Examples of Nucleon Correlations Effects on Nuclear Structure and Reactions

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APCTP Focus Program in Nuclear Physic 2019,
Pohang, Republic of Korea

Some Examples:

- Nucleon momentum distributions
- Spectral functions
- Natural orbitals
- Overlap functions (one- and two- body)
- (*p,d*), (*e,e'p*), (*e,e'pp*) reactions
- Exotic nuclei (structure)
- Exotic nuclei (processes)
- Superscaling in electron- and neutrino(antineutrino)–nuclei scattering
- Information on the nucleon momentum distribution from the scaling function

Theoretical Correlation Methods Used:

- The Coherent Density Fluctuation Model (CDFM) [Sofia, 1979-till now]

  based on the delta-function approximation for the overlap and energy kernels of the Generator Coordinate Method

- The Generator Coordinate Method

- The Jastrow Correlation Method

- The Natural Orbital and Overlap Functions Representations

- The Nuclear Density Functional Theory

…and others

Coherent Density Fluctuation Model (CDFM)

- A.N. Antonov, I.Zh. Petkov, V. Nikolaev, P.E. Hodgson (1979, 1980, 1982, 1985, 1988, 1993, ...)

$$\rho(\mathbf{r},\mathbf{r}') = \int_0^\infty dx |\mathcal{F}(x)|^2 \rho_x(\mathbf{r},\mathbf{r}') \tag{1}$$

$$\rho_x(\mathbf{r},\mathbf{r}') = 3\rho_0(x) \frac{j_1(k_F(x)|\mathbf{r}-\mathbf{r}'|)}{(k_F(x)|\mathbf{r}-\mathbf{r}'|)} \Theta\left(x - \frac{|\mathbf{r}+\mathbf{r}'|}{2}\right) \tag{2}$$

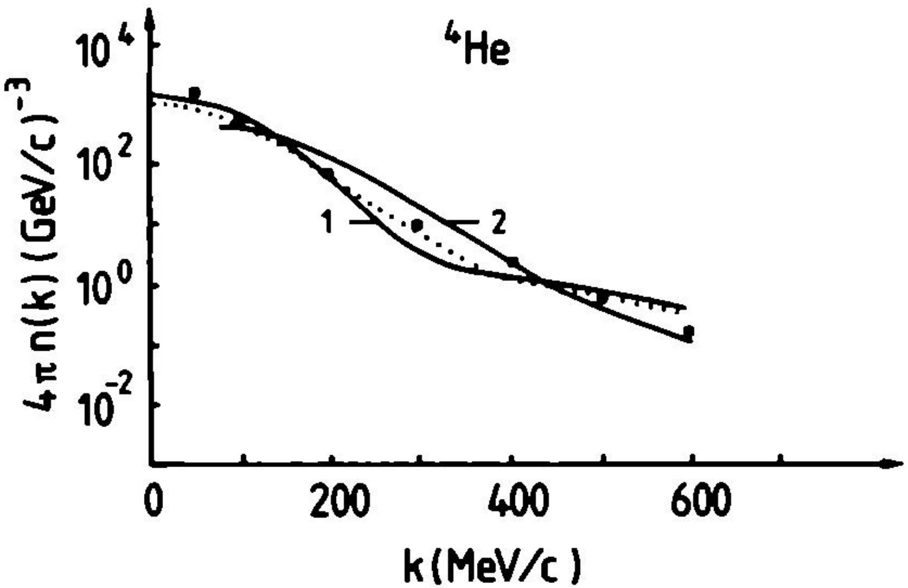
$$k_F(x) = \left(\frac{3\pi^2}{2}\rho_0(x)\right)^{1/3} \equiv \frac{\beta}{x}; \quad \rho_0(x) = \frac{3A}{4\pi x^3} \tag{3}$$

$$\beta = \left(\frac{9\pi A}{8}\right)^{1/3} \simeq 1.52 A^{1/3} \tag{4}$$

$$\rho(\mathbf{r}) = \int_0^\infty dx |\mathcal{F}(x)|^2 \rho_0(x) \Theta(x - |\mathbf{r}|) \tag{5}$$

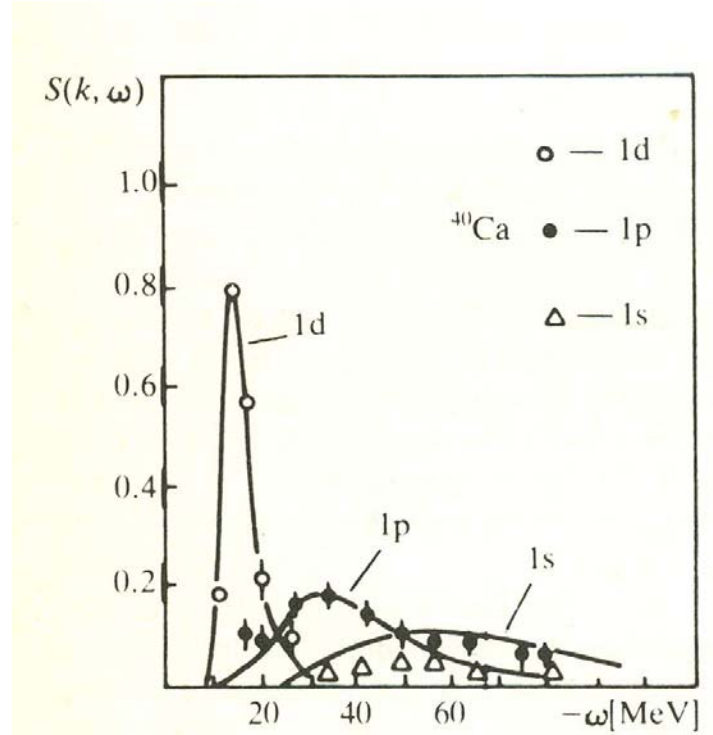
$$|\mathcal{F}(x)|^2 = -\frac{1}{\rho_0(x)} \left.\frac{d\rho(r)}{dr}\right|_{r=x}; \quad \left(\frac{d\rho}{dr} \leq 0\right); \quad \int_0^\infty dx |\mathcal{F}(x)|^2 = 1 \tag{6}$$

$$n(\mathbf{k}) = \int_0^\infty dx |\mathcal{F}(x)|^2 \frac{4}{3}\pi x^3 \Theta(k_F(x) - |\mathbf{k}|) \tag{7}$$



Nucleon momentum distribution for ^{4}He: the black squares are the exp. data, the exp (S)-method (dotted line), the correlation method of Akaishi (curve 1) and the CDFM (curve 2).
Normalization: $\int n(\mathbf{k})d\mathbf{k}=1$

