Nuclear Schiff moment of Ac-227 calculated within the nuclear DFT framework

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UNIVERSITY of York

Outline

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★ Schiff Theorem and Nuclear Schiff Moment

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- ★ Nuclear Laboratory Schiff Moment

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- ★ Nuclear Laboratory Schiff Moment
- ★ Nuclear Density Functional Theory

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- ★ Nuclear Laboratory Schiff Moment of ^{227}Ac

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- ★ Nuclear Density Functional Theory
- ★ Nuclear Laboratory Schiff Moment of ^{227}Ac
- ★ Summary and Outlook

1

EDM and Fundamental Symmetries

The non-zero expectation value of the operator

$$\hat{\mathbf{d}} = \sum_a e_a \mathbf{R}_a, \quad a = 1, \ ..., \ Z$$

in a stationary state of an atom with a certain value $\hat{\boldsymbol{J}}$ of angular momentum requires simultaneous $\hat{\mathscr{P}}$- and $\hat{\mathscr{T}}$- violation.

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- ★ An atom can acquire an EDM from the nucleus.
- ★ A nucleus acquires an EDM from either nucleon EDM or $\hat{\mathscr{P}}, \hat{\mathscr{T}}$ -violating interaction between nucleons and pions.

2

Schiff Theorem

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L. I. Schiff, Phys. Rev. **132**, 2194 (1963)

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Electrostatic potential of a nucleus:

$$\varphi(\boldsymbol{R}) = \int \frac{e\rho(\boldsymbol{r})}{|\boldsymbol{R}-\boldsymbol{r}|} d^3r + \frac{1}{Z}(\boldsymbol{d}\cdot\boldsymbol{\nabla}_R) \int \frac{\rho(\boldsymbol{r})}{|\boldsymbol{R}-\boldsymbol{r}|} d^3r$$

$$\int d^3r\, \rho(\boldsymbol{r}) = Z; \qquad \boldsymbol{d} = \int e\boldsymbol{r}\rho(\boldsymbol{r})\, d^3r; \qquad \boldsymbol{R} = \text{electron coordinate}$$

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Taylor expansion: $$\frac{1}{|\boldsymbol{R}-\boldsymbol{r}|} = \frac{1}{R} - \boldsymbol{r}\cdot\boldsymbol{\nabla}_R \frac{1}{R} + \frac{1}{2}(\boldsymbol{r}\cdot\boldsymbol{\nabla}_R)^2\frac{1}{R} - \cdots$$

3

Nuclear Schiff Moment

V. Spevak *et al.*, PRC **56**, 1357 (1997)

3

Nuclear Schiff Moment

$$\varphi(\mathbf{R}) = \int d^3r\, e\rho(\mathbf{r}) \left\{ \frac{1}{R} - (\mathbf{r}\cdot\boldsymbol{\nabla}_R)\frac{1}{R} + \frac{1}{2}(\mathbf{r}\cdot\boldsymbol{\nabla}_R)^2\frac{1}{R} - \cdots \right\}$$

$$+ \frac{1}{Z}(\mathbf{d}\cdot\boldsymbol{\nabla}_R) \int d^3r\, \rho(\mathbf{r}) \left\{ \frac{1}{R} - (\mathbf{r}\cdot\boldsymbol{\nabla}_R)\frac{1}{R} + \frac{1}{2}(\mathbf{r}\cdot\boldsymbol{\nabla}_R)^2\frac{1}{R} - \cdots \right\}$$

$$= \frac{eZ}{R} - (\mathbf{d}\cdot\boldsymbol{\nabla}_R)\frac{1}{R} + \frac{1}{2}\int d^3r\, e\rho(\mathbf{r})(\mathbf{r}\cdot\boldsymbol{\nabla}_R)^2\frac{1}{R} - \frac{1}{6}\int d^3r\, e\rho(\mathbf{r})(\mathbf{r}\cdot\boldsymbol{\nabla}_R)^3\frac{1}{R} + \cdots$$

$$+ \frac{1}{Z}(\mathbf{d}\cdot\boldsymbol{\nabla}_R)\frac{Z}{R} - \frac{1}{Z}(\mathbf{d}\cdot\boldsymbol{\nabla}_R)\int d^3r\, \rho(\mathbf{r})(\mathbf{r}\cdot\boldsymbol{\nabla}_R)\frac{1}{R} + \frac{1}{Z}(\mathbf{d}\cdot\boldsymbol{\nabla}_R)\int d^3r\, \frac{1}{2}\rho(\mathbf{r})(\mathbf{r}\cdot\boldsymbol{\nabla}_R)^2\frac{1}{R}$$

$$- \cdots$$

$$= \frac{eZ}{R} + \frac{1}{6}\Theta_{\alpha\beta}\, \nabla_{R;\alpha}\nabla_{R;\beta}\frac{1}{R} - Ze\frac{4\pi}{6}\overline{r_{\rm ch}^2}\,\delta(\mathbf{R}) - \frac{1}{Ze}(\mathbf{d}\cdot\boldsymbol{\nabla}_R)^2\frac{1}{R} + \varphi^{(3)}(\mathbf{R}) \cdots .$$

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Nuclear Schiff Moment

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PRC **56**, 1357
(1997)

4

Nuclear Schiff Moment

$$\Theta_{\alpha\beta} = \int d^3r \; e\rho(\mathbf{r}) \cdot 3T^{(2)}_{\alpha\beta} \quad \text{(Traceless quadrupole tensor)}$$

$$T^{(2)}_{\alpha\beta} = r_\alpha r_\beta - \frac{1}{3} r^2 \delta_{\alpha\beta}$$

$$\overline{r^2_{\text{ch}}} = \frac{1}{Z} \int d^3r \; \rho(\mathbf{r}) r^2 \quad \text{(Mean-square charge radius)}$$

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$$\varphi^{(3)}(\mathbf{R}) = -\frac{1}{6} \int d^3r \; e\rho(\mathbf{r}) \; r_\alpha r_\beta r_\gamma \; \nabla_{R;\alpha} \nabla_{R;\beta} \nabla_{R;\gamma} \frac{1}{R}$$
$$+ \frac{1}{2Z} (\mathbf{d} \cdot \boldsymbol{\nabla}_R) \nabla_{R;\alpha} \nabla_{R;\beta} \frac{1}{R} \int d^3r \; \rho(\mathbf{r}) r_\alpha r_\beta$$
$$= \varphi^{(3)}_{\text{octupole}}(\mathbf{R}) + \varphi^{(3)}_{\text{Schiff}}(\mathbf{R}) + \frac{1}{6Ze} (\mathbf{d} \cdot \boldsymbol{\nabla}_R) \Theta_{\alpha\beta} \nabla_{R;\alpha} \nabla_{R;\beta} \frac{1}{R}$$

5

Nuclear Schiff Moment

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5

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$$\varphi^{(3)}_{\text{octupole}}(\mathbf{R}) = -\frac{1}{6} Q_{\alpha\beta\gamma} \nabla_{R;\alpha} \nabla_{R;\beta} \nabla_{R;\gamma} \frac{1}{R}; \quad Q_{\alpha\beta\gamma} = \int d^3r \; e\rho(\mathbf{r}) T^{(3)}_{\alpha\beta\gamma}$$

$$T^{(3)}_{\alpha\beta\gamma} = r_\alpha r_\beta r_\gamma - \frac{1}{5} r^2 (r_\alpha \delta_{\beta\gamma} + r_\beta \delta_{\alpha\gamma} + r_\gamma \delta_{\alpha\beta})$$

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Nuclear Schiff moment:

$$\boldsymbol{S} = \frac{1}{10} \left(\int d^3r \; e\rho(\boldsymbol{r}) r^2 \boldsymbol{r} - \frac{5}{3} \boldsymbol{d} \frac{1}{Z} \int d^3r \; \rho(\boldsymbol{r}) r^2 \right)$$

V. Spevak *et al.*, PRC **56**, 1357 (1997)

Nuclear Laboratory Schiff Moment

C. Maples, Nuclear Data Sheets **22**, 275, 277-323 (1977)

J. Dobaczewski *et al.*, PRL **121**, 232501 (2018) and the supplemental material

Nuclear Laboratory Schiff Moment

$$S_{\text{lab}} \approx \sum_{i\neq 0} \frac{\langle \Psi_0 | \hat{S}_0 | \Psi_i \rangle \langle \Psi_i | \hat{V}_{\text{PT}} | \Psi_0 \rangle}{E_0 - E_i} + \text{c.c.}$$

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6

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$$\hat{S}_0 = \frac{e}{10}\sqrt{\frac{4\pi}{3}} \sum_p \left(r_p^3 - \frac{5}{3}\overline{r^2_{\text{ch}}} r_p \right) Y_0^1(\Omega_p) \quad \text{(Schiff operator)}$$

$$\hat{V}_{\text{PT}} = \text{P,T-violating } NN \text{ interaction}$$

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$$S_{\rm lab} \approx \sum_{i \neq 0} \frac{\langle \Psi_0 | \hat{S}_0 | \Psi_i \rangle \langle \Psi_i | \hat{V}_{\rm PT} | \Psi_0 \rangle}{E_0 - E_i} + \text{c.c.}$$

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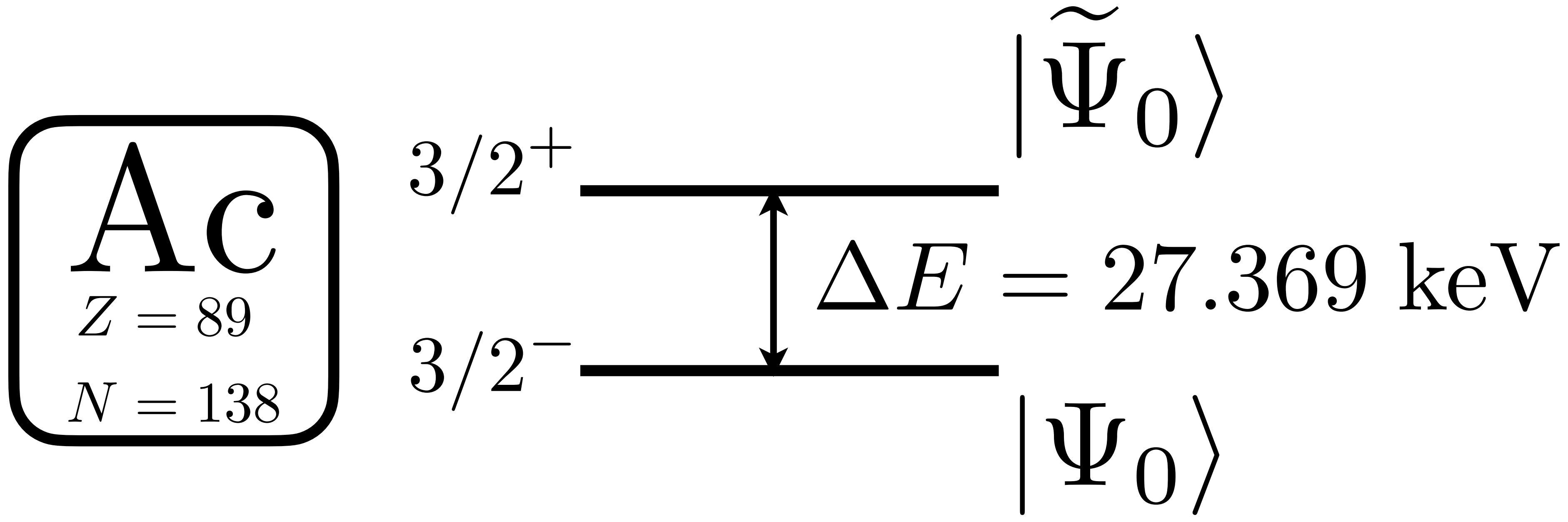

