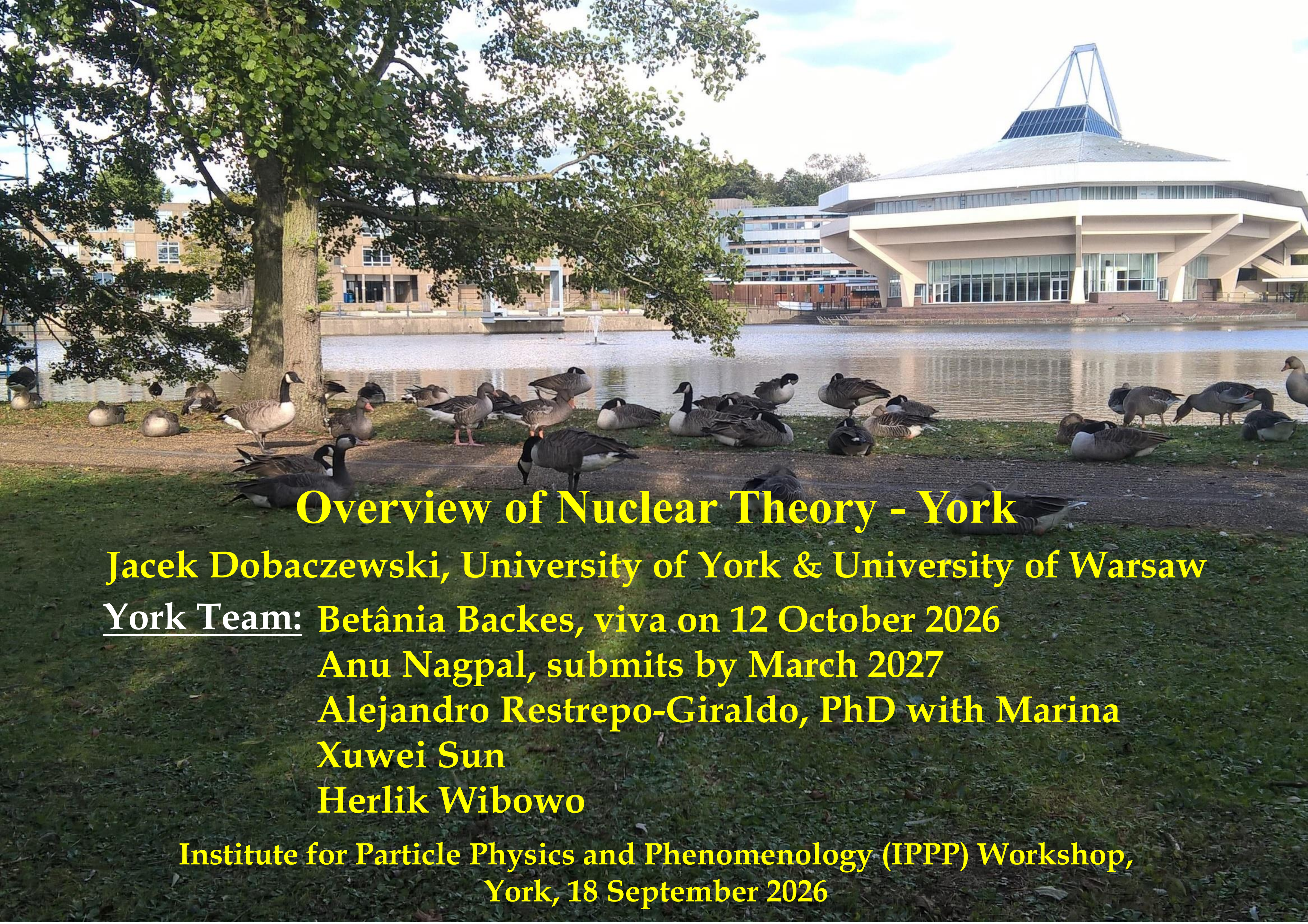

Overview of Nuclear Theory - York

Jacek Dobaczewski, University of York & University of Warsaw

York Team: Betânia Backes, viva on 12 October 2026
Anu Nagpal, submits by March 2027
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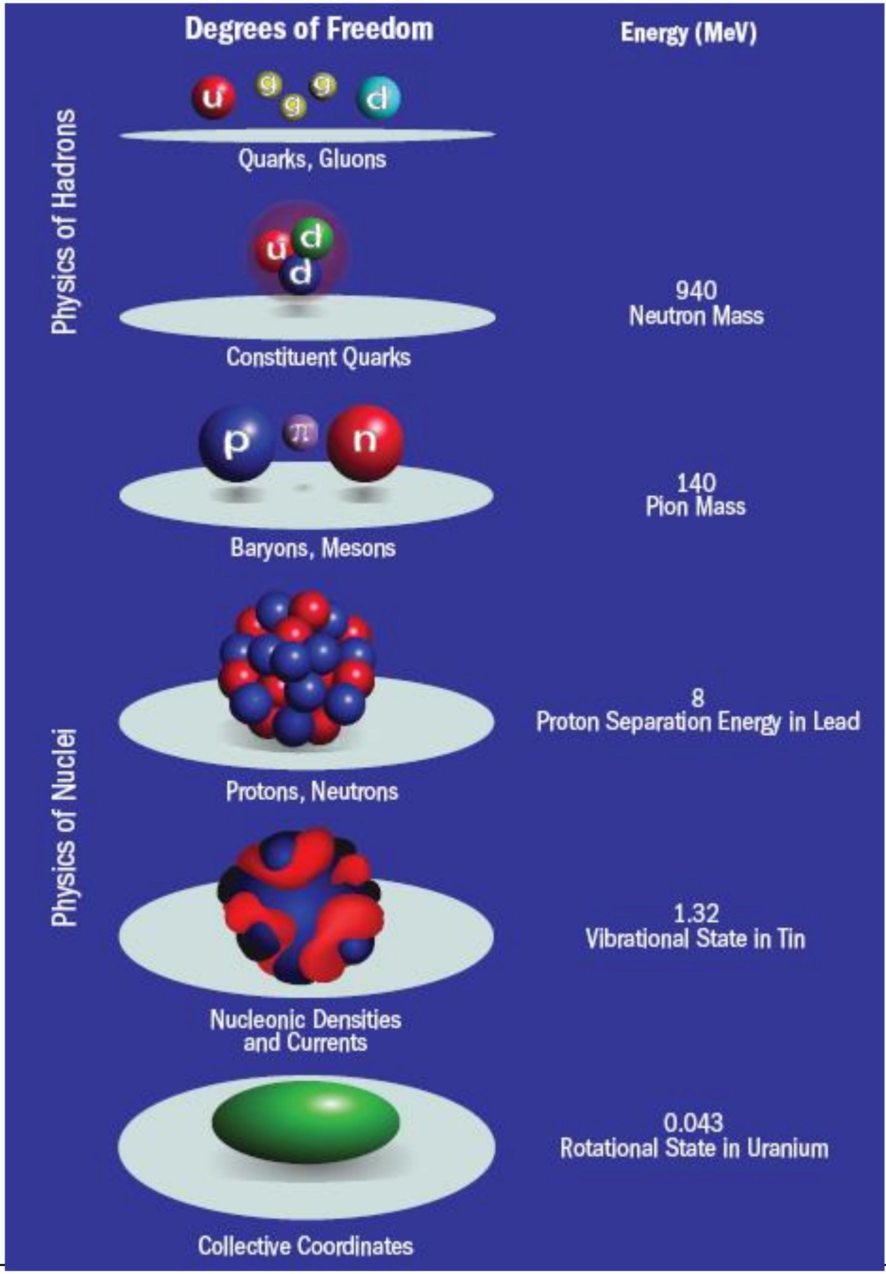
Institute for Particle Physics and Phenomenology (IPPP) Workshop,
York, 18 September 2026

