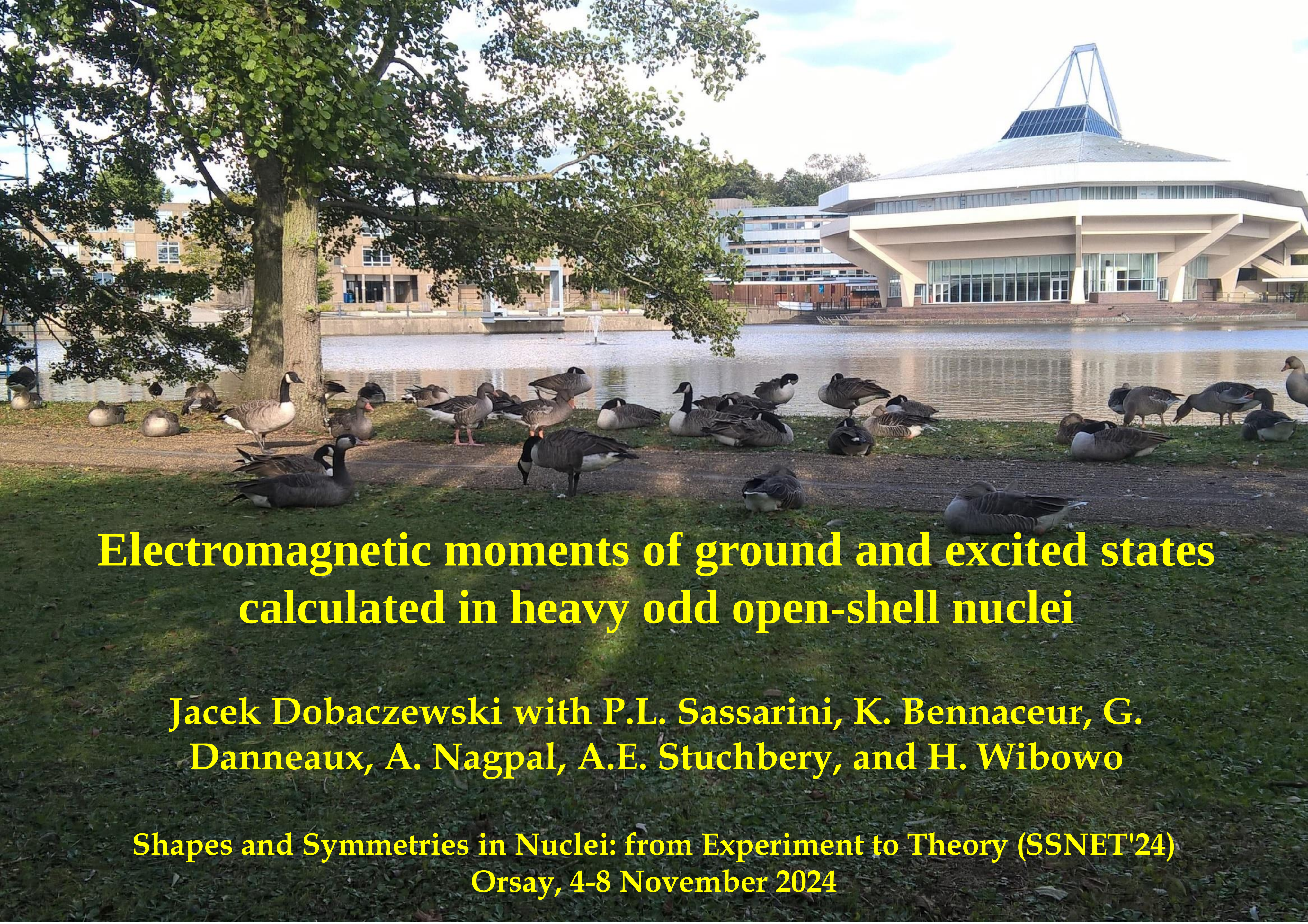


# Electromagnetic moments of ground and excited states calculated in heavy odd open-shell nuclei


**Jacek Dobaczewski with P.L. Sassarini, K. Bennaceur, G. Danneaux, A. Nagpal, A.E. Stuchbery, and H. Wibowo**

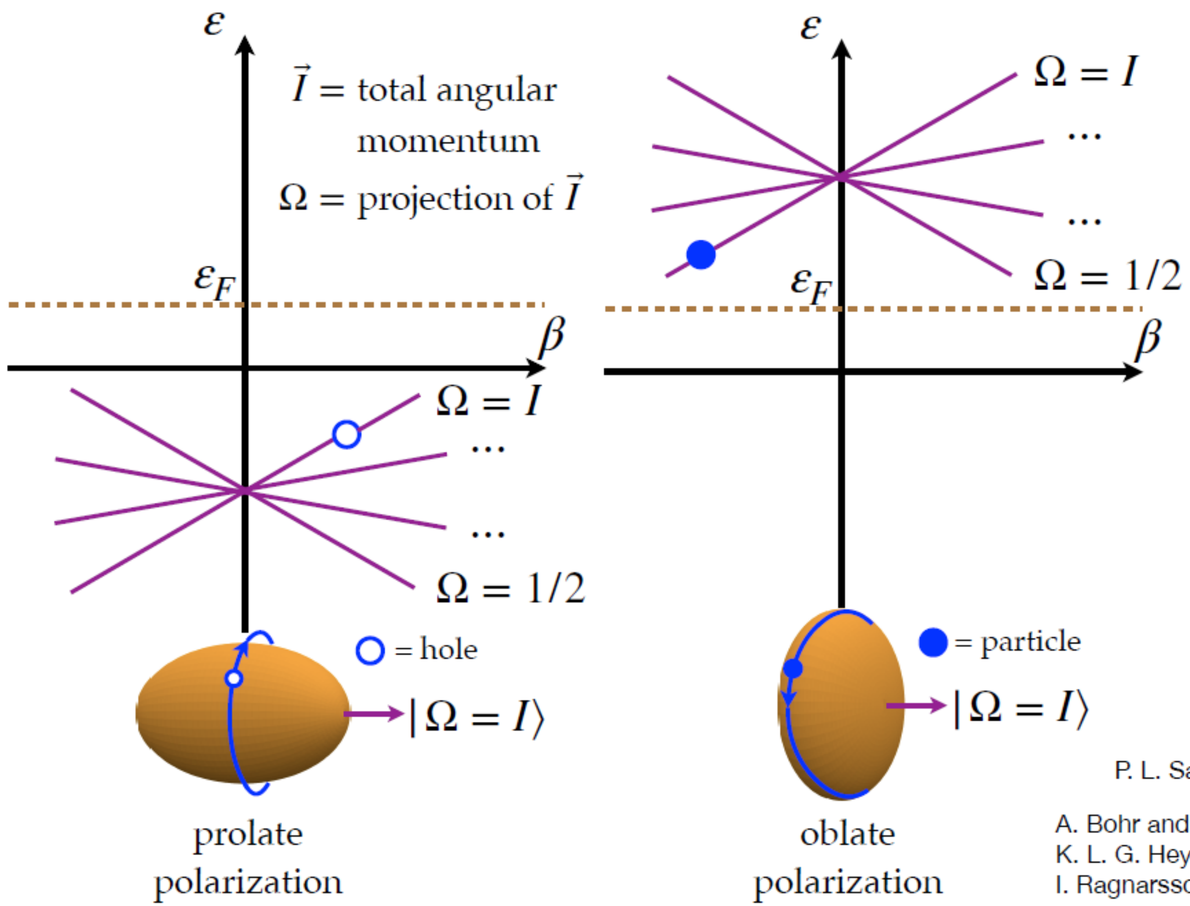


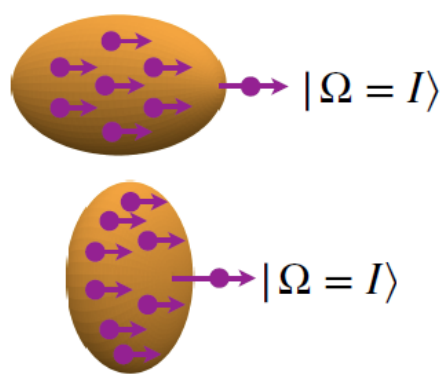
Shapes and Symmetries in Nuclei: from Experiment to Theory (SSNET'24)
Orsay, 4-8 November 2024


# Outline

1. Methodology
   a) Polarization
   b) Self-consistency
   c) Symmetry restoration
2. Excited quasiparticle states in odd-N open-shell isotopes from gadolinium to osmium
3. Conclusions

# Shape and spin polarization




Landau parameter $g_0'$ ($g_0' = 1.7$)

$$g_0' = N_0\left(2C_1^s + 2C_1^T(3\pi^2\rho_0/2)^{2/3}\right)$$

$$\frac{1}{N_0} \approx 150\frac{m}{m^*}\,\mathrm{MeV}\cdot\mathrm{fm}^3$$

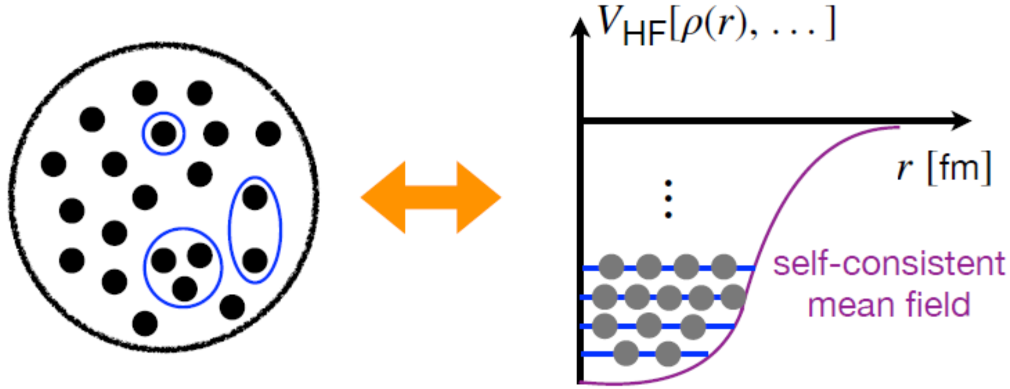
P. L. Sassarini et al., J. Phys. G: Nucl. Part. Phys. **49**, 11LT01 (2022)

