THE ROLE OF THE NUCLEAR MEDIUM IN HIGH ENERGY SCATTERING
(Hadrons in nuclei: new theoretical and experimental developments)

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*Nuclear Physics at JPARC, June 2007*
OUTLINE

. Introduction: the standard model of nuclei

. Hadrons in nuclei-1. Nucleon-Nucleon correlations: the new wave


. Summary and conclusions
1. INTRODUCTION

High energy particles are impinging on a nucleus: what do they see? *Independent particles*, $F_A(x, Q^2) = AF_2^N(x, Q^2)$ Or something else *e.g.* $F_A(x, Q^2) \neq AF_2^N(x, Q^2)$?

We know the answer → *EMC EFFECT*

Particles sees a complex many-body system. How do we describe it?
1.2 The standard model of nuclei

\[ \hat{H} \Psi_n = E_n \Psi_n, \quad \text{with:} \quad \hat{H} = -\frac{\hbar^2}{2m} \sum_i \hat{\nabla}_i^2 + \frac{1}{2} \sum_{i<j} \hat{v}_{ij} \]

where

\[ \hat{v}_{ij} = \sum_n v^{(n)}(r_{ij}) \hat{O}^{(n)}_{ij} \]
\[ \hat{O}^{(n)}_{ij} = [1, \sigma_i \cdot \sigma_j, \hat{S}_{ij}, (L \cdot S)_{ij}, ...] \otimes [1, \tau_i \cdot \tau_j] . \]

The same operatorial dependence is cast onto \( \Psi_o \):

\[ \Psi_o = \hat{F} \phi_o \]

where \( \phi_o \) is the mean-field wave function and

\[ \hat{F} = \hat{S} \prod_{i<j} f_{ij} = \hat{S} \prod_{i<j} \sum_n f^{(n)}(r_{ij}) \hat{O}^{(n)}_{ij} \]

is a correlation operator.
1.3 The ground state energy - A novel approach

- The ground state energy $E_0$ is given by:

$$E_0 = -\frac{\hbar^2}{2m} \int d\mathbf{r} \left[ \hat{\nabla}^2 \rho^{(1)}(\mathbf{r}, \mathbf{r}') \right]_{\mathbf{r}=\mathbf{r}'} + \sum_n \int d\mathbf{r}_1 d\mathbf{r}_2 \hat{\upsilon}^{(n)}(\rho^{(2)}_n(\mathbf{r}_1, \mathbf{r}_2))$$

$$\rightarrow \rho^{(1)}(\mathbf{r}, \mathbf{r}') = A \int \frac{A}{\prod_{j=2}^A d\mathbf{r}_j} \Psi_o^\dagger(\mathbf{r}, \mathbf{r}_2 \ldots, \mathbf{r}_A) \Psi_o(\mathbf{r}', \mathbf{r}_2 \ldots, \mathbf{r}_A)$$

$$\rightarrow \rho^{(2)}_n(\mathbf{r}_1, \mathbf{r}_2) = \frac{A(A-1)}{2} \int \frac{A}{\prod_{j=3}^A d\mathbf{r}_j} \Psi_o^\dagger(\mathbf{r}_1 \ldots, \mathbf{r}_A) \hat{O}_{12}^{(n)}(\mathbf{r}_1 \ldots, \mathbf{r}_A) \Psi_o(\mathbf{r}_1 \ldots, \mathbf{r}_A)$$

- $\rho^{(1)}(\mathbf{r}, \mathbf{r}')$ and $\rho^{(2)}_n(\mathbf{r}_1, \mathbf{r}_2)$ are cluster expanded;