Bulg. J. Phys. **13**, 110 (1986)



Spectral functions for ^{40}Ca in CDFM

Z. Phys. A **304**, 239 (1982)

Natural Orbitals

- Löwdin (1955)

$$\rho(\mathbf{r},\mathbf{r}') = \sum_\alpha N_\alpha \psi^*_\alpha(\mathbf{r})\psi_\alpha(\mathbf{r}') \tag{1}$$

$$0 \le N_\alpha \le 1, \quad \sum_\alpha N_\alpha = A \tag{2}$$

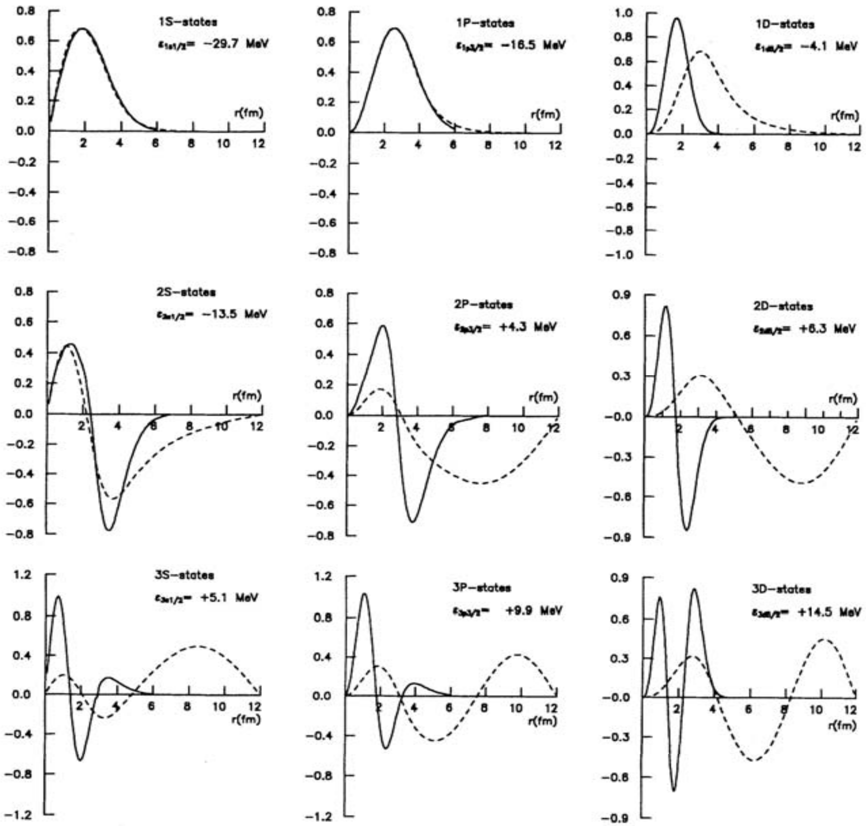
$$\rho(\mathbf{r}) = \sum_\alpha N_\alpha |\psi_\alpha(\mathbf{r})|^2 \tag{3}$$

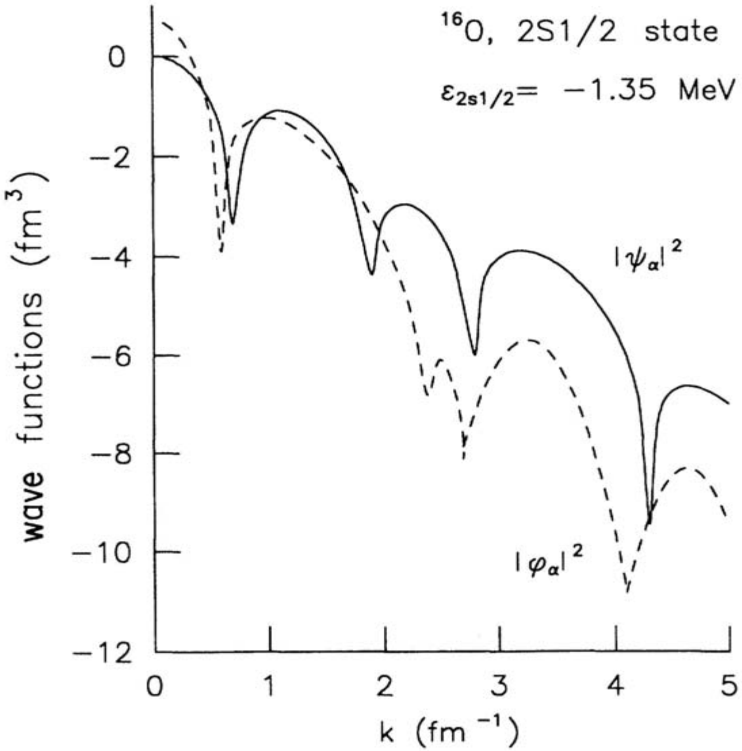
$$n(\mathbf{k}) = \sum_\alpha N_\alpha |\psi_\alpha(\mathbf{k})|^2 \tag{4}$$

$\{\psi_\alpha(\mathbf{r})\}$: complete orthonormal set

$$\int \rho(\mathbf{r},\mathbf{r}')\psi_\alpha(\mathbf{r}')d\mathbf{r}' = N_\alpha\psi_\alpha(\mathbf{r}) \tag{5}$$

$$\int \rho(\mathbf{k},\mathbf{k}')\psi_\alpha(\mathbf{k}')d\mathbf{k}' = N_\alpha\psi_\alpha(\mathbf{k}) \tag{6}$$





Phys. Rev. C **48**, 74 (1993)

Overlap Functions

- One-body overlap functions

$$\phi_\alpha(\mathbf{r}) = \left\langle \Psi_\alpha^{(A-1)} \middle| a(\mathbf{r}) \middle| \Psi^{(A)} \right\rangle \tag{1}$$

Spectroscopic factor:

