The Polarized EMC Effect

Ian Cloët
Argonne National Laboratory

Polarized light-ion physics with an EIC

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The EMC Effect

- Measurement of the *EMC effect* created a new paradigm regarding QCD and nuclear structure.
- 30+ years after discovery a broad consensus on explanation is lacking.
- *Valence quarks in nucleus carry less momentum than in a nucleon*.

Understanding origin is critical for a QCD based description of nuclei.

Modern QCD motivated explanations based around medium modification of the bound nucleons.

- *Is modification caused by mean-fields which modify all nucleons all the time or by SRCs which modify some nucleons some of the time?*

Many nuclear physicists think nuclear structure provides explanation.
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Nucleons in Nuclei

Nuclei are extremely dense:
- proton rms radius is $r_p \approx 0.85$ fm, corresponds hard sphere $r_p \approx 1.10$ fm
- ideal packing gives $\rho \approx 0.13$ fm$^{-3}$; nuclear matter density is $\rho \approx 0.16$ fm$^{-3}$
- 20% of nucleon volume inside other nucleons – nucleon centers $\sim 2$ fm apart

For realistic charge distribution 25% of proton charge at distances $r > 1$ fm

*Natural to expect that nucleon properties are modified by nuclear medium – even at the mean-field level*
- in contrast to traditional nuclear physics

Understanding validity of two viewpoints remains key challenge for nuclear physics – *a new paradigm or deep insights into color confinement in QCD*
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- Understanding validity of two viewpoints remains key challenge for nuclear physics
  - a new paradigm or deep insights into color confinement in QCD
**Understanding the EMC effect**

- **The puzzle posed by the EMC effect will only be solved by conducting new experiments that expose novel aspects of the EMC effect**

- Measurements should help distinguish between explanations of EMC effect e.g. whether *all nucleons* are modified by the medium or only those in SRCs

- Important examples are measurements of the **EMC effect in polarized structure functions** & the **flavor dependence of EMC effect**

- A JLab experiment has been approved to measure the spin structure of $^7\text{Li}$

- Flavor dependence will be accessed via JLab DIS experiments on $^{40}\text{Ca}$ & $^{48}\text{Ca}$ – *but parity violating DIS stands to play the pivotal role (maybe at EIC)*

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**Graphs:**

1. **EMC effect**
   - $Q^2 = 5 \text{ GeV}^2$
   - $\rho = 0.16 \text{ fm}^{-3}$

2. **Polarized EMC effect**
   - $Z/N = 82/126$ (lead)
   - $F_{2A}/F_{2D}$
   - $d_{A}/d_{f}$
   - $u_{A}/u_{f}$

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**References:**

Theory approaches to EMC effect

To address the EMC effect must determine nuclear quark distributions:

\[ q_A(x_A) = \frac{P^+}{A} \int \frac{d\xi^-}{2\pi} e^{iP^+ x_A \xi^- / A} \langle A, P | \bar{\psi}_q(0) \gamma^+ \psi_q(\xi^-) | A, P \rangle \]

Common to approximate using convolution formalism

\[ q_A(x_A) = \sum_{\alpha, \kappa} \int_0^A dy_A \int_0^1 dx \, \delta(x_A - y_A x) \, f_{\alpha, \kappa}(y_A) \, q_{\alpha, \kappa}(x) \]

\( \alpha = \) (bound) protons, neutrons, pions, deltas. . .
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- \( \alpha = \) (bound) protons, neutrons, pions, deltas. . .
- \( q_{\alpha}(x) \) light-cone distribution of quarks \( q \) in bound hadron \( \alpha \)
- \( f_{\alpha}(y_A) \) light-cone distribution of hadrons \( \alpha \) in nucleus
Modern GFMC or VMC nucleon momentum distributions have significant high momentum tails.