Outline

1. Energy scales in nuclear physics
2. Nuclear density functional theory (DFT)
3. Symmetry restoration
4. Electromagnetic moments in nuclear DFT
5. Radiative decay and electromagnetic moments in ^{229}Th
6. Coulomb energies in ^{229}Th
7. Meson exchange currents in nuclear DFT
8. Electric dipole moments (EDM)
9. Anapole moments
10. Self-interaction in nuclear DFT
11. Multipole tomography of atomic nuclei
12. Conclusions

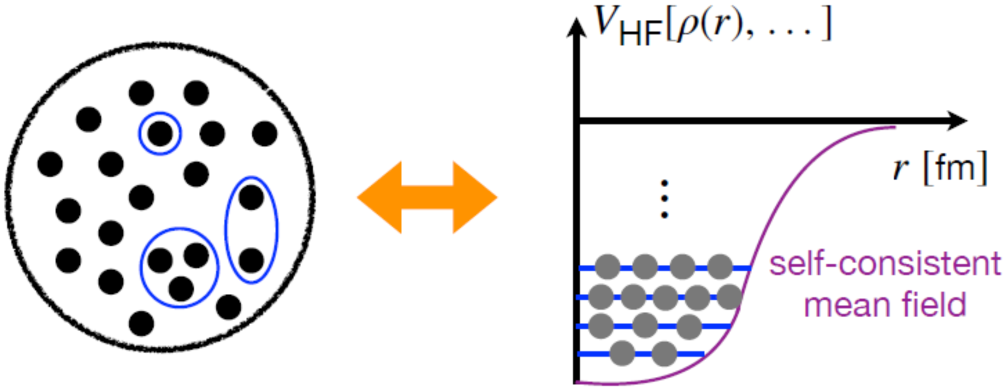
Energy scales in nuclear physics

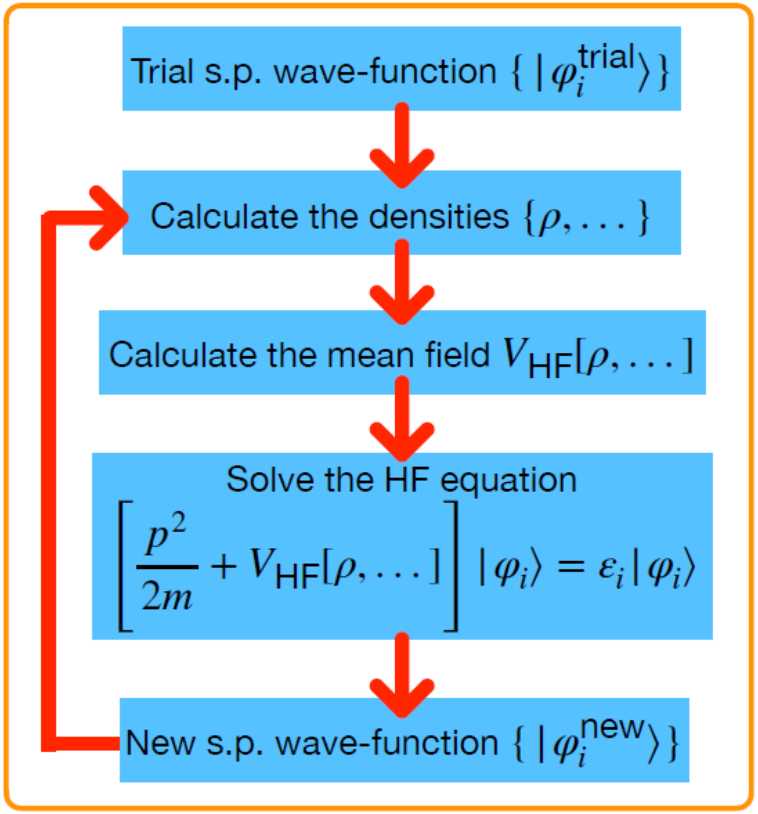
G. Bertsch *et al.*, SciDAC Review 6, 42 (2007)



Nuclear Structure

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.

