Isospin Dependence of the EMC Effect and Short Range Correlations

Barak Schmookler
Scale Separation in the Nucleus

Weak Binding: MeV

Strong Binding: GeV
The EMC Effect

![Graph showing the EMC Effect with expectation and reality curves for Fe-56 and quark velocity versus $x_B$.]
The EMC Effect – Quarks Move “Slower” in the Nucleus

\[
\frac{F_{2}^{Fe} / 56}{(F_{2}^{d}/2)}
\]

Expectation

Reality

(anti) shadowing

EMC

Fermi Motion

Quark Velocity

\(x_B\)
The EMC Effect – Quarks Move “Slower” in the Nucleus

35 Years, 1000+ Papers Still No Consensus!!!

O. Hen et al., Rev. Mod. Phys. 89, 045002 (2017)
We Can Study the Structure of Complex Objects with Inclusive Scattering

\[ \sigma = \pi R^2 \]
Energy Transfer:
\[ \nu = E - E' \]

Four-Momentum Transfer Squared:
\[ Q^2 = -q^2 = 4EE' \sin^2 \left( \frac{\theta_e}{2} \right) \]

Mass of X:
\[ W = \sqrt{(P + q)^2} = \sqrt{M^2 + 2M\nu - Q^2} \]

Bjorken x:
\[ x_B = \frac{Q^2}{2M\nu} \]
Deep Inelastic Scattering (DIS):

Provides information on the underlying Partonic structure of the Nucleons
DIS and the EMC Effect

Assumed to be equivalent to per-nucleon Cross-Section ratio

\[ \frac{F_{2e}^{Fe}}{F_{2d}^{F}} \]

(anti) shadowing

Expectation

Reality

EMC

Fermi Motion

Quark Velocity

\[ x_B \]
The EMC Effect: Universal Nuclear Effect


The EMC Effect: **Universal** Nuclear Effect

\[ \frac{\sigma_A}{\sigma_d} \]


The EMC Effect: Universal **Nuclear** Effect

![Graphs showing the EMC Effect for different elements](image)

Thomas Jefferson National Accelerator Facility (JLab)
The CLAS Detector in Hall B at JLab
The CLAS Detector in Hall B at JLab

5.01 GeV Incident Electrons

Liquid Hydrogen or Deuterium

C, Al, Fe, or Pb
Our New EMC Effect Measurements

\[ \frac{\sigma_A}{\sigma_D} \]

- **$^{12}\text{C}/^2\text{D}$**
- **$^{27}\text{Al}/^2\text{D}$**
- **$^{56}\text{Fe}/^2\text{D}$**
- **$^{208}\text{Pb}/^2\text{D}$**
Our New EMC Effect Measurements

\( \frac{\sigma_A}{\sigma_D} / (\sigma_D/2) \)

\( ^{12}\text{C}/^2\text{D} \)

\( ^{27}\text{Al}/^2\text{D} \)

\( ^{56}\text{Fe}/^2\text{D} \)

- This Work
- Published Data (SLAC)
- Published Data (JLab)
Our New EMC Effect Measurements

\[ \frac{(\sigma_A/A)}{(\sigma_D/2)} \]

- **$^{12}\text{C}/^2\text{D}$**
- **$^{27}\text{Al}/^2\text{D}$**
- **$^{56}\text{Fe}/^2\text{D}$**

- **This Work**
- **Published Data (SLAC)**
- **Published Data (JLab)**
Current Explanations of the EMC Effect

- Two leading approaches for describing the EMC effect:
  - All nucleons are slightly modified when bound in nuclei
  - Nucleons are unmodified most of the time, but are modified significantly when they fluctuate into Short Range Correlation (SRC) pairs
Observed EMC-SRC Correlation

\[ \chi^2 / \text{ndf} = 5.673 / 5 \]

\[ a = -0.07004 \pm 0.003658 \]

Short Range Correlations (SRC)

Nucleon pairs that are close together in the nucleus

Momentum space: *high relative* and *low c.m. momentum*, compared to the Fermi momentum ($k_F$)
Short Range Correlations (SRC)

Nucleon pairs that are close together in the nucleus

**Momentum space**: *high relative* and *low c.m. momentum*, compared to the Fermi momentum \( (k_F) \)
Short Range Correlations (SRC)

Scaling: High-momentum component of nuclear wave function is deuteron-like.