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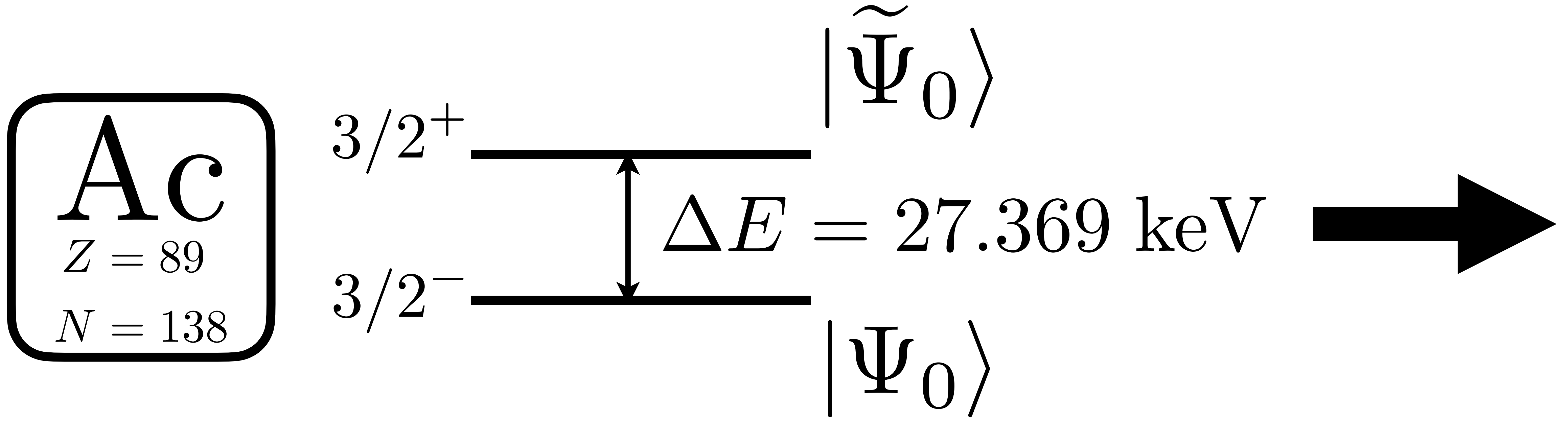

$$S_{\text{lab}} \approx -2\text{Re}\left\{ \frac{\langle \Psi_0 | \hat{S}_0 | \widetilde{\Psi}_0 \rangle \langle \widetilde{\Psi}_0 | \hat{V}_{\text{PT}} | \Psi_0 \rangle}{\Delta E} \right\}$$

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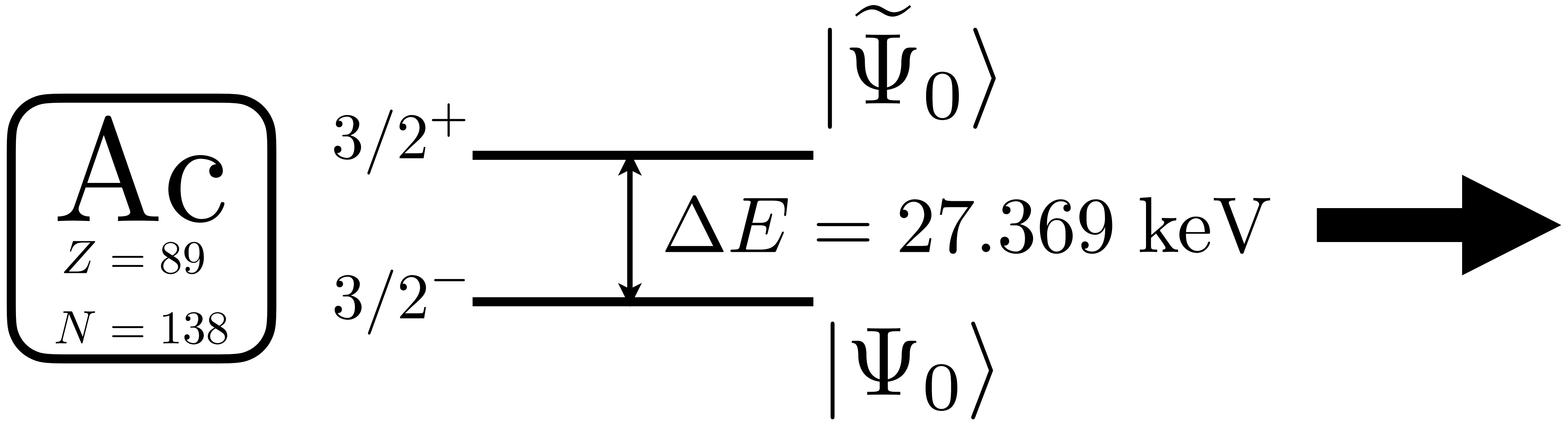

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$$\hat{Q}_0^3 = e \sum_p r_p^3 Y_0^3(\Omega_p) \quad \text{(Octupole operator)}$$

C. Maples, Nuclear Data Sheets **22**, 275, 277-323 (1977)

J. Dobaczewski *et al.*, PRL **121**, 232501 (2018) and the supplemental material

7

Rigid Deformation Approximation

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7

Rigid Deformation Approximation

Reduced matrix elements:

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$$\langle \Psi^{J_1,+} || \hat{X}^{\lambda} || \Psi^{J_2,-} \rangle_{\mathrm{rigid}} = \sqrt{2J_2+1} \langle J_2 K \lambda 0 | J_1 K \rangle \langle \Phi_1 | \hat{X}^{\lambda}_0 | \Phi_2 \rangle$$

intrinsic expectation value

Rigid Deformation Approximation

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intrinsic expectation value

Laboratory matrix elements:

$$\langle \Psi^{J_1,+}_{M_1} | \hat{X}^{\lambda}_{\mu} | \Psi^{J_2,-}_{M_2} \rangle_{\rm rigid} = \frac{1}{\sqrt{2J_1+1}} \langle J_2 M_2 \lambda \mu | J_1 M_1 \rangle \times \langle \Psi^{J_1,+} || \hat{X}^{\lambda} || \Psi^{J_2,-} \rangle_{\rm rigid}$$

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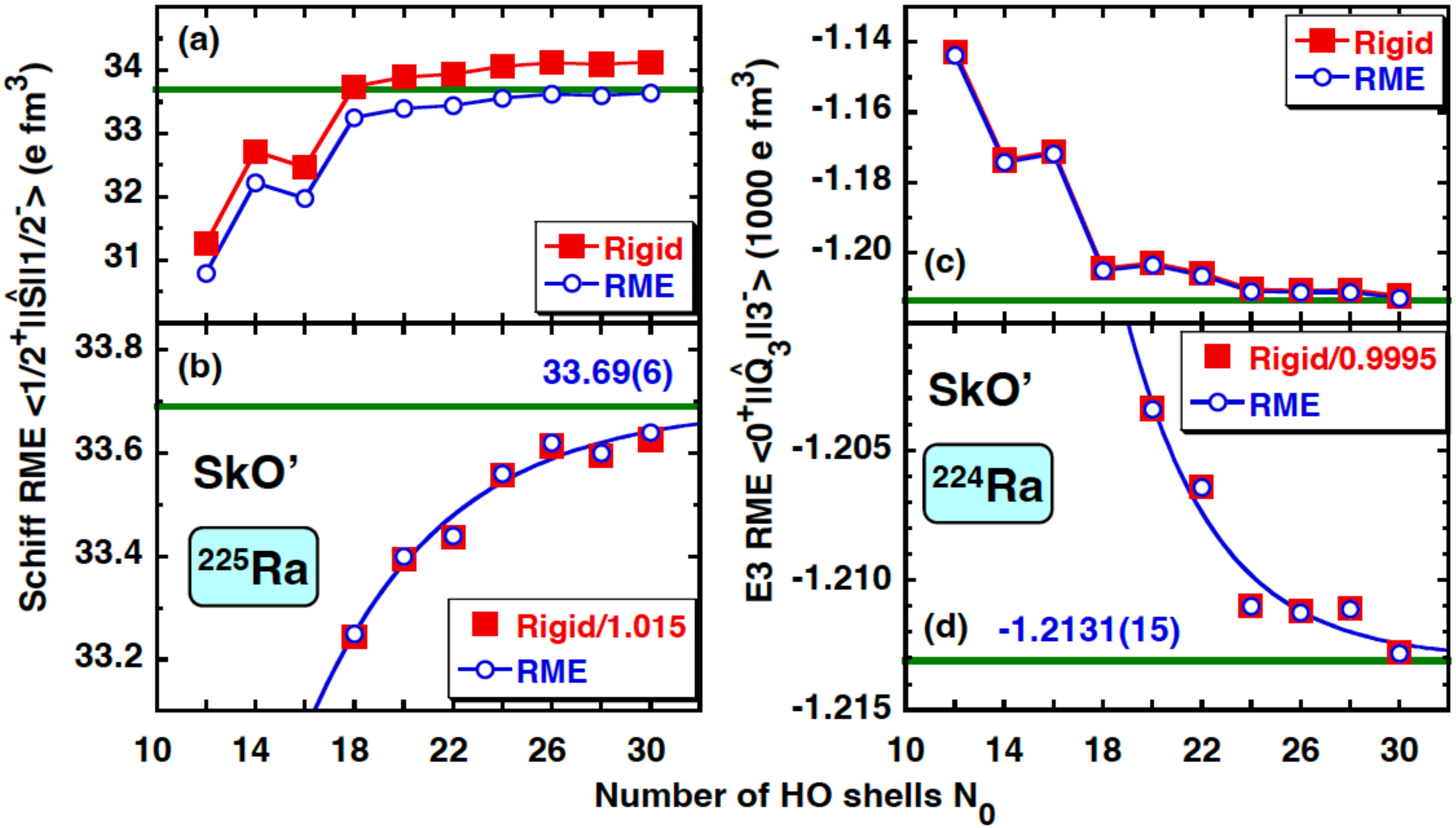
$$J_1 = J_2 = M_1 = M_2 = K$$

$$\langle J K 1 0 | J K \rangle = \frac{K}{\sqrt{J(J+1)}} \quad \Rightarrow \quad \langle \Psi_0 | \hat{S}_0 | \widetilde{\Psi}_0 \rangle_{\mathrm{rigid}} = \frac{J}{J+1} S_{\mathrm{int}}$$

$$\langle J K 0 0 | J K \rangle = 1 \quad \Rightarrow \quad \langle \widetilde{\Psi}_0 | \hat{V}_{\mathrm{PT}} | \Psi_0 \rangle_{\mathrm{rigid}} = \langle \hat{V}_{\mathrm{PT}} \rangle_{\mathrm{int}}$$