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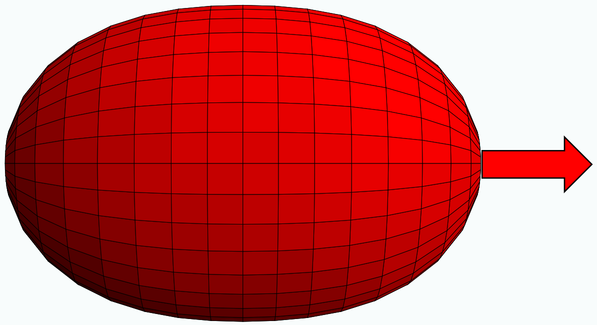
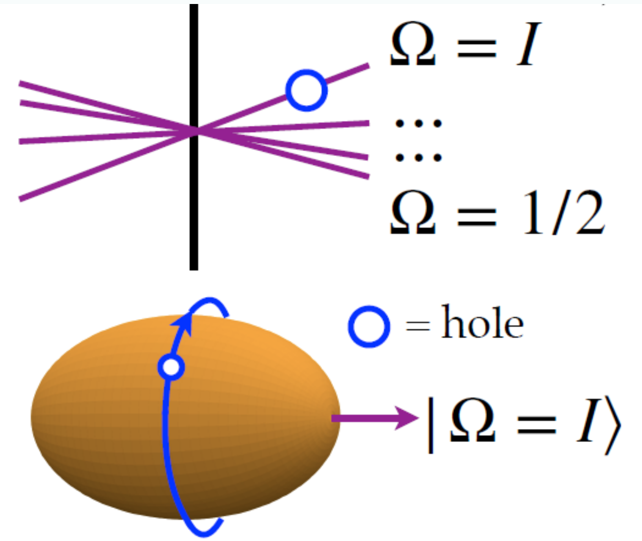
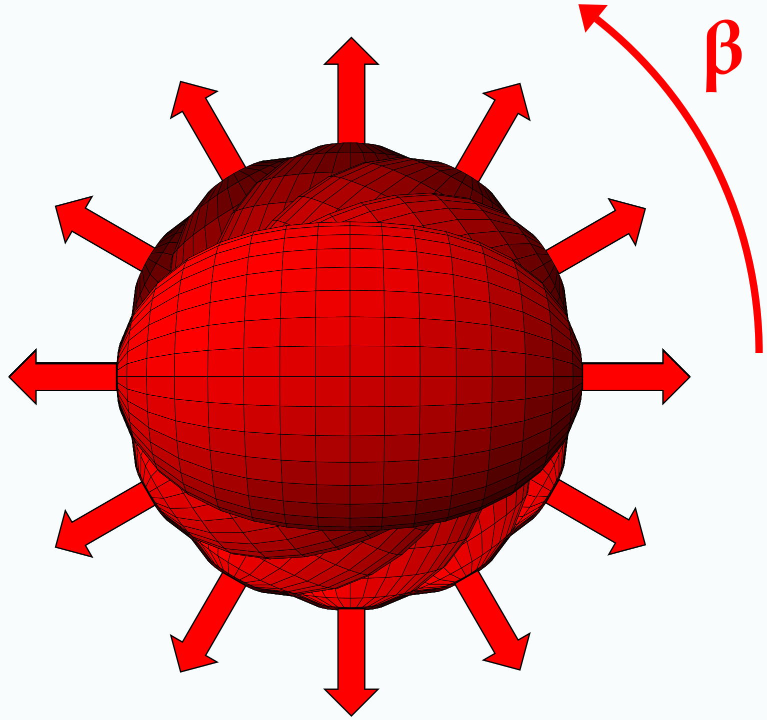
Symmetry restoration

“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.

Electromagnetic moments in nuclear DFT

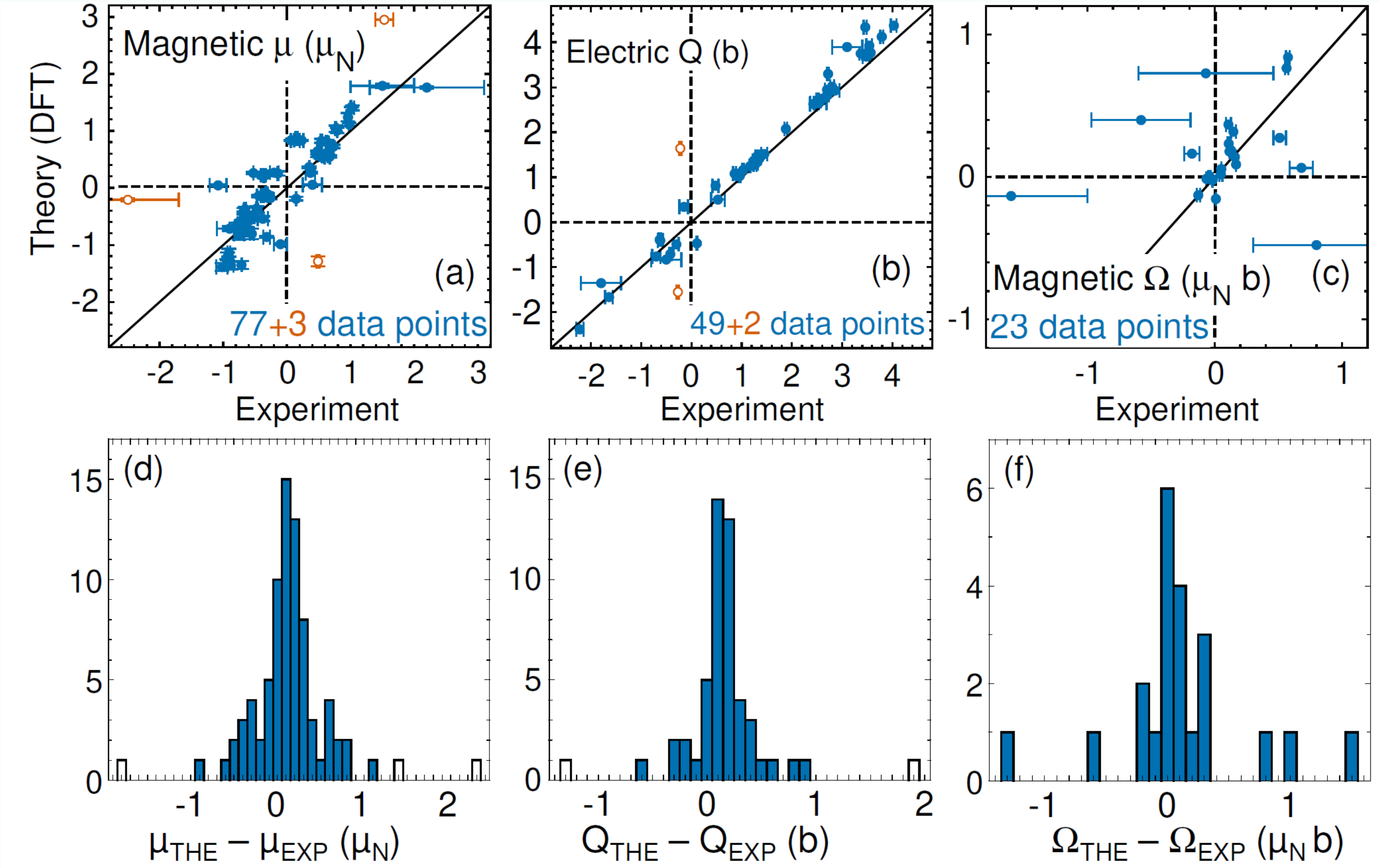
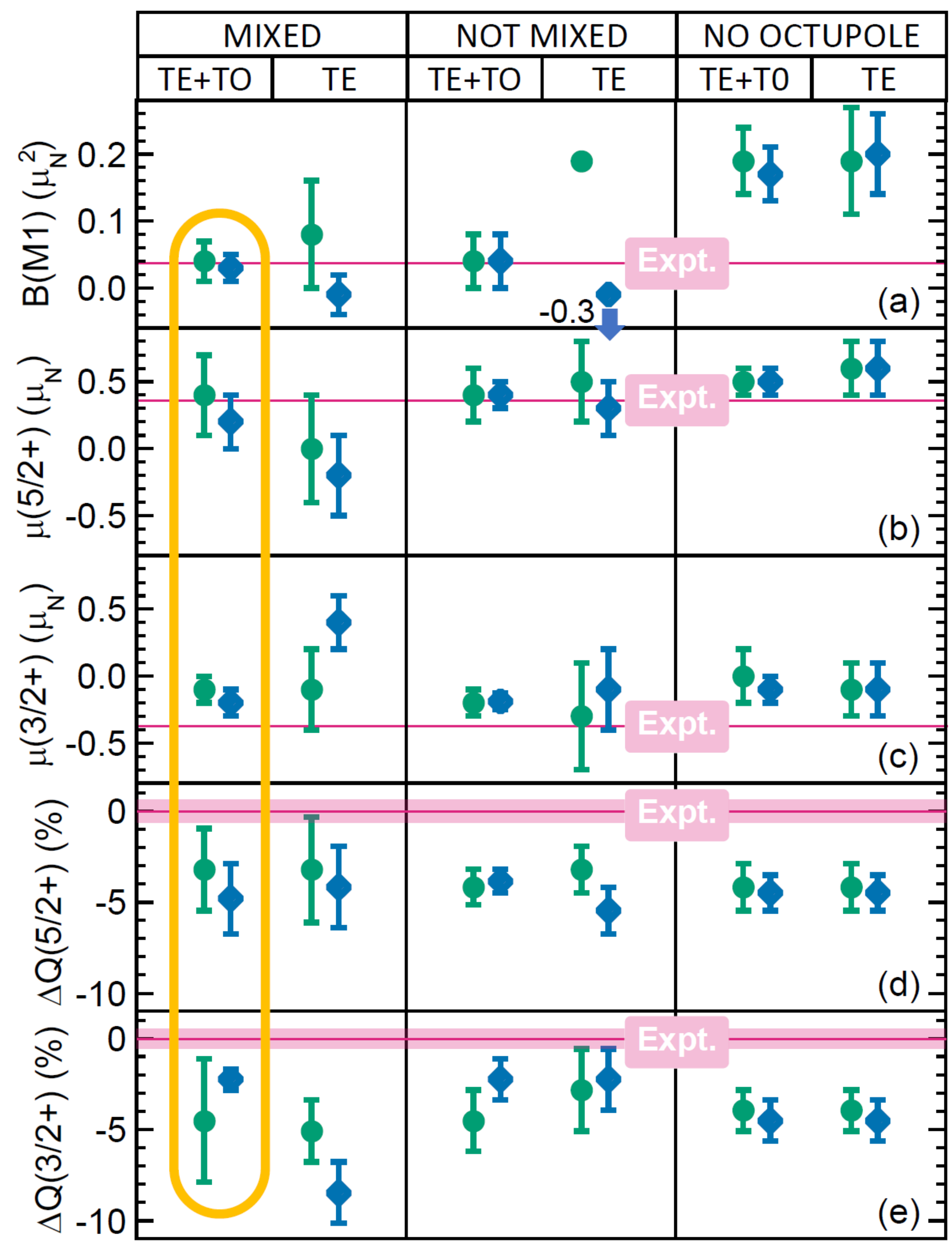


