Measurements of the Flavor Dependence of the EMC Effect Using Parity-Violating Deep Inelastic Scattering

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August 2, 2016
Outline

- Motivation
- Proposed Experiment
- Anticipated Results and Systematics
Collaboration

Spokespeople

- Seamus Riordan - Stony Brook University
- John Arrington - Argonne National Laboratory
- Rakitha Beminiwattha - Syracuse

and the SoLID Collaboration
QCD in Nucleons and Nuclei

QCD Questions

- How do we reconcile the picture of quarks and gluons with nucleons and nuclei?
- What is the nature of bound nucleons and how are they modified?
- Is there a direct connection between nuclear and parton-level modification observables?
DIS with leptons offers picture into partonic distributions

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

\[F_2(x, Q^2) = x \sum_q e_q^2 \left( q(x, Q^2) + \bar{q}(x, Q^2) \right),\]

\[F_L \approx F_2 - 2xF_1\]

- Highly successful for our modern picture of quark degrees of freedom and pQCD
- PDFs have been well determined over a broad range after decades of study
DIS with leptons offers picture into partonic distributions

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

\[ F_2(x, Q^2) = x \sum_q e_q^2 \left( q(x, Q^2) + \bar{q}(x, Q^2) \right), \]

\[ F_L \approx F_2 - 2xF_1 \]

Highly successful for our modern picture of quark degrees of freedom and pQCD

PDFs have been well determined over a broad range after decades of study
PVDIS proves new flavor combinations $\rightarrow$ isovector properties

$$A_{PV} \sim \left| \frac{\gamma^*}{\gamma} \right|^2 \sim 100 - 1000 \text{ ppm}$$

$$\approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ a_1(x) + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3(x) \right], \quad y = 1 - \frac{E'}{E}$$

$$a_1(x) = 2 \frac{\sum C_{1q} e_q (q + \bar{q})}{\sum e_q^2 (q + \bar{q})}, \quad a_3(x) = 2 \frac{\sum C_{2q} e_q (q - \bar{q})}{\sum e_q^2 (q + \bar{q})}$$

**Effective Weak Couplings**

$$C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W = -0.19 \quad C_{2u} = -\frac{1}{2} + 2 \sin^2 \theta_W = -0.03$$

$$C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W = 0.34 \quad C_{2d} = \frac{1}{2} + 2 \sin^2 \theta_W = 0.03$$
PVDIS proves new flavor combinations → isovector properties

\[
A_{PV} \sim \frac{\gamma^* \gamma^* Z^*}{\gamma^*} \sim 100 - 1000 \text{ ppm}
\]

\[
\approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ a_1(x) + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3(x) \right], \quad y = 1 - \frac{E'}{E}
\]

Symmetric nucleus limit

\[
a_1 \approx \frac{9}{5} - 4\sin^2 \theta_W - \frac{12}{25} \frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots
\]

where \( u_A = u \) in \( p \) and \( u \) in \( n \)
EMC Effect

Nuclear Modification

- First observed in 1984 by EMC collaboration
- Showed reduced presence of partons in \( 0.3 < x < 0.7 \)
- Generally greater effect as one pushes to higher \( A \)
- Not due to simple binding effects - real modification of structure

General assumption of \( u \leftrightarrow d \) for \( p \leftrightarrow n \)

PVDIS can test this

J. Gomez et al., PRD49 4348 (1994)
Neutrino scattering (charged current and neutral current) is sensitive to different flavor combinations

Pachos-Wolfenstein relation:

\[
R_{PW} \equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} = \lim_{i.s.} \frac{1}{2} - \sin^2 \theta_W
\]

Asymmetric nuclei (iron) need corrections

CSV or IVEMC could play very important role and are not well constrained by data
Existing fits to world data show controversy

Studies partitioning data between lepton/Drell Yan and $\nu$ show significant incompatibilities in nuclear corrections using common PDFs

I. Schienbein et al. PRD77 054013 (2008); I. Schienbein et al. PRD80 094004 (2009)
SRC show strong preference to n-p pairs over p-p pairs
Also show strong correlation to “plateau” parameter for $x > 1$ SFs
SRC show strong preference to n-p pairs over p-p pairs
Also show strong correlation to “plateau” parameter for \( x > 1 \) SFs
Preliminary models make predictions of deviations for asymmetric nuclei

Arrington, EPJ Web Conf. 113, 01011 (2016)
Cloet et al. make predictions based on mean field calculations which give reasonable reproductions of SFs.

Explicit isovector terms are included constrained by nuclear physics data such as the symmetry energy.

Few percent effect in $a_2$, larger at larger $x$.

Cloet et al. PRL102 252301 (2009), Cloet et al. PRL109 182301 (2012)
Varying weights in fits between lepton/Drell Yan and $\nu$ can show tension between data sets.

nCTEQ fits show dramatic differences in a similar vein at CBT.