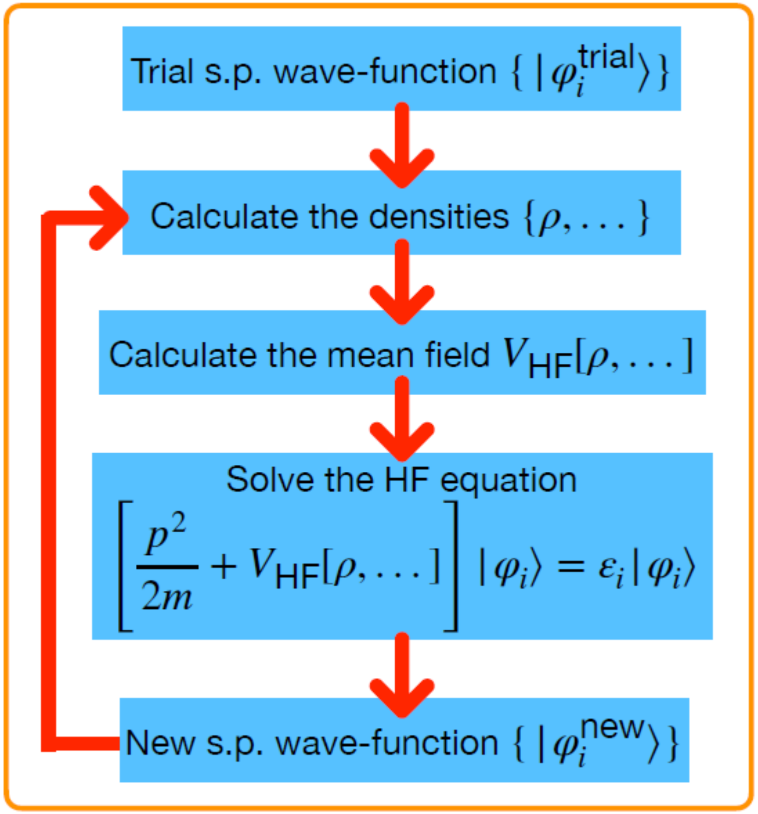
A. Bohr and B. R. Mottelson, *Nuclear Structure* Vol. 1
K. L. G. Heyde, *The Nuclear Shell Model*
I. Ragnarsson and S. G. Nilsson, *Shapes and Shells in Nuclear Structure*

**Picture courtesy of H. Wibowo**

**In nuclear-DFT, we align the total angular momenta of odd nuclei along the intrinsic axial-symmetry axis with broken spherical and time-reversal symmetries. We fully account for the self-consistent charge, spin, and current polarizations, in particular through the inclusion of the crucial time-odd mean-field components of the functional.**

# Nuclear density functional theory




Energy density functional

$\mathscr{E}[\rho(\mathrm{r}), \mathrm{s}(\mathrm{r}), \tau(\mathrm{r}), \mathrm{T}(\mathrm{r}), \mathrm{j}(\mathrm{r}), \overleftrightarrow{J}(\mathrm{r})]$

Coupling constants

$T\text{-even}: \; C_t^{\rho}, C_t^{\Delta\rho}, C_t^{\tau}, C_t^{J}, C_t^{\nabla J}$