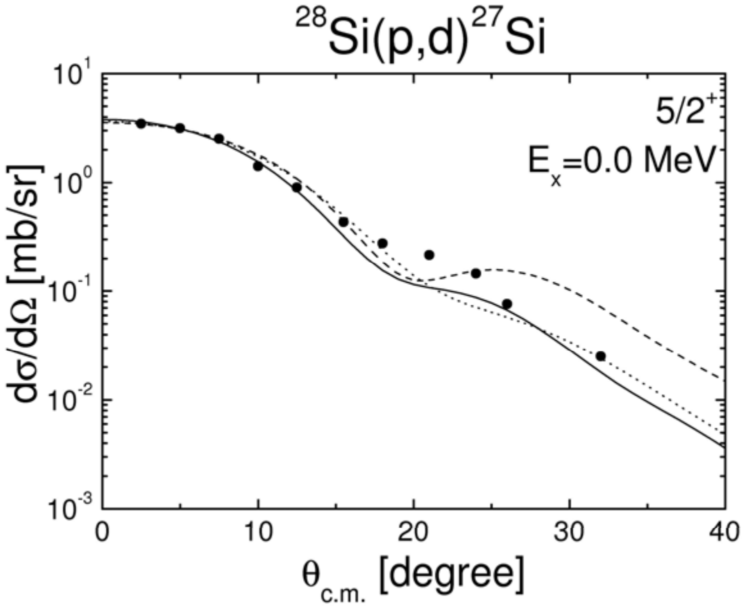
$$S_\alpha = \langle \phi_\alpha | \phi_\alpha \rangle \tag{2}$$

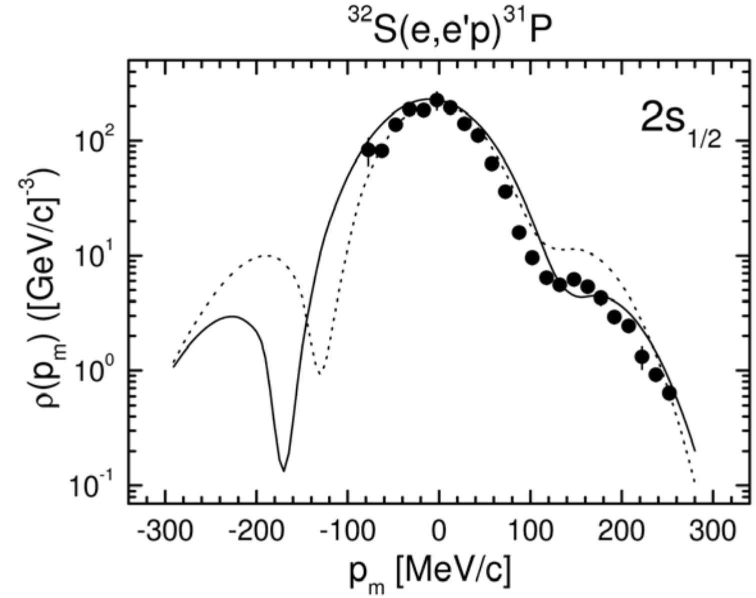
$$\tilde{\phi}_\alpha(\mathbf{r}) = S_\alpha^{-1/2} \phi_\alpha(\mathbf{r}) \tag{3}$$

$$\rho(\boldsymbol{r}, \boldsymbol{r}') = \sum_\alpha \phi_\alpha^*(\boldsymbol{r}) \phi_\alpha(\boldsymbol{r}') = \sum_\alpha S_\alpha \tilde{\phi}_\alpha^*(\boldsymbol{r}) \tilde{\phi}_\alpha(\boldsymbol{r}') \tag{4}$$

D. Van Neck *et al.*, Phys. Lett. B **314**, 255 (1993):

$$\phi_{n_0lj}(r) = \frac{\rho_{lj}(r, a)}{C_{n_0lj}\ \exp(-k_{n_0lj}\, a)/a} \tag{5}$$





Phys. Rev. C **66**, 064308 (2002)

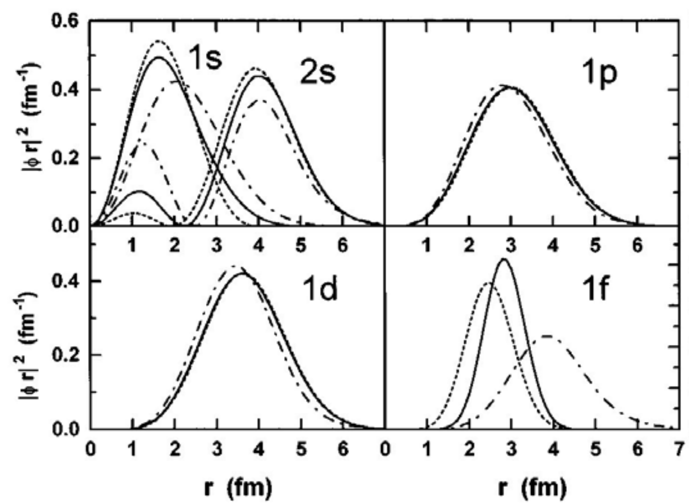


FIG. 1. Overlap functions (solid line), self-consistent Hartree-Fock single-particle wave functions (dot-dashed line), and natural orbitals (dashed line) for the nucleus ^{40}Ca.

Phys. Rev. C **53**, 1254 (1996)

$$\Phi_{\alpha_0 JSLlL_R}(r,R) = \frac{\rho^{(2)}_{JSLlL_R}(r,R;a,b)}{\Phi_{\alpha_0 JSLlL_R}(a,b)} \tag{25}$$

$$= \frac{\rho^{(2)}_{JSLlL_R}(r,R;a,b)}{N\exp\{-k\sqrt{[b^2+(1/4)a^2]}\}[b^2+(1/4)a^2]^{-5/2}}. \tag{26}$$

Phys. Rev. C **59**, 722 (1999)

Removal of $^1S_0$ and $^3P_1$ (pp) pairs from $^{16}O(e,e'pp)^{14}C_{g.s.}$

Partial waves: $^{2S+1}l_L; \quad \vec{L} = \vec{l} + \vec{L_R}$

Phys. Rev. C **68**, 014617 (2003)

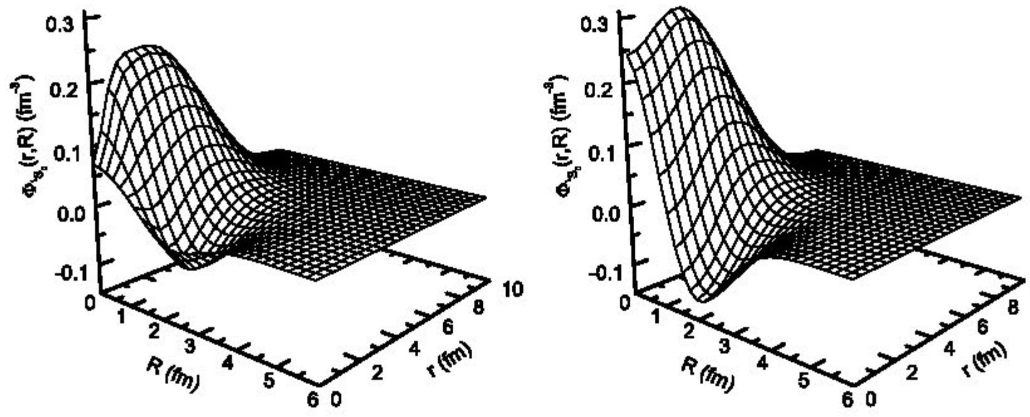


FIG. 1. The $^1S_0$ two-proton overlap functions for the nucleus ^{16}O leading to the 0^+ ground state of ^{14}C extracted from the JCM (left) and uncorrelated (right) two-body density matrices.