Indicates momentum distributions contain SRCs: \( \sim 20\% \) for \( ^{12}\text{C} \)

Light-cone momentum distribution of nucleons in nucleus is given by

\[
f(y_A) = \int \frac{d^3 \vec{p}}{(2\pi)^3} \delta \left( y_A - \frac{p^+}{P^+} \right) \rho(p)
\]
Quarks, Nuclei, and the NJL model

- this is just a modern interpretation of the Nambu–Jona-Lasinio (NJL) model
- model is a Lagrangian based covariant QFT, exhibits dynamical chiral symmetry breaking & quark confinement; elements can be QCD motivated via the DSEs

Quark confinement is implemented via proper-time regularization

- quark propagator: \([\slashed{p} - m + i\varepsilon]^{-1} \rightarrow Z(p^2)[\slashed{p} - M + i\varepsilon]^{-1}\)
- wave function renormalization vanishes at quark mass-shell: \(Z(p^2 = M^2) = 0\)
- confinement is critical for our description of nuclei and nuclear matter

![Graph 1](image1.png)

![Graph 2](image2.png)
Nucleon Electromagnetic Form Factors

- Nucleon = quark+diquark
- Form factors given by Feynman diagrams:

Calculation satisfies electromagnetic gauge invariance; includes

- dressed quark–photon vertex with $\rho$ and $\omega$ contributions
- contributions from a pion cloud

Nucleon Electromagnetic Form Factors

- Nucleon = quark+diquark
- Form factors given by Feynman diagrams:

\[
\frac{1}{2} p + k = \frac{1}{2} p - k
\]

Calculation satisfies electromagnetic gauge invariance; includes:

- dressed quark–photon vertex with ρ and ω contributions
- contributions from a pion cloud
**Nucleon quark distributions**

- **Nucleon** = quark+diquark

**PDFs given by Feynman diagrams:** $\langle \gamma^+ \rangle$

- Covariant, correct support; satisfies sum rules, Soffer bound & positivity

$$\langle q(x) - \bar{q}(x) \rangle = N_q, \quad \langle x u(x) + x d(x) + \ldots \rangle = 1, \quad |\Delta q(x)|, \quad |\Delta_T q(x)| \leq q(x)$$

NJL at Finite Density

Finite density (mean-field) Lagrangian: $\bar{q}q$ interaction in $\sigma$, $\omega$, $\rho$ channels

$$\mathcal{L} = \bar{\psi}_q (i \not{\partial} - M^* - \mathcal{V}_q) \psi_q + \mathcal{L}'_I$$

Fundamental physics – mean fields couple to the quarks in nucleons

Quark propagator:

$$S(k)^{-1} = \frac{k}{k} - M + i\varepsilon \rightarrow S_q(k)^{-1} = \frac{k}{k} - M^* - \mathcal{V}_q + i\varepsilon$$

Hadronization + mean-field $\implies$ effective potential (solve self-consistently)

$$\mathcal{E} = \mathcal{E}_V + \mathcal{E}_p + \mathcal{E}_n - \frac{\omega_0^2}{4G_\omega} - \frac{\rho_0^2}{4G_\rho}$$

$\mathcal{E}_V =$ vacuum energy

$\mathcal{E}_{p(n)} = $ energy of nucleons moving in $\sigma$, $\omega$, $\rho$ mean-fields
Nucleons in the Nuclear Medium

For nuclei, we find that quarks bind together into color singlet nucleons

- however contrary to traditional nuclear physics approaches these quarks feel the presence of the nuclear environment

- as a consequence bound nucleons are modified by the nuclear medium

Modification of the bound nucleon wave function by the nuclear medium is a natural consequence of quark level approaches to nuclear structure

For a proton in nuclear matter find

- Dirac & charge radii each increase by about 8%; Pauli & magnetic radii by 4%
- $F_{2p}(0)$ decreases; however $F_{2p}/2M_N$ almost constant – $\mu_p$ almost constant
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\begin{itemize}
  \item \text{free current}
  \item \text{NM current ($\rho_B = 0.16 \text{ fm}^{-3}$)}
  \item \text{empirical}
\end{itemize}
EMC and Polarized EMC effects

- Definition of polarized EMC effect:
  - ratio equals unity if no medium effects

Large polarized EMC effect results because in-medium quarks are more relativistic ($M^* < M$)

- lower components of quark wave functions are enhanced and these usually have larger orbital angular momentum
- *in-medium we find that quark spin is converted to orbital angular momentum*

A large polarized EMC effect would be difficult to accommodate within traditional nuclear physics and many other explanations of the EMC effect

\[
\Delta R = \frac{g_{1A}}{g_{1A}^{\text{naive}}} = \frac{g_{1A}}{P_p g_{1p} + P_n g_{1n}}
\]

\[Q^2 = 5 \text{ GeV}^2 \]
\[
\rho = 0.16 \text{ fm}^{-3}
\]
Spin-dependent cross-section is suppressed by $1/A$
- should choose light nucleus with spin carried by proton e.g. $^7\text{Li}$, $^{11}\text{B}$, ... 