$T\text{-odd}: \; C_t^{s}, C_t^{\Delta s}, C_t^{T}, C_t^{j}, C_t^{\nabla j}$

Parametrization: UNEDF1

Hartree-Fock (HF) equation

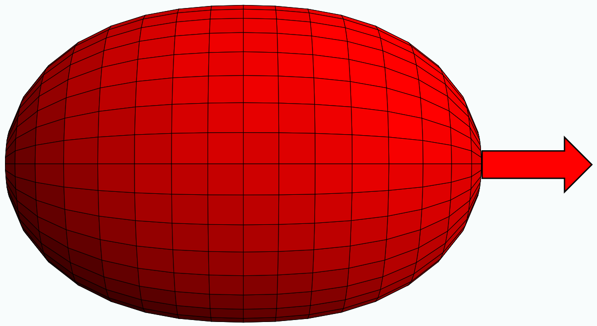
M. Kortelainen et al., Phys. Rev. C **85**, 024304 (2012)

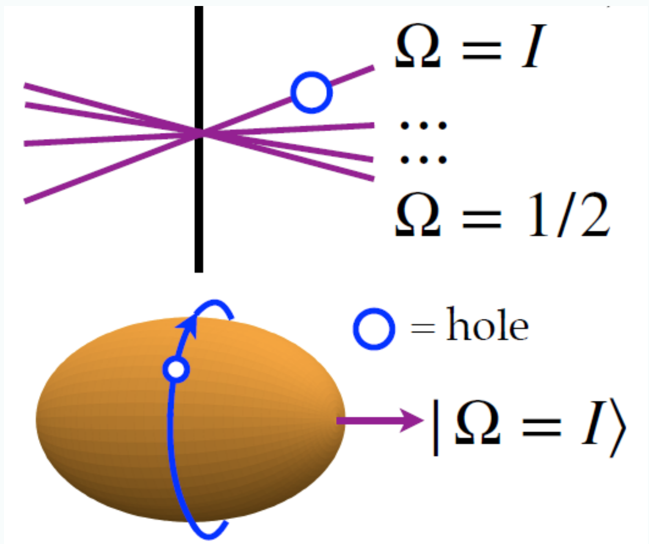
Picture courtesy of H. Wibowo

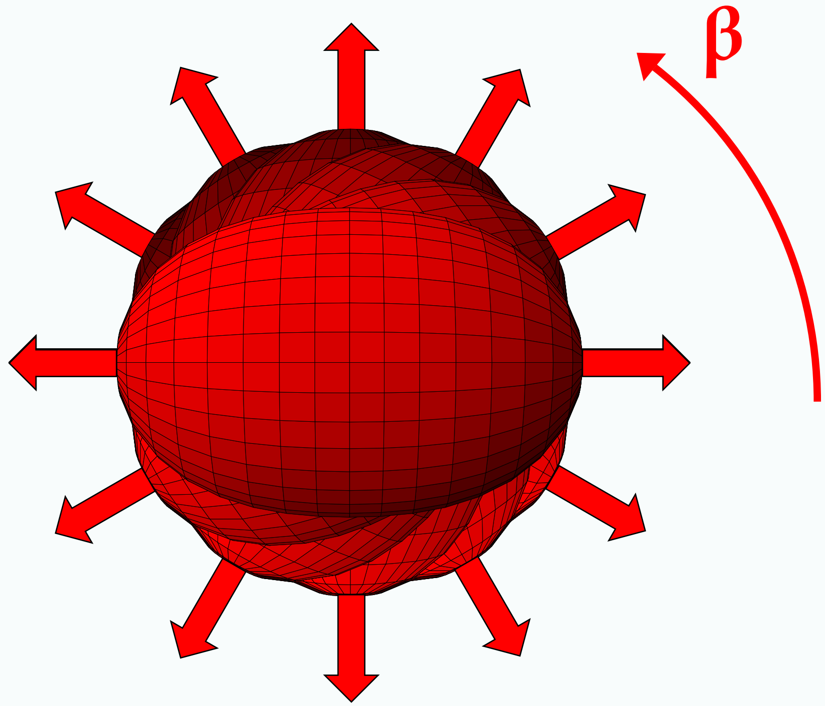
**Self-consistent equations are solved iteratively, which includes the polarization effects summed up to all orders without recurring to the lowest order perturbative coupling.**