8

Accuracy of Rigid Deformation Approximation



J. Dobaczewski *et al.*, PRL **121**, 232501 (2018) and the supplemental material

P, T-violating interaction

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$$\hat{V}_{\rm PT}(\boldsymbol{r}_1-\boldsymbol{r}_2) = -\frac{gm_\pi^2}{8\pi m_N}\left\{(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot(\boldsymbol{r}_1-\boldsymbol{r}_2)\left[\bar{g}_0\vec{\tau}_1\cdot\vec{\tau}_2-\frac{\bar{g}_1}{2}(\tau_{1z}+\tau_{2z})+\bar{g}_2(3\tau_{1z}\tau_{2z}-\vec{\tau}_1\cdot\vec{\tau}_2)\right]\right.$$
$$\left.-\frac{\bar{g}_1}{2}(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot(\boldsymbol{r}_1-\boldsymbol{r}_2)(\tau_{1z}-\tau_{2z})\right\}\frac{\exp(-m_\pi|\boldsymbol{r}_1-\boldsymbol{r}_2|)}{m_\pi|\boldsymbol{r}_1-\boldsymbol{r}_2|^2}\left[1+\frac{1}{m_\pi|\boldsymbol{r}_1-\boldsymbol{r}_2|}\right]$$
$$+\frac{1}{2m_N^3}[\bar{c}_1+\bar{c}_2\vec{\tau}_1\cdot\vec{\tau}_2](\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\boldsymbol{\nabla}\delta^3(\boldsymbol{r}_1-\boldsymbol{r}_2),$$

C. M. Maekawa, E. Mereghetti, J. de Vries, and U. van Kolck, Nucl. Phys. **A872**, 117 (2011)
W. C. Haxton and E. M. Henley, Phys. Rev. Lett. **51**, 1937 (1983)
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$$\left.-\frac{\bar{g}_1}{2}(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot(\boldsymbol{r}_1-\boldsymbol{r}_2)(\tau_{1z}-\tau_{2z})\right\}\frac{\exp(-m_\pi|\boldsymbol{r}_1-\boldsymbol{r}_2|)}{m_\pi|\boldsymbol{r}_1-\boldsymbol{r}_2|^2}\left[1+\frac{1}{m_\pi|\boldsymbol{r}_1-\boldsymbol{r}_2|}\right]$$
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Nuclear Laboratory Schiff Moment

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Rigid deformation approximation:

$$\langle \Psi_0 | \hat{S}_0 | \widetilde{\Psi}_0 \rangle_{\text{rigid}} = \frac{J}{J+1} S_{\text{int}}$$

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S_{int} and $\langle \hat{V}_{\text{PT}} \rangle_{\text{int}}$ are calculated within nuclear DFT.

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$$a_i = -\frac{2J}{J+1} \frac{S_{\text{int}} v_i}{\Delta E} \quad \text{and} \quad b_i = -\frac{2J}{J+1} \frac{S_{\text{int}} w_i}{\Delta E}$$

11 Nuclear Density Functional Theory (A primer)

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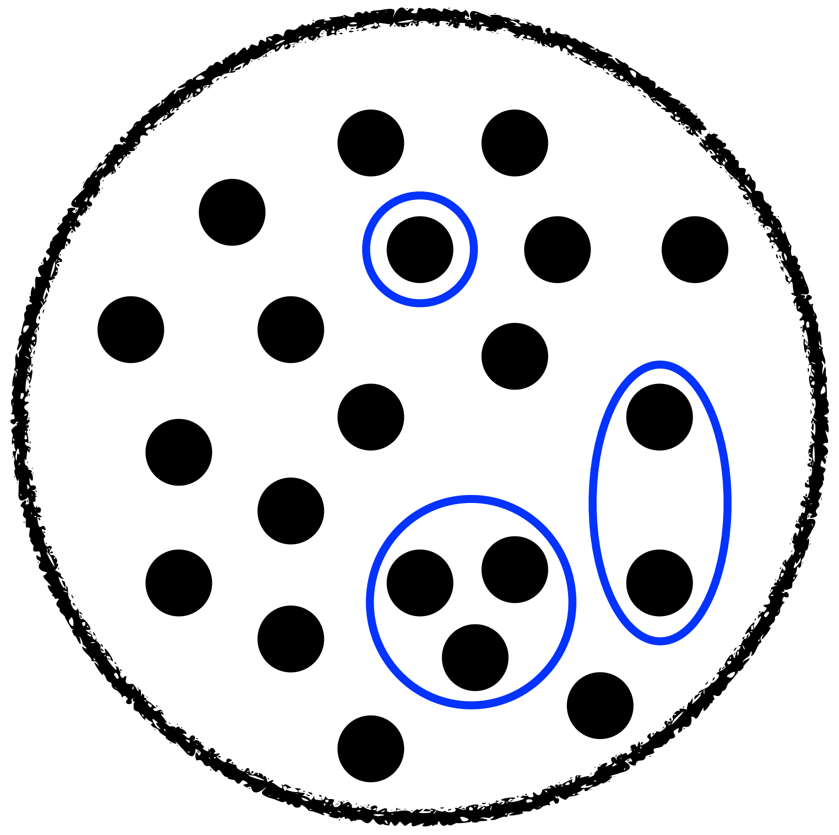

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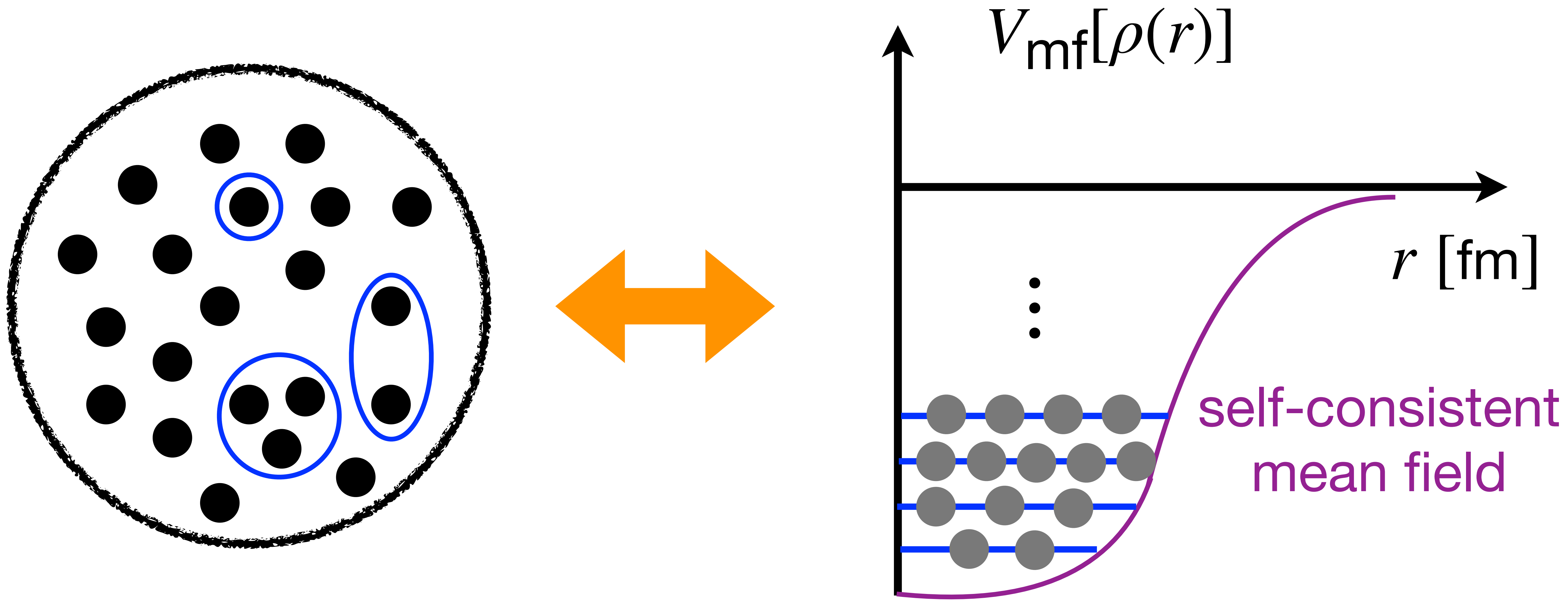

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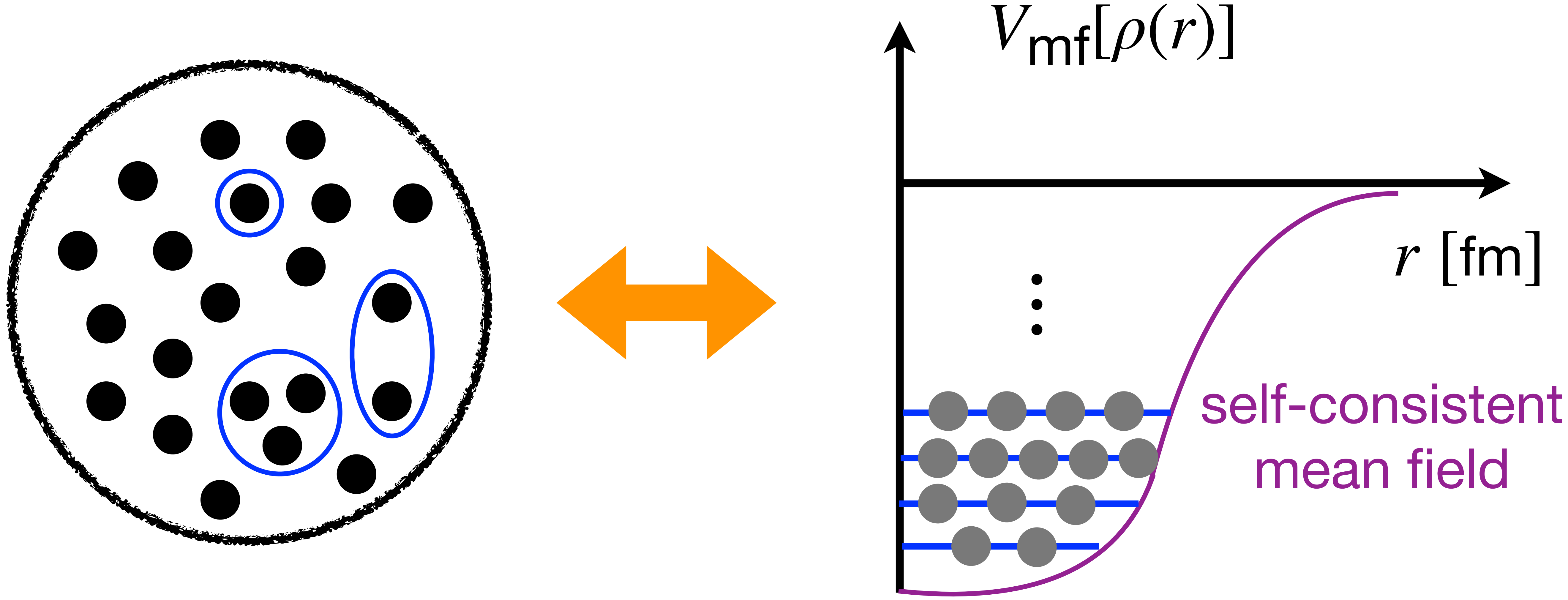