\( a_2 \): Probability of finding a high momentum nucleon in nucleus A relative to deuterium

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\[ a_2: \text{Probability of finding a high momentum nucleon in nucleus } A \text{ relative to deuterium} \]

Isospin Dependence: Dominated by neutron-proton pairs

Quasi-Elastic (QE) Scattering:

Provides information on how the Nucleons move in the Nucleus
QE Scattering: Impulse Approximation

QE A(e,e'N)X scattering:

\[ S(P_m, E_m) \]

\[ \frac{d^6\sigma}{d\nu d\Omega_e dE_p d\Omega_p} \propto \sigma_{eN} \times S(P_m, E_m) \]

\( S(P_m, E_m) \) is the spectral function – the probability of finding a nucleon with a given momentum and removal energy
QE Scattering: Impulse Approximation

QE A(e,e'N)X scattering:

\[ S(P_m, E_m) \] is the spectral function – the probability of finding a nucleon with a given momentum and removal energy.

Inclusive QE scattering is an integral over the above cross-section.
What can be done with Inclusive Scattering

Minimum Momentum of Struck Nucleon

\[(q + p_A - p_{A-1})^2 = p_f^2 = m_N^2\]
What can be done with Inclusive Scattering

Fixed $Q^2$

Minimum Momentum of Struck Nucleon

\[(q + p_A - p_{A-1})^2 = p_f^2 = m_N^2\]
Our New $a_2$ Measurements

![Graphs showing measurements for different isotopes](image)

- $^{12}\text{C}/^{2}\text{D}$
- $^{27}\text{Al}/^{2}\text{D}$
- $^{56}\text{Fe}/^{2}\text{D}$
- $^{208}\text{Pb}/^{2}\text{D}$

*Legend:*
- **This Work**
- **Published Data**
Our New $a_2$ Measurements

Cross-Section scales for large $x_B$!
Our New $a_2$ Measurements

Cross-Section scales for large $x_B$!

Red lines are the measured $a_2$ values
Back to the EMC-SRC Correlation

Bound = 'Quasi Free' + Modified SRCs
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\[ F_2^A = (Z - n_{SRC}^A)F_2^p + n_{SRC}^A(F_2^{p*} + F_2^{n*}) + (N - n_{SRC}^A)F_2^n \]
Bound = 'Quasi Free' + Modified SRCs

\[ F_2^A = (Z - n_{SRC}^A)F_2^p + n_{SRC}^A(F_2^{p*} + F_2^{n*}) \]
\[ + (N - n_{SRC}^A)F_2^n \]
\[ = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n) \]

\[ \Delta F_2^{p(n)} = F_2^{p*(n*)} - F_2^{p(n)} \]
Bound = 'Quasi Free' + Modified SRCs

\[ F^A_2 = (Z - n^A_{SRC})F^p_2 + n^A_{SRC}(F^{p*}_2 + F^{n*}_2) \]
\[ + (N - n^A_{SRC})F^n_2 \]
\[ = ZF^p_2 + NF^n_2 + n^A_{SRC}(\Delta F^p_2 + \Delta F^n_2) \]

\[ \Delta F^{p(n)}_2 = F^{p*(n*)}_2 - F^{p(n)}_2 \]

\[ F^d_2 = F^p_2 + F^n_2 + n^d_{SRC}(\Delta F^p_2 + \Delta F^n_2) \]
Our Model's Prediction for the EMC Effect

\[ \frac{F_2^A/A}{F_2^d/2} = (a_2 - 2N/A) (n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + 2 \cdot \frac{Z - N}{Z + N} \cdot \frac{F_2^p}{F_2^d} + 2 \frac{N}{A} \]

\[ a_2 = \frac{n_{SRC}^A/A}{n_{SRC}^d/2} \]
Our Model's Prediction for the EMC Effect

\[
\frac{F_{2}^A / A}{F_{2}^d / 2} = (a_2 - 2 \frac{N}{A}) \left( n_{SRC}^d \frac{\Delta F_{2}^p + \Delta F_{2}^n}{F_{2}^d} \right) + 2 \cdot \frac{Z - N}{Z + N} \cdot \frac{F_{2}^p}{F_{2}^d} + 2 \frac{N}{A}
\]

Universal?
\[
\frac{F_2^A / A}{F_2^d / 2} = (a_2 - 2 \frac{N}{A})(n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d}) + 2 \cdot \frac{Z - N}{Z + N} \cdot \frac{F_2^p}{F_2^d} + 2 \frac{N}{A}
\]
\[
\frac{F_2^A / A}{F_2^d / 2} = (a_2 - 2\frac{N}{A}) \left( n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} \right) + 2 \cdot \frac{Z - N}{Z + N} \cdot \frac{F_2^p}{F_2^d} + 2\frac{N}{A}
\]
EMC Universal Modification Function

![Graph showing EMC Universal Modification Function with data points for SLAC, JLab - Hall C, and This Work.]
np-SRC Fluctuations in Nuclei