Effect in $^7\text{Li}$ is slightly suppressed because it is a light nucleus and proton does not carry all the spin  
(simple WF: $P_p = 13/15$ \& $P_n = 2/15$)

Experiment now approved at JLab [E12-14-001] to measure spin structure functions of $^7\text{Li}$  
(GFMC: $P_p = 0.86$ \& $P_n = 0.04$)

*Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in $^7\text{Li}$*
Without medium modification both EMC & polarized EMC effects disappear.

Polarized EMC effect is smaller than the EMC effect – this is natural within standard nuclear theory and also from SRC perspective.

Large splitting very difficult without mean-field medium modification.
Nuclear spin sum

<table>
<thead>
<tr>
<th>Proton spin states</th>
<th>( \Delta u )</th>
<th>( \Delta d )</th>
<th>( \Sigma )</th>
<th>( g_A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>0.97</td>
<td>-0.30</td>
<td>0.67</td>
<td>1.267</td>
</tr>
<tr>
<td>( ^7\text{Li} )</td>
<td>0.91</td>
<td>-0.29</td>
<td>0.62</td>
<td>1.19</td>
</tr>
<tr>
<td>( ^{11}\text{B} )</td>
<td>0.88</td>
<td>-0.28</td>
<td>0.60</td>
<td>1.16</td>
</tr>
<tr>
<td>( ^{15}\text{N} )</td>
<td>0.87</td>
<td>-0.28</td>
<td>0.59</td>
<td>1.15</td>
</tr>
<tr>
<td>( ^{27}\text{Al} )</td>
<td>0.87</td>
<td>-0.28</td>
<td>0.59</td>
<td>1.15</td>
</tr>
<tr>
<td>Nuclear Matter</td>
<td>0.79</td>
<td>-0.26</td>
<td>0.53</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Angular momentum of nucleon: \( J = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g \)

- in medium \( M^* < M \) and therefore quarks are more relativistic
- lower components of quark wavefunctions are enhanced
- quark lower components usually have larger angular momentum
- \( \Delta q(x) \) very sensitive to lower components

Therefore, in-medium quark spin \( \rightarrow \) orbital angular momentum
Explanations of EMC effect using SRCs also invoke medium modification
- since about 20% of nucleons are involved in SRCs, need medium modifications about 5 times larger than in mean-field models

For polarized EMC effect only 2–3% of nucleons are involved in SRCs
- it would therefore be natural for SRCs to produce a smaller polarized EMC effect

Observation of a large polarized EMC effect would imply that SRCs are less likely to be the mechanism responsible for the EMC effect
Flavor dependence of EMC effect

Find that EMC effect is basically a result of binding at the quark level

- for $N > Z$ nuclei, $d$-quarks feel more repulsion than $u$-quarks: $V_d > V_u$
- therefore $u$ quarks are more bound than $d$ quarks

Find isovector mean-field shifts momentum from $u$-quarks to $d$-quarks

$$q(x) = \frac{p^+}{p^+ - V^+} q_0 \left( \frac{p^+}{p^+ - V^+} x - \frac{V_q^+}{p^+ - V^+} \right)$$

SRCs shift momentum from $n$ to $p$ – therefore opposite to mean-field – SRCs are also predominately isoscalar
**Flavor dependence of EMC effect**

[iCC, W. Bentz and A. W. Thomas, Phys. Rev. Lett. 102, 252301 (2009)]

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- SRCs shift momentum from $n$ to $p$ – *therefore opposite to mean-field* – SRCs are also predominately isoscalar
A Reassessment of the NuTeV anomaly

Paschos-Wolfenstein ratio motivated NuTeV study:

\[ R_{PW} = \frac{\sigma_{\nu A}^{NC} - \sigma_{\bar{\nu} A}^{NC}}{\sigma_{\nu A}^{CC} - \sigma_{\bar{\nu} A}^{CC}} \]

\[ N \approx Z \frac{1}{2} - \sin^2 \theta_W \]

\[ + \left( 1 - \frac{7}{3} \sin^2 \theta_W \right) \frac{\langle x u_A - x d_A \rangle}{\langle x u_A + x d_A \rangle} \]

- **NuTeV**: \( \sin^2 \theta_W = 0.2277 \pm 0.0013 \text{ (stat)} \pm 0.0009 \text{ (syst)} \) [Zeller et al. PRL. 88, 091802 (2002)]