# Time-odd spin alignment & symmetry restoration

“Intrinsic”
Symmetry broken





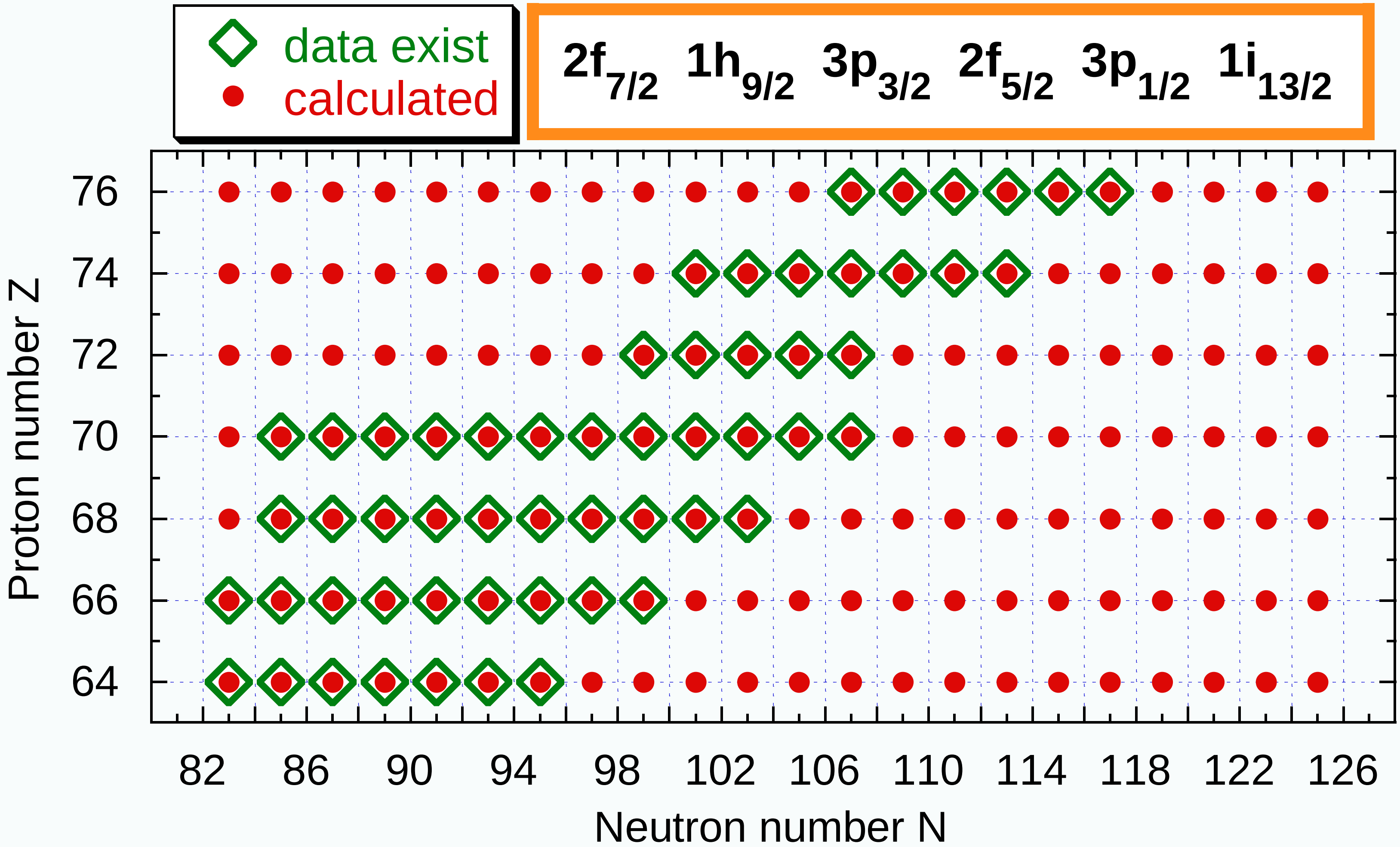

“Laboratory”
Symmetry restored

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

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

**Spectroscopic moments are determined for symmetry-restored wave functions without using effective charges or effective g-factors and compared with experimental data.**

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




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

**Standard UNEDF1 nuclear functional used, no parameters (re)adjusted in this work**

**81 measured magnetic dipole moments (plus 3 rotational bands)**

**53 measured electric quadrupole moments (plus 3 rotational bands)**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UNIVERSITY of York



Science & Technology Facilities Council
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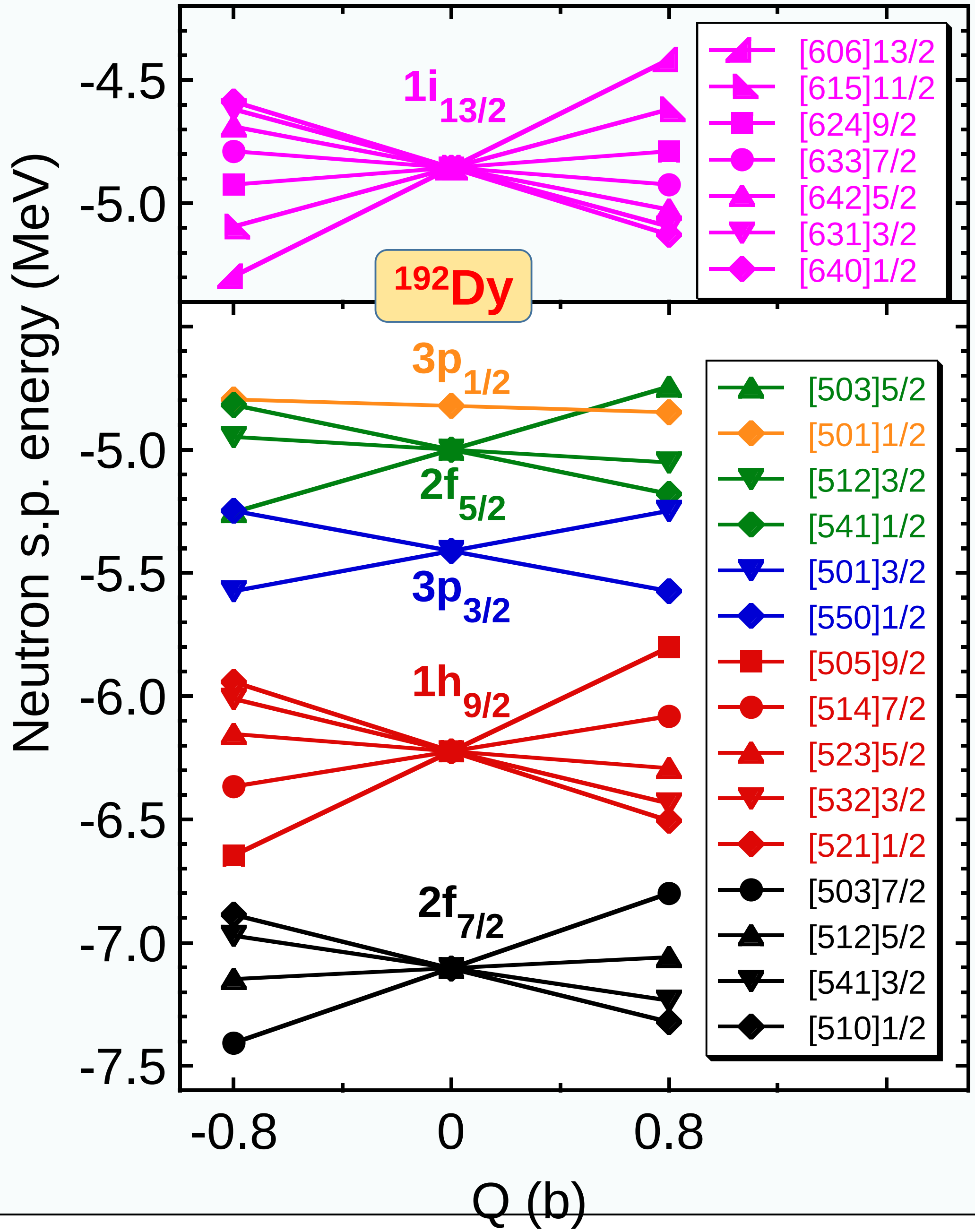
# How to calculate odd nuclei in nuclear DFT?