Figure 6: Summary comparison of the experimental and theoretical DFT magnetic dipole moments μ, (a) and (d), electric quadrupole moments Q, (b) and (e), in odd-N, even-Z isotopes between gadolinium and osmium (panels adapted from Reference (67). Panels (c) and (f) show the analogous comparison of the magnetic octupole moments Ω across the mass chart. Open symbols and bars denote the outliers, see text.

J. Dobaczewski *et al.*, arXiv:2511.04632

Radiative decay and electromagnetic moments in ^{229}Th

We determined the magnetic dipole transition strength B(M1:3/2+→5/2+) between the isomeric and ground states of ^{229}Th and discussed the effects of parity breaking, configuration mixing, and time-odd core polarization. Without parameter adjustment, the obtained results favorably compare with the experimental data but also indicate the need to systematically adjust the octupole degrees of freedom in future functional parametrizations.



A. Restrepo-Giraldo *et al.*, to be published

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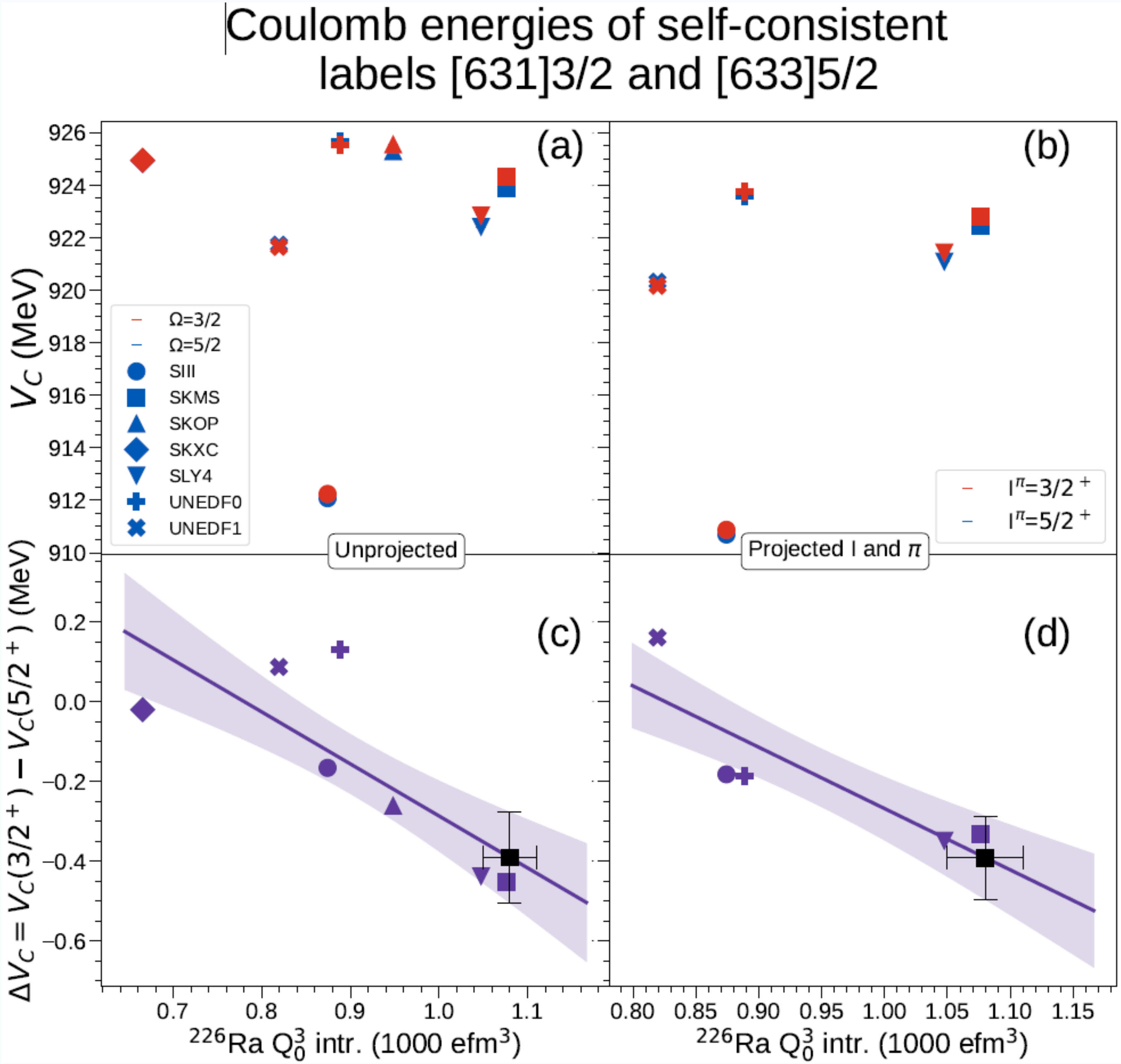
Coulomb energies in ^{229}Th



