Experimental Overview of Past and Future Studies of the EMC Effect

Dave Gaskell - JLab
February 14, 2013

INT Workshop on Nuclear Structure and Dynamics at Short Distance
Outline

• Measurements of $\sigma_A/\sigma_D$
  – Early measurements
  – $x, Q^2$, nuclear dependence, universality

• JLab results and implications
  – EMC effect and local density
  – EMC-SRC connection
  – Flavor dependence
  – Nuclear dependence of $R=\sigma_L/\sigma_T$

• Summary
Typical nuclear binding energies $\rightarrow$ MeV while DIS scales $\rightarrow$ GeV

Naïve expectation:

$$F_2^A(x) = ZF_2^p(x) + (A-Z)F_2^n(x)$$

More sophisticated approach includes effects from Fermi motion

$$F_2^A(x) = \sum_i \int_x^{M_A/m_N} dy f_i(y) F_2^N(x/y)$$

Quark distributions in nuclei were not expected to be significantly different (below $x=0.6$)

$$F_2^{Fe}/(ZF_2^p + (A-Z)F_2^n)$$

Bodek and Ritchie
PRD 23, 1070 (1981)
First Measurement of the EMC Effect

• First published measurement of nuclear dependence of $F_2$ by the European Muon Collaboration in 1983

• Observed 2 mysterious effects
  – Significant enhancement at small $x$ $\rightarrow$ Nuclear Pions! (see my thesis)
  – Depletion at large $x$ $\rightarrow$ the “EMC Effect”

• Enhancement at $x<0.1$ later went away

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Confirmation of the Effect

SLAC re-analysis of old solid target data used for measurements of cryotarget wall backgrounds

→ Effect for $x > 0.3$ confirmed
→ No large excess at very low $x$

*Bodek et al, PRL 50, 1431 (1983) and PRL 51, 534 (1983)*
Subsequent Measurements

A program of dedicated measurements quickly followed.

The resulting data is remarkably consistent over a large range of beam energies and species.
# EMC Effect Measurements

<table>
<thead>
<tr>
<th>Laboratory/collaboration</th>
<th>Beam</th>
<th>Energy (GeV)</th>
<th>Target</th>
<th>Year</th>
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<tbody>
<tr>
<td>SLAC E139</td>
<td>e</td>
<td>8-24.5</td>
<td>$D, ^4\text{He}, \text{Be, C, Ca, Fe, Ag, Au}$</td>
<td>1994, 1984</td>
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<td>SLAC E140</td>
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<td>CERN NMC</td>
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<td>$^6\text{Li}, ^{12}\text{C}, ^{40}\text{Ca}$</td>
<td>1992</td>
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<td>$\mu$</td>
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<td>$D, ^4\text{He}, \text{C, Ca}$</td>
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<tr>
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<td>Be, C, Al, Ca, Fe, Sn, Pb</td>
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<td>200</td>
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<td>1987</td>
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<tr>
<td></td>
<td>$\mu$</td>
<td>280</td>
<td>$D, \text{N, Fe}$</td>
<td>1985</td>
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<tr>
<td>CERN EMC</td>
<td>$\mu$</td>
<td>100-280</td>
<td>$D, \text{Cu}$</td>
<td>1993</td>
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<tr>
<td></td>
<td>$\mu$</td>
<td>280</td>
<td>$D, \text{C, Ca}$</td>
<td>1988</td>
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<td>$\mu$</td>
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<td>$D, \text{C, Cu, Sn}$</td>
<td>1988</td>
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<td>H, $D, \text{Fe}$</td>
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<td>$\mu$</td>
<td>490</td>
<td>$D, \text{Xe}$</td>
<td>1992</td>
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<td>DESY HERMES</td>
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<td>$D, ^3\text{He}, \text{N, Kr}$</td>
<td>2000, 2003</td>
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<td>Jefferson Lab</td>
<td>e</td>
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<td>$D, ^3\text{He}, ^4\text{He}, \text{Be, C, Cu, Au}$</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>e</td>
<td>6</td>
<td>$D, \text{C, Cu, Au}$</td>
<td>2004 (thesis)</td>
</tr>
</tbody>
</table>

Nuclear dependence of structure functions

Experimentally, we measure cross sections (and the ratios of cross sections)