- the wave function and correlation functions which minimize the ground-state energy are used to calculate the expectation value of any operator at the same order.
A linked cluster expansion suitable for the treatment of ground-state properties of complex nuclei, as well as of various particle-nucleus scattering processes, has been used to calculate the ground-state energy, density, and momentum distribution of $^{16}$O and $^{40}$Ca in terms of realistic interactions. First, a benchmark calculation for the ground-state energy is performed with the truncated $V8'$ potential and consisting of the comparison of our results with the ones obtained by the Fermi hypernetted chain approach, adopting in both cases the same mean-field wave functions and the same correlation functions. The results exhibited a nice agreement between the two methods. Therefore the approach has been applied to the calculation of the ground-state energy, density, and momentum distributions of $^{16}$O and $^{40}$Ca by use of the full $V8'$ potential, and again a satisfactory agreement was found with the results based on more advanced approaches in which higher-order cluster contributions are taken into account. It appears therefore that the cluster expansion approach can provide accurate approximations for various diagonal and nondiagonal density matrices, so that it could be used for a reliable evaluation of nuclear effects in various medium- and high-energy scattering processes off nuclear targets. The developed approach can be readily generalized to the treatment of Glauber-type final-state interaction effects in inclusive, semi-inclusive, and exclusive processes off nuclei at medium and high energies.

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PACS number(s): 21.60.-n, 21.10.Dr, 27.20.+n, 27.40.+z
ground state energy: $^{16}O - \text{Argonne V8'}$

<table>
<thead>
<tr>
<th>$\langle V_c \rangle$</th>
<th>$\langle V_\sigma \rangle$</th>
<th>$\langle V_\tau \rangle$</th>
<th>$\langle V_{\sigma\tau} \rangle$</th>
<th>$\langle V_S \rangle$</th>
<th>$\langle V_{S\tau} \rangle$</th>
<th>$\langle V \rangle$</th>
<th>$\langle T \rangle$</th>
<th>E</th>
<th>E/A MeV</th>
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</thead>
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<td>$\eta - \text{exp}$</td>
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<td>-9.47</td>
<td>-171.32</td>
<td>-0.003</td>
<td>-172.89</td>
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<td>323.50</td>
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<td>FHNC</td>
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<td>-10.61</td>
<td>-180.00</td>
<td>-0.07</td>
<td>-160.32</td>
<td>-390.30</td>
<td>325.18</td>
<td>-65.12</td>
</tr>
</tbody>
</table>

correlation functions: Central, Spin-Isospin, Tensor
Momentum distributions and tensor forces

\[ k > 1.5 \text{ fm}^{-1}: \quad \rightarrow \quad \text{Tensor correlations!} \]

\[ 16\text{O} \]

\[ k \]

\[ \text{Mean Field} \]
\[ \text{First order} \]
\[ \text{First + Second order} \]

\[ \text{VMC} \]

\[ 16\text{O} \]

\[ \text{Mean Field} \]
\[ \text{Central} \]
\[ \text{Central + Tensor} \]

\[ \text{VMC} \]

\[ n(k) \text{ [fm}^3\text{]} \]
1.4 The Nucleon Spectral Function and correlations

\[ P_A(|k|, E) = P_0(|k|, E) + P_1(|k|, E) \]

\[ P_0(|k|, E) = \sum_{\alpha < \alpha_F} \tilde{n}_\alpha(|k|) \delta(E - |\epsilon_\alpha|) \quad \int \tilde{n}_\alpha dk < 1 \]

\[ P_1(|k|, E) = \sum_{f \neq \alpha} \left| \int dr \, e^{i \mathbf{k} \cdot \mathbf{r}} \, G_{f0}(\mathbf{r}) \right|^2 \delta[E - (E_{fA-1}^f - E_A)] \]

\( P_0 \) - renormalized shell model  \( P_1 \) - correlations

A=3 and \( \infty \) Theory OK Complex Nuclei - Models

The Few-Nucleon Correlation Model (FNC) (F & S, CdA, Simula)

\[ P_1^A(|k|, E) = \int d\mathbf{P}_{cm} \, n_{rel}^A \left(|k - \mathbf{P}_{cm}/2|\right) n_{cm}^A(|\mathbf{P}_{cm}|) \cdot \]

\[ \cdot \delta \left[ E - E_{thr}^{(2)} - \frac{(A-2)}{2M(A-1)} \cdot \left( k - \frac{(A-1)\mathbf{P}_{cm}}{(A-2)} \right)^2 \right] \]
Spectral Function - $^{16}O$

$P_0(k, E)$

$M \ (E = \epsilon_\alpha) : 80\%$

$P_1(k, E)$

Correlations $\ (E \simeq k^2/2m_N) : 20\%$

*S. Simula, CdA - PRC 53 (1996)*
Realistic model of the nucleon spectral function in few- and many-nucleon systems

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By analyzing the high-momentum features of the nucleon momentum distribution in light and complex nuclei, it is argued that the basic two-nucleon configurations generating the structure of the nucleon spectral function at high values of the nucleon momentum and removal energy can be properly described by a factorized ansatz for the nuclear wave function, which leads to a nucleon spectral function in the form of a convolution integral involving the momentum distributions describing the relative and center-of-mass motion of a correlated nucleon-nucleon pair embedded in the medium. The spectral functions of $^3$He and infinite nuclear matter resulting from the convolution formula and from many-body calculations are compared, and a very good agreement in a wide range of values of nucleon momentum and removal energy is found. Applications of the model to the analysis of inclusive and exclusive processes are presented, illustrating those features of the cross section which are sensitive to that part of the spectral function which is governed by short-range and tensor nucleon-nucleon correlations.

PACS number(s): 21.10.Jx, 21.65.+f, 24.10.Cn, 27.10.+h
Interpretation of the Processes $^3\text{He}(e, e'p)^2\text{H}$ and $^3\text{He}(e, e'p)(pn)$ at High Missing Momenta

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Using realistic three-body wave functions corresponding to the AV18 interaction, it is shown that the effects of the final state interaction in the exclusive processes $^3\text{He}(e, e'p)^2\text{H}$ and $^3\text{He}(e, e'p)(pn)$, can be successfully treated in terms of a generalized eikonal approximation based upon the direct calculation of the Feynman diagrams describing the rescattering of the struck nucleon. The relevant role played by the double rescattering contribution at high values of the missing momentum is illustrated.

DOI: 10.1103/PhysRevLett.95.052502 PACS numbers: 24.10.-i, 25.10.+s, 25.30.Dh, 25.30.Fj

\[
d^6\sigma/dE_e'de' \ d\Omega_e' \ d\Omega_p \ dE_m \quad [\text{pb MeV}^{-1} \text{sr}^{-1}]
\]

$^3\text{He}(e, e'p)(np)$: correlation bumps at $E_m \sim \frac{p_m^2}{2m_n}$ clearly seen
Obtaining information on SRC is useful in various fields of physics:

- check of the standard model of nuclei;
- the structure of cold nuclear matter at high densities;
- EoS of neutron stars;
- quark-gluon physics.
Old and persistent question: Why nuclei do not collapse into a system of size of a nucleon/ quark soup?

Traditional answer: Short-range repulsion between nucleons - repulsive core

Strong repulsion at $r < r_c \approx 0.4 \text{ fm} !!!$

Does it make sense to speak in this situation about nucleons since

$$r_N = \left( \langle r_{p.e.m.}^2 \rangle \right)^{1/2} \approx 0.8 \text{ fm} \quad \text{and} \quad r_c \ll 2r_N \quad ?$$

Quark distribution in the nucleon is $\rho_N(r) = \exp(-\mu r), \mu = 0.8 \text{ GeV}$

$2\rho_N(r_c/2) = \rho_N(0) \quad \Rightarrow \quad r_c = 0.35 \text{ fm}$

F&S 75

Short-range NN correlations (SRC) have densities comparable to the density in the center of the nucleon - drops of cold dense nuclear matter
Study of cold dense nuclear matter complementary to study of hot dense nuclear matter

Dynamics of neutron star formation and structure

 SRC in nuclei

Quark vs. hadronic degrees of freedom in nuclei

NN interaction: short range repulsive core and the role played by the tensor force

Most important configurations are singlet even and triplet even
NEW WAVE

IN THE EXPERIMENTAL STUDY OF CORRELATIONS:

RECENT ORIGINAL AND DEDICATED EXPERIMENTS

WITH

LEPTONIC

&

HADRONIC

PROBES
THE NEW WAVE

(from F. Truffaut, *Jules et Jim*, the movie (FR, 1961))

INCLUSIVE LEPTON SCATTERING $A(e, e')X$ at JLAB
Measurement of Two- and Three-Nucleon Short-Range Correlation Probabilities in Nuclei


The observed “scaling” means that the electrons probe the high-momentum nucleons in the 2/3-nucleon phase, and the scaling factors determine the per-nucleon probability of the 2/3N-SRC phase in nuclei with A>3 relative to 3He.

The probabilities for 3-nucleon SRC are smaller by one order of magnitude relative to the 2N SRC.

For 12C:

2N-SRC(np,pp,nn) = 0.20 ± 0.045%

3N-SRC Less than 1% of total
THE NEW WAVE

HADRON SCATTERING

$A(p, 2p + n)X$

at BNL
Directional correlation

$(p, 2pn)$

$P_n > 220 \text{ MeV/c}$

$P_n < 220 \text{ MeV/c}$

The EVA/BNL collaboration
Evidence for Strong Dominance of Proton-Neutron Correlations in Nuclei

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We analyze recent data from high-momentum-transfer (p, pp) and (p, ppn) reactions on carbon. For this analysis, the two-nucleon short-range correlation (NN-SRC) model for backward nucleon emission is extended to include the motion of the NN pair in the mean field. The model is found to describe major characteristics of the data. Our analysis demonstrates that the removal of a proton from the nucleus with initial momentum 275–550 MeV/c is 92⁺⁸⁻¹₈% of the time accompanied by the emission of a correlated neutron that carries momentum roughly equal and opposite to the initial proton momentum. This indicates that the probabilities of pp or nn SRCs in the nucleus are at least a factor of 6 smaller than that of pn SRCs. Our result is the first estimate of the isospin structure of NN-SRCs in nuclei, and may have important implication for modeling the equation of state of asymmetric nuclear matter.

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PACS numbers: 21.60.–n, 21.65.+f, 24.10.–i, 25.40.Ep
Using the above values of $R$, $T_n$, and $F$, we estimate $P_{pn/pX}$ from Eq. (6). Figure 3 shows the $\sigma$ dependence of $P_{pn/pX}$ for $F = 0.36$, 0.43, and 0.55, respectively. Since $P_{pn/pX} \lesssim 1$, there is an interesting correlation between $\sigma$ and $P_{pn/pX}$, which allows us to put a constraint on $\sigma$. For evaluate $P_{pn/pX}$ we use the magnitude of $\sigma^{\text{exp}} = 143 \pm 17$ MeV/$c$ extracted from the same data set [7]. This value is in excellent agreement with the theoretical expectation of 139 MeV/$c$ of Ref. [16]. Note that $\sigma^{\text{exp}}$ dictates the removal of a fast proton is accompanied by the emission of a fast recoil neutron. It allows us also to estimate an upper limit of the ratio of absolute probabilities of $pp$- to $pn$-SRCs [21]:

$$
\frac{P_{pp}}{P_{pn}} \lesssim \frac{1}{2}(1 - P_{pn/pX}) = 0.04^{+0.09}_{-0.04}.
$$

This result can be used to estimate separately the absolute probabilities of $pn$, $pp$, and $nn$ SRCs in the nuclear wave function. For this we use the total probability of $NN$-SRCs $P_{NN}(^{12}\text{C}) = 0.20 \pm 0.042$ obtained by combining the

THE NEW WAVE

FUTURE EXPERIMENTS

at

JLAB
Studying Short-Range Correlations in Nuclei at the Repulsive Core Limit via the Triple Coincidence 
\((e, e'pN)\) Reaction

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Tel Aviv University, Tel Aviv, Israel

W. Bertozzi, S. Gilad (spokesperson), J. Huang, B. Moffit (spokesperson), P. Monaghan, N. Muangma, A. Puckett, Y. Qiang, and X. Zhan, 

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V. Sulkosky
THE NEW WAVE

(new wave: Ryuichi Sakamoto, JP)

FUTURE EXPERIMENTS at JPARC?
\[ A(p, 2p)X \quad A(p, 2pN) \]

- Higher cross sections

- FSI also increase but reliable theoretical approaches based upon Glauber multiple scattering are available

- Correlations

- Beyond the standard model of nuclei (exotic components in the nuclear wave function)

- Color transparency
Data from EVA experiment

FIG. 11. (a) (top frame) The nuclear transparency ratio $T_{\text{CH}}$ as a function of beam momentum. (b) (bottom frame) The nuclear transparency $T_{pp}$ as a function of the incident beam momentum. The events in these plots are selected using the cuts of Eq. (9), and a restriction on the polar angles as described in the text. The errors shown here are statistical errors, which dominate for these measurements.

- Eikonal approximation calculation with proper normalization of the wave function (Frankfurt, Zhalov, MS) agrees well the 5.9 GeV data.

- Significant effect for $p= 9$ GeV where $l_{\text{coh}}= 2.7$ fm. 10 GeV is sufficient to suppress to some extent expansion effects. Hence one can use energies above 10 GeV to study other aspects of the dynamics.

- Glauber level transparency for 11.5 -14.2 GeV a problem for all models as $24 \text{ GeV}^2 \leq s' \leq 30 \text{ GeV}^2$ since it is too broad for a resonance of for interference of quark exchange and Landshoff mechanisms.
Energy dependence of the nuclear transparency calculated in the quantum diffusion model with $\Delta m^2 = 0.7\text{GeV}^2$ as compared to the expectations of the Glauber model.
SRC in scattering at high energies

- SRC: are they relevant only in dedicated medium energy experiments?

- exact many-body wave functions (Foldy & Walecka):

\[
|\Psi(r_1, \ldots, r_A)|^2 = \prod_{j=1}^{A} \rho(r_j) + \sum_{i<j=1}^{A} \Delta(r_i, r_j) \prod_{k \neq (il)}^{A} \rho(r_k) + \\
+ \sum_{(i<j) \neq (k<l)} \Delta(r_i, r_j) \Delta(r_k, r_l) \prod_{m \neq i,j,k,l} \rho(r_m) + \ldots
\]

(1)

where the two-body contraction \( \Delta \) is

\[
\Delta(r_i, r_j) = \rho^{(2)}(r_i, r_j) - \rho^{(1)}(r_i) \rho^{(1)}(r_j);
\]
The total neutron – Nucleus cross section at high energies:

\[ \sigma_{\text{tot}} = \frac{4\pi}{\kappa} \text{Im} \left[ F_{00}(0) \right] \]

\[ F_{00}(q) = \frac{ik}{2\pi} \int d^2b_n e^{i\mathbf{q} \cdot \mathbf{b}_n} \left[ 1 - e^{i\chi_{\text{opt}}(\mathbf{b}_n)} \right] \]

\[ e^{i\chi_{\text{opt}}(\mathbf{b}_n)} = \int \prod_{j=1}^{A} dr_j \prod_{j=1}^{A} [1 - \Gamma(\mathbf{b}_n - s_j)] |\Psi_0(\mathbf{r}_1, ..., \mathbf{r}_A)|^2 \delta \left( \frac{1}{A} \sum \mathbf{r}_j \right). \]

The usual approximation in Glauber-type calculations

\[ |\Psi(\mathbf{r}_1, ..., \mathbf{r}_A)|^2 = \prod_{j=1}^{A} \rho(\mathbf{r}_j) \text{ i.e. } \Delta(\mathbf{r}_i, \mathbf{r}_j) = 0 \]

if correlations are taken into account i.e.

\[ \Delta(\mathbf{r}_i, \mathbf{r}_j) = \rho^{(2)}(\mathbf{r}_i, \mathbf{r}_j) - \rho^{(1)}(\mathbf{r}_i) \rho^{(1)}(\mathbf{r}_j) \neq 0; \]

\[ \sigma_{\text{tot}} = \sigma_G^{(1)} + \sigma_G^{(2)} \]
Glauber + Inelastic shadowing

(Diffractive excitation of the projectile)

(Glauber)

(Inelastic Shadowing)

total neutron-Nucleus cross section:

\[ \sigma_{\text{tot}} = \sigma_G^{(1)} + \sigma_G^{(2)} + \Delta \sigma_{\text{in}} \]
RESULTS

No adjustable parameters

M. Alvioli, CdA, I. Marchino, H. Morita and V. Palli,
nucl-th:07053613
HADRONS in NUCLEI-2. TAGGED STRUCTURE FUNCTIONS AND HADRONIZATION

The Semi-Inclusive DIS process \( A(e,e'B)X \) process within the Spectator Mechanism

The quark-gluon debris propagates through the nucleus

\[
\frac{d\sigma^A}{dx dQ^2 dP_{A-1}} \propto F_2^{N/A}(x_A, Q^2, p_1^2) N_A(|\vec{p}_1|) \quad \vec{p}_1 \equiv -\vec{P}_{A-1}
\]

Bound Nucleon Structure Function
PWIA:

\[ N_A(|p_1|) \quad \text{Nucleon Momentum Distribution} \]

Quark-gluon debris rescattering (FSI):

\[ N_A(|P_1|) \rightarrow \text{Distorted (D) Momentum Distributions} \]

\[ N^D_A(P_{A-1}) = \left| \int \phi(b, z) e^{-\frac{1}{2}S(b, z)} \right|^2 \]

\[ S(b, z) = \int d\zeta' \rho_A(b, z') \sigma_{eff}(\zeta' - z) \]

evaluated within Glauber theory \textit{but} \rightarrow \text{time-dependent profile function}

\[ \Gamma^{NN}(b_1 - b_i) \rightarrow \Gamma^{N*N}(b_1 - b_i, z_i - z_1) \]
The hadronization model:


The formation of the final hadrons occurs during and after the propagation of the created nucleon debris through the nucleus, with a sequence of soft and hard production processes.

Soft production $\rightarrow Q < \lambda = 0.65 \, GeV$ npQCD, string model

Hard production $\rightarrow Q > \lambda = 0.65 \, GeV$ pQCD, gluon radiation model.
The EFFECTIVE Debris-Nucleon CROSS SECTION

\[ \sigma_{\text{eff}}(t) = \sigma_{\text{tot}}^{NN} + \sigma_{\text{tot}}^{MN} \left[ n_M(t) + n_G(t) \right] \]

- Steep rise with time (distance).
- \(Q^2\) and \(x_{Bj}\) dependence due to gluon radiation mechanism.
$^2\text{H}(e,e'p)X$ theory vs. experiment

\[ F_{2n}(x,Q^2) \ \langle n_D(p_s,\cos\theta_{pq}) \rangle [(\text{GeV}/c)^{-3}] \]

M. Alvioli, CdA et al., nucl-th:07053617
4. CONCLUSIONS

- Reliable predictions of the full correlated structure of the nucleus are being produced;
- A new wave of experimental studies at medium energies aimed at mapping the intermediate and short range structure of nuclei is going on; first results confirm the basic validity of the two-nucleon correlation picture of SRC;
- Much remains to be done (e.g. the core region and the isospin structure of NN correlations, the medium effects on the nucleon properties (tagged structure functions, etc); to this end the extension of the experiments to higher energies using both leptonic and hadronic probes would be extremely useful.