





T. Miyagi *et al.*, arXiv:2311.14383

Thank you