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

\[
F_2(x) = \sum_i e_i^2 x q_i(x)
\]

\[
R = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1} \left( 1 + 4 \frac{M^2 x^2}{Q^2} \right) - 1
\]

In the limit \( R_A = R_D \)

\[
\sigma_A/\sigma_D = F_2^A/F_2^D
\]

Experiments almost always display cross section ratios, \( \sigma_A/\sigma_D \)

→ Often these ratios are labeled or called \( F_2^A/F_2^D \)

→ Sometimes there is an additional uncertainty estimated to account for the \( \sigma \rightarrow F_2 \) translation. Sometimes there is not.
Isoscalar Corrections

In the case of nuclei where $N \neq Z$, need to remove the “trivial” change in nuclear cross section due to $\sigma_n \neq \sigma_p$

$\rightarrow$ Different experiments often use slightly different parameterizations/estimates for this correction

\[ \frac{F_2^n}{F_2^p} \]

- SLAC param. (1-0.8x)
- CTEQ
- NMC fit

Isoscalar correction applied to data
Properties of the EMC Effect

Global properties of the EMC effect

1. Universal x-dependence

![Graph showing shadowing and anti-shadowing in the EMC region.](image)

- Shadowing
- Anti-shadowing
- Fermi motion
x Dependence

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

\( A = 3 \) for
\( ^3\text{He} \)

\( A = 4 \) for
\( ^4\text{He} \)

\( A = 9 \) for
\( \text{Be} \)

\( A = 12 \) for
\( \text{C (N)} \)

\[ x \]

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \]

\[ \sigma_A / \sigma_D \]

\[ 0.8 \quad 0.8 \quad 1 \quad 1.2 \]

\[ \text{JLab E03103} \quad \text{HERMES} \]

\[ \text{NMC (Be/C x C/D)} \quad \text{SLAC E139} \quad \text{JLab E03103} \]

\[ \text{NMC} \quad \text{SLAC E139} \quad \text{JLab E03103} \quad \text{HERMES (N)} \]
\textbf{x Dependence}

\begin{itemize}
  \item \textbf{Al} \quad A=27
    \begin{itemize}
      \item NMC (Al/C x C/D)
      \item SLAC E139
    \end{itemize}
  
  \item \textbf{Ca} \quad A=40
    \begin{itemize}
      \item NMC
      \item SLAC E139
    \end{itemize}
  
  \item \textbf{Ag/Sn} \quad A=108/119
    \begin{itemize}
      \item NMC (Sn/C x C/D)
      \item SLAC E139 (Ag)
      \item EMC (Sn)
    \end{itemize}
  
  \item \textbf{Au/Pb} \quad A=197/208
    \begin{itemize}
      \item NMC (Pb/C x C/D)
      \item SLAC E139 (Au)
    \end{itemize}
\end{itemize}
Properties of the EMC Effect

Global properties of the EMC effect

1. Universal $x$-dependence
2. Little $Q^2$ dependence*
Q^2 Dependence of the EMC Effect


(*) $Q^2$ Dependence of Sn/C

NMC measured non-zero $Q^2$ dependence in Sn/C ratio at low small $x$

→ This result is in some tension with other NMC C/D and HERMES Kr/D results

Properties of the EMC Effect

Global properties of the EMC effect

1. Universal x-dependence
2. Little $Q^2$ dependence
3. EMC effect increases with $A$
   → Anti-shadowing region shows little nuclear dependence
A-Dependence of EMC Effect

A-Dependence of EMC Effect

\[ \rho = \frac{3A}{4\pi R_e^3} \quad R_e^2 = \frac{5\langle r^2 \rangle}{3} \]

\[ \langle r^2 \rangle = \text{RMS electron scattering radius} \]

SLAC E139: Gomez et al, PRD 49, 4348 (1992)
EMC Effect Measurements at Large $x$

SLAC E139 provided the most extensive and precise data set for $x > 0.2$

Measured $\sigma_A/\sigma_D$ for $A = 4$ to 197
- $^4\text{He}$, $^9\text{Be}$, C, $^{27}\text{Al}$, $^{40}\text{Ca}$, $^{56}\text{Fe}$, $^{108}\text{Ag}$, and $^{197}\text{Au}$
→ Best determination of the $A$ dependence
→ Verified that the $x$ dependence was roughly constant