## 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

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

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

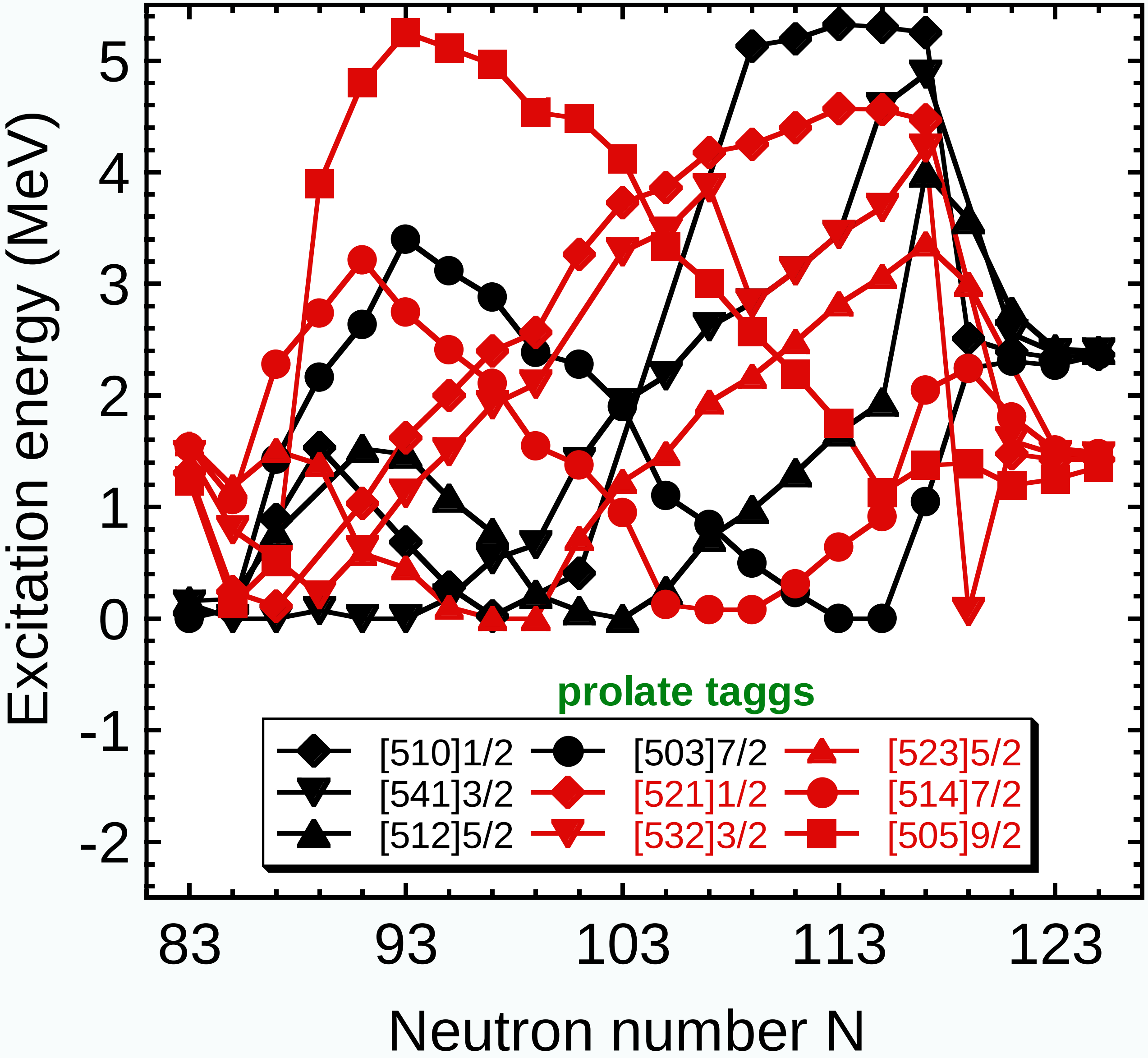
$$= a^+_\nu \prod_{\nu \neq \mu > 0} \left(u_\mu + v_\mu a^+_{\bar{\mu}} a^+_\mu\right) |0\rangle$$