A. Restrepo-Giraldo *et al.*, to be published

Meson exchange currents in nuclear DFT

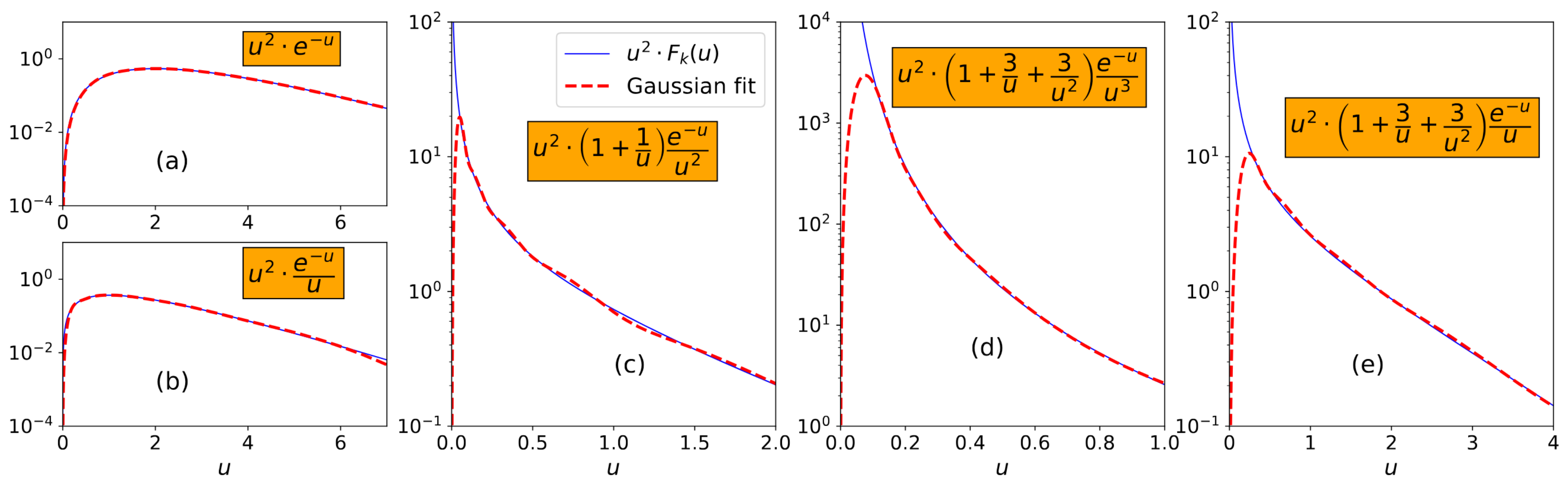
The two-body operator (40) has two terms, called the intrinsic term,

$$\hat{\boldsymbol{\mu}}_{2\mathrm{b}}^{\mathrm{int}}(\boldsymbol{r}_1,\boldsymbol{r}_2) = -\frac{g_A^2 m_\pi}{32\pi F_\pi^2}(\hat{\boldsymbol{\tau}}_1\times\hat{\boldsymbol{\tau}}_2)_z\left\{\left(1+\frac{1}{u}\right)\left[(\hat{\boldsymbol{\sigma}}_1\times\hat{\boldsymbol{\sigma}}_2)\cdot\hat{\boldsymbol{r}}\right]\hat{\boldsymbol{r}} - (\hat{\boldsymbol{\sigma}}_1\times\hat{\boldsymbol{\sigma}}_2)\right\}e^{-u},$$

and the Sachs term,

$$\hat{\boldsymbol{\mu}}_{2\mathrm{b}}^{\mathrm{Sachs}}(\boldsymbol{r}_1,\boldsymbol{r}_2) = -\frac{m_\pi^3 g_A^2}{96\pi F_\pi^2}(\hat{\boldsymbol{\tau}}_1\times\hat{\boldsymbol{\tau}}_2)_z(\boldsymbol{R}\times\boldsymbol{r})\left[\hat{S}_{12}\left(1+\frac{3}{u}+\frac{3}{u^2}\right)+\hat{\boldsymbol{\sigma}}_1\cdot\hat{\boldsymbol{\sigma}}_2\right]\frac{e^{-u}}{u}.$$