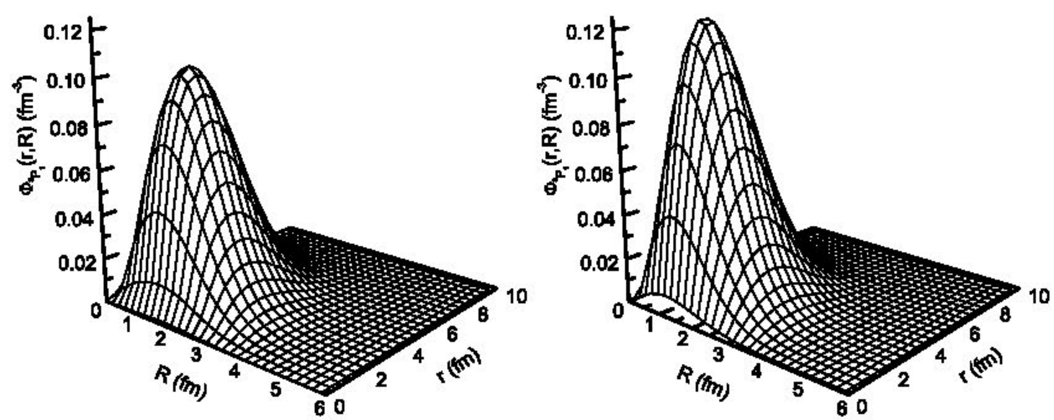
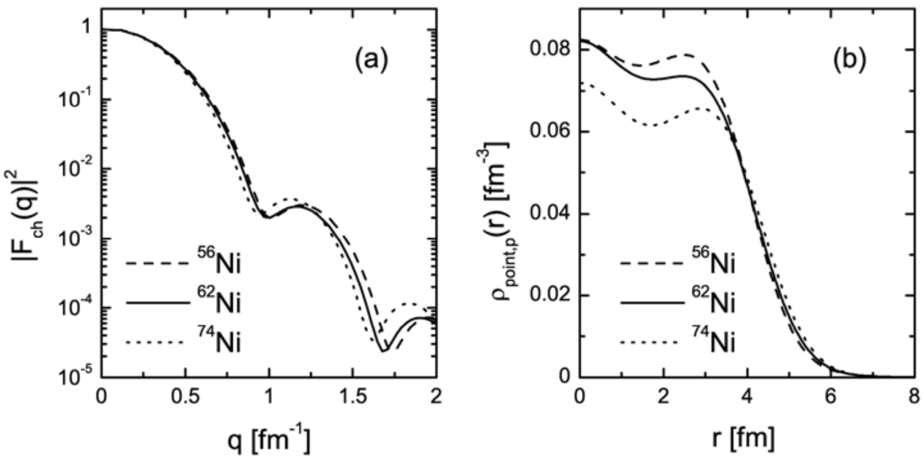
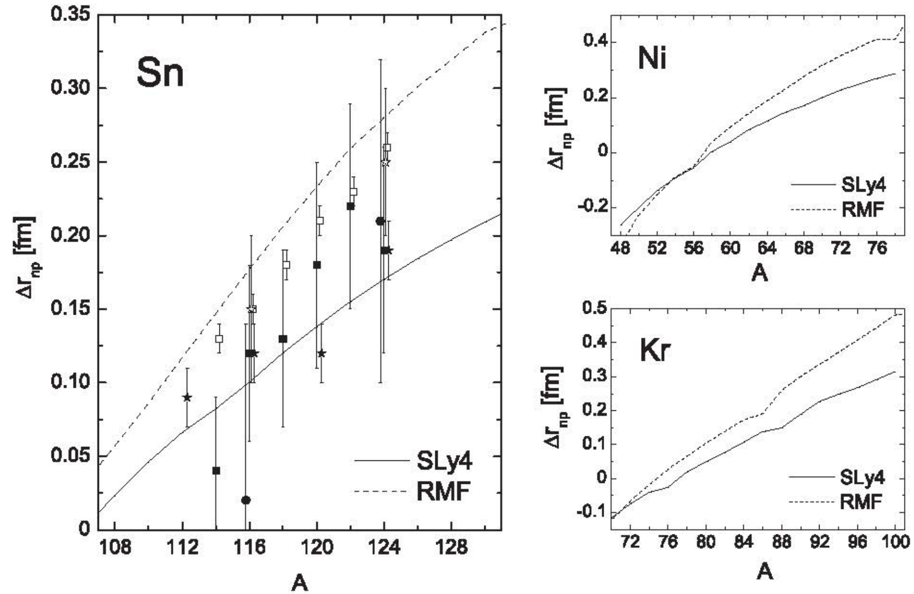


FIG. 2. The $^3P_1$ two-proton overlap functions for the nucleus ^{16}O leading to the 0^+ ground state of ^{14}C extracted from the JCM (left) and uncorrelated (right) two-body density matrices.