- **Standard Model**: \( \sin^2 \theta_W = 0.2227 \pm 0.0004 \ \Leftrightarrow \ 3\sigma \rightarrow \text{“NuTeV anomaly”} \)

- **Using NuTeV functionals**: \( \sin^2 \theta_W = 0.2221 \pm 0.0013 \text{ (stat)} \pm 0.0020 \text{ (syst)} \)

Corrections from the EMC effect (~1.5 \( \sigma \)) and charge symmetry violation (~1.5 \( \sigma \)) brings NuTeV result into agreement with the Standard Model consistent with mean-field expectation – momentum shifted from \( u \) to \( d \) quarks
**Parity-Violating DIS**


\[ Z/N = 26/30 \text{ (iron)} \]

\[ Q^2 = 5 \text{ GeV}^2 \]

\[ a_2^{\text{naive}} \]

\[ 0.8 \]

\[ 0.9 \]

\[ 1 \]

\[ 1.1 \]

\[ x_A \]

\[ a_2(x_A) \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

**PV DIS – \( \gamma Z \) interference:**

\[
\sum_X \begin{vmatrix}
\begin{array}{c}
\ell \\
\ell' \\
\gamma
\end{array}
\end{vmatrix}
\begin{vmatrix}
\begin{array}{c}
X_A
\end{array}
\end{vmatrix}
\begin{vmatrix}
\begin{array}{c}
X_A
\end{array}
\end{vmatrix}
\begin{vmatrix}
\begin{array}{c}
Z^0
\end{array}
\end{vmatrix}
\begin{vmatrix}
\begin{array}{c}
X_A
\end{array}
\end{vmatrix}
\end{vmatrix}^2
\]

\[ A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \frac{N_{\sim Z}}{9} - 4 \sin^2 \theta_W - \frac{12}{25} \frac{u_+(x) - d_+(x)}{u_+(x) + d_+(x)} \]

- Deviation from naive expectation: momentum shifted from \( u \) to \( d \)-quarks
- \( F_2^{\gamma Z}(x) \) has markedly different flavour dependence compared with \( F_2^{\gamma}(x) \)
- Measurement of both enables an extraction of \( u(x) \) and \( d(x) \) separately

Proposal to measure \( a_2 \) of \( ^{48}\text{Ca} \) was deferred – hopefully approved soon
**Parity-Violating DIS**

\[ Q^2 = 5 \text{ GeV}^2 \]
\[ Z/N = 20/28 \ (\text{calcium-48}) \]

\[ a_2(x_A) = a_2 \text{ naïve} - \frac{9}{5} - 4 \sin^2 \theta_W \]

\[ Z/N = 82/126 \ (\text{lead}) \]
\[ Q^2 = 5 \text{ GeV}^2 \]
\[ a_2(x_A) = a_2 \text{ naïve} - \frac{9}{5} - 4 \sin^2 \theta_W \]

**PV DIS – γ Z interference:**

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A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \propto a_2(x) = -2g_A^e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \]
\[ N \approx Z \frac{9}{5} - 4 \sin^2 \theta_W - \frac{12}{25} \frac{u_A^+(x) - d_A^+(x)}{u_A^+(x) + d_A^+(x)} \]

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Charged Current Processes

The reaction $e^\mp A \rightarrow \nu (\bar{\nu}) X$ has incredible promise for shedding new light on nucleon and nuclear PDFs.

- at EIC neutrino energy can be reconstructed from final state

Parton model expressions for $W^\pm$ structure functions

$$F_1^{W^+} = \bar{u} + d + s + \bar{c}$$
$$F_3^{W^+} = -\bar{u} + d + s - \bar{c}$$
$$F_1^{W^-} = u + \bar{d} + \bar{s} + c$$
$$F_3^{W^-} = u - \bar{d} - \bar{s} + c$$

Would provide much needed data on flavour structure of both valence and sea quark distribution functions.