Energy density functional (EDF): $$\mathcal{E} = \int d^3r\, \mathcal{H}(\mathbf{r})$$

$$\mathcal{H}(\mathbf{r}) = \frac{\hbar^2}{2m}\tau(\mathbf{r}) - \frac{1}{2}C\rho^2(\mathbf{r}), \quad \rho(\mathbf{r}) = \sum_i^A \phi_i(\mathbf{r})\phi_i^*(\mathbf{r}),$$

$$\tau(\mathbf{r}) = \sum_{i=1}^A (\boldsymbol{\nabla}\phi_i(\mathbf{r})) \cdot (\boldsymbol{\nabla}\phi_i^*(\mathbf{r}))$$

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Variational principle:

$$\frac{\delta \mathcal{E}}{\delta \phi_i^*(\mathbf{r})} = 0$$

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Kohn-Sham equation:

$$\left[-\frac{\hbar^2}{2m}\nabla^2 - C\rho(\mathbf{r})\right]\phi_i(\mathbf{r}) = \epsilon_i \phi_i(\mathbf{r})$$

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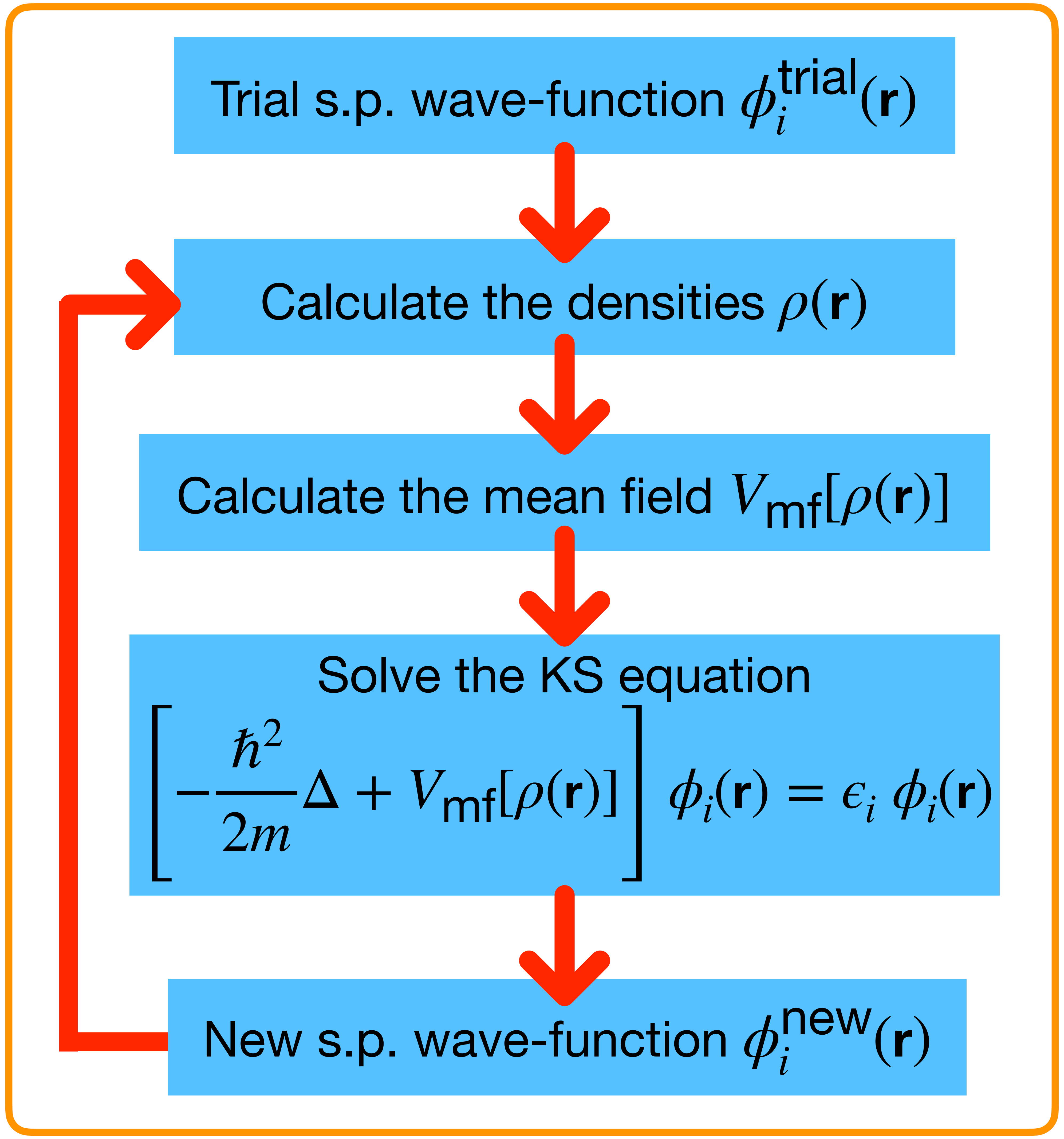

Nuclear Density Functional Theory (This work)

Total energy: $\mathcal{E} = \mathcal{E}^{\text{kin.}} + \mathcal{E}^{\text{Skyrme}} + \mathcal{E}^{\text{Coul.}} + \mathcal{E}^{\text{mult.}} + \mathcal{E}^{\text{cran.}}$

$$\mathcal{E}^{\text{kin.}} = \frac{\hbar^2}{2m}\left(1-\frac{1}{A}\right)\int d^3r\,[\tau_p(\mathbf{r})+\tau_n(\mathbf{r})]$$

$$\mathcal{E}^{\text{mult.}} = \sum_{\lambda\mu} C_{\lambda\mu}\left[\langle\hat{Q}_{\lambda\mu}\rangle - \bar{Q}_{\lambda\mu}\right]^2$$

$$\mathcal{E}^{\text{cran.}} = -\omega_y\langle\hat{J}_y\rangle$$

$$\begin{aligned}\mathcal{E}^{\text{Skyrme}} &= \int d^3r \sum_{t=0,1}\Big\{C_t^{\rho}\rho_t^2(\mathbf{r}) + C_t^{s}s_t^2(\mathbf{r}) + C_t^{\Delta\rho}\rho_t(\mathbf{r})\nabla^2\rho_t(\mathbf{r}) + C_t^{\tau}\rho_t(\mathbf{r})\tau_t(\mathbf{r}) + \\ &\quad + C_t^{J}\overleftrightarrow{J}_t^2(\mathbf{r}) + C_t^{\Delta s}\mathbf{s}_t(\mathbf{r})\cdot\nabla^2\mathbf{s}_t(\mathbf{r}) + C_t^{T}\mathbf{s}_t(\mathbf{r})\cdot\mathbf{T}_t(\mathbf{r}) + C_t^{j}j_t^2(\mathbf{r}) + \\ &\quad + C_t^{\nabla J}\rho_t(\mathbf{r})\boldsymbol{\nabla}\cdot\mathbf{J}_t(\mathbf{r}) + C_t^{\nabla j}\mathbf{s}_t(\mathbf{r})\cdot[\boldsymbol{\nabla}\times\mathbf{j}_t(\mathbf{r})]\Big\} \\ &= \sum_{t=0,1}\int d^3r\,\Big\{\mathcal{H}_t^{\text{even}}(\mathbf{r}) + \mathcal{H}_t^{\text{odd}}(\mathbf{r})\Big\},\end{aligned}$$

Nuclear Density Functional Theory (This work)

$$\mathcal{H}_t^{\mathrm{even}}(\mathbf{r}) = C_t^{\rho}\rho_t^2(\mathbf{r}) + C_t^{\Delta\rho}\rho_t(\mathbf{r})\nabla^2\rho_t(\mathbf{r}) + C_t^{\tau}\rho_t(\mathbf{r})\tau_t(\mathbf{r}) + C_t^{J}\overleftrightarrow{J}_t^2(\mathbf{r}) + C_t^{\nabla J}\rho_t(\mathbf{r})\boldsymbol{\nabla}\cdot\mathbf{J}_t(\mathbf{r}),$$

$$\mathcal{H}_t^{\mathrm{odd}}(\mathbf{r}) = C_t^{s}s_t^2(\mathbf{r}) + C_t^{\Delta s}\mathbf{s}_t(\mathbf{r})\cdot\nabla^2\mathbf{s}_t(\mathbf{r}) + C_t^{T}\mathbf{s}_t(\mathbf{r})\cdot\mathbf{T}_t(\mathbf{r}) + C_t^{j}j_t^2(\mathbf{r}) + C_t^{\nabla j}\mathbf{s}_t(\mathbf{r})\cdot\left[\boldsymbol{\nabla}\times\mathbf{j}_t(\mathbf{r})\right].$$

P. Ring and P. Schuck, *The Nuclear Many-Body Problem*
J. Dobaczewski *et al.*, CPC 180, 2361 (2009)

J. Dobaczewski and J. Dudek, CPC 102, 166 (1997)

Nuclear Density Functional Theory (This work)

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★ 7 parametrizations of Skyrme energy density functional (EDF) have been used.

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- ★ Hartree-Fock-Bogoliubov (HFB) equations are solved.

$$\begin{pmatrix} \hat{h}' - \lambda & \Delta \\ -\Delta^* & -\hat{h}'^* + \lambda \end{pmatrix} \begin{pmatrix} \chi_k^{\text{upper}} \\ \chi_k^{\text{lower}} \end{pmatrix} = \begin{pmatrix} \chi_k^{\text{upper}} \\ \chi_k^{\text{lower}} \end{pmatrix} E_k$$

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Single-particle Routhian operators:

$$\hat{h}'_n = -\frac{\hbar^2}{2m}\nabla^2 + \left(\Gamma_0^{\text{even}} + \Gamma_0^{\text{odd}} + \Gamma_1^{\text{even}} + \Gamma_1^{\text{odd}}\right) + \hat{U}^{\text{mult.}} - \omega_y\hat{J}_y$$

$$\hat{h}'_p = -\frac{\hbar^2}{2m}\nabla^2 + \left(\Gamma_0^{\text{even}} + \Gamma_0^{\text{odd}} - \Gamma_1^{\text{even}} - \Gamma_1^{\text{odd}}\right) + U^{\text{Coul.}} + \hat{U}^{\text{mult.}} - \omega_y\hat{J}_y$$

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15

Nuclear Density Functional Theory (This work)

J. Dobaczewski and J. Dudek, CPC 102, 166 (1997)

M. Athanasakis-Kaklamanakis, *et al.*,
Nature 648, 562-568 (2025)

Nuclear Density Functional Theory (This work)

Multipole constraints:

J. Dobaczewski and J. Dudek, CPC 102, 166 (1997)

$$\hat{U}^{\mathrm{mult.}} = 2\sum_{\lambda\mu} C_{\lambda\mu}\left[\langle\hat{Q}_{\lambda\mu}\rangle - \bar{Q}_{\lambda\mu}\right]\hat{Q}_{\lambda\mu}$$

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Anti-symmetric pairing potential Δ depends on the standard form factor of zero-range density-dependent pairing force:

$$f(\mathbf{r}) = V_0 + V_1\rho^{\alpha}(\mathbf{r})$$

$V_{0,p}$ was adjusted to reproduce the experimental pairing gap of ^{227}Ac isotope.