Exotic Nuclei (Structure)



Phys. Rev C **72**, 044307 (2005)



Phys. Rev. C **76**, 044322 (2007)

Exotic Nuclei (processes)

Microscopic optical potential; elastic scattering; breakup reactions

$$U_{opt}(r) = N_R V^F(r) + i N_I W^H(r) \tag{1}$$

1. Direct and exchange parts of the real OP (ReOP)

Folding:

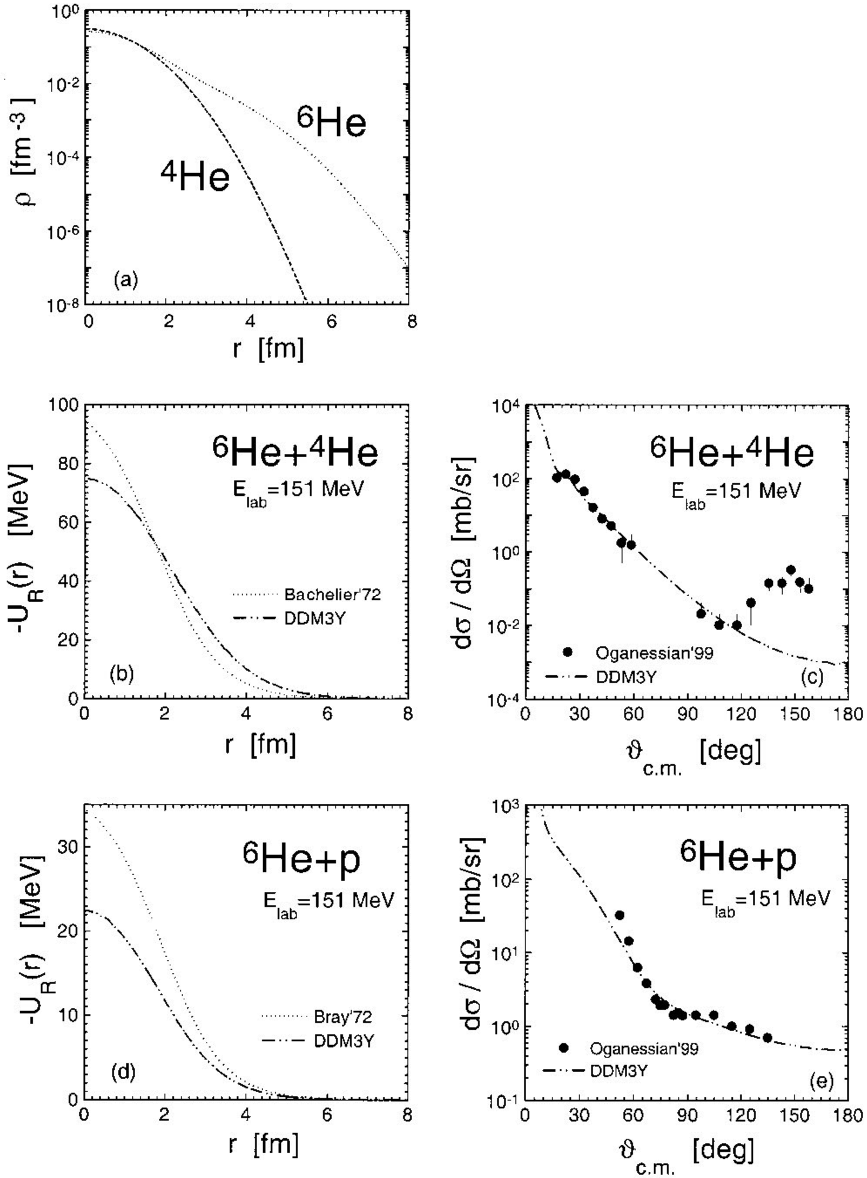
$$V^F(r) = V^D(r) + V^{EX}(r) \tag{2}$$

$V^D_{IS}, V^D_{IV}, V^{EX}_{IS}, V^{EX}_{IV}$

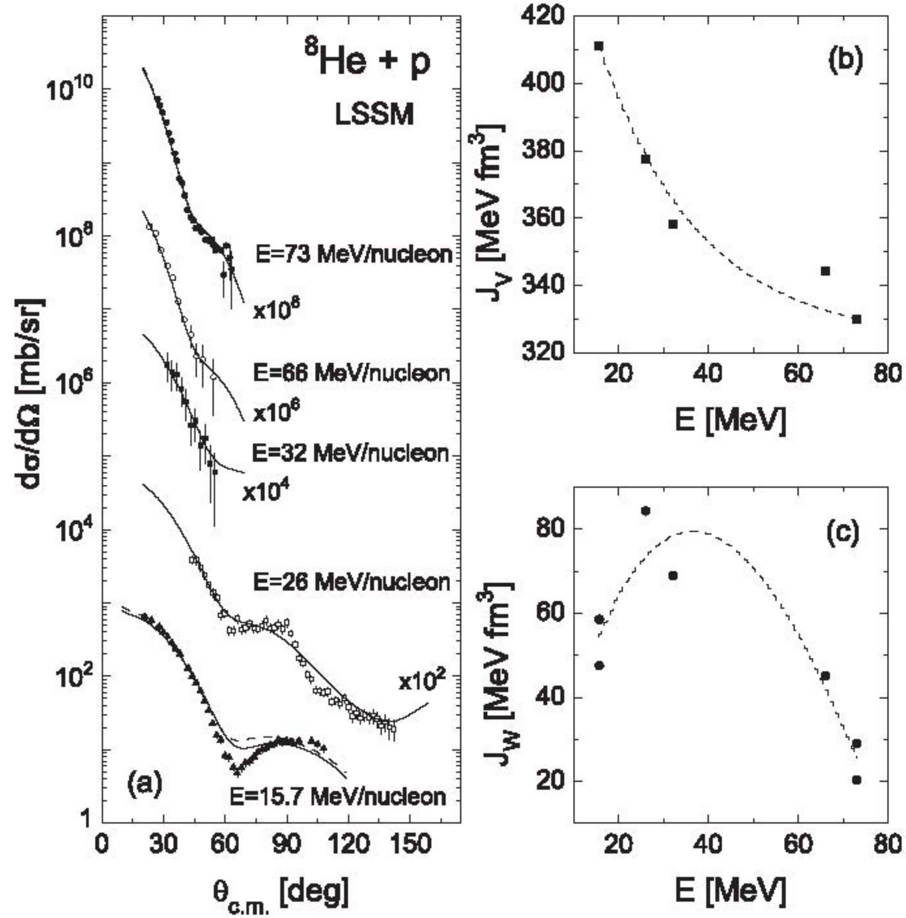
$v^D_{(00)(01)}(\rho, E), v^{EX}_{(00)(01)}(\rho, E)$ – M3Y effective interactions