Flavor dependence can also be test using e.g. SIDIS, $\pi^+ / \pi^-$ Drell-Yan, PVDIS, $\nu$-DIS & $W$-production at RHIC.
Quasi-Elastic Scattering

First hints for QCD effects in nuclei came from quasi-elastic electron scattering:

\[ \frac{d^2 \sigma}{d \Omega \, d \omega} = \sigma_{\text{Mott}} \left[ \frac{q^4}{|q|^4} R_L(\omega, |q|) + f(|q|, \theta) R_T(\omega, |q|) \right] \]

in measurements at MIT Bates in 1980 on Fe, which were later confirmed at Saclay in 1984

These experiments, and most others following, observed a quenching of the Coulomb Sum Rule (CSR):

\[ S_L(|q|) = \int_{\omega+} |q| \, d\omega \frac{R_L(\omega, |q|)}{Z \, G^2_{Ep}(Q^2) + N \, G^2_{En}(Q^2)} \]

despite widespread expectation that the CSR should approach unity for \(|q| \gg k_F\)

Observation of quenching began one of the most controversial issues in nuclear physics – which remains to this day
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Coulomb Sum Rule

- QE scattering is sensitive to internal structural properties of bound nucleons
- quenching of the CSR can be naturally explained by slight modification of bound nucleon EM form factors
- natural consequence of QCD models

Two state-of-the-art theory results exist, both from Argonne:

- the GFMC result, with no explicit QCD effects, finds no quenching
- QCD motivated framework finds a dramatic quenching; 50% relativistic effects & 50% medium modification

Jefferson Lab has revisited QE scattering & this impasse stands to be resolved shortly

confirmation of either result will be an important milestone in QCD nuclear physics
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Deuteron
**The Deuteron**

The deuteron is the simplest nucleus, consisting primarily of a proton + neutron with 2.2 MeV binding.

- However, the deuteron is greater than the sum of its parts – it has numerous properties not found in either of its primary constituents.

**Unique properties of deuteron:**

- A quadrupole moment
- Has additional spin-independent leading-twist PDF called $b_1^q(x)$
- Gluon transversity PDF
- Has numerous additional TMDs and GPDs associated with tensor polarization

Deuteron is the idea system to study QCD aspects of $NN$ interaction.
BONuS data suggestive of an EMC effect that is difficult to explain with traditional nuclear physics

For DIS on spin-1 target 4 additional structure functions $b_1\ldots 4(x)$ appear; in Bjorken limit just one $b_1(x)$ [Hoodbhoy, Jaffe and Manohar, Nucl. Phys. B 312, 571 (1989)]

$$b_1(x) = \sum_q e^2_q \left[ b_1^q(x) + \bar{b}_1^q(x) \right], \quad b_1^q = \frac{1}{2} \theta_q = \frac{1}{4} \left[ 2 q^{(\lambda=0)} - q^{(\lambda=1)} - q^{(\lambda=-1)} \right]$$

Seems impossible to explain HERMES data with only bound nucleon degrees of freedom
**Deuteron DIS Structure**

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- Seems impossible to explain HERMES data with only bound nucleon degrees of freedom.
Spin-1 TMDs – Tensor Polarization

Tensor polarized TMDs have a number of surprising features

\[
\theta(x, k_T^2) = \theta_{LL}(x, k_T^2) - \frac{k_T^2}{2 m_n^2} \theta_{TT}(x, k_T^2)
\]

TMDs \( \theta_{LL}(x, k_T^2) \) & \( \theta_{LT}(x, k_T^2) \) identically vanishes at \( x = 1/2 \) for all \( k_T^2 \)

- \( x = 1/2 \) corresponds to zero relative momentum between (the two) constituents, that is, \( s \)-wave contributions
- therefore \( \theta_{LL} \) & \( \theta_{LT} \) only receive contributions from \( L \geq 1 \) components of the wave function – sensitive measure of orbital angular momentum

Features hard to determine from a few moments – difficult for lattice QCD
Deuterons spin-independent impact-parameter PDFs
- tensor polarized along $z$-axis – donut shape is clear
- longitudinally polarized along $x$-axis

Does the gluon donut align with the quark donut – does this change with $x$ – incredible insight into $NN$ interaction possible at an EIC

[Adam Freese, I. C. Cloët, to appear]
Conclusion

Understanding the EMC effect is a critical step towards a QCD based description of nuclei

- approved JLab experiment to measure polarized EMC effect in $^7\text{Li}$
- PVDIS experiment on $^{48}\text{Ca}$ would provide critical information on flavor dependence of the EMC effect

EIC would be transformational for understanding QCD and nuclei

- quark and gluon GPDs and TMDs of: proton, deuteron, triton, $^3\text{He}$, $^4\text{He}$
- quark and gluon PDFs of $^7\text{Li}$, $^{11}\text{B}$, $^{19}\text{F}$
- must have flavor separation – e.g. $s$-quarks

Unprecedented opportunity to study $NN$ interaction and nuclei with QCD d.o.f