M. Athanasakis-Kaklamanakis, *et al.*,
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16 How do we calculate the ground state of an odd nucleus?

P. Ring and P. Schuck, *The Nuclear Many-Body Problem*
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$$|\Psi\rangle_{\mathrm{HFB}}^{\mathrm{even}} = \prod_{\mu>0} \left(u_\mu + v_\mu \hat{a}_{\bar{\mu}}^\dagger \hat{a}_\mu^\dagger \right) |0\rangle$$

$$|\Psi\rangle_{\mathrm{HFB}}^{\mathrm{odd}} = \hat{\beta}_\nu^\dagger |\Psi\rangle_{\mathrm{HFB}}^{\mathrm{even}} = \hat{a}_\nu^\dagger \prod_{\nu\neq\mu>0} \left(u_\mu + v_\mu \hat{a}_{\bar{\mu}}^\dagger \hat{a}_\mu^\dagger \right) |0\rangle$$

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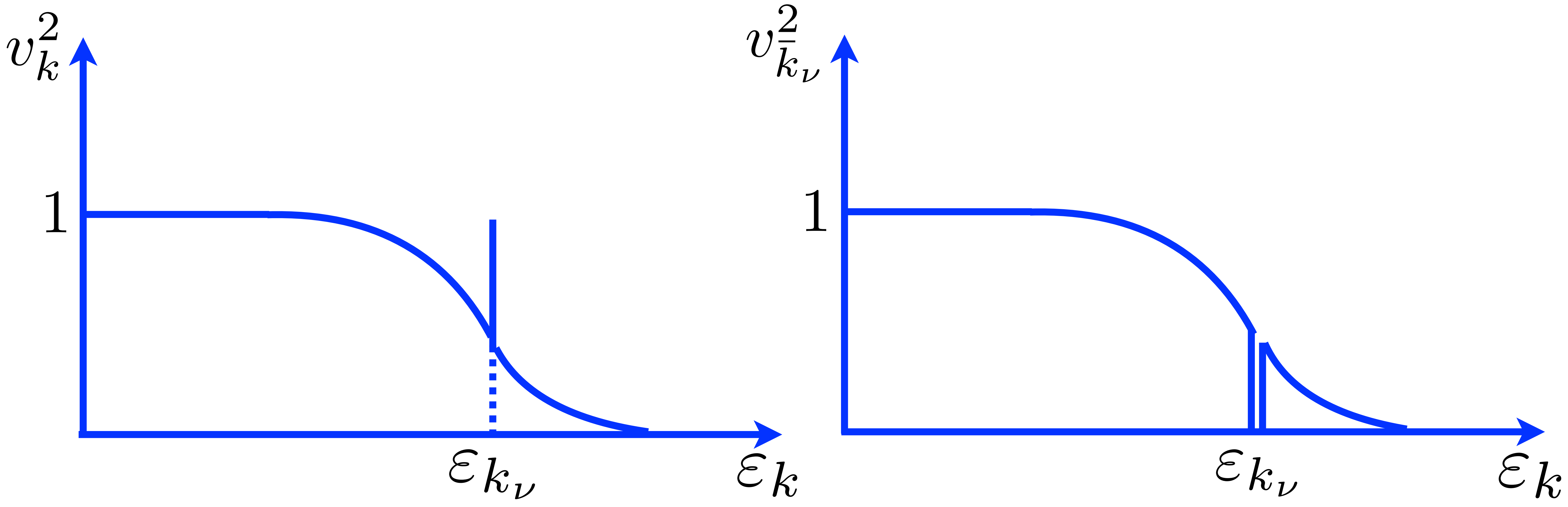
$$|\Psi\rangle_{\rm HFB}^{\rm even} = \prod_{\mu>0} \left(u_\mu + v_\mu \hat{a}^\dagger_{\bar{\mu}} \hat{a}^\dagger_\mu\right) |0\rangle$$

$$|\Psi\rangle_{\rm HFB}^{\rm odd} = \hat{\beta}^\dagger_\nu |\Psi\rangle_{\rm HFB}^{\rm even} = \hat{a}^\dagger_\nu \prod_{\nu\neq\mu>0} \left(u_\mu + v_\mu \hat{a}^\dagger_{\bar{\mu}} \hat{a}^\dagger_\mu\right) |0\rangle$$



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J. Dobaczewski *et al*., Comp. Phys. Commun. **180**, 2361 (2009)

H. Wibowo *et al*., J. Phys. G: Nucl. Part. Phys. 52, 6 (2025)

Two-step procedure to determine the ground state of an odd nucleus:

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★ **Tagging mechanism**: $\max\left\{\langle\phi_\ell|\chi_k^{\text{upper}}\rangle, \langle\phi_\ell|\chi_k^{\text{lower}}\rangle\right\}$

Quasiparticle blocked state was tagged by $\pi[532]3/2^-$.

Calculations were performed using HFODD code.

T. Duguet, P. Bonche, P. -H. Helen and J. Meyer, Phys. Rev. C **65**, 014310 (2001)
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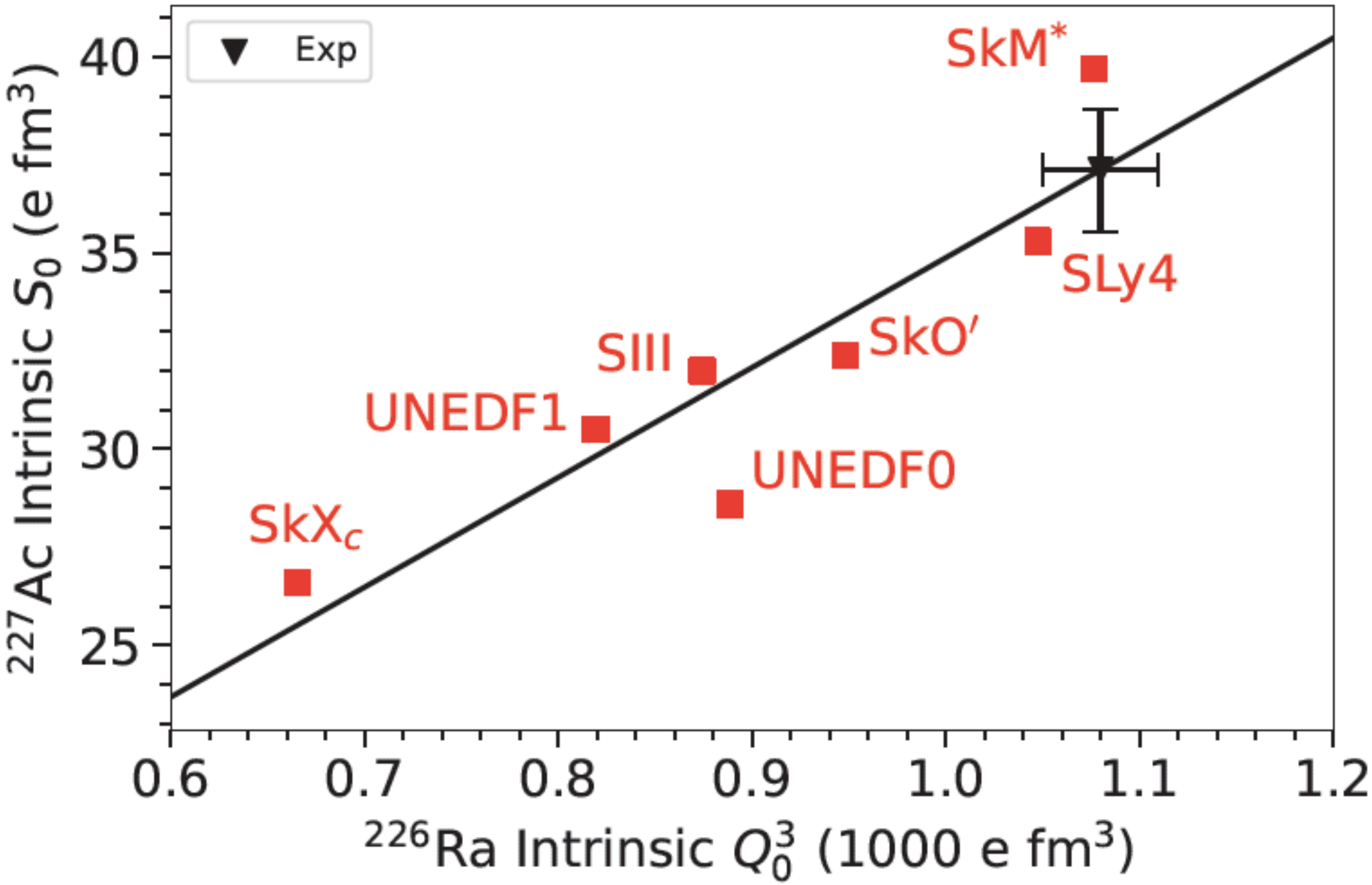
18 Correlation between Octupole and Schiff Moments