2. Imaginary part of the OP (ImOP) within the high-energy approximation

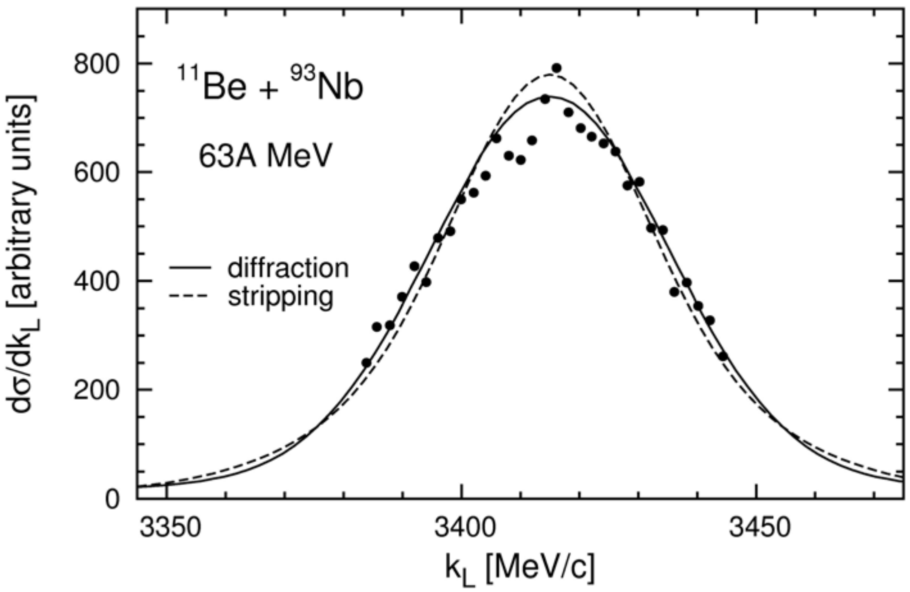
$$W^H(r) = -\frac{1}{2\pi^2}\frac{E}{k}\bar{\sigma}_{NN}\int_0^\infty j_0(qr)\rho_p(q)\rho_t(q)f_{NN}(q)q^2 dq \tag{3}$$



M. Avrigeanu *et al.*, Phys. Rev. C **62**, 017001 (2000)

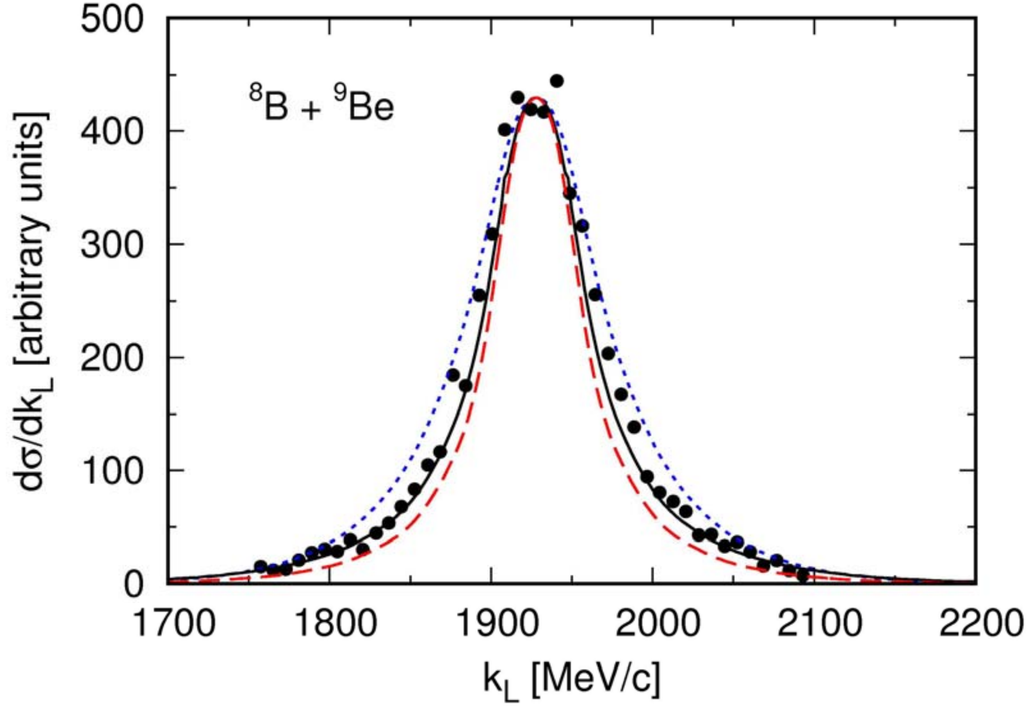


Phys. Rev. C **80**, 024609 (2009)



Phys. Rev. C **91**, 034606 (2015)

Eur. Phus J A **53**, 31 (2017)



Superscaling in Electron- and Neutrino- Nuclei Scattering

PWIA; $(e, e\prime N)$:

$$\left[\frac{d\sigma}{d\epsilon' d\Omega' dp_N d\Omega_N}\right]^{PWIA}_{(e,e'N)} = K\sigma^{eN}(q,\omega;p,\mathcal{E},\phi_N)S(p,\mathcal{E}) \tag{1}$$

$$F(q,\omega) \cong \frac{[d\sigma/d\epsilon' d\Omega']_{(e,e')}}{\overline{\sigma}^{eN}(q,\omega;p=|y|,\mathcal{E}=0)} \tag{2}$$

RFG:

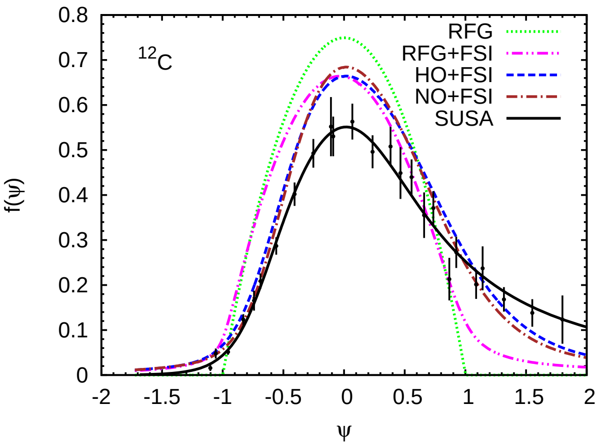
$$f_{\mathrm{RFG}}(\psi') \simeq \frac{3}{4}\left(1-\psi'^2\right)\theta\left(1-\psi'^2\right) \tag{3}$$

$$S(p,\mathcal{E}) = \sum_i 2(2j_i+1)n_i(p)L_{\Gamma_i}(\mathcal{E}-\mathcal{E}_i); \tag{4}$$