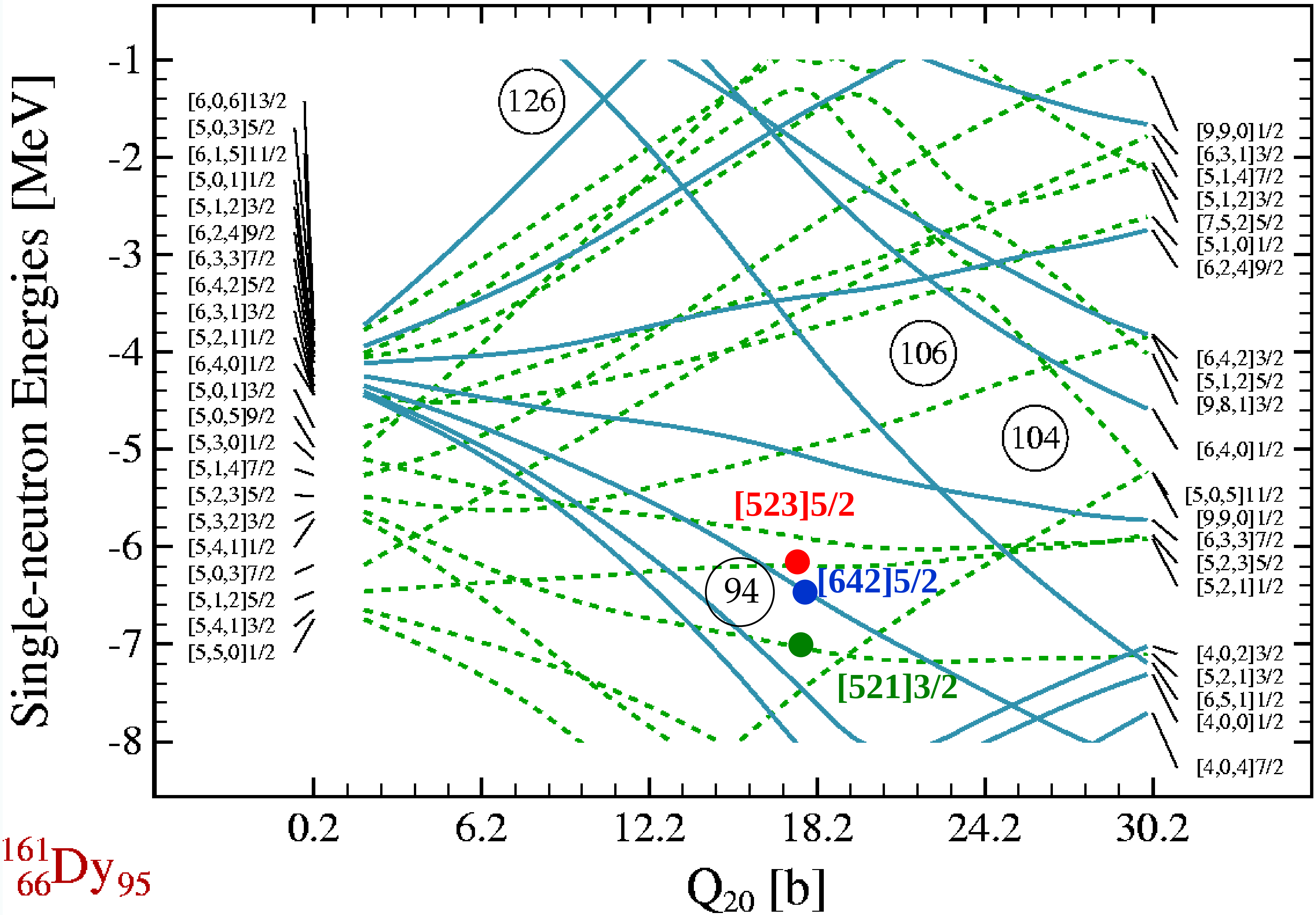
## tagging quasiparticle states

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

Jacek Dobaczewski
University of York

# Excitation energies of odd dysprosium isotopes

