Precision Measurement of the Neutron Asymmetry $A_n^1$ at Large $x_{Bj}$ using CEBAF at 11 GeV

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Z.-E. Meziani (contact person), X. Ji

- Physics motivation.
- CEBAF uniqueness.
- Experimental procedure.
- Projected results.
- Summary.
Polarized Deep Inelastic Electron Scattering

\[ x = \frac{Q^2}{2M \nu} \]  
Fraction of nucleon momentum carried by the struck quark

\[ Q^2 = 4\text{-momentum transfer of the virtual photon}, \quad \nu = \text{energy transfer}, \quad \theta = \text{scattering angle} \]

- All information about the nucleon vertex is contained in

\[ F_2 \] and \[ F_1 \] the unpolarized (spin averaged) structure functions,

and

\[ g_1 \] and \[ g_2 \] the spin dependent structure functions
Quark-Parton Model

In the Bjorken scaling limit

\[ F_1(x) = \frac{1}{2} e_i^2 f_i(x) \quad g_1(x) = \frac{1}{2} e_i^2 q_i(x) \]

\[ f_i(x) = q_i(x) + q_i(x) \]

\[ q_i(x) = q_i(x) - q_i(x) \]

\[ q_i(x) \quad \text{quark momentum distributions of flavor } i \]

\[ (\quad \text{parallel (antiparallel) to the nucleon spin} \quad ) \]

Observables of interest

\[ A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{q_i(x)}{f_i(x)} \]

\[ R^{np}(x) = \frac{F_2^n(x)}{F_p^2(x)} \]
Photon-Nucleon Asymmetry

Parallel Asymmetry

\[
\frac{\sigma_{\uparrow \downarrow} - \sigma_{\uparrow \uparrow}}{\sigma_{\uparrow \downarrow} + \sigma_{\uparrow \uparrow}} = A_{\parallel} = D \left( A_1 + \eta A_2 \right)
\]

Perpendicular Asymmetry

\[
\frac{\sigma_{\uparrow \downarrow} - \sigma_{\downarrow \downarrow}}{\sigma_{\uparrow \downarrow} + \sigma_{\downarrow \downarrow}} = A_{\perp} = d \left( A_2 - \zeta A_1 \right)
\]

Kinematics Factors

\[
D = \frac{(1 - E' \varepsilon/E)}{(1 + \varepsilon R)}, \quad R(x, Q^2) = \frac{\sigma_T}{\sigma_L}
\]

\[
d = D \sqrt{2\varepsilon/(1+\varepsilon)}
\]

\[
\eta = \varepsilon \sqrt{Q^2} / (E - E'\varepsilon)
\]

\[
\zeta = \eta (1+\varepsilon)/2\varepsilon
\]
SU(6) Predictions

Polarized Neutron Static Wave Function in SU(6)

S=0 and S=1 components of the wave function are equiprobable leading to the following predictions

\[ R^{np} = \frac{2}{3}, \quad A_1^p = \frac{5}{9}, \quad A_1^n = 0 \]
Neutron

\[ A_1^n \]

Proton

\[ A_1^p \]
Broken SU(6) Predictions

- Low x region : Dominated by sea quarks. Quantitative predictions are difficult.

- High x region: Dominated by valence quarks. Predictions are possible.

\[ |n \uparrow \rangle = \frac{1}{\sqrt{2}} |d \uparrow (du)_{S=0} \rangle + \frac{1}{\sqrt{18}} |d \uparrow (ud)_{S=1} \rangle - \frac{1}{3} |d \downarrow (ud)_{S=1} \rangle - \frac{1}{3} |u \uparrow (dd)_{S=1} \rangle - \frac{\sqrt{2}}{3} |u \downarrow (dd)_{S=1} \rangle \]

SU(6) symmetry breaks:

- \( R^{n,p} \rightarrow 1/4 \) as \( x \rightarrow 1 \).

- \( \vec{S}_i \cdot \vec{S}_j \delta^3(\vec{r}_{ij}) \) interaction (N - Δ mass splitting, etc...)

Both \( |d \uparrow (du)_{S=0} \rangle \) dominates.

What about \( A^{n,p}_1 \) ?

Recent paper by N. Isgur
\begin{align*}
\mathcal{A}_1^p & \quad \text{Proton} \\
\mathcal{A}_1^n & \quad \text{Neutron}
\end{align*}

\begin{align*}
\mathcal{A}_1^p & \quad \text{SLAC E143} \\
\mathcal{A}_1^p & \quad \text{EMC} \\
\mathcal{A}_1^p & \quad \text{SMC}
\end{align*}

\begin{align*}
\mathcal{A}_1^n & \quad \text{SLAC E142} (^{3}\text{He}) \\
\mathcal{A}_1^n & \quad \text{SLAC E143} (^{3}\text{D}) \\
\mathcal{A}_1^n & \quad \text{SLAC E154} (^{3}\text{He})
\end{align*}

Single-Spin Semi-Inclusive Pion Production Asymmetries: $p^+ p \rightarrow \pi X$

Data are from Fermilab E704 experiment:

Calculations are by M. Boglione and E. Leader

\[ A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \]

Soffer Bound
\[ |\Delta_T q(x)| \leq \frac{1}{2} [q(x) + \Delta q(x)] \]

pQCD
\[ \frac{\Delta q(x)}{q(x)} \rightarrow 1 \]

GS-GRV
T. Gehrmann and W. J. Stirling
Phys. Rev. D53 (1996) 6100,
and
M. Glück, E. Reya and W. Vogelsang

LSS-BSS
E. Leader, A. V. Sidorov, and D. B. Stamenov
and
S. Brodsky, M. Burkhardt and I. Schmidt,
Predictions for the Neutron Asymmetry $A_{n1}^n$
Physics Overview as $x \rightarrow 1$

<table>
<thead>
<tr>
<th>Diquark Spin State</th>
<th>$F^n_{2}/F^p_{2}$</th>
<th>$A^p_{1}$</th>
<th>$A^n_{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S=1$ and $S=0$ equiprobable: SU(6)</td>
<td>$2/3$</td>
<td>$5/9$</td>
<td>$0$</td>
</tr>
<tr>
<td>$S=1$ suppressed, $S=0$ retained</td>
<td>$1/4$</td>
<td>$+1$</td>
<td>$+1$</td>
</tr>
<tr>
<td>$S = 1, S_Z = 1$ suppressed</td>
<td>$3/7$</td>
<td>$+1$</td>
<td>$+1$</td>
</tr>
<tr>
<td>$S = 1, S_Z = 0$ and $S = 0$ retained</td>
<td>$d/u=1/5$</td>
<td>$u/u$ $\rightarrow 1$</td>
<td>$d/d$ $\rightarrow 1$</td>
</tