Nucleons in Nuclei

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Definition of Terms: What are Nucleons?

- Stationary solutions of the QCD Lagrangian with $A = 1$, $l = \frac{1}{2}$; $S = B = C = T = 0$ and $s = \frac{1}{2}$
- Bound systems of 3 light valence quarks ($uud$ or $udd$) and a large number of sea quarks ($qq$) and gluons
- Describable as a superposition of Fock states, including bare $qqq$, and excitations of the chiral condensate ("pion cloud"); solitons
- Characterized by SFs, FFs, GPDs, WFs...
- ...your definition here...
- Classical Nuclear Physics: “Structure-less” hard objects
What are Nuclei?

• Stationary solutions of the QCD Lagrangian with $A = 2, 3, \ldots$, $I = 0, \frac{1}{2}, \ldots$; $S^*) = B = C = T = 0$ and $s = 0, \frac{1}{2}, 1\ldots$

• Bound systems of 3A light valence quarks ($u$ and $d$) and a large number of sea quarks ($qq$) and gluons

• Describable as a superposition of Fock states, including A bare $qqq$ clusters, and excitations of the chiral condensate (“pion cloud, sigma field…”)

• ...

• (Structure-less) nucleons bound together by a potential?

*) NOTE: $S < 0 \rightarrow$ hypernuclei = important test bed!
Nucleon-Nucleon Potentials

- OBE
  \[ \pi \rho \omega \sigma_1 \sigma_2 \] (CD Bonn, Machleidt 2000)

- Chiral EFT
  Ultimately: (L)QCD!

Figure 2. In an impressive tour-de-force, scientists have now calculated the properties and structure of light nuclei with LQCD. Shown here are the magnetic moments of the proton, neutron, deuteron, \(^3\)He and triton. The red dashed lines show the experimentally measured values. The solid bands are the result of LQCD calculations with a pion mass of 805 MeV.
Features of “nucleon models” for nuclei

- Mean field potential ↔ “Fermi motion”
- (Tensor) correlations ↔ High momentum components

Nucleons:
- ~65% in single-particle orbitals
- ~25% in NN correlations
  - Almost all high momentum nucleons

\[ a_2 \]

\[ A(e,e'p) \]

\[ (\sigma_A/A)/(\sigma_C/2) \]

\[ 3^\text{He} \quad 4^\text{He} \quad 6^\text{He} \quad 9^\text{Be} \quad 12^\text{C} \quad 19^\text{Au} \quad 63^\text{Cu} \]

\[ 0.8 \quad 1 \quad 1.2 \quad 1.4 \quad 1.6 \quad 1.8 \]
Features of “nucleon models” for nuclei

- Mean field potential ↔ “Fermi motion”
- (Tensor) correlations ↔ High momentum components

Figure 5: The short distance structure of $^{12}\text{C}$ as deduced from recent measurements.

I.3 SRC and the EMC effect

The size of the EMC effect in a given nucleus is linearly correlated with the probability for a nucleon in that nucleus to belong to an NN SRC pair (see Fig. 6) [29,49]. The dependence of the EMC effect on high momentum nucleons was first proposed in [30]. This strongly suggests that the EMC effect is due to high momentum nucleons in nuclei. Since almost all high-momentum nucleons in nuclei belong to SRC nucleon pairs, we can select the nucleons on which we observe the EMC effect by detecting their SRC partners that recoil backwards in coincidence with the scattered electrons.

Figure 6: The negative of the EMC slope plotted vs. the relative probability that a nucleon belongs to an NN SRC pair for a variety of nuclei (see details in [29, 49]).

$^n$-$p$ pairs

$^p$-$p$ pairs

$^n$-$n$ pairs

$^{12}\text{C}$

60-70% Single nucleons

10-20%

20±5%

2N-SRC

74-92%

$4.75\pm1\%$

n-p pairs

$4.75\pm1\%$

p-p pairs

$4.75\pm1\%$

n-n pairs

Long range correlations

$96\pm23\%$

$9.5\pm2\%$

$60\pm70\%$

$10\pm20\%$

$20\pm5\%$

$2N$-SRC

$4.75\pm1\%$

Minority

Majority

$1/\mathbf{k}^4$

$\mathbf{k}_f$
A little detour:
Are “SRCs” really Short-range?
What is commonly meant by “SRC”?

![Diagram](image)

Shell model occupation numbers for different nuclei, showing the common meaning of "SRC".

- For $A(e,e'p)$ reactions, look for correlated nucleon partners.
- For $P_{\text{miss}} < 600$ MeV/c, all nucleons are part of 2N SRC pairs: 90% np, 5% pp (nn).

Inclusive $A(e,e') \times > 1.4$: momenta above Fermi edge (< 300 MeV/c)

Adapted from Ciofi degli Atti
What is commonly meant by “SRC”?

Results from A(e,e’pN) and A(p,p’NN) measurements. pn pairs dominate even if N >> Z.
Major source of correlated strength in $n^{[1]}(p)$?

1. $1.5 \lesssim p \lesssim 3$ fm$^{-1}$ is dominated by tensor correlations
2. central correlations substantial at $p \gtrsim 3.5$ fm$^{-1}$

... but are they SHORT RANGE?

Jan Ryckebusch (Ghent University)
Quantum numbers of SRC-susceptible IPM pairs?

\( n^{[1], \text{corr}} \) stems from correlation operators acting on IPM pairs. What are relative quantum numbers \((n\ell)\) of those IPM pairs?

Major source of SRC: correlations acting on \((n = 0 \ell = 0)\) IPM pairs
Example Deuteron: Potential

- OBE
  - Chiral
  - Determined by phase shifts

1π Exchange
2π Exchange

S-state solution for square potential with range 2 fm and depth -37 MeV
Example: $E_{\text{cm}} = 20$ MeV
Example Deuteron: Potential

• Alternative: Square potential with short-range repulsive core 0...0.3 fm, and same square well 0.3...2.3 fm

Change in Wave Function
$E_{cm} = 20$ MeV
Spatial Distribution in D

- Piarulli & Schiavilla 2015

- **S-state:** $r_{RMS} = 3.93$ fm
- **D-state:** $r_{RMS} = 2.47$ fm
- **Total:** $r_{RMS} = 3.86$ fm
Momentum Distribution in D

Argonne V18 Potential

$\Delta \text{Prob}(p \ldots p + \Delta p)$

S-state: $p_{\text{RMS}} = 105 \text{ MeV/c}$
D-state: $p_{\text{RMS}} = 372 \text{ MeV/c}$
Total: $p_{\text{RMS}} = 136 \text{ MeV/c}$

$\beta > 0.5$

$\Delta \text{Prob}(p \ldots p + \Delta p)$
for simple square potential
with
$R(\text{core}) = 0 \ldots 0.5$

$p_{\text{RMS}} = 100 \text{ MeV/c}$
for all cases!

Increasing Width of Core
Are nucleons modified in nuclei?

• Are electrons modified in atoms?
  – Binding energy = $\frac{1}{2} \alpha^2$ times mass – only 0.0027%
  – Classical picture: Unchanged electron in electrostatic potential of nucleus – good to amazing accuracy
  – But in QED: Electrons do have structure...
    – ...and therefore are “modified” in atoms
Are nucleons modified in nuclei?

• Are atoms modified in molecules?
  – Obviously!
  – QM picture: Atoms are deformed or even share electrons to form molecules
  – Clearly, electron distributions in space and momentum space are strongly modified
  – Binding energy a good fraction of atomic binding energy ($H_2$ binding energy $\frac{1}{3}$ of electron binding in H)
Are nucleons modified in nuclei?

- Nucleons:
  - bound by up to nearly 1% of their mass!
  - very rich internal structure
  - Therefore somewhere in between atoms and molecules?

Why do we care?

- Nuclei used as "nucleon targets" (e.g. D, $^3\text{He}$ for n, the heavier nuclei for DM detection, neutrinos - NuTeV!)
- Consequences for nuclear structure (from nuclei to neutron stars; Equation of State) and $p/A$ colliders
- Necessary ingredient for a fundamental (QCD-based) understanding of nuclear binding
- Necessary for understanding ALL QCD bound states

Anatomy of a Neutron Star

Equilibrium composition determined by

$\%$ Charge neutrality

$\%$ Equilibrium with respect to weak interacting processes

$\varepsilon q_i \rho_i = 0$

$i \sum \varepsilon b_1 \rightarrow b_2 + l + \nu_l$

$b_2 + l \rightarrow b_1 + \nu_l$

$\varepsilon \mu_i = b_i \mu_n - q_i \mu_e - \mu_{\nu e}$

$\mu_i = \frac{\partial \varepsilon}{\partial \rho_i}$

$Q^2 = 100 \text{ GeV}^2$

al., PRD 87, 094012 (2013)
Universality of the EMC Effect and SRC Scaling

EMC: Size of effect (slope) grows with $A^{3/10}$ for $x > 1.4$

Experimental Evidence

\[
\frac{F_2^A}{ZF_2^p + NF_2^n}
\]

- Blue circles: SLAC E139 (Fe)
- Red asterisks: EMC (Cu)
Recent determinations of nuclear PDFs

**Valence & Sea**


EPS: K. J. Eskola, H. Paukkunen
C. A. Salgado, JHEP 0904 (2009) 065

**GLUON**

DSSZ: Daniel de Florian, Rodolfo Sassot, Pia Zurita, Marco Stratmann, Phys. Rev. D 85, 074028

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**Nuclear PDF Fits**

**HKN07 (NLO)**

**EPS09**

**DSSZ**

**HKN07 (NLO)**

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**Process** | **Reaction** | **Subprocess** | **PDFs probed** | **x**
---|---|---|---|---
αA/μμA → αX/μ + X | γ + q → q, q | 0.01 ≤ x ≤ 1
(D, He, Li, Be, C, N, Al, Ca) | | |
(Fe, Cu, Kr, Ag, Sn, W, Au, Pb) | | |
νA → ν + X | W^+ q → q^- | 0.04 ≤ x ≤ 1
[Fe, Pb] | | |
AA → (Z → l^- + l^-) + X | u, d, s → Z, d, s | 0.01 ≤ x ≤ 0.1
[D, C, Ca, Fe, Xe, W, Pb] | | |
dA → π + X | g, g → g, g, g | 0.01 ≤ x ≤ 0.1
[Au] | | |

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**Experimental data: nuclear PDFs**

- BCDMS, EMC, NMC
- SLAC/NMC
- KP fit A
- EPS A
- DSSZ
- HKN07

**EPS**

- BCDMS, EMC, NMC
- SLAC/NMC
- KP fit B
- EPS
- DSSZ
- HKN07

**DSSZ**

- BCDMS, EMC, NMC
- SLAC/NMC
- KP fit C
- DSSZ
- HKN07

**HKN**

- BCDMS, EMC, NMC
- SLAC/NMC
- KP fit D
- HKN07

**March 2, 2015 38/42**

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**Schienbein et al., PRD 80, 094004 (2009)**

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Recent Experimental Evidence

$4^\text{He}$/d

J. Seely, PRL 103, 202301 (2009)

$(\sigma_A/\sigma_D)\text{CORR}$

$-dR_{\text{EMC}}/dx$

Effective Nuclear Density [fm$^{-3}$]

$^{9}\text{Be}$

$^{4}\text{He}$

$^{12}\text{C}$

$^{3}\text{He}$
An interesting connection

- **EMC vs. SRC**
  - Both due to high local density?
  - EMC effect more pronounced in high-momentum/SRC nucleons?

![Graph showing EMC vs. SRC](image)


Probability of a nucleon inside the nucleus to be in a “short-range” (tensor) correlation (dominated by pn correlations 10:1)
Possible Explanations

- EMC $\propto A$: ruled out by $^4\text{He}$
- EMC $\propto$ average nuclear density: ruled out by $^9\text{Be}$
- EMC $\propto$ local density. Consistent with binding models (e.g., quark-meson coupling; quarks rearrange themselves inside nucleons due to scalar/vector field)
- EMC $\propto$ virtuality of struck nucleon *) $\Rightarrow$ mostly in high-momentum (SRC) nucleons.
- Nucleon swelling, $x$ rescaling, $Q^2$ rescaling, pion enhancement, suppression of point-like configurations...

*) $E_N = M_A - E_{\text{recoil}}$ where $E_{\text{recoil}} \geq \sqrt{M_{A-1}^2 + p^2}$

$M^{*2} = E_N^2 - p^2 < M_N^2$ "off-shell mass"; $M^* \approx M_N - BE - \frac{p^2}{2M} \frac{M_A}{M_{A-1}}$

$x^* = \frac{Q^2}{2(E_N \nu - \vec{p} \cdot \vec{q})} \approx \frac{x}{\alpha} ; \quad \alpha = \frac{E_N - \vec{p} \cdot \vec{q}}{M_N} ; \quad \langle \alpha \rangle < 1$
BUT: Are fast nucleons REALLY “more off-shell”?

- Basic argument: \( E_N = M_A - E_{\text{recoil}} \) where \( E_{\text{recoil}} \geq \sqrt{M_{A-1}^2 + p^2} \)

\[
M^* = E_N^2 - p^2 < M_N^2 \text{ "off-shell mass";} \quad M^* \approx M_N - BE - \frac{p^2}{2M} \frac{M_A}{M_{A-1}}
\]

- Rescale \( x \) to \( x^* = \frac{Q^2}{2(E_N \nu - \vec{p} \cdot \vec{q})} \approx \frac{x}{\alpha} \); \( \alpha = \frac{E_N - \vec{p} \cdot \vec{q}}{M_N} \); \( \langle \alpha \rangle < 1 \)

- Effective \( x \) is larger, therefore SFs are suppressed at high \( x \).

- ...or other off-shell effects modifying structure functions:
  Kulagin-Petti, Frankfurt-Strikman, Melnitchouk-Thomas,...
Are fast nucleons more off-shell?

Counterexample: The Deuteron

- Toy Hilbert space spanned by basis vectors $|u\rangle, |w\rangle$; $|\psi\rangle = \sqrt{1-\alpha}|u\rangle + \sqrt{\alpha}|w\rangle$
- S-state has kinetic energy 11.7 MeV, D-state 142 MeV. Assume both are bound by $\approx 5$-6 MeV and the Tensor force creates a transition matrix element of size -32 MeV
- $\Rightarrow \mathbf{H} = \begin{pmatrix} 5 & -32 \\ -32 & 137 \end{pmatrix}$. Solve $\mathbf{H} \begin{pmatrix} \sqrt{1-\alpha} \\ \sqrt{\alpha} \end{pmatrix} = E \begin{pmatrix} \sqrt{1-\alpha} \\ \sqrt{\alpha} \end{pmatrix}$ $\Rightarrow E = -2.2$ MeV and $\alpha = P_D = 5$

- Observations:
  - Binding energy and D-state probability of “real deuteron” are reproduced.
  - Actual binding only due to Tensor Force – this is confirmed by full calculations!
  - S-state and D-state WFs are NOT eigenstates of the Hamiltonian!
  - Therefore: It makes little sense to say “N in D-state is more off-shell than N in S-state”
  - However: Need proper 4-momentum conservation prescription for scattering...
EMC-effect in the Deuteron?

EMC effect in deuteron

Predicted by theory...
(W. Melnitchouk, private comm.)

...and first hints seen in BONuS experiment
Further Experimental Evidence

• Form Factors for $p$ in $^4$He at JLab

However, alternative explanations in standard nuclear models (incl. MEC, FSI etc.) exist

“One would have expected that probing few-body systems at very high $Q$ might have revealed a new role for quark degrees-of-freedom at short distances. Except for their implicit role in determining the effective forces and currents (as well as nucleon electromagnetic form factors), the models discussed in this review do not include any such effects.” Marcucci et al., arXive 1504.05063
List of data ”in the can” or to come

• JLab 6 GeV:
  – E02-109/E04-001/E06-009: $R_A-R_D$, $R_D-R_p$ (res. region)
  – CLAS: data mining initiative -> tagged $F_{2A}/F_{2D}$
  – GPDs in $^4$He (CLAS EG6)

• Minerva, Seaquest

• In-medium FF experiments at Mainz (Piasetzky et al.)

Sat 15:20 - Douglas Higinbotham
Now underway

No model predicts dbar/ubar <1.

$$\frac{d^2\sigma}{dx_1dx_2} = \frac{4\pi\alpha^2}{9x_1x_2} s \sum e^2 [\bar{q}_t(x_t)q_b(x_b) + q_t(x_t)\bar{q}_b(x_b)]$$

Now underway
The Future

• JLab 12: EMC ($F_2$, R) in a huge number of nuclei, including $^3$He, $^3$H (Marathon)
• Form factor modifications
• SRC ($^3$He, $^3$H, $^{40}$Ca, $^{48}$Ca...)
• Deuteron $b_1$, pol. EMC, GPDs; TMDs?
• tagged (several)
  – BONuS
  – Marathon
  – LAD in Hall C
  – BAND in Hall B
  – ALERT in Hall B
• superfast quarks at $x>1,...$
• EIC: sea/gluon PDFs, shadowing, anti-shadowing, tagged EMC effect,...
EMC experiments with 12 GeV

- E12-14-002: Medium modifications of $R$ and of separated structure functions
- E12-10-008: $^3$-$^4$He, $^6$-$^7$Li, $^{10}$-$^{11}$B, Be, C, $^{40}$-$^{48}$Ca, Cu
Experimental Evidence – a different view

EMC Effect in Carbon - Jefferson Lab Data

- F2D
- F2C

12 GeV experiment to measure superfast quarks at high $Q^2$

$Q^2 = 2.5 \text{ [GeV/c]}^2$

SRC Plateau

Fermi Motion

EMC Slope

E02-019

$7.4 \text{ (GeV/c)}^2$

$^{12}$C, 5.77, 50°

$x = 1$

$y = 0$
Isospin-dependent EMC effect?

Interaction of quarks with isovector-vector mean-field $\rho^0$ induces differences between $u$ & $d$ medium modifications

$Z/N = 82/126$ (lead)

$F_{2A}/F_{2D}$

$u$ feels vector attraction, $d$ feels additional repulsion

important implications for NuTeV “anomaly”
Polarized EMC effect?

- **QMC**
  - $g_{1p}^A / g_{1p}$
  - $F_{2N}^A / F_{2N}$
  - $Q^2 = 5 \text{ GeV}^2$
  - $\rho = 0.16 \text{ fm}^{-3}$

- **Cloet et al., PRL 95, 052302**

- **7Li**
  - I. Cloët, W. Bentz, A.

- **Experiment:** $^9\text{Be}$

- **Unpolarized EMC effect**
- **Polarized EMC effect:** $R_{As}^{3/2}$
- **Polarized EMC effect:** $R_{As}^{3/2} g_{1A}^H / (g_{1p}^H + g_{1n}^H)$

- **Nuclear matter, $Q^2 = 10 \text{ GeV}^2$**
  - **Valence + sea**
  - **CQS**
  - **Valence only**

- J. Smith, J. Miller

Polarized EMC effect?

E12-14-001 with CLAS12 at JLab: Ratio of $g_1$ and $A_1$ for $^7$Li vs. free p
Tensor $P_{zz} = (p_+ + p_-) - 2p_0$

$(\uparrow + \downarrow) - 2 \uparrow$

First Result from HERMES

Conventional Nuclear Models predict 0

$$b_1 = \frac{1}{2} \sum_q e_q^2 (\delta_T q + \delta_T \bar{q})$$

$$\delta_T q = q^{(0)} - \frac{q^{(+1)} + q^{(-1)}}{2}$$
Spectator Tagging

\[ p_n = \left( M_D - E_S, -\vec{p}_S \right); \alpha_n = 2 - \alpha_S \quad M^{*2} = p_n^\mu p_{n\mu} \]

\[ x = \frac{Q^2}{2p_n^\mu q_\mu} \approx \frac{Q^2}{2Mv(2-\alpha_S)} \]

\[ W^{*2} = (p_n + q)^2 = M^{*2} + 2\left((M_D - E_s)v - \vec{p}_n \cdot \vec{q}\right) - Q^2 \]

\[ \approx M^{*2} + 2Mv(2-\alpha_S) - Q^2 \]
Using tagging to **enhance** binding effects:

$p_s > 300 \text{ MeV/c} \rightarrow E12-11-107$

O. Hen, L. Weinstein, S. Gilad, S. Wood

$D(e,e'p_s)X$ with HMS/SHMS and “LAD”
Using tagging to **enhance** binding effects: n tagging

O. Hen, L. Weinstein, E. Piasetzky, H. Hakobyan

\[ \text{D}(e,e'n_s)X \text{ with CLAS12 and “BAND”} \]

Advantage: Very far backwards spectators; free p SF is precisely known
Tagged EMC Effect
“ALERT”

N. Baltzel, R. Dupré, K. Hafidi, M. Hattawy, S. Stepanyan

FIG. 8: The schematic layout of the CLAS12 baseline design.

B. Low Energy Recoil Detector
In addition to the Forward Detector package, we require a low energy recoil detector which has adequate momentum and spatial resolution, and good particle identification for recoiling charge particles (p, $^2$H, $^3$H, $^3$He). We investigate the feasibility of using the CLAS12 Central Detector and the BoNuS Detector [40, 46]. As those seem not suitable for the proposed measurement we propose a new detector for our measurement, that could also be suitable for the BoNuS12 experiment [46].

1. Central Detector
CLAS12 Central Detector [45] is designed to detect various charged particles over a wide momentum and angular range. The main detector package includes:

- Solenoid Magnet: provides a central longitudinal magnetic field up to 5 Tesla, serves as a clear space filled with helium, its outer radius is 6 mm.
- An array of plastic scintillators placed inside the gaseous chamber. The total thickness of the scintillators will be 50 mm. It is covered by a light proof thin layer of Mylar.

The different elements are all covering 2$\pi$ and 400 mm long.

FIG. 13: The schematic layout of the new recoil detector design, view from the beam direction.

The drift chamber is a 400 mm long cylinder with an inner radius of 30 mm and an outer radius of 66 mm. It is composed of 8 layers of wires. The extremities of the wires are placed on circles of radius increasing by 4 mm, the smallest circle having a radius of 32 mm. In the same layer a wire is placed each 4 mm on the cylinder. With a low pressure chamber and a well chosen gas, we expect to reach a spatial resolution of 200 microns and an integration lower than 400 ns. In order to avoid electronics on the end cap, the wires have a stereo angle to determine the position along the beam axis. In this note the stereo...
**Electron-Ion Collider**

Measurements with $A \geq 56$ (Fe):
- eA/μA DIS (E-139, E-665, EMC, NMC)
- νA DIS (CCFR, CDHSW, CHORUS, NuTeV)
- DY (E772, E866)

$Q^2$ (GeV$^2$)

EMC effect in tagged DIS $e + D \to e' + p + X$, backward kinematics

$E_i/\gamma = 0.90 \text{ GeV, } \gamma = 0.01, s < 0.96$

$p_{\text{off}} = 55 \text{ MeV, } m_{\text{off}} = 220 \text{ MeV}/c$

$Q^2 = 5 \text{ GeV}^2$

$R_{\text{valence}}^{(Pb)}$

$R_{\text{sea}}^{(Pb)}$

$R_{\text{gluon}}^{(Pb)}$

$s = 0.3-0.4, \quad Q^2 = 20-30 \text{ GeV}^2$

$\alpha_S = 0.89-0.91$ (backward)

$L_{\text{int}} = 10^7 \text{ ab}^{-1}, \quad s_{\text{NN}} = 1000 \text{ GeV}^2$

$\gamma = 0.01, s < 0.96$

$Q^2 (\text{GeV}^2)$

$R_{\gamma}^{(Pb)}(x, Q^2 = 5 \text{ GeV}^2)$
Shadowing in D?

Result of destructive interference among the amplitudes for the interaction with 1, 2, 3,... nucleons in the target

Impulse approx. Shadowing correction 1-2% leading-twist shadowing

Expected to increase with spectator momentum in tagged SFs
Gives rise to 1% tensor asymmetry at small x

Work by V. Guzey
Conclusions

• 30 years of data on the EMC effect – but no universally accepted detailed theoretical description => urgently needed to interpret upcoming experiments!
• Recently entered era of high precision data, calculable nuclei and new probes (Drell-Yan, $\nu_s$, pol., tagging)
• Rich experimental program at Jefferson Lab: Our best hope to finally figure out “EMC slope” => We must deliver!
• Beyond: EIC can make significant contributions (sea quarks, shadowing...) => priority for US nuclear community
• We must go from “cartoons” to microscopic models of nuclear structure with relevant QCD degrees of freedom implemented “ab initio” in both SSFs and binding => Traditional nuclear structure theory and high energy theory should collaborate!
Reminder: structure functions (spin 1/2)

\[
F_2(x, Q^2) = 2xF_1(x, Q^2) \frac{1 + R(x, Q^2)}{1 + \gamma^2} \to 2xF_1(x)
\]

\[
g_T(x, Q^2) = F_1(x, Q^2) \frac{A_2(x, Q^2)}{\gamma} \to \int_x^1 g_1(y) \frac{dy}{y}
\]

\[
g_2(x, Q^2) = g_T(x, Q^2) - g_1(x, Q^2)
\]

\[
A_1(x, Q^2) = \frac{g_1(x, Q^2) - \gamma^2g_2(x, Q^2)}{F_1(x, Q^2)}
\]

\[
= (1 + \gamma^2) \frac{g_1(x, Q^2)}{F_1(x, Q^2)} - \gamma A_2(x, Q^2) \to \frac{g_1(x)}{F_1(x)}
\]

\[
\frac{d\sigma^{+/-}}{d\Omega dE'} = \sigma_M \left[ \frac{F_2}{\nu} \frac{1 + \epsilon R}{\epsilon(1 + R)} \pm 2\tan^2 \frac{\theta_e}{2} \left( \frac{E + E' \cos \theta_e + Q^2/\nu}{M\nu} g_1 - \frac{2xF_1 A_2}{\sqrt{Q^2}} \right) \right]
\]

\[
A_{||} = \frac{d\sigma^+-d\sigma^-}{d\sigma^+ + d\sigma^-} = D \left( A_1(\nu, Q^2) + \eta A_2(\nu, Q^2) \right) = D \left( (1 + \gamma^2) \frac{g_1}{F_1} + (\eta - \gamma) A_2 \right)
\]

\[
x = Q^2/2M\nu, \gamma = \sqrt{Q^2/\nu}, R = \sigma_L/\sigma_T, \sigma_M = \frac{4E'^2\alpha^2 \cos^2 \theta}{Q^2 \frac{2}{\gamma}}, \epsilon = (1 + 2[1 + 1/\gamma^2] \tan^2 \frac{\theta_e}{2})^{-1}
\]

\[
D = \frac{1-\epsilon E'/E}{1+\epsilon R}, \eta = \frac{\epsilon \sqrt{Q^2}}{E-\epsilon E'}
\]
Structure functions for $^7$Li (spin 3/2)

$$A_{\text{meas}}^{\parallel} = \frac{N^+ - N^-}{N^+ + N^-} \propto P_z \frac{g_1^{\parallel} + \frac{P_{zzz}}{P_z} g_1^{zzz} + C(A_2)}{F_2^0 + \frac{1}{2} P_{zz} F_{zzz}^0}$$

$$g_1^\parallel = \frac{9}{10} g_1^A + \frac{3}{10} g_1^A$$

$$g_1^{zzz} = \frac{3}{10} g_1^A - \frac{9}{10} g_1^A$$

$$F_2^0 = \frac{1}{2} F_{2A}^{3/2} + \frac{3}{2} F_{2A}^{3/2} + 1/2$$

$$F_{zzz}^{zz} = F_{2A}^{3/2} + 3/2 - F_{2A}^{3/2} + 1/2$$

The final EMC ratios:

$$R_{\text{unpol}} = \frac{F_2^0}{Z F_{2p} + N F_{2n}}$$

$$R_{\text{pol}} = \frac{g_1^\parallel}{g_1^N}$$

$$P_z = n_{+3/2} + 1/3 n_{+1/2} - 1/3 n_{-1/2} - n_{-3/2}$$

$$P_{zz} = n_{+3/2} - n_{+1/2} - n_{-1/2} + n_{-3/2}$$

$$P_{zzz} = 1/3 \ast n_{+3/2} - n_{+1/2} + n_{-1/2} - 1/3 \ast n_{-3/2}$$
FSI (Example deuteron)

D(e,e'p_s)X

(BONuS)

D(e,e')X

FIG. 5: (Color online) Ratio of the deuteron F_D^2 structure function with FSIs to that computed in the plane-wave (PW) approximation at Q^2 = 5 GeV^2, using only the on-shell amplitude in Eq. (32) [(a)] and including also the off-shell contribution of Eq. (37) [(b)]. The results with the resonance region contributions alone (black solid lines) are compared with those including a continuum component with a Gaussian distribution (blue dashed) and a uniform distribution (red dotted). The arrow along the x-axis indicates the boundary at W = 2 GeV between the resonance and DIS regions for free nucleon kinematics.

Strong enhancement of the ratio above unity for x > 1 which is largely independent of the details of the distribution of the intermediate state masses. The Q^2 dependence of the FSI contributions is illustrated in Fig. 6 for F_D^2 calculated in terms of on-shell only amplitudes and including the off-shell corrections. Here the bands envelope the range of intermediate state mass distributions considered in Fig. 5, including the resonance components and the models for the DIS continuum. For the on-shell part of the FSI amplitude in Eq. (32) the largest effect is seen at the lowest Q^2 values, where...

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Unpolarized EMC effect in $^7$Li. The curves indexed with various numbers are the results from the same “Standard Nuclear Model” we used before, for 4 different $Q^2$ bins (in the kinematics of the proposed measurement). The dark blue curve is from the QMC model by Thomas/Cloët/Benz. The small inset is for “no offshell” (Fermi motion only).
Data with random variation

Figure 1: Comparison of R1 and R2 with different models (NNM, SNM, QMC, MSS, CQS) across various x values.

- X-axis represents the variable x.
- Y-axis represents the data values for R1 and R2.
- Different markers and colors denote the models and their corresponding data points.
- Random variation is evident in the data points for each model.