Building on the SLAC data
→ Higher precision data for $^4\text{He}$
→ Addition of $^3\text{He}$
→ Precision data at large $x$
JLab E03103

E03103 in Hall C at Jefferson Lab ran Fall 2004

→ Measured EMC ratios for light nuclei \( ^3\text{He}, \, ^4\text{He}, \, \text{Be}, \, \text{and C} \)

→ Results consistent with previous world data

→ Examined nuclear dependence a la E139

New definition of “size” of the EMC effect

→ Slope of line fit from \( x=0.35 \) to 0.7

Definition assumes shape of the EMC effect is universal for nuclei

→ Data *not inconsistent* with this assumption

→ Normalization errors mean we can only confirm this at 1-1.5% level
E03103 measured $\sigma_A/\sigma_D$ for $^3\text{He}$, $^4\text{He}$, Be, C

$\rightarrow$ $^3\text{He}$, $^4\text{He}$, C, EMC effect scales well with density

Scaled nuclear density $= (A-1)/A <\rho>$

$\rightarrow$ remove contribution from struck nucleon

$<\rho>$ from ab initio few-body calculations

E03103 measured $\sigma_A/\sigma_D$ for $^3$He, $^4$He, Be, C

$\rightarrow$ $^3$He, $^4$He, C, EMC effect scales well with density
$\rightarrow$ Be does not fit the trend

Scaled nuclear density = $(A-1)/A <\rho>$$

$<\rho>$ from ab initio few-body calculations

EMC Effect and Local Nuclear Density

$^9$Be has low average density
→ Large component of structure is $2\alpha+n$
→ Most nucleons in tight, $\alpha$-like configurations

EMC effect driven by *local* rather than *average* nuclear density

“Local density” is appealing in that it makes sense intuitively – can we make this more quantitative?
Weinstein et al observed linear correlation between size of EMC effect and Short Range Correlation “plateau”

→ Observing Short Range Correlations requires measurements at $x>1$
→ Reaction dynamics very different – DIS vs. QE scattering, why the same nuclear dependence?
Nuclear Dependence of EMC and SRCs

Detailed study of nuclear dependence of EMC effect and SRCs (see N. Fomin’s talk from Monday) does not favor either picture.

Can we distinguish between these two pictures via some new observable? → Flavor dependence of the EMC effect

High virtuality

\[ a_2 \sim \text{number of high momentum nucleons} \]

Local density

\[ R_{2N} \sim \text{number of nucleons “close” together} \]

Arrington et al, PRC 86, 065204 (2012)
Flavor dependence and SRCs

High momentum nucleons from SRCs emerge from tensor part of $NN$ interaction – $np$ pairs dominate

→ Probability to find 2 nucleons “close” together nearly the same for $np$, $nn$, $pp$

For $r_{12} < 1.7$ fm:

$$P_{pp} = P_{nn} \approx 0.8 P_{np}$$

If EMC effect due to high virtuality, flavor dependence of EMC effect emerges naturally

→ If EMC effect from local density, $np/pp/nn$ pairs all contribute (roughly) equally

Flavor dependence and SRCs

High momentum nucleons in the nucleus come primarily from $np$ pairs

$\rightarrow$ The relative probability to find a high momentum proton is larger than for neutron for $N>Z$ nuclei

$$n_p^A(p) \approx \frac{1}{2x_p} a_2(A, y)n_d(p) \quad x_p = \frac{Z}{A}$$

$$n_n^A(p) \approx \frac{1}{2x_n} a_2(A, y)n_d(p) \quad x_n = \frac{A - Z}{A}$$

Probability to find SRC

Under the assumption the EMC effect comes from “high virtuality” (high momentum nucleons), effect driven by protons (u-quark dominates) $\rightarrow$ similar flavor dependence is seen in some “mean-field” approaches

$u_A = \frac{Z\tilde{u}_p + N\tilde{d}_p}{A}$
$d_A = \frac{Z\tilde{d}_p + N\tilde{u}_p}{A}$
Flavor Dependence of the EMC Effect

Mean-field calculations predict a flavor dependent EMC effect for $N\neq Z$ nuclei

$Q^2 = 5.0 \text{ GeV}^2$

Gold

Flavour dependent EMC ratios

Cloët, Bentz, and Thomas, PRL 102, 252301 (2009)