Neutron + Proton \neq np-SRC
Additional Slides
Inelastic Electron-Proton Inclusive Scattering

\[
\frac{d^2 \sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4} \left[ \frac{2}{M} \frac{F_1(x_B, Q^2)}{\sin^2 \frac{\theta_e}{2}} + \frac{F_2(x_B, Q^2)}{\nu \cos^2 \frac{\theta_e}{2}} \right]
\]
Inelastic Electron-Proton Inclusive Scattering

Structure Functions

\[
\frac{d^2 \sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4} \left[ 2 \frac{F_1(x_B, Q^2)}{M} \sin^2 \frac{\theta_e}{2} + \frac{F_2(x_B, Q^2)}{\nu} \cos^2 \frac{\theta_e}{2} \right]
\]

\[F_1(x_B, Q^2) \rightarrow F_1(x_B)\]
\[F_2(x_B, Q^2) \rightarrow F_2(x_B)\]
Structure functions in DIS
Structure functions in DIS

\[ F_2(x_B) = 2x_B F_1(x_B) = \sum_i e_i^2 x_B [q_i(x_B) + \bar{q}_i(x_B)] \]

3 Quarks at Rest
3 Interacting Quarks, with Sea
Compare DIS on Deuterium

\[ \frac{F_d}{F_p} \]

vs

\[ x_B \]

We want to Extract Cross-Section Ratios to Deuterium

- Bin data in $x_B$
We want to Extract Cross-Section Ratios to Deuterium

• Bin data in $x_B$

• Apply the following corrections:
We want to Extract Cross-Section Ratios to Deuterium

- Bin data in $x_B$
- Apply the following corrections:
  - Luminosity Corrections
We want to Extract Cross-Section Ratios to Deuterium

- Bin data in $x_B$
- Apply the following corrections:
  - ✔ Luminosity Corrections
  - ✔ Acceptance Corrections
We want to Extract Cross-Section Ratios to Deuterium

- Bin data in $x_B$
- Apply the following corrections:
  - Luminosity Corrections
  - Acceptance Corrections
  - Radiative and Coulomb Corrections
We want to Extract Cross-Section Ratios to Deuterium

- Bin data in $x_B$
- Apply the following corrections:
  - Luminosity Corrections
  - Acceptance Corrections
  - Radiative and Coulomb Corrections
  - Bin-Centering Corrections

![Cross-Section Plot](Image)
EMC Effect: Spectator Tagging

- Tagged measurements beyond the Deuteron?
- Signature of Correlations at a collider?
Short Range Correlations (SRC)

Nucleon pairs that are close together in the nucleus

Momentum space: *high relative* and *low c.m. momentum*, compared to the Fermi momentum \((k_F)\)
Focus on Neutron-Rich Nuclei

M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)
Focus on Neutron-Rich Nuclei

**Prediction**: EMC effect will show no growth for neutrons...

M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)
Focus on Neutron-Rich Nuclei

**Prediction:** EMC effect will show no growth for neutrons and grow for protons

M. Duer et al. (CLAS Collaboration), Nature, In-Print (2018)
Calculate Per-Neutron (Per-Proton) Ratios

Per-Neutron: \[ \frac{\sigma_A/N}{\sigma_D/1} \]

Per-Proton: \[ \frac{\sigma_A/Z}{\sigma_D/1} \]
Calculate Per-Neutron (Per-Proton) Ratios

**Per-Neutron:**\[ \frac{\sigma_A/N}{\sigma_D/1} \]

\[ \frac{F_{2}^{A}/N}{F_{2}^{d}/1} = (a_{2}^{n} - 1)(n_{SRC}^{d} \frac{\Delta F_{2}^{p} + \Delta F_{2}^{n}}{F_{2}^{d}}) + \left( \frac{Z}{N} - 1 \right) \cdot \frac{F_{2}^{p}}{F_{2}^{d}} + 1 \]

**Per-Proton:**\[ \frac{\sigma_A/Z}{\sigma_D/1} \]

\[ \frac{F_{2}^{A}/Z}{F_{2}^{d}/1} = (a_{2}^{p} - \frac{N}{Z})(n_{SRC}^{d} \frac{\Delta F_{2}^{p} + \Delta F_{2}^{n}}{F_{2}^{d}}) + \left( \frac{Z}{N} - 1 \right) \cdot \frac{F_{2}^{p}}{F_{2}^{d}} + \frac{N}{Z} \]
New EMC-SRC Correlation
Isoscalar Corrections for DIS Ratios

Correction Factor:

\[
\frac{A}{2} \cdot \left(1 + \frac{F_2^n}{F_2^p}\right) \frac{Z + N \cdot \frac{F_2^n}{F_2^p}}{Z}
\]

\[F_2^d = F_2^p + F_2^n + n_{SRC}^d (\Delta F_2^p + \Delta F_2^n)\]
New EMC-SRC Correlation: Version II
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