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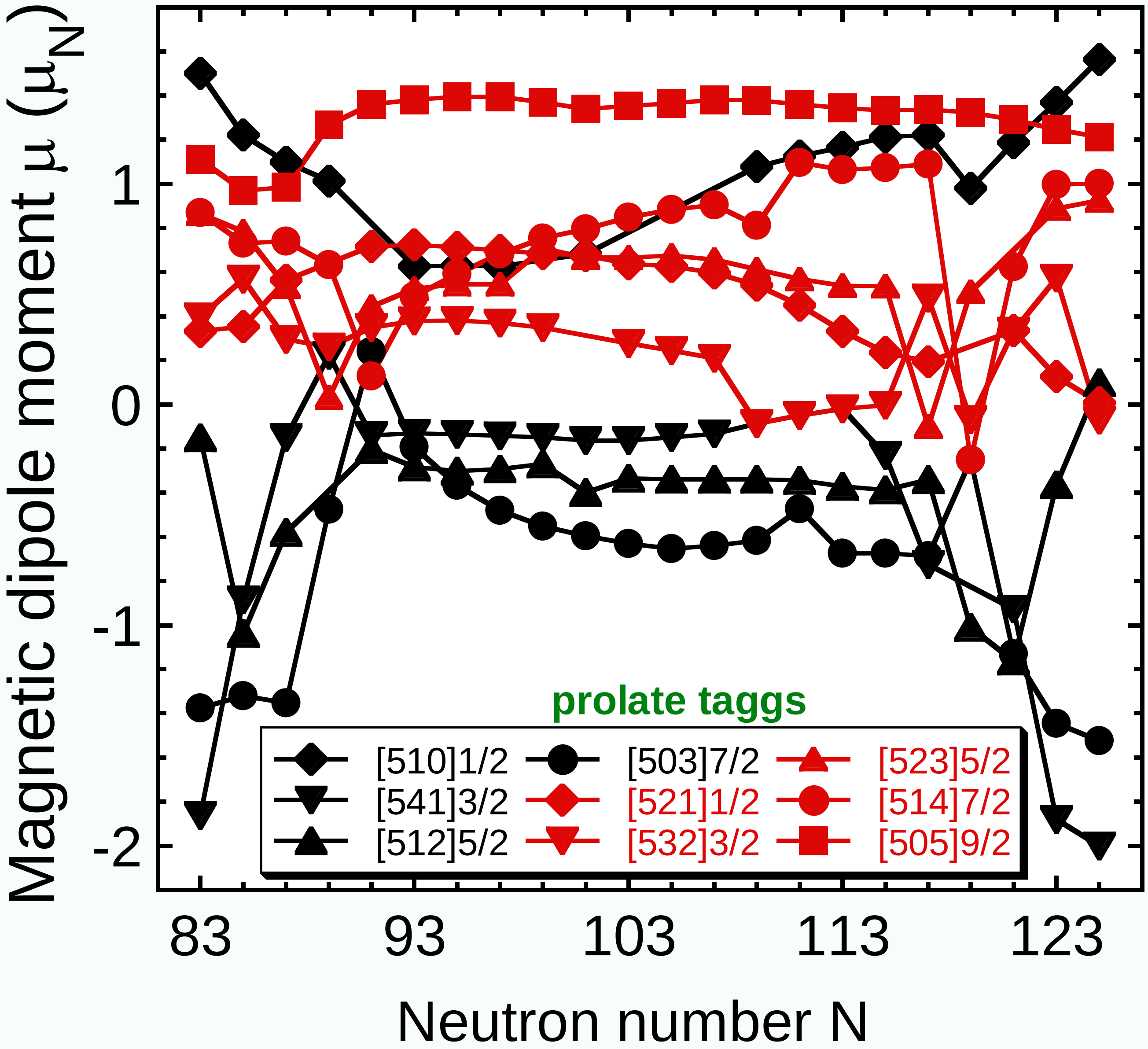
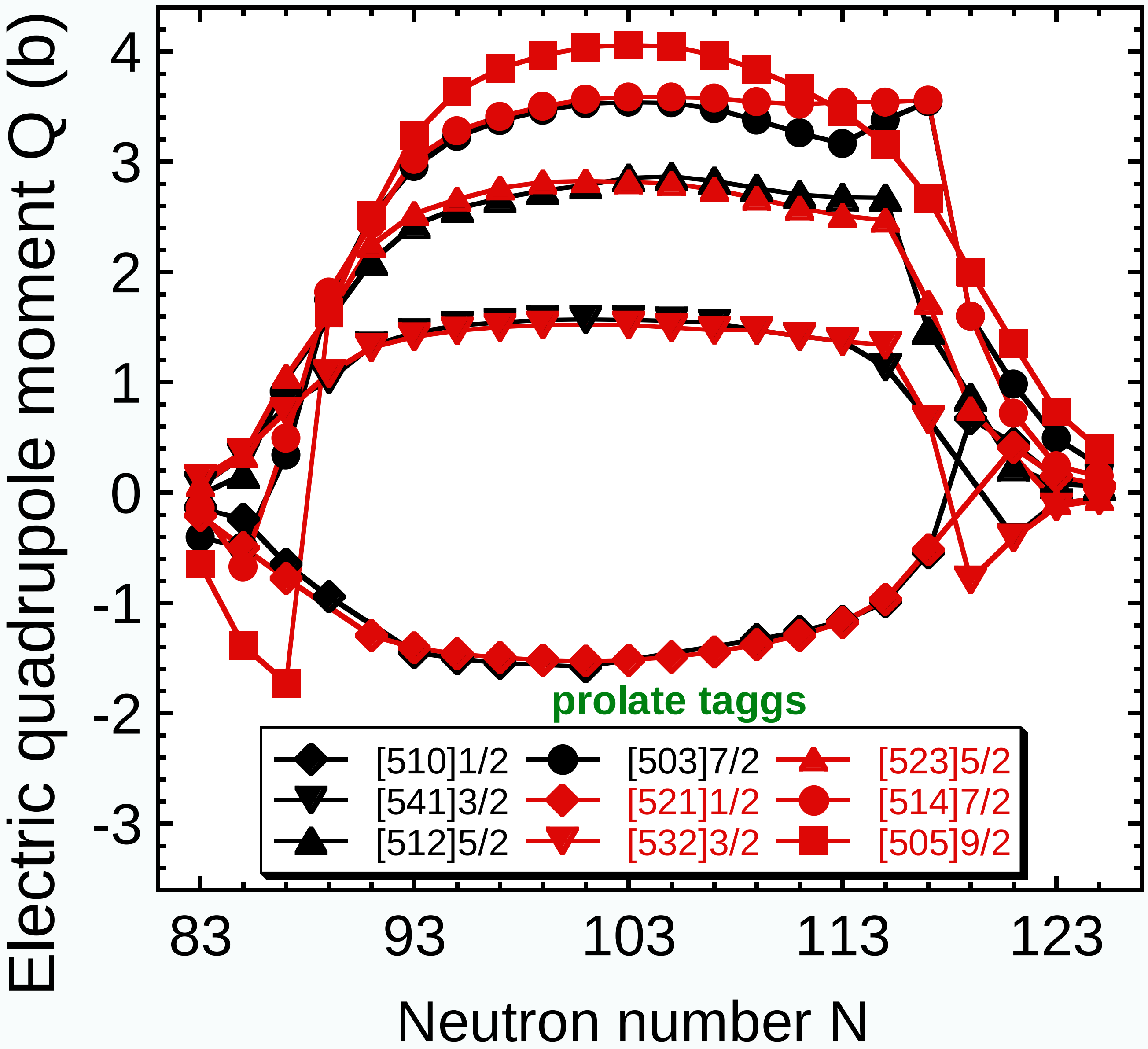
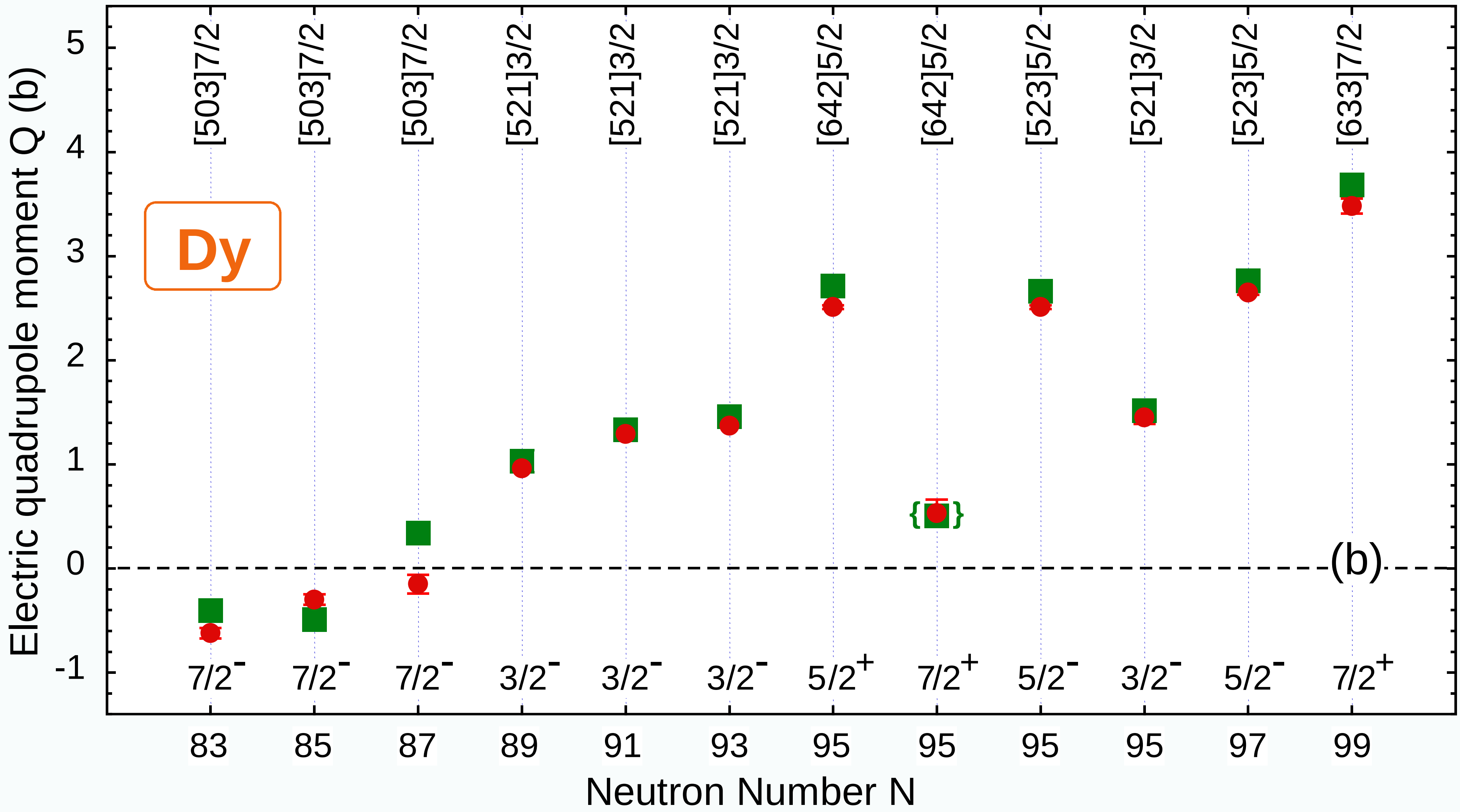
# Magnetic moments of odd dysprosium isotopes