Medium modified quark distributions

$$u_A = \frac{Z\tilde{u}_p + N\tilde{d}_p}{A} \quad d_A = \frac{Z\tilde{d}_p + N\tilde{u}_p}{A}$$

Free nucleon quark distributions

$$u_0 = \frac{Zu_p + Nd_p}{A} \quad d_0 = \frac{Zd_p + Nu_p}{A}$$

Isovector-vector mean field ($\rho$) causes $u$ ($d$) quark to feel additional vector attraction (repulsion) in $N\neq Z$ nuclei

Experimentally, this flavor dependence has not been observed directly
EMC Flavor Dependence: Pion Drell-Yan

Pion-induced Drell-Yan sensitive to potential flavor dependence, but existing data lack precision

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Flavor Ind.</th>
<th>Flavor dep.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA3</td>
<td>1.3</td>
<td>0.5</td>
</tr>
<tr>
<td>NA10</td>
<td>0.60</td>
<td>2.5</td>
</tr>
<tr>
<td>Omega (low $Q^2$)</td>
<td>6.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Omega (high $Q^2$)</td>
<td>1.4</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Dutta, Peng, Cloët, DG, PRC 83, 042201 (2011)
**Pion Drell-Yan at COMPASS**

160 GeV pions on gold

\[
\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}
\]

\[
\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}
\]

*Dutta et al, PRC 83, 042201 (2011)*

First measurements on NH3 (and nuclear targets) planned for 2014

\[
\frac{d\sigma_{\pi^\pm A}}{dx_{\pi}dx_2} = \frac{4\pi\alpha^2}{9sx_{\pi}x_2} \sum_q e_q^2[q_{\pi^\pm}(x_{\pi})\bar{q}_A(x_2) + \bar{q}_{\pi^\pm}(x_{\pi})q_A(x_2)]
\]
Semi-Inclusive DIS

Assuming factorization holds, SIDIS acts as a “flavor tag” for struck quark
\[ \rightarrow \text{Similar to polarized quark distribution extractions} \]

\[ q_f(x) = \text{quark distribution} \]

\[ D_f^h(z) \text{ – fragmentation function} \]

\[ \text{quark of flavor } f \rightarrow \text{hadron } h \]

\[ \frac{d\sigma}{dx dQ^2 dz} = \frac{\sum_f e_f^2 q_f(x) D_f^h(z) \left( \frac{d\sigma}{dx dQ^2} \right)}{\sum_f e_f^2 q_f(x)} \]

\[ x = \text{fraction of proton momentum carried by quark} \]

\[ z = \frac{E_{\text{hadron}}}{\nu} \]
Semi-Inclusive DIS

Extract flavor dependence via semi-inclusive pion yields from gold and deuterium

Super-ratio

\[
\frac{Y_{\pi^+}^{Au}}{Y_{\pi^-}^{Au}} / \frac{Y_{\pi^+}^{D}}{Y_{\pi^-}^{D}}
\]

Difference ratio

\[
\frac{Y_{\pi^+}^{Au}}{Y_{\pi^-}^{Au}} - \frac{Y_{\pi^+}^{D}}{Y_{\pi^-}^{D}}
\]

Toy model:

- \(u_V\) only: EMC effect due to modification of \(u_A\) only
- \(d_V\) only: EMC effect due to modification of \(d_A\) only

Nuclear PDFs (no flavor dep.)

- \(F_2^A\) unchanged

EMC effect entirely due to \(d\) quarks

EMC effect entirely due to \(u\) quarks

Cloet et al.
SIDIS - Interpretability

Hadronization is modified in the nuclear medium
→ Probability for quark $f$ to form hadron $h$ changes
→ Depends on $A$, hadron kinematics

Complicates interpretation of SIDIS measurements of flavor dependence if effect different for $\pi^+$ and $\pi^-$

→ This can be checked with measurements at $x=0.3$ (no EMC effect)
Flavor dependence of EMC effect can also be explored via parity violating DIS

\[
A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}} \left[ a_2(x) + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3(x) \right]
\]

suppressed

quark weak vector couplings

\[
a_2(x) = \frac{2 \sum_q e_q q_v^q [q_A(x) + \bar{q}_A(x)]}{\sum_q e^2_q [q_A(x) + \bar{q}_A(x)]}
\]