M. Athanasakis-Kaklamanakis, *et al.*, Nature 648, 562-568 (2025)

J. Dobaczewski, *et al.*, arXiv:2511.04632v2 (2025)

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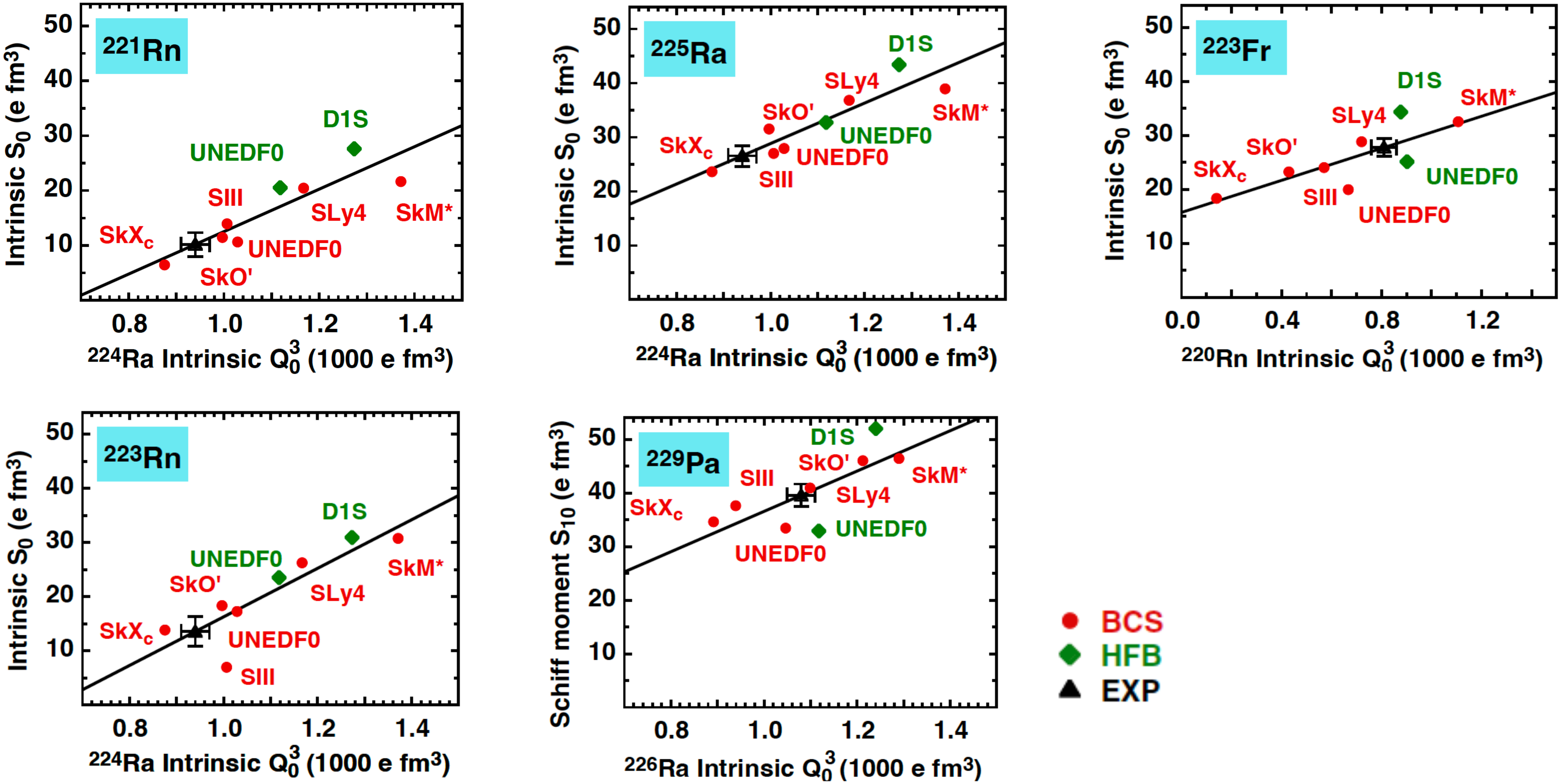

Estimated Intrinsic Schiff Moment

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Intrinsic Schiff moment: $$S_0(\mathrm{est}) = a + bQ_0^3(\mathrm{exp})$$

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Intrinsic Schiff moment: $$S_0(\mathrm{est}) = a + bQ_0^3(\mathrm{exp})$$

Measured Octupole moment: $$Q_0^3(^{226}\mathrm{Ra}) = 1080(30)\ \mathrm{e\ fm}^3$$

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Total uncertainty: $$\Delta S_0(\mathrm{est}) = \sqrt{[\Delta S_0(\mathrm{the})]^2 + [\Delta S_0(\mathrm{exp})]^2}$$

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Theoretical uncertainty: $$[\Delta S_0(\mathrm{the})]^2 = \mathcal{C}_{aa} + 2\mathcal{C}_{ab}\bar{Q}_0^3(\mathrm{exp}) + \mathcal{C}_{bb}[\bar{Q}_0^3(\mathrm{exp})]^2$$

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$$S_0(^{227}\mathrm{Ac}) = 37.1(1.6)\ \mathrm{e\ fm}^3$$

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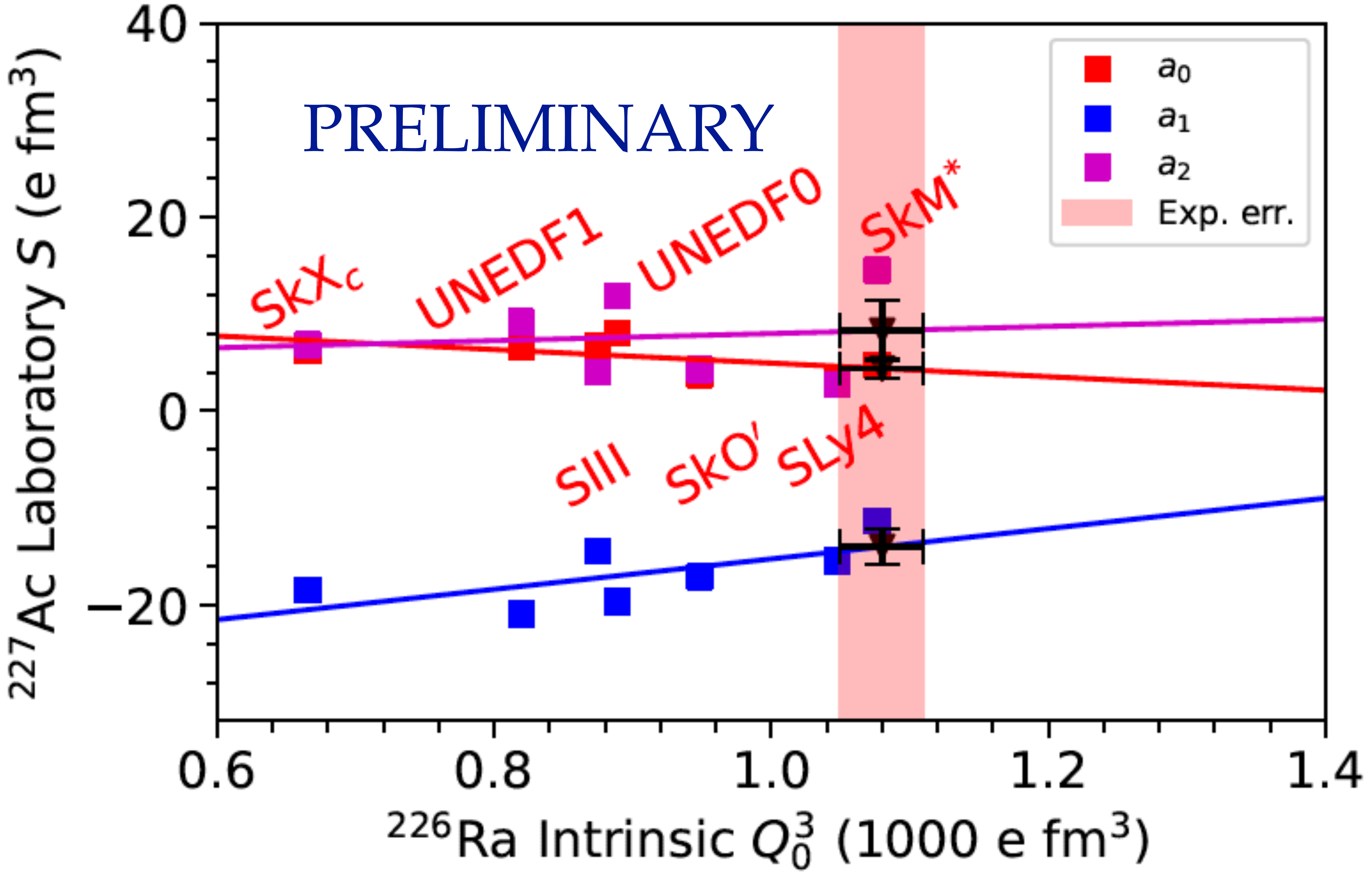
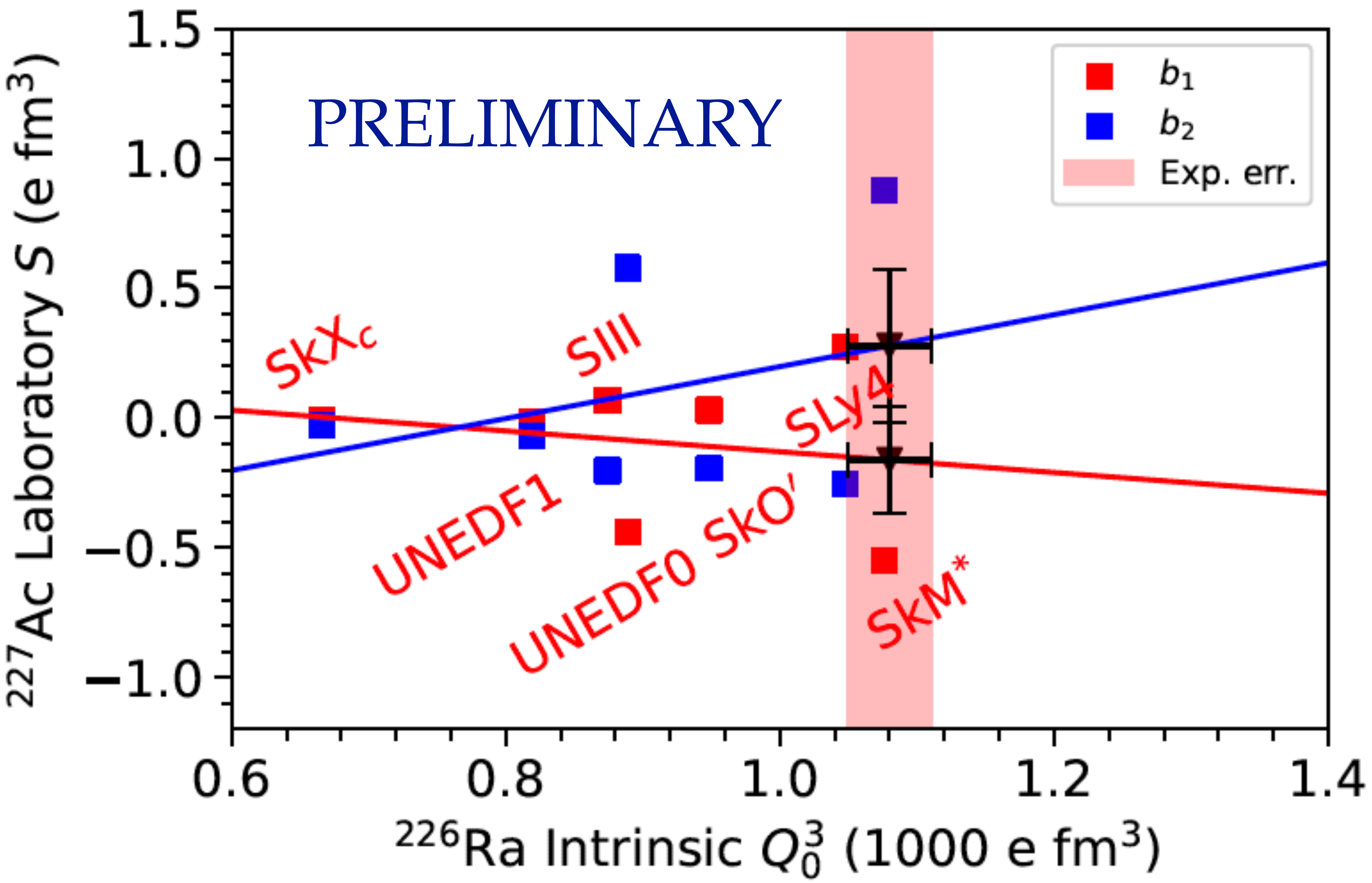
Estimated Laboratory Schiff Moment