# Electric moments of odd dysprosium isotopes



# Dysprosium electric moments vs. data





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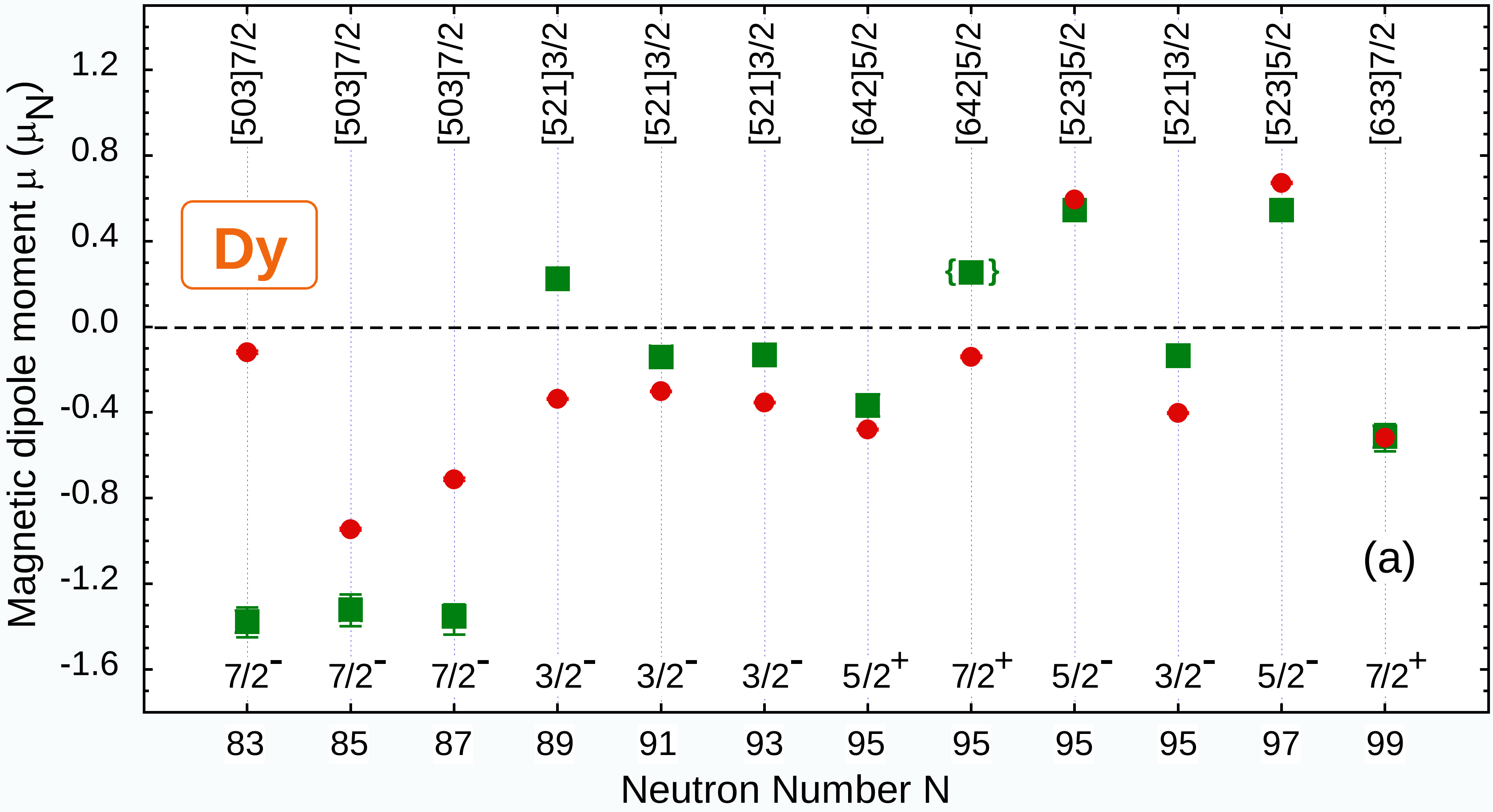
# Dysprosium magnetic moments vs. data

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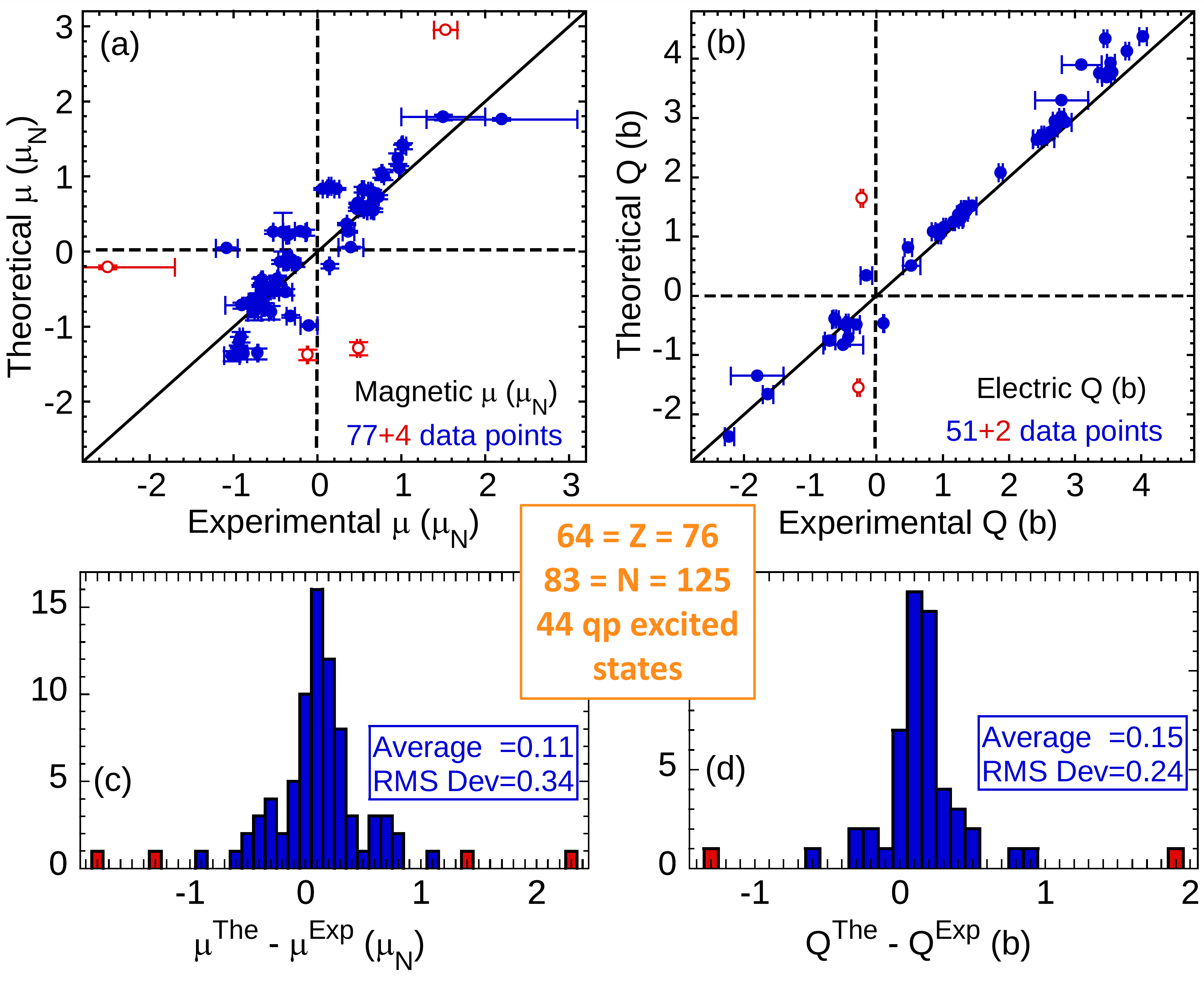
# Summary of results obtained in the Gd – Os isotopes




64 = Z = 76
83 = N = 125
44 qp excited states

# Conclusions

1. For the first time, in the nuclear theory, we can systematically **calculate spectroscopic electromagnetic moments** in odd open-shell nuclei with arbitrary particle numbers and (axial) deformations.
2. Large nuclear-DFT single-particle phase space (well beyond the valence space) allows for using the **bare effective charges** and **g-factors**. (No adjustable "effective" values are needed.)
3. The calculated **magnetic dipole moments μ** and **electric quadrupole moments Q** reproduce the known experimental data in odd-N open-shell isotopes of Gd-Os.
4. It is essential to **simultaneously** take into account:
   a) Polarization
   b) Self-consistency
   c) Symmetry restoration
5. The effects of the extended T-odd sector, triaxiality, octupolarity, two-body currents, K-mixing, and configuration interaction (…) **remain to be studied**.

# Thank you