Few percent effect in $a_2$
Varying weights in fits between lepton/Drell Yan and $\nu$ can show tension between data sets.

nCTEQ fits show dramatic differences in a similar vein at CBT.

Few percent effect in $a_2$.
Neutral currents will provide access to isovector observables.
Present data demands $\sim 1\%$ level for significant tests.
$\text{LD}_2$ will constrain CSV as isoscalar target (as well as $R_{\gamma Z}$).
Asymmetric target will test isovector dependence - larger $A$ gives larger EMC, larger $Z - N$ gives IV enhancement.

Symmetric nucleus limit:

$$ a_1 \simeq \frac{9}{5} - 4 \sin^2 \theta_W - \frac{12}{25} \frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots $$

$a_1$ from Cloet-Bentz-Thomas for $^{48}\text{Ca}$
Other Methods

PVDIS offers highest sensitivity and is required for full picture

$a_1$ from CBT, $^{48}$Ca $x/X_0=12\%$, 60 days, 80$\mu$A

PVEMC EMC (this prop.) E12-10-008

<table>
<thead>
<tr>
<th></th>
<th>PVEMC</th>
<th>EMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>0.7-1.3%</td>
<td>0.8-1.1%</td>
</tr>
<tr>
<td>Systematics</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>CBT $x$-dependence</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>CBT sensitivity</td>
<td>$5.6\sigma$</td>
<td>$&lt;3\sigma$</td>
</tr>
</tbody>
</table>
PVDIS naturally sensitive to flavor differences
DIS and PVDIS allows for flavor determination
Other processes such as tagged SIDIS and $\pi$ Drell-Yan offer complementary information
Experiments such as SRC help motivate and tie into this program
Experimental configuration practically identical to approved SoLID PVDIS measurement
- Lead baffles serve as momentum collimators
- GEMs, Cherenkov, and calorimeter provide tracking and PID
- Rates are better or comparable to existing LD$_2$ measurement
Target - $^{48}$Ca

- $^{48}$Ca target provides good balance between asymmetric target and not too high Z
- Has very good thermal conductance and high melting point - have operational experience with previous program and upcoming CREX
- 12% radiator - photons and photoproduced pions are main background concerns
- Requesting 60 days at 80 $\mu$A 11 GeV production (71 days total) to get $\sim 1\%$ stat uncertainties across a broad range of $x$.
- In the context of the CBT model, this is few sigma in very simple interpolation model.
- *This provides new and useful constraints in a sector where there is little data.*
Rates and Backgrounds

- Trigger defined by coincidence between Cherenkov and shower - 150 kHz total anticipated with background (well below SoLID spec)
- Pion contamination no worse than 4% in any given bin (worst at high $x$)
- GEM rates comparable to or smaller than design for LD$_2$

<table>
<thead>
<tr>
<th>Particle</th>
<th>DAQ Coin. Trig. Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS $e^-$</td>
<td>$P &gt; 1$ GeV: 144, $P &gt; 3$ GeV: 61</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$P &gt; 1$ GeV: 11, $P &gt; 3$ GeV: 7</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$P &gt; 1$ GeV: 0.4, $P &gt; 3$ GeV: 0.2</td>
</tr>
<tr>
<td>Total</td>
<td>155, 68</td>
</tr>
</tbody>
</table>
Iron of magnet is significant shield of neutrons that contribute to site boundary limits

<table>
<thead>
<tr>
<th></th>
<th>$^{48}$Ca Flux (Hz/µA)</th>
<th>$^{48}$Ca Dose (80 µA for 60 days) (m$^{-2}$)</th>
<th>LD$_2$ Flux (Hz/µA)</th>
<th>LD$_2$ Dose (50 µA for 60 days) (m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>with Solenoid Self-Shielding</td>
<td>2.93E+07</td>
<td>6.02E+12</td>
<td>2.62E+07</td>
<td>3.36E+12</td>
</tr>
<tr>
<td>without Solenoid Self-Shielding</td>
<td>5.55E+08</td>
<td>1.14E+14</td>
<td>3.53E+08</td>
<td>4.53E+13</td>
</tr>
</tbody>
</table>

- Calculated to be factor of 2 smaller than CREX
Iron of magnet is significant shield of neutrons that contribution to site boundary limits

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Estimated DOSE (m$^{-2}$)</th>
<th>Measured DOSE (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PREX-I</td>
<td>4.50E+12</td>
<td>4.2</td>
</tr>
<tr>
<td>PREX-II</td>
<td>5.80E+12</td>
<td>5.4</td>
</tr>
<tr>
<td>CREX</td>
<td>1.50E+13</td>
<td>9.2</td>
</tr>
<tr>
<td>PVDIS-LD$_2$</td>
<td>3.40E+12</td>
<td>3.2</td>
</tr>
<tr>
<td>PVDIS-$_{^{48}}$Ca</td>
<td>6.00E+12</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Calculated to be factor of 2 smaller than CREX
Many potential nuclear effects come into play as this sector is not presently well constrained.

Requires measurements from LD$_2$ and LH$_2$ for information on size of nuclear effects.

Existing free PDFS (recent CJ12) have poor $d/u$ constraint.

Projected 12 GeV $d/u$ Extractions.
Systematics

- Many potential nuclear effects come into play as this sector is not presently well constrained.
- Requires measurements from LD$_2$ and LH$_2$ for information on size of nuclear effects.
- Higher twist effects will also be constrained by LD$_2$ using same kinematics, but also 6.6 GeV beam.
- Charge symmetry violation will also be explored to better precision.
- Nuclear dependence of $R^{\gamma Z}$ is an open question.
Systematics and Experimental uncertainties

- Polarimetry and pions are main contributions
- Radiative working group has been established for PVDIS
- Total errors:

<table>
<thead>
<tr>
<th>Effect</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarimetry</td>
<td>0.4</td>
</tr>
<tr>
<td>$R^Z / R^\gamma / HT$</td>
<td>0.2</td>
</tr>
<tr>
<td>Pions (bin-to-bin)</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>Radiative Corrections (bin-to-bin)</td>
<td>0.5-0.1</td>
</tr>
<tr>
<td>Total for any given bin</td>
<td>$\sim 0.5-0.7$</td>
</tr>
</tbody>
</table>

- Statistical uncertainty dominates any given bin
Status

- PAC 42 - Deferred
  - “novel and well developed proposal”
  - Site boundary limits were a concern
  - Cross section measurement sensitivity wasn’t formally studied
- PAC 44 - Deferred Again
  - Informally - workshop to organize between efforts and converge theory, radiation effects on the hall, target cost
  - Full report not out - usually six weeks or so after PAC
Summary

- Nuclear modification has many open important questions for our understanding of QCD
- PVDIS on asymmetric targets offers best opportunity to uncover isovector dependence in modification
- 60 days production will offer critical new information, help test leading hypotheses, and help resolve the NuTeV anomaly
- Proposal deferred twice by PAC in light of DIS ratio measurement
Why not $^{40}$Ca?

$^{40}$Ca in CJ12 nPDF fit is green curve

- Would require similar beamtime commitment (60 days)
- $^{40}$Ca tests isoscalar prediction - but isoscalar PDFs significantly cancel!
- Existing SoLID program has LD$_2$ planned which is sensitive to and constrains on a similar level effects such as charge symmetry violation
- $^{40}$Ca would be useful if we need to search for effects such as modification-induced CSV - presently hard to argue for a commitment
Radiation from this experiment is on the level of the existing LD$_2$ measurement

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>E-Range (MeV)</th>
<th>$^{48}\text{Ca}$ (W/µA)</th>
<th>LD$_2$ (W/µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e$^{\pm}$</td>
<td>E &lt; 10</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>E &gt; 10</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>n</td>
<td>E &lt; 10</td>
<td>0.0002</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td>E &gt; 10</td>
<td>0.005</td>
<td>0.010</td>
</tr>
<tr>
<td>γ</td>
<td>E &lt; 10</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>E &gt; 10</td>
<td>0.04</td>
<td>0.04</td>
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Iron of magnet is significant shield of neutrons that contribute to site boundary limits

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<td>5.6</td>
<td>n/a</td>
</tr>
</tbody>
</table>

- Calculated to be factor of 2 smaller than CREX
Radiation on ECAL

Table: Neutrons Flux at the Front of the ECAL

<table>
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<tr>
<th>E range (MeV)</th>
<th>$^{48}$Ca Flux (Hz/cm²)</th>
<th>LD$_2$ Flux (Hz/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons</td>
<td>$E &lt; 10$</td>
<td>1.68E+06</td>
</tr>
<tr>
<td></td>
<td>$E &gt; 10$</td>
<td>3.66E+04</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.72E+06</td>
</tr>
</tbody>
</table>

- Total dose (neutron and EM) similar to LD$_2$
- Estimated 100 kRad on active components
Varying weights in fits between lepton/Drell Yan and $\nu$ can show tension between data sets.

nCTEQ fits show dramatic differences in a similar vein at CBT.