$$a_0 = 4.4(10)\ e \cdot \mathrm{fm}^3$$

$$a_1 = -14.0(18)\ e \cdot \mathrm{fm}^3$$

$$a_2 = 8.3(31)\ e \cdot \mathrm{fm}^3$$

$$b_1 = -0.2(2)\ e \cdot \mathrm{fm}^3$$

$$b_2 = 0.3(3)\ e \cdot \mathrm{fm}^3$$

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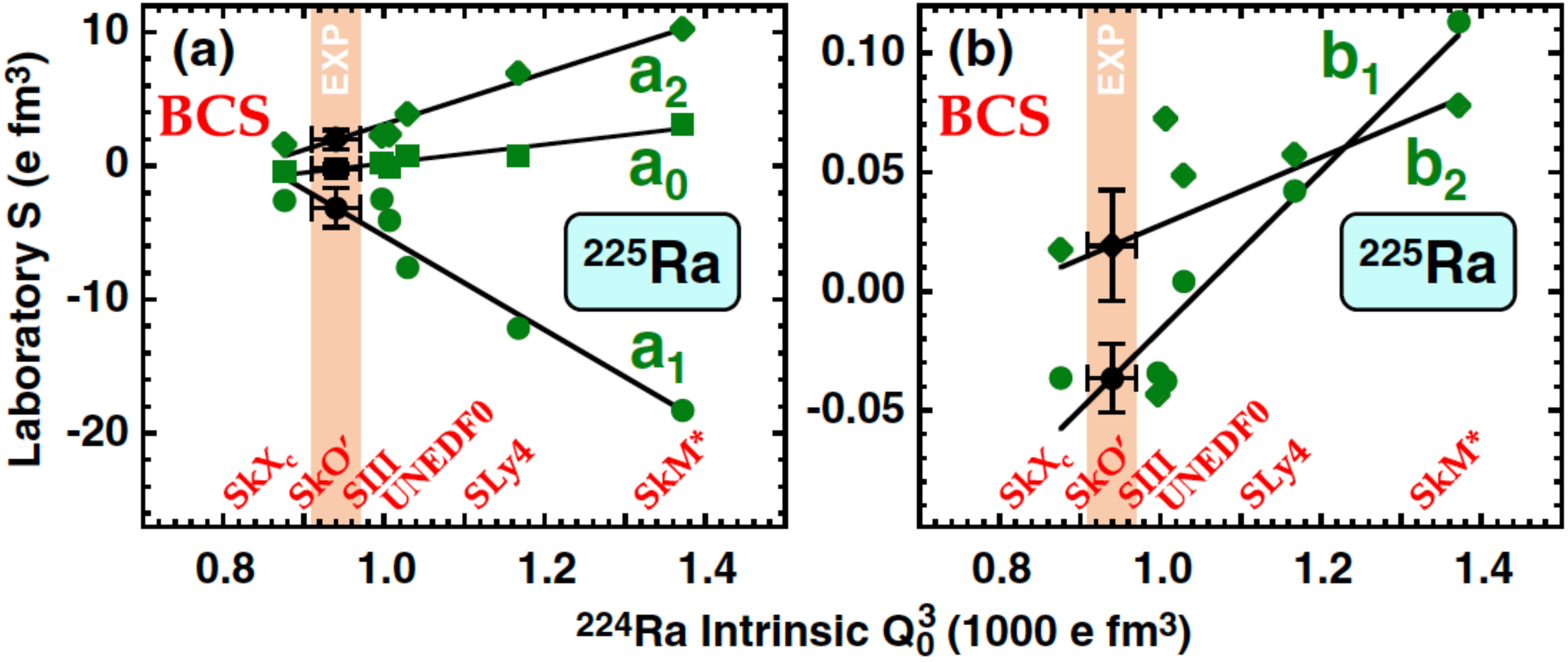

TABLE I. Coefficients a_0, a_1, a_2, b_1, and b_2 (in e fm^3) [from Eq. (5)], determined by regression analysis. For ^{221}Rn and ^{223}Rn we show values propagated to the experimental octupole moment of ^{220}Rn, whereas for ^{223}Fr, ^{225}Ra, and ^{229}Pa we show averages of those propagated to ^{224}Ra and ^{226}Ra. Details are in the Supplemental Material [34]. Values determined with a precision better than 25% are in boldface and those compatible with zero are in italics.

	a_0	a_1	a_2	b_1	b_2
^{221}Rn	*−0.04(10)*	**−1.7(3)**	**0.67(10)**	−0.015(5)	−0.007(4)
^{223}Rn	*−0.08(8)*	**−2.4(4)**	**0.86(10)**	−0.031(9)	*−0.008(8)*
^{223}Fr	*0.07(20)*	*−0.8(7)*	*0.05(40)*	0.018(8)	−0.016(10)
^{225}Ra	*0.2(6)*	−5(3)	3.3(1.5)	*−0.01(3)*	0.03(2)
^{229}Pa	**−1.2(3)**	*−0.9(9)*	*−0.3(5)*	**0.036(8)**	0.032(18)
^{227}Ac	4.4(10)	−14.0(18)	8.3(31)	−0.2(2)	0.3(3)

J. Dobaczewski *et al.*, PRL **121**, 232501 (2018) and the supplemental material

M. Athanasakis-Kaklamanakis, *et al.*, Nature 648, 562-568 (2025)

Summary and Outlook

Summary

Outlook

Summary and Outlook

Summary

★ There is a strong correlation between the intrinsic nuclear Schiff moment of ^{227}Ac and the intrinsic octupole moment of ^{226}Ra.

Outlook

Summary and Outlook

Summary

- ★ There is a strong correlation between the intrinsic nuclear Schiff moment of ^{227}Ac and the intrinsic octupole moment of ^{226}Ra.
- ★ The obtained value of the intrinsic nuclear Schiff moment of ^{227}Ac is 37.1 ± 1.6 e fm^3.

Outlook

Summary and Outlook

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Outlook

- To find different observables that have a strong correlation with the nuclear Schiff moment.
- Adding nucleon piece of Schiff operator:

$$\mathbf{S}^n = \frac{1}{6}\sum_{i=1}^{A}\left(r_i^2 - \langle r^2\rangle_{\mathrm{ch}}\right)\mathbf{d}_i$$

$$S_{\mathrm{lab}} = a_0 g\bar{g}_0 + a_1 g\bar{g}_1 + a_2 g\bar{g}_2 + b_1\bar{c}_1 + b_2\bar{c}_2 + a_p d_p + a_n d_n$$

J. Engel, Ann. Rev. Nucl. Part. Sci. 75, 129 (2025)

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Back Up Slides

EDM and Fundamental Symmetries

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- The necessity of parity symmetry breaking

EDM and Fundamental Symmetries

★ The necessity of parity symmetry breaking

$$\langle \hat{\mathbf{d}} \rangle \equiv \langle jm | \hat{\mathbf{d}} | jm \rangle$$

$$\hat{\pi}^{-1} = \hat{\pi}^{\dagger} = \hat{\pi}$$

$$\hat{\pi} | jm \rangle \equiv \hat{\pi} | n\ell jm \rangle = (-1)^{\ell} | n\ell jm \rangle, \quad \ell = 0,\ 1,\ 2,\ \ldots,\ n$$

$$\langle \hat{\mathbf{d}} \rangle = \langle jm | \hat{\pi}^{\dagger} \hat{\pi} \hat{\mathbf{d}} \hat{\pi}^{\dagger} \hat{\pi} | jm \rangle = (-1)^{2\ell} \langle jm | (-\hat{\mathbf{d}}) | jm \rangle = -\langle \hat{\mathbf{d}} \rangle$$

$$\langle \hat{\mathbf{d}} \rangle = 0.$$

★ The necessity of time-reversal symmetry breaking

★ The necessity of time-reversal symmetry breaking

$$|\widetilde{\alpha}\rangle = \hat{\Theta}|\alpha\rangle \quad \text{and} \quad |\widetilde{\beta}\rangle = \hat{\Theta}|\beta\rangle$$

$$\langle\widetilde{\beta}|\widetilde{\alpha}\rangle = \langle\beta|\alpha\rangle^* = \langle\alpha|\beta\rangle$$

$$\langle\beta|\hat{A}|\alpha\rangle = \langle\widetilde{\alpha}|\hat{\Theta}\hat{A}^\dagger\hat{\Theta}^{-1}|\widetilde{\beta}\rangle = \langle\widetilde{\alpha}|\hat{\Theta}\hat{A}\hat{\Theta}^{-1}|\widetilde{\beta}\rangle$$

$$\langle\alpha', jm'|\hat{V}_q|\alpha, jm\rangle = \frac{\langle\alpha', jm|\hat{\mathbf{J}}\cdot\hat{\mathbf{V}}|\alpha, jm\rangle}{\hbar^2 j(j+1)}\langle jm'|\hat{J}_q|jm\rangle$$

$$\langle jm|\hat{\mathbf{d}}|jm\rangle = c\langle jm|\hat{\mathbf{J}}|jm\rangle, \quad c \text{ is a real constant and } m\text{-independent.}$$

$$\langle jm'|\hat{\mathbf{d}}\cdot\hat{\mathbf{J}}|jm\rangle = \frac{\langle jm00|jm'\rangle}{\sqrt{2j+1}}\langle j||\hat{\mathbf{d}}\cdot\hat{\mathbf{J}}||j\rangle = \delta_{mm'}\frac{\langle j||\hat{\mathbf{d}}\cdot\hat{\mathbf{J}}||j\rangle}{\sqrt{2j+1}}$$

$$\begin{aligned}
\langle jm|\hat{\mathbf{d}}|jm\rangle &= \langle\widetilde{jm}|\hat{\Theta}\hat{\mathbf{d}}\hat{\Theta}^{-1}|\widetilde{jm}\rangle = +\langle\widetilde{jm}|\hat{\mathbf{d}}|\widetilde{jm}\rangle = (-1)^{2(j-m)}\langle j(-m)|\hat{\mathbf{d}}|j(-m)\rangle \\
\langle jm|\hat{\mathbf{J}}|jm\rangle &= \langle\widetilde{jm}|\hat{\Theta}\hat{\mathbf{J}}\hat{\Theta}^{-1}|\widetilde{jm}\rangle = -\langle\widetilde{jm}|\hat{\mathbf{J}}|\widetilde{jm}\rangle = -(-1)^{2(j-m)}\langle j(-m)|\hat{\mathbf{J}}|j(-m)\rangle \\
\langle j(-m)|\hat{\mathbf{d}}|j(-m)\rangle &= -c\langle j(-m)|\hat{\mathbf{J}}|j(-m)\rangle \\
|\widetilde{jm}\rangle &= (-1)^{j-m}|j(-m)\rangle \\
\langle jm|\hat{\mathbf{d}}|jm\rangle &= -c\langle jm|\hat{\mathbf{J}}|jm\rangle \\
\langle jm|\hat{\mathbf{d}}|jm\rangle &= 0
\end{aligned}$$

$$\langle jm|\hat{\mathbf{d}}|jm\rangle = \langle\widetilde{jm}|\hat{\Theta}\hat{\mathbf{d}}\hat{\Theta}^{-1}|\widetilde{jm}\rangle = +\langle\widetilde{jm}|\hat{\mathbf{d}}|\widetilde{jm}\rangle = (-1)^{2(j-m)}\langle j(-m)|\hat{\mathbf{d}}|j(-m)\rangle$$

$$\langle jm|\hat{\mathbf{J}}|jm\rangle = \langle\widetilde{jm}|\hat{\Theta}\hat{\mathbf{J}}\hat{\Theta}^{-1}|\widetilde{jm}\rangle = -\langle\widetilde{jm}|\hat{\mathbf{J}}|\widetilde{jm}\rangle = -(-1)^{2(j-m)}\langle j(-m)|\hat{\mathbf{J}}|j(-m)\rangle$$

$$\langle j(-m)|\hat{\mathbf{d}}|j(-m)\rangle = -c\langle j(-m)|\hat{\mathbf{J}}|j(-m)\rangle$$

$$|\widetilde{jm}\rangle = (-1)^{j-m}|j(-m)\rangle$$

$$\langle jm|\hat{\mathbf{d}}|jm\rangle = -c\langle jm|\hat{\mathbf{J}}|jm\rangle$$

$$\langle jm|\hat{\mathbf{d}}|jm\rangle = 0$$

★ Therefore, the non-zero $\langle\hat{\mathbf{d}}\rangle$ requires parity and time-reversal symmetry to be broken simultaneously.