R. Seutin *et al.* Phys. Rev. C 108 (2023) 054005; T. Miyagi *et al.* Phys. Rev. Lett. 132 (2024) 232503



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

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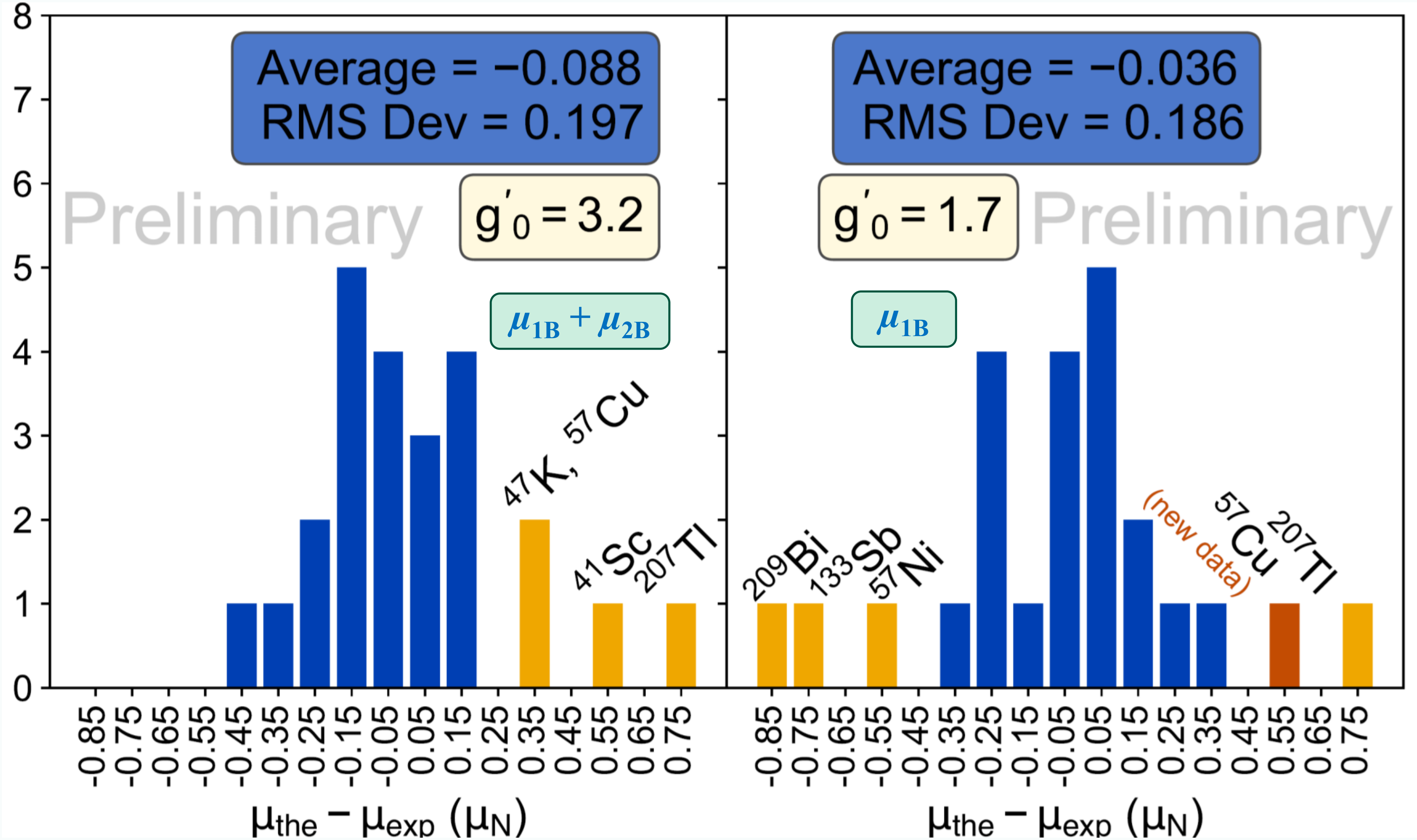
Meson exchange currents in nuclear DFT



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

Electric dipole moments in nuclear DFT

The nuclear Schiff operator is defined as follows,

$$\hat{S}_z = \frac{e}{10}\sum_p \left(r_p^2 - \frac{5}{3}\langle r^2\rangle_{\mathbf{ch}}\right) z_p \qquad 1.$$

The laboratory Schiff moment, S_z^{lab}, is determined using second-order perturbation theory,

$$S_z^{\mathrm{lab}} \approx \sum_{i\neq 0} \frac{\langle\Psi_0|\hat{S}_z|\Psi_i\rangle\langle\Psi_i|\hat{V}_{\mathbf{PT}}|\Psi_0\rangle}{E_0 - E_i} + \mathbf{c.c.}, \qquad 2.$$

where $|\Psi_0\rangle$ is the ground state and the sum is over excited states. The P,T-violating NN interaction, $\hat{V}_{\mathbf{PT}}$ reads as follows,

$$\begin{aligned}\hat{V}_{\mathbf{PT}}(\boldsymbol{r}_1 - \boldsymbol{r}_2) = &-\frac{g m_\pi^2}{8\pi m_N}\Big\{(\hat{\boldsymbol{\sigma}}_1 - \hat{\boldsymbol{\sigma}}_2)\cdot(\boldsymbol{r}_1 - \boldsymbol{r}_2)\Big[\bar{g}_0 \hat{\vec{\tau}}_1\cdot\hat{\vec{\tau}}_2 - \frac{\bar{g}_1}{2}(\hat{\tau}_{1z} + \hat{\tau}_{2z}) + \\ &+ \bar{g}_2(3\hat{\tau}_{1z}\hat{\tau}_{2z} - \hat{\vec{\tau}}_1\cdot\hat{\vec{\tau}}_2)\Big] - \frac{\bar{g}_1}{2}(\hat{\boldsymbol{\sigma}}_1 + \hat{\boldsymbol{\sigma}}_2)\cdot(\boldsymbol{r}_1 - \boldsymbol{r}_2)(\hat{\tau}_{1z} - \hat{\tau}_{2z})\Big\} \\ &\times \frac{e^{-m_\pi r}}{m_\pi r^2}\left[1 + \frac{1}{m_\pi r}\right] + \frac{1}{2m_N^3}\left[\bar{c}_1 + \bar{c}_2\hat{\vec{\tau}}_1\cdot\hat{\vec{\tau}}_2\right](\hat{\boldsymbol{\sigma}}_1 - \hat{\boldsymbol{\sigma}}_2)\cdot\boldsymbol{\nabla}\delta^3(\boldsymbol{r}_1 - \boldsymbol{r}_2). \qquad 3.\end{aligned}$$

The linearity of $\hat{V}_{\mathbf{PT}}$ allows us to express the laboratory Schiff moment, S_z^{lab}, as a linear combination of the unknown coupling constants with the coefficients calculated in DFT, that is,

$$S_z^{\mathrm{lab}} = a_0 g\bar{g}_0 + a_1 g\bar{g}_1 + a_2 g\bar{g}_2 + b_1\bar{c}_1 + b_2\bar{c}_2. \qquad 4.$$

M. Athanasakis-Kaklamanakis ,…, H. Wibowo *et al.*, Nature 648, 562 (2025)

Our results highlight the potential of ^{227}AcF for exceptionally sensitive searches of CP violation.

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Anapole moments in nuclear DFT

The nuclear anapole operator is the lowest-order parity non-conservation (PNC), time-reversal-odd multipole operator defined by Haxton, Liu, and Ramsey-Musolf as follows,

$$\hat{a}_\eta = -\frac{M^2}{9}\int \mathrm{d}^3\boldsymbol{r}\, r^2 \left[\hat{j}_\eta(\boldsymbol{r}) + \sqrt{2\pi}\left[Y_2(\theta,\phi)\otimes\hat{\boldsymbol{j}}(\boldsymbol{r})\right]_{1\eta}\right], \qquad 5.$$

Analogous to the laboratory Schiff moment, S_z^{lab}, the laboratory anapole moment is

$$a_z^{\mathrm{lab}} \approx \sum_{i\neq 0}\frac{\langle\Psi_0|\hat{a}_z|\Psi_i\rangle\langle\Psi_i|\hat{V}_{\mathrm{PNC}}|\Psi_0\rangle}{E_0-E_i} + \mathbf{c.c.}, \qquad 6.$$

where $\hat{V}_{\mathrm{PNC}}$ is used in the form of the Desplanques Donoghue, and Holstein (DDH) potential, and has the form as follows,

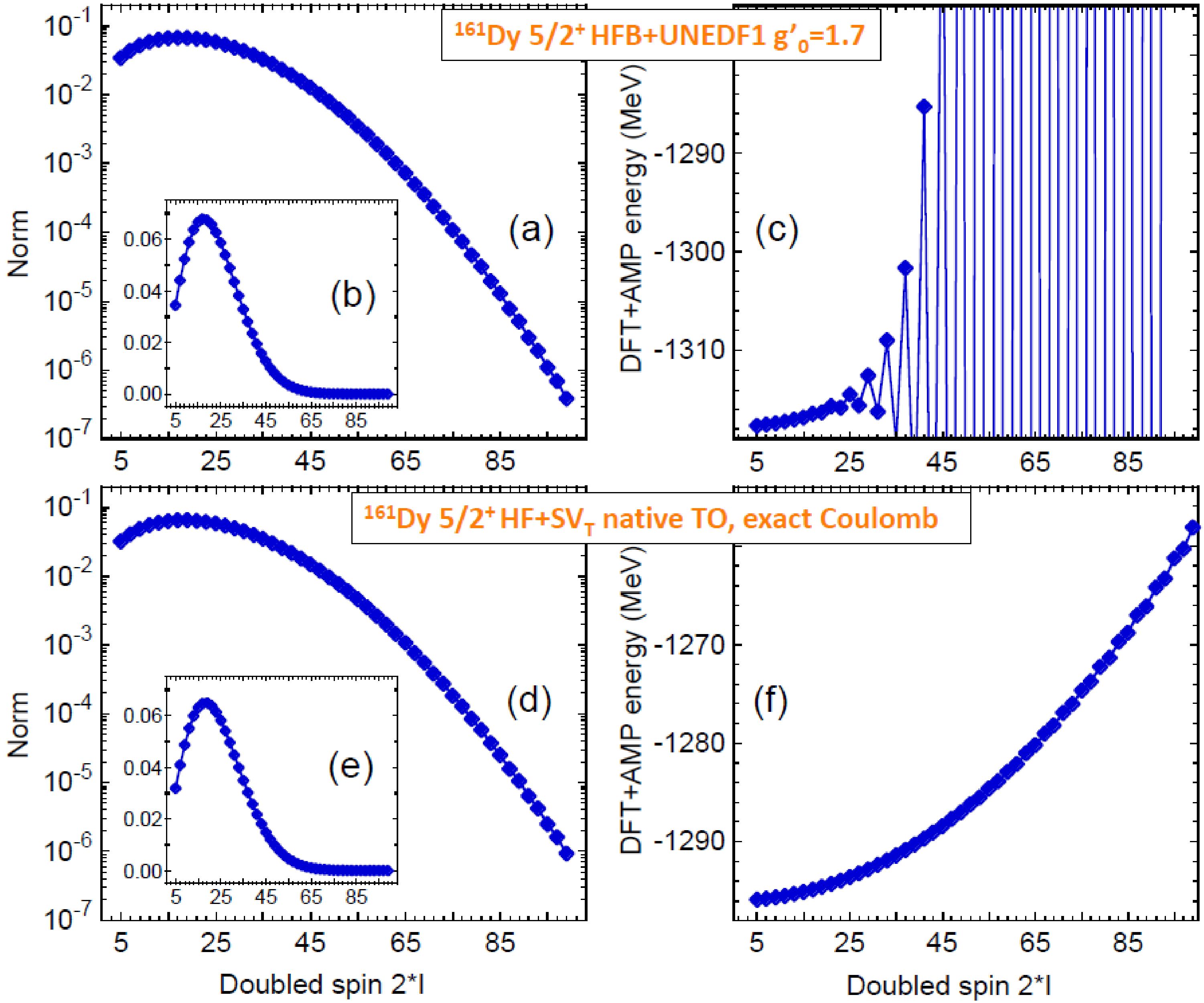
$$\begin{aligned}
\hat{V}^{\mathrm{DDH}}(\boldsymbol{r}) = {}& \frac{i}{2\sqrt{2}}h_\pi^1 g_{\pi NN}\left(\hat{\boldsymbol{\tau}}_1\times\hat{\boldsymbol{\tau}}_2\right)_z\left(\hat{\boldsymbol{\sigma}}_1+\hat{\boldsymbol{\sigma}}_2\right)\cdot\frac{1}{2M}\left[\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\pi(r)\right] \\
& - g_\rho\left(h_\rho^0\hat{\boldsymbol{\tau}}_1\cdot\hat{\boldsymbol{\tau}}_2 + \tfrac{1}{2}h_\rho^1(\hat{\boldsymbol{\tau}}_1+\hat{\boldsymbol{\tau}}_2)_z + \tfrac{1}{2\sqrt{6}}h_\rho^2(3\hat{\tau}_{1z}\hat{\tau}_{2z}-\hat{\boldsymbol{\tau}}_1\cdot\hat{\boldsymbol{\tau}}_2)\right) \\
& \quad\times\frac{1}{2M}\left((\hat{\boldsymbol{\sigma}}_1-\hat{\boldsymbol{\sigma}}_2)\cdot\left\{\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\rho(r)\right\} + i(1+\chi_V)(\hat{\boldsymbol{\sigma}}_1\times\hat{\boldsymbol{\sigma}}_2)\cdot\left[\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\rho(r)\right]\right) \\
& - g_\omega\left(h_\omega^0 + \tfrac{1}{2}h_\omega^1\left(\hat{\boldsymbol{\tau}}_1+\hat{\boldsymbol{\tau}}_2\right)_z\right) \\
& \quad\times\frac{1}{2M}\left((\hat{\boldsymbol{\sigma}}_1-\hat{\boldsymbol{\sigma}}_2)\cdot\left\{\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\omega(r)\right\} + i(1+\chi_S)(\hat{\boldsymbol{\sigma}}_1\times\hat{\boldsymbol{\sigma}}_2)\cdot\left[\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\omega(r)\right]\right) \\
& + \tfrac{1}{2}\left(\hat{\boldsymbol{\tau}}_1-\hat{\boldsymbol{\tau}}_2\right)_z\left(\hat{\boldsymbol{\sigma}}_1+\hat{\boldsymbol{\sigma}}_2\right)\cdot\frac{1}{2M}\left(g_\rho h_\rho^1\left\{\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\rho(r)\right\} - g_\omega h_\omega^1\left\{\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\omega(r)\right\}\right) \\
& - \tfrac{i}{2}g_\rho h_\rho^{1'}\left(\hat{\boldsymbol{\tau}}_1\times\hat{\boldsymbol{\tau}}_2\right)_z\left(\hat{\boldsymbol{\sigma}}_1+\hat{\boldsymbol{\sigma}}_2\right)\cdot\frac{1}{2M}\left[\hat{\boldsymbol{p}}_1-\hat{\boldsymbol{p}}_2,\omega_\rho(r)\right].
\end{aligned} \qquad 7.$$