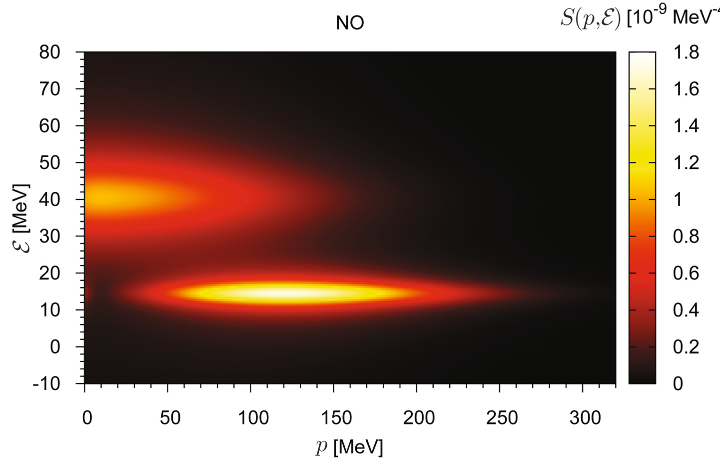
$$L_{\Gamma_i}(\mathcal{E}-\mathcal{E}_i) = \frac{1}{\pi}\frac{\Gamma_i/2}{(\mathcal{E}-\mathcal{E}_i)^2+(\Gamma_i/2)^2}; \tag{5}$$

$$(\Gamma_{1p} = 6 \text{ MeV and } \Gamma_{1s} = 20 \text{ MeV})$$

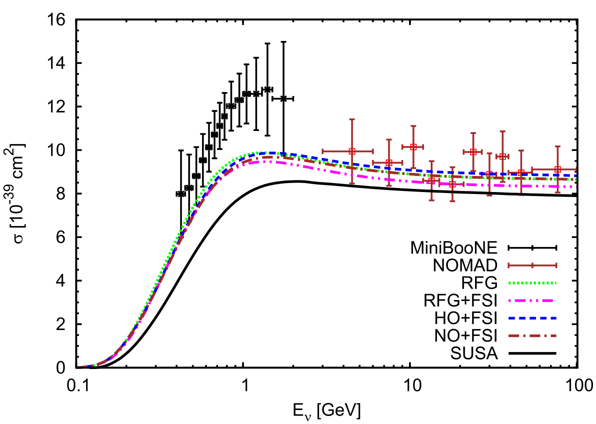
$$\rho(\mathbf{r},\mathbf{r}') = \sum_\alpha N_\alpha \varphi^*_\alpha(\mathbf{r})\varphi_\alpha(\mathbf{r}');\ \left[0 \le N_\alpha \le 1; \sum_\alpha N_\alpha = A\right]; \tag{6}$$



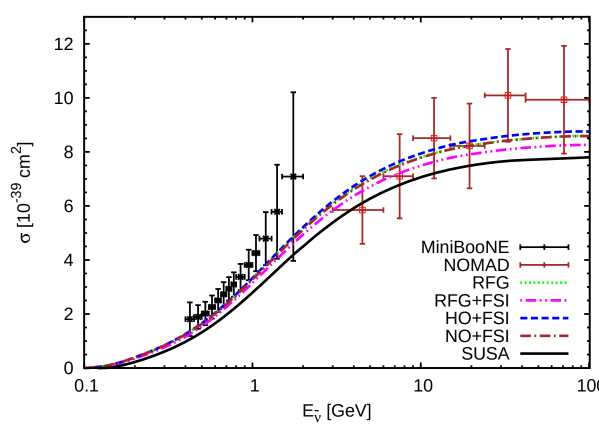
Phys. Rev. C **89**, 014607 (2014)



Phys. Rev. C **91**, 034607 (2015)



Phys. Rev. C **89**, 014607 (2014)



Phys. Rev. C **89**, 014607 (2014)

Information on the nucleon momentum distributions from the scaling function

– Amado, Woloshyn (1976–77):

$$n(k) \xrightarrow[k\to\infty]{} \left[\frac{\widetilde{V}_{\rm NN}(k)}{k^2}\right]^2 \qquad (1)$$

(unknown if k or k/A must be large)

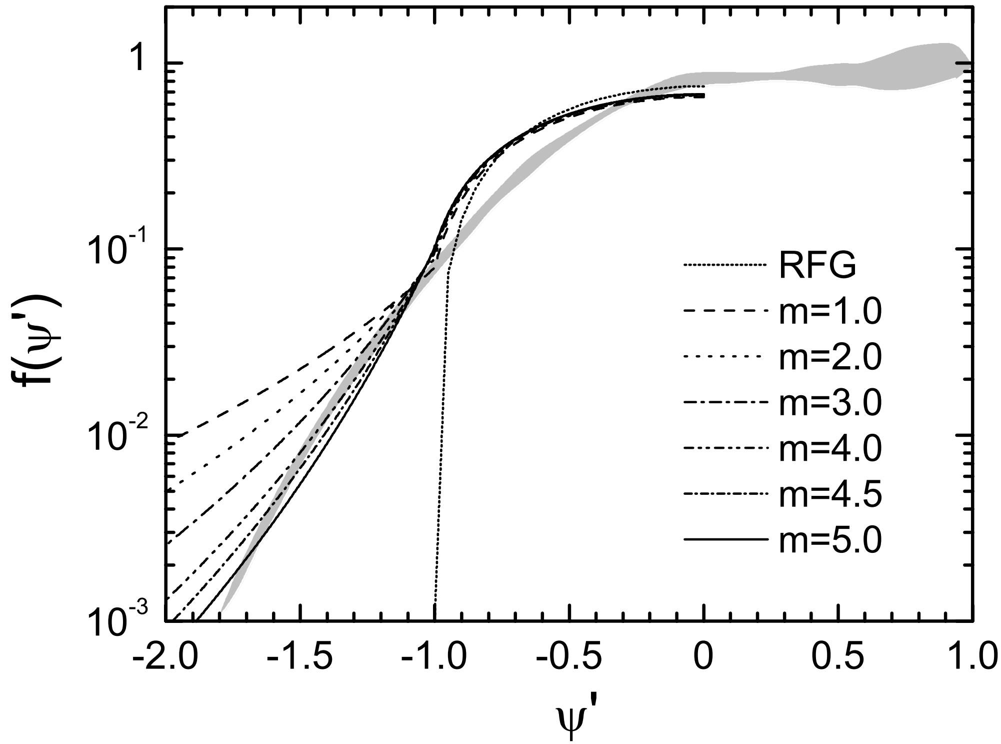
$$f(\psi') = 0.12\left(\frac{1+m}{2+m}\right)\frac{1}{|\psi'|^{2+m}} \qquad (2)$$

$$n(k) \sim \frac{1}{k^{4+m}}; \quad \text{Results: } m \simeq 4.5 \qquad (3)$$

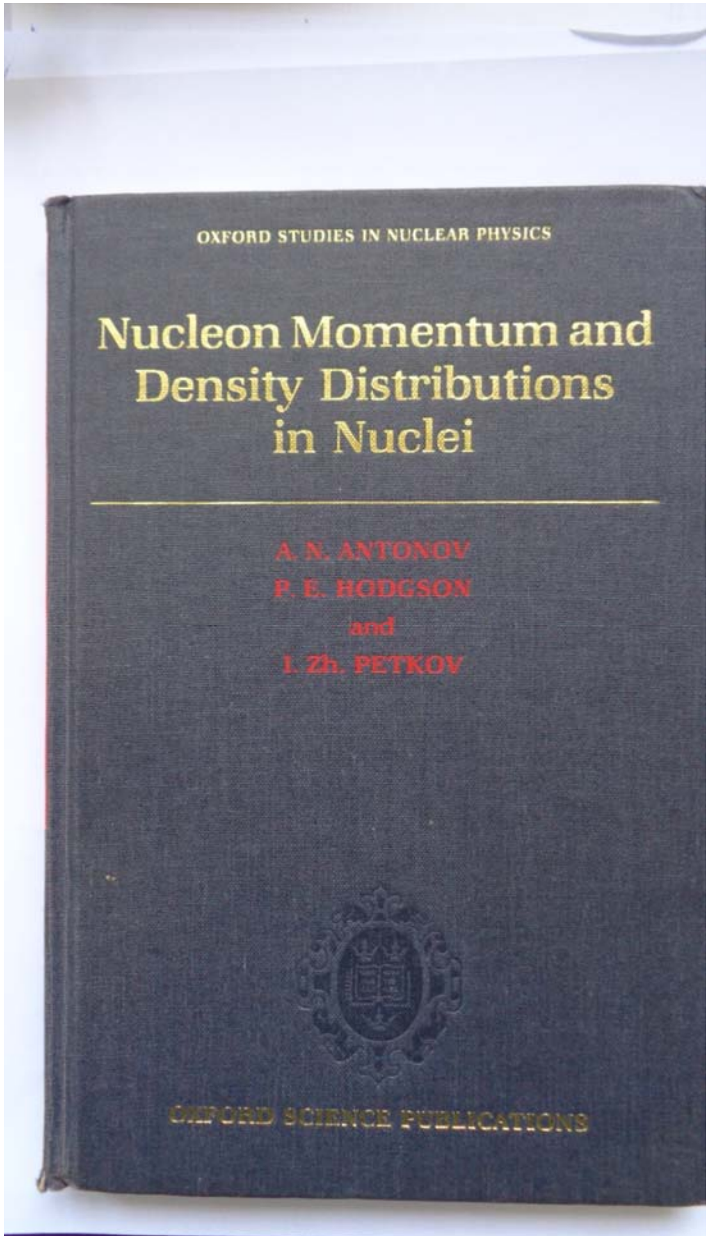
For $m = 4$ $\qquad V_{NN}(r) \sim \frac{1}{r} \quad (\text{at } r \to 0)$

For $m = 5$ $\qquad V_{NN}(r) \sim \frac{1}{r^{1/2}} \quad (\text{at } r \to 0)$

Phys. Rev. C **75**, 034319 (2007)



$f(\psi')$ $[n(k) \sim 1/k^{4+m}]$, $(m = 1 \ldots 5)$; Phys. Rev. C **75**, 034319 (2007)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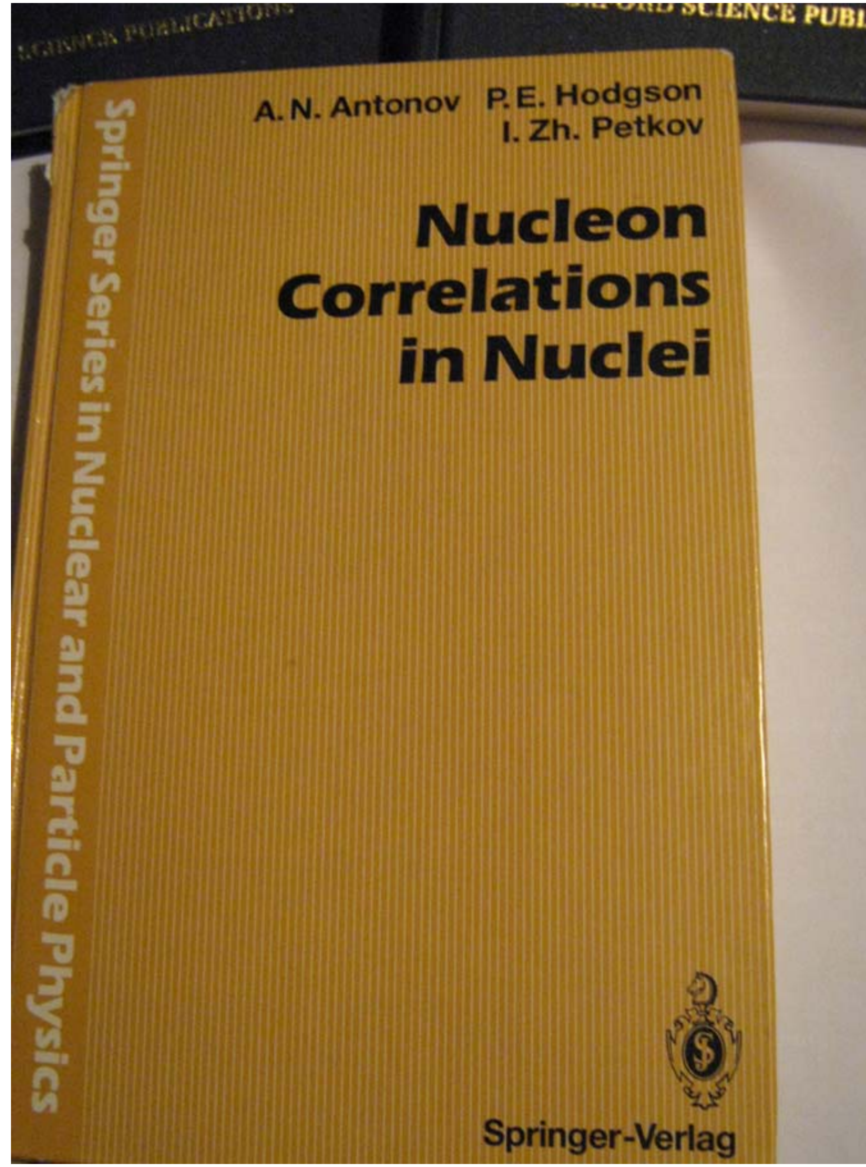
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