Few percent effect in $a_2$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{48Ca_from_nCTEQ.png}
\caption{48Ca from nCTEQ}
\end{figure}
## GEM Rates

<table>
<thead>
<tr>
<th>GEM plane</th>
<th>LD\textsubscript{2} background (kHz/mm\textsuperscript{2}/µA)</th>
<th>\textsuperscript{48}Ca EM background (kHz/mm\textsuperscript{2}/µA)</th>
<th>\textsuperscript{48}Ca EM background (no baffles) (kHz/mm\textsuperscript{2}/µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.8</td>
<td>4.8</td>
<td>49.4</td>
</tr>
<tr>
<td>2</td>
<td>3.0</td>
<td>2.1</td>
<td>32.3</td>
</tr>
<tr>
<td>3</td>
<td>1.1</td>
<td>0.8</td>
<td>9.9</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>0.5</td>
<td>6.4</td>
</tr>
</tbody>
</table>
## ECal Trigger Rates

<table>
<thead>
<tr>
<th>region</th>
<th>full</th>
<th>high</th>
<th>low</th>
</tr>
</thead>
<tbody>
<tr>
<td>rate entering the EC (kHz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^-$</td>
<td>240</td>
<td>129</td>
<td>111</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$5.9 \times 10^5$</td>
<td>$3.0 \times 10^5$</td>
<td>$3.0 \times 10^5$</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$2.7 \times 10^5$</td>
<td>$1.5 \times 10^5$</td>
<td>$1.2 \times 10^5$</td>
</tr>
<tr>
<td>$\gamma(\pi^0)$</td>
<td>$7.0 \times 10^7$</td>
<td>$3.5 \times 10^7$</td>
<td>$3.5 \times 10^7$</td>
</tr>
<tr>
<td>$p^+$</td>
<td>$4.8 \times 10^5$</td>
<td>$2.1 \times 10^5$</td>
<td>$2.7 \times 10^5$</td>
</tr>
<tr>
<td>sum</td>
<td>$7.1 \times 10^7$</td>
<td>$3.6 \times 10^7$</td>
<td>$3.6 \times 10^7$</td>
</tr>
</tbody>
</table>

| Rate for $p < 1$ GeV (kHz) |           |           |           |
| sum                     | $8.4 \times 10^8$ | $4.2 \times 10^8$ | $4.2 \times 10^7$ |

| trigger rate for $p > 1$ GeV (kHz) |           |           |           |
| $e^-$      | 152       | 82        | 70        |
| $\pi^-$    | $4.0 \times 10^3$ | $2.2 \times 10^3$ | $1.8 \times 10^3$ |
| $\pi^+$    | $0.2 \times 10^3$ | $0.1 \times 10^3$ | $0.1 \times 10^3$ |
| $\gamma(\pi^0)$ | 3 | 3 | 0 |
| $p$        | $1.6 \times 10^3$ | $0.9 \times 10^3$ | $0.7 \times 10^3$ |
| sum        | $5.9 \times 10^3$ | $3.3 \times 10^3$ | $2.6 \times 10^3$ |

| trigger rate for $p < 1$ GeV (kHz) |           |           |           |
| sum | $2.8 \times 10^3$ | $1.4 \times 10^3$ | $1.4 \times 10^3$ |

| Total trigger rate (kHz) |           |           |           |
| total | $8.7 \times 10^3$ | $4.7 \times 10^3$ | $4.0 \times 10^3$ |
### Cerenkov Trigger Rates

<table>
<thead>
<tr>
<th></th>
<th>Total Rate for $p &gt; 0.0$ GeV (kHz)</th>
<th>Rate for $p &gt; 3.0$ GeV (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS $\pi^-$</td>
<td>240</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>$5.9 \times 10^5$</td>
<td>$1.6 \times 10^3$</td>
</tr>
<tr>
<td>DIS $\pi^+$</td>
<td>2.7 $\times 10^5$</td>
<td>40</td>
</tr>
<tr>
<td>DIS $\gamma(\pi^0)$</td>
<td>$7.0 \times 10^7$</td>
<td>40</td>
</tr>
<tr>
<td>DIS $p$</td>
<td>$4.8 \times 10^5$</td>
<td>4</td>
</tr>
<tr>
<td>Sum</td>
<td>$7.1 \times 10^7$</td>
<td>$1.7 \times 10^3$</td>
</tr>
</tbody>
</table>

**Trigger Rate from Cherenkov (kHz)**

<table>
<thead>
<tr>
<th></th>
<th>Trigger Rate for $p &gt; 1.0$ GeV (kHz)</th>
<th>Trigger Rate for $p &gt; 3.0$ GeV (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS $\pi^-$</td>
<td>223</td>
<td>66</td>
</tr>
<tr>
<td>DIS $\pi^+$</td>
<td>193</td>
<td>49</td>
</tr>
<tr>
<td>DIS $\gamma(\pi^0)$</td>
<td>22</td>
<td>1.6</td>
</tr>
<tr>
<td>DIS $p$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>438</td>
<td>116</td>
</tr>
<tr>
<td>Radiation Type</td>
<td>E-Range (MeV)</td>
<td>Incident Radiation Power</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{48}$Ca $(W/\mu A)$</td>
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<tr>
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<td>$E &lt; 10$</td>
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<tr>
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