W.C. Haxton *et al.*, Phys. Rev. C 65 (2002) 045502

B. Desplanques *et al.*, Ann. Phys. 124 (1980) 449

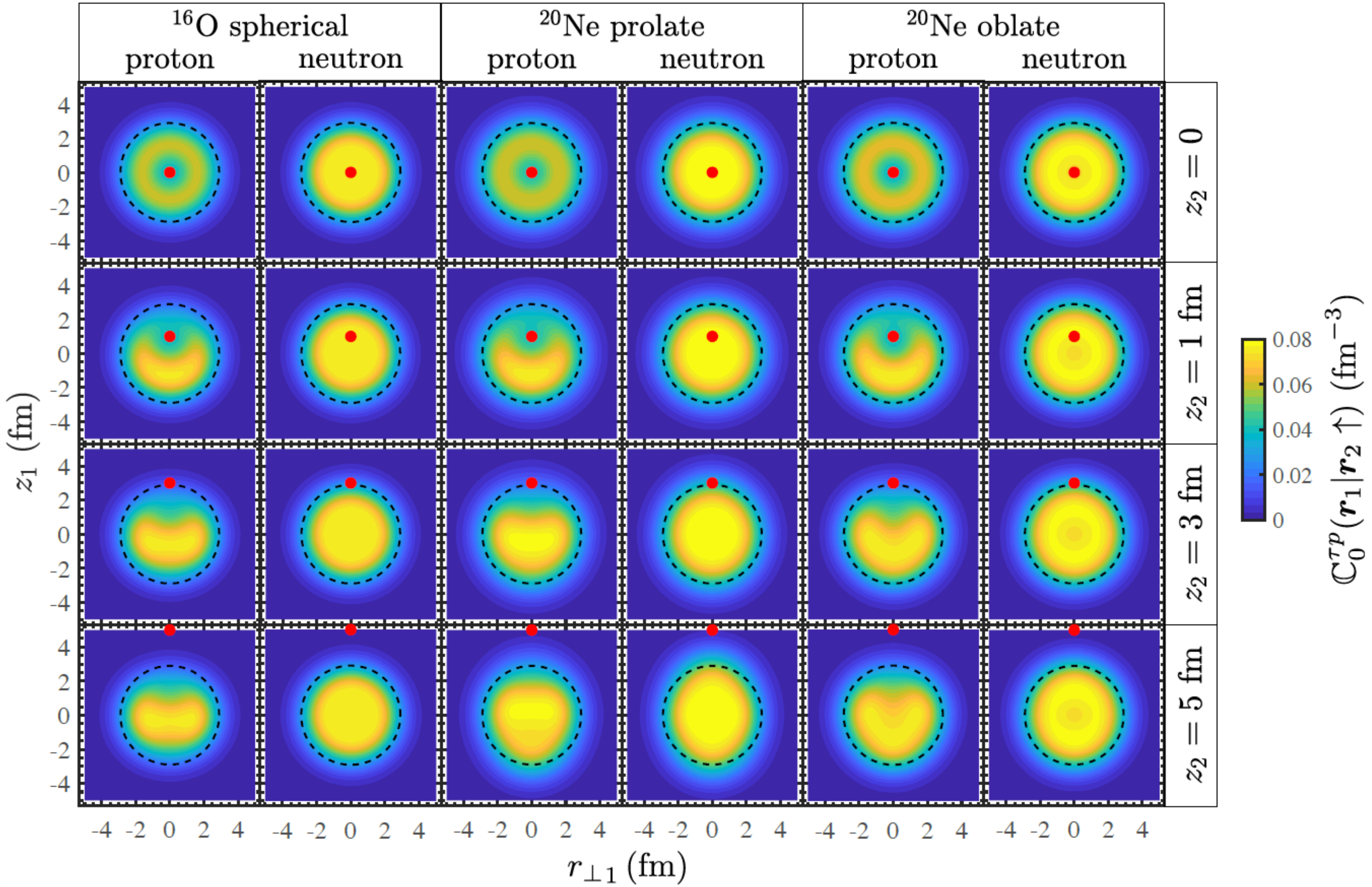
J. Dobaczewski *et al.*, arXiv:2511.04632

Self-interaction in nuclear DFT



A.V. Afanasjev, ... , J. Dobaczewski *et al.*, to be published

Multipole tomography of atomic nuclei



J. Dobaczewski *et al.*, Phys. Rev. Res. 7, 043159 (2025)

X. Sun *et al.*, arXiv:2605.26088

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Conclusions

1. Nuclear DFT is the theory of choice to determine the low-energy properties of open-shell nuclei of arbitrary particle numbers, deformations, and angular momentum.

2. Symmetry breaking followed by symmetry restoration allows for an efficient description of emergent nuclear phenomena.

3. Large nuclear-DFT single-particle phase space (well beyond the valence space) and self-consistency allow for treating various polarisation effects to all orders.

Thank you