Avoids complications due to hadronization issues

**CBT model predicts 5% effect at x=0.6**
Measuring Flavor Dependence with PVDIS

Experimentally – simpler to measure super-ratio
\[ \rightarrow \text{Certain systematics are reduced (beam polarization)} \]
\[ \rightarrow \text{Less sensitivity to absolute value of weak vector couplings} \]

Note that even the “no flavor dependence” calculation not identically 1.0
\[ \rightarrow \text{Must compare experimental result to the “naïve” estimate} \]
\[ \rightarrow \text{Naïve estimate has some dependence on nucleon PDFs} \]
\[ \rightarrow \text{May be non-negligible contribution to uncertainty} \]
SOLID experiment at JLab (P. Souder, spokesperson) – use PVDIS to look for physics beyond Standard Model, $d/u$ at large $x$

→ awarded 169 days for H and D running
→ no time for solid target running (flavor dependent EMC) requested yet
Flavor Dependence with inclusive DIS

Several alternatives for accessing flavor dependence of EMC effect

→ Pion DY @ COMPASS: sufficient statistical precision at large $x$?
→ SIDIS @ JLab: hadron attenuation and factorization concerns
→ PVDIS @ JLab: SOLID experiment requires significant $\$, long time scale

Would like something “easy” that can be done on a short time scale

Inclusive DIS on nucleus with same $A$ and $\rho$ but different ratio $N/Z$
Flavor dependence from $^{40}\text{Ca}$ and $^{48}\text{Ca}$

CBT model predicts a ~3% effect for $^{48}\text{Ca}$ at $x=0.6$

$\rightarrow N/Z = 1.4$

Assuming no flavor dependence, difference between $^{40}\text{Ca}$ and $^{48}\text{Ca}$ should be less than < 1%

Will be measured at JLab @ 12 GeV

E12-10-008
Spokespersons: Arrington, Gaskell, Daniel
E12-06-118: The MARATHON experiment

Spokespeople: G. Petratos, J. Gomez, R. Holt, R. Ransome

EMC effect with $A=3$ mirror nuclei

→ “Free” $n/p$ (d/u) ratios extracted using “known” corrections to difference in EMC effect in $^3\text{He}/^3\text{H}$; additional flavor dependence could impact extraction
Hall C experiments will provide more inclusive data
\( \rightarrow \) E12-06-105 \( x > 1 \)
\( \rightarrow \) E12-10-008 EMC Effect

Will provide additional data on light and medium-heavy targets
\( \rightarrow \) \( ^2 \text{H}, ^3 \text{He}, ^4 \text{He} \)
\( \rightarrow \) \( ^6 \text{Li}, ^7 \text{Li}, \text{Be}, ^{10} \text{B}, ^{11} \text{B}, \text{C} \)
\( \rightarrow \) \( \text{Al}, ^{40} \text{Ca}, ^{48} \text{Ca}, \text{Cu} \)

First running in Hall C after completion of 12 GeV Upgrade will include a few days for EMC/\( x > 1 \) measurements on \( ^{10} \text{B}, ^{11} \text{B}, \) and Al (parasitic)
E12-11-107: In-Medium Structure Functions

Measure structure function of high momentum nucleon in deuterium by tagging the spectator
→ Final state interactions cancelled by taking double ratios
→ Requires new, large acceptance proton/neutron detector at back angles

$d(e,e'p)$

Spokespersons: O. Hen, L. Weinstein, S. Gilad, S. Wood
Light to Heavy Nuclei

• New JLab data, new method of characterizing “size” of EMC effect gave insight into nuclear dependence of EMC effect.
  – Same dependence observed for A/D ratios at x>1
  – Correlation between EMC effect and SRCs
  – Local density vs. high virtuality $\rightarrow$ flavor dependence?

• Some interesting effects have also been observed for heavy targets
E03-103 also measured EMC ratios for Cu and Au – analysis at the relatively low 6 GeV beam energy complicated by **Coulomb Corrections**

Electrons scattering from nuclei can be accelerated/decelerated in the Coulomb field of the nucleus

→ This effect is NOT part of the hadronic structure of the nucleus we wish to study
→ Important to remove/correct for apparent changes in the cross section due to Coulomb effects

In a very simple picture – Coulomb field induces a change in kinematics in the reaction

\[
E_e \rightarrow E_e + V_0
\]

\[
E_e' \rightarrow E_e' - V_0
\]

\[V_0=3\alpha(Z-1)/2R\]

Electrostatic potential energy at center of nucleus
Coulomb Corrections in QE Processes

Importance of Coulomb Corrections in quasi-elastic processes well known

Gueye et al., PRC60, 044308 (1999)

Distorted Wave Born Approximation calculations are possible – but difficult to apply to experimental cross sections

→ Instead use Effective Momentum Approximation (EMA) tuned to agree with DWBA calculations

EMA: \( E_e \rightarrow E_e + V_0 \quad E_e' \rightarrow E_e' - V_0 \) with “focusing factor” \( F^2 = (1-V_0/E) \)

\( V_0 \rightarrow (4/5)V_0, \quad V_0=3\alpha(Z-1)/2R \quad V_0 = 10 \text{ MeV for Cu, 20 MeV for Au} \)

E03103: EMC Effect in Gold

$\sigma_A / \sigma_D$ for Gold
A=197  Z=79

SLAC E-139
$E_e \sim 8-25$ GeV
$E_{e'} \sim 4-8$ GeV

JLab E03-103
$E_e \sim 6$ GeV
$E_{e'} \sim 1-2$ GeV

No Coulomb Corrections applied
E03103: EMC Effect in Gold

\[ \frac{\sigma_A}{\sigma_D} \text{ for Gold} \]
A=197 Z=79

SLAC E-139
\[ E_e \sim 8-25 \text{ GeV} \]
\[ E_e' \sim 4-8 \text{ GeV} \]

JLab E03-103
\[ E_e \sim 6 \text{ GeV} \]
\[ E_e' \sim 1-2 \text{ GeV} \]

with Coulomb Corrections (both data sets)
$R_A - R_D$

E03103 shows good agreement with E139 data for smaller $A$ → agreement not as good for heavier targets. Why?

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

$F_2(x) = \sum e_i^2 x q_i(x)$ ← Quark distribution functions

$$\frac{d\sigma}{d\Omega dE'} = \Gamma [\sigma_T(\nu,Q^2) + \varepsilon \sigma_L(\nu,Q^2)] \quad F_1 \propto \sigma_T \quad F_2 \text{ linear combination of } \sigma_T \text{ and } \sigma_L$$

Measurements of EMC effect often assume $\sigma_A/\sigma_D = F_2^A/F_2^D$ → this is true if $R=\sigma_L/\sigma_T$ is the same for $A$ and $D$

E139 data mostly at large $\varepsilon$ – JLab data at small $\varepsilon$ → if $RA \neq RD$, this might explain the difference

→ Motivated us to re-examine earlier experiments that measured nuclear dependence of $R$
E140 measured $\varepsilon$ dependence of cross section ratios $\sigma_A/\sigma_D$ for

$x = 0.2, 0.35, 0.5$

$Q^2 = 1.0, 1.5, 2.5, 5.0 \text{ GeV}^2$

Iron and Gold targets

$R_A - R_D$ consistent with zero within errors

[No Coulomb corrections were applied]

Large $\varepsilon$ data: $E_e \sim 6-15 \text{ GeV} \quad E_{e'} \sim 3.6-8 \text{ GeV}$

Low $\varepsilon$ data: $E_e \sim 3.7-10 \text{ GeV} \quad E_{e'} \sim 1-2.6 \text{ GeV}$
$R_A - R_D$: E140 Re-analysis

Re-analyzed E140 data using Effective Momentum Approximation for published “Born”-level cross sections
→ Total consistency requires application to radiative corrections model as well

Including Coulomb Corrections yields result 1.5 $\sigma$ from zero when averaged over $x$

$R_A - R_D = -2E-4 +/- 0.02$

$R_A - R_D = -0.03 +/- 0.02$
Interesting result from E140 re-analysis motivated more detailed study
→ $x=0.5$, $Q^2=5$ GeV$^2$

→ Include E139 Fe data
→ Include JLab data
  Cu, $Q^2=4-4.4$ GeV$^2$

Normalization uncertainties between experiments treated as extra point-to-point errors

No Coulomb Corrections → combined analysis still yields
$R_A - R_D \sim 0$

$R_A - R_D = -0.035 +/- 0.042$
Interesting result from E140 re-analysis motivated more detailed study
→ \( x=0.5, Q^2=5 \text{ GeV}^2 \)

→ Include E139 Fe data
→ Include JLab data
  Cu, \( Q^2=4-4.4 \text{ GeV}^2 \)

Normalization uncertainties between experiments treated as extra point-to-point errors

\[ R_A-R_D = -0.084 \pm 0.040 \]

Application of Coulomb Corrections \( R_A-R_D \) 2 \( \sigma \) from zero
2007 Nuclear target ratios
→ 300 LT separations for $R_A - R_D$ for $Q^2 > 1.5$ GeV$^2$

→ Precision extraction of separated structure functions on D, Al, C, Fe/Cu
→ Search for nuclear effects in $F_L$, $R$
→ Neutron and p-n moment extractions (compare to lattice calculations)
→ Allow study of quark-hadron duality for neutron, nuclei separated structure functions

$F_2$, $F_L$, $R$ on Deuterium and heavier targets
World Data on $R_A/R_D$

SLAC E140: *PRD* 49, 5641 (1994)
$R_A/R_D$ for Fe, Au
Only true Rosenbluth separated data

NMC:
$R_{Ca}/R_C$
$R_{Sn}/R_C$
Multiple beam energies, $R_A/R_C$
extracted using $Q^2$ dep. fit at fixed $x$

HERMES:
$R_A/R_D$ for Kr, N, $^3$He
Fit $\varepsilon$ dependence at fixed $x$ for
single beam energy (changing $Q^2$)
Other Hints of non-zero $R_A - R_D$

NMC results for $R_{Sn} - R_C$ systematically larger than zero

$R_{Sn} - R_C = 0.040 \pm 0.026$ (stat) $\pm 0.020$ (sys)

→ Averaged over $x=0.0125 - 0.45$
→ $<Q^2> = 10 \text{ GeV}^2$

What are the consequences for A/D ratios for $F_1$ and $F_2$ if this is true?

V. Guzey et al, PRC 86 045201 (2012)
Consequences of $R_A-R_D > 0$

\[
\frac{\sigma_A}{\sigma_D} = \frac{F_1^A(x)}{F_1^D(x)} \left[ 1 + \frac{\epsilon (R_A - R_D)}{1 + \epsilon R_D} \right]
\]

- $F_1$ ratio purely transverse
- Anti-shadowing disappears for $F_1$ ratio, remains for $F_2$
- Anti-shadowing from longitudinal photons?

More discussion in Thia Keppel’s talk next week

V. Guzey et al, PRC 86 045201 (2012)
A Dependence of Anti-quark Distributions

- Drell-Yan process sensitive to anti-quark distributions in the target
- E772 measured no $A$ dependence over limited $x$ range, with limited precision
- E906 will measure up to $x=0.4$

D.M. Alde et al., PRL 64: 2479 (1990)
A Dependence of Anti-quark Distributions

- Drell-Yan process sensitive to anti-quark distributions in the target
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- E906 will measure up to $x=0.4$

E906 underway …
Nuclear Dependence of $R$

- Conventional wisdom was that there was little or no difference between $R$ in heavy nuclei and free nucleon
- Recent JLab data suggests $R_A - R_D < 0$ at large $x$
  - Alternatively, Coulomb Corrections are not under control
  - Better calculations and/or experimental tests needed
- Re-examination of high energy NMC data suggests $R_A - R_D > 0$
  - How can this be consistent with JLab + SLAC data?
  - $Q^2$ dependent? Problems with either data set?
- More data is needed – a systematic study over large range of $Q^2$ and $x$
Summary

• The EMC effect has been with us for 30 years and motivated intense experimental (and theoretical) study
• Amazingly, it seems there is still much to learn
  – What is the link between SRCs and the EMC effect?
  – Does the EMC effect depend on quark flavor?
  – Does $\sigma_A/\sigma_D = F_2^A/F_2^D$ for all $x$ and $Q^2$?
• Many of these questions will be addressed at JLab after the 12 GeV upgrade
• Issues I did not discuss
  – Polarized EMC effect
  – Low $x$ measurements $\rightarrow$ EIC
  – Several other processes that aim to quantify the modification of nucleons in the nucleus