Schiff Theorem

$$\hat{H}_{\text{atom}} = \hat{H}_{\text{el.}} + \hat{H}_{\text{nucl.}} - \sum_a e\varphi(\mathbf{R}_a)$$

$$\varphi(\mathbf{R}) = \int d^3x \, \frac{e\rho(\mathbf{r})}{|\mathbf{R} - \mathbf{r}|}$$

$$\hat{H}_{\text{ext.}} = e\sum_a \mathbf{R}_a \cdot \mathbf{E}_0 - \hat{\mathbf{d}} \cdot \mathbf{E}_0$$

$$\hat{\mathcal{H}} = \hat{H}_{\text{atom}} + \hat{H}_{\text{ext.}} = \hat{H}_{\text{atom}} + e\sum_a \mathbf{R}_a \cdot \mathbf{E}_0 - \hat{\mathbf{d}} \cdot \mathbf{E}_0$$

$$\hat{\mathcal{H}}' = e^{i\hat{U}}\hat{\mathcal{H}}e^{-i\hat{U}} \approx \hat{\mathcal{H}} + i[\hat{U}, \hat{\mathcal{H}}]$$

$$\hat{U} = \frac{\langle \hat{\mathbf{d}} \rangle}{Ze} \cdot \sum_a \hat{\mathbf{P}}_a$$

N. Auerbach and V. Zelevinsky, J. Phys. G: Part. Nucl. Phys. **35**, 093101 (2008)

$$i[\hat{U}, \hat{\mathcal{H}}] = \frac{1}{Z}\langle \hat{\mathbf{d}} \rangle \cdot [\mathbf{E}_e + Z\mathbf{E}_0]$$

$$\mathbf{E}_e \equiv -\sum_a \boldsymbol{\nabla}_a \varphi(\mathbf{R}_a) \equiv \text{Electric field on nucleus generated by electrons.}$$

$$\langle \Psi | [\hat{U}, \hat{\mathcal{H}}] | \Psi \rangle = \langle \Psi | \hat{U} \hat{\mathcal{H}} | \Psi \rangle - \langle \Psi | \hat{\mathcal{H}} \hat{U} | \Psi \rangle \propto (E - E) = 0$$

$$Z\mathbf{E}_0 + \langle \mathbf{E}_e \rangle = 0 \rightarrow \langle \mathbf{E}_e \rangle = -Z\mathbf{E}_0 \quad \text{(Schiff theorem)}$$

$$\begin{aligned} \hat{\mathcal{H}}' &= \hat{H}_{\text{atom}} + \hat{H}_{\text{ext.}} + i[\hat{U}, \hat{\mathcal{H}}] \\ &= \hat{H}_{\text{atom}} + \hat{H}_{\text{ext.}} - (\hat{\mathbf{d}} - \langle \hat{\mathbf{d}} \rangle) \cdot \mathbf{E}_0 + e \sum_a \mathbf{R}_a \cdot \mathbf{E}_0 + \sum_a e\varphi'(\mathbf{R}_a) \end{aligned}$$

$$\varphi'(\mathbf{R}_a) = \varphi(\mathbf{R}_a) + \frac{1}{Ze}\langle \hat{\mathbf{d}} \rangle \cdot \boldsymbol{\nabla}_a \varphi(\mathbf{R}_a)$$

N. Auerbach and V. Zelevinsky, J. Phys. G: Part. Nucl. Phys. **35**, 093101 (2008)

Linear Regression Analysis

$$\chi^2 = \sum_i \left[S_0(i) - a - bQ_0^3(i)\right]^2$$

$$\bar{b} = \frac{\langle S_0 Q_0^3\rangle - \langle S_0\rangle\langle Q_0^3\rangle}{\langle [Q_0^3(i)]^2\rangle - \langle Q_0^3\rangle^2}$$

$$\bar{a} = \langle S_0\rangle - \bar{b}\langle Q_0^3\rangle$$

$$\langle S_0\rangle = \frac{1}{N_d}\sum_i S_0(i), \quad \langle Q_0^3\rangle = \frac{1}{N_d}\sum_i Q_0^3(i),$$

$$\langle S_0 Q_0^3\rangle = \frac{1}{N_d}\sum_i S_0(i) Q_0^3(i), \quad \langle [Q_0^3(i)]^2\rangle = \frac{1}{N_d}\sum_i \left[Q_0^3(i)\right]^2$$

$$s = \frac{\chi_0^2}{N_d - N_p} \qquad \mathcal{C} = s\mathcal{M}^{-1} \qquad \mathcal{M}_{ij} = \frac{1}{2}\frac{\partial}{\partial p_i}\frac{\partial}{\partial p_j}\chi^2\bigg|_{\mathbf{p}=\bar{\mathbf{p}}}$$

$$\mathcal{C}_{aa} = \frac{s}{N_d}\frac{\langle [Q_0^3]^2\rangle}{\langle [Q_0^3]^2\rangle - \langle Q_0^3\rangle^2},$$

$$\mathcal{C}_{ab} = \mathcal{C}_{ba} = -\frac{s}{N_d}\frac{\langle Q_0^3\rangle}{\langle [Q_0^3]^2\rangle - \langle Q_0^3\rangle^2}$$

$$\mathcal{C}_{bb} = \frac{s}{N_d}\frac{1}{\langle [Q_0^3]^2\rangle - \langle Q_0^3\rangle^2}.$$

J. Dobaczewski et al., J. Phys. G: Nucl. Part. Phys. **41**, 074001 (2014)

Different definitions of octuple moment

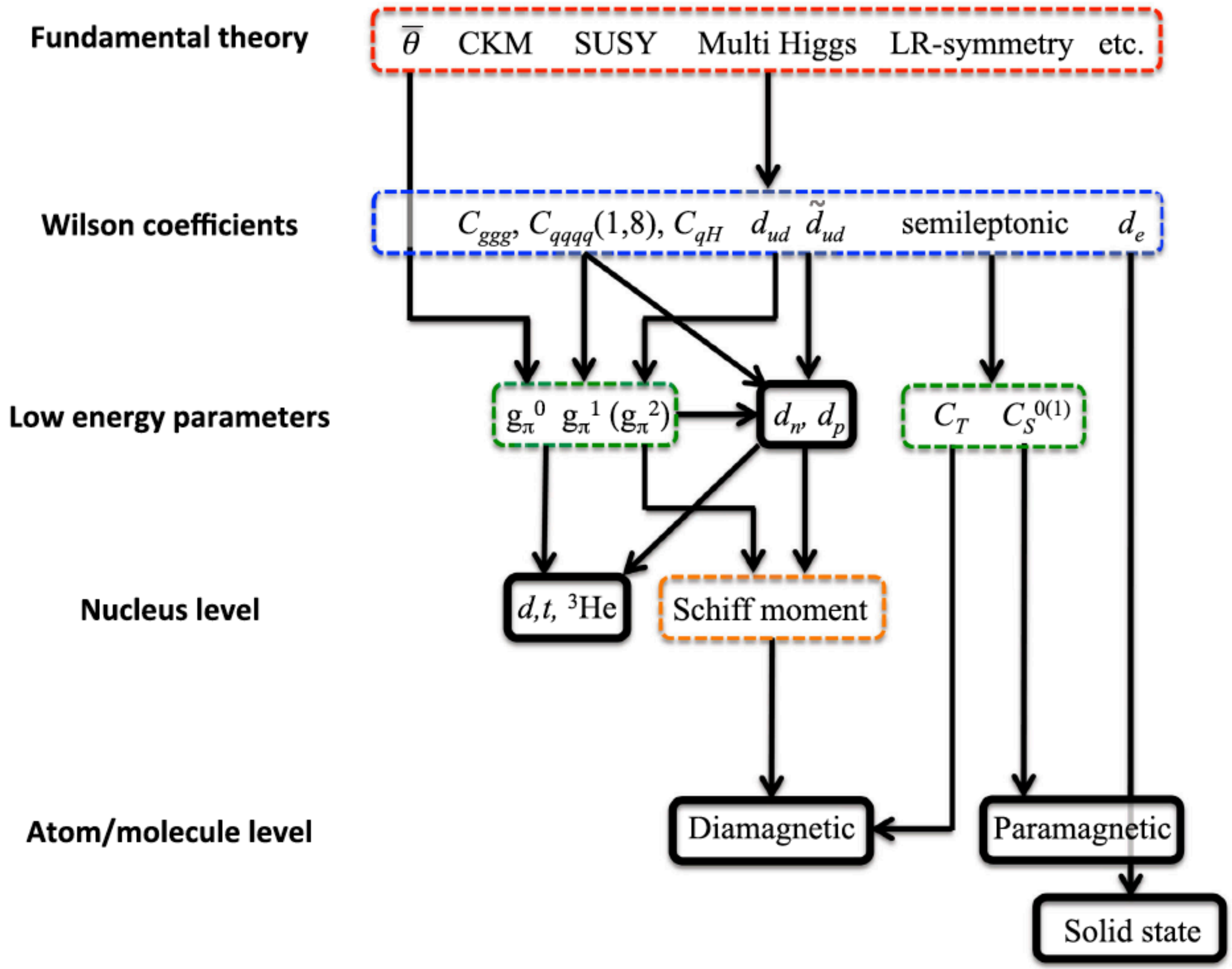
$$Q_0^3 = e\sqrt{\frac{16\pi}{7}}\sum_p r_p^3 Y_0^3(\Omega_p)$$ (definition 1)

$$\hat{Q}_0^3 = e\sum_p r_p^3 Y_0^3(\Omega_p)$$ (definition 2)

$$\begin{aligned} Q_0^3(\mathrm{exp}) &= 810(50)\ \mathrm{e\ fm}^3 \quad (^{220}\mathrm{Rn}) \\ &= 940(30)\ \mathrm{e\ fm}^3 \quad (^{224}\mathrm{Ra}) \\ &= 1080(30)\ \mathrm{e\ fm}^3 \quad (^{226}\mathrm{Ra}) \end{aligned}$$

L. P. Gaffney *et al.*, Nature (London) **497**, 199 (2013)

H. Wollersheim *et al.*, Nucl. Phys. A **556**, 261 (1993)



Chupp *et al.*, Rev. Mod. Phys. **91**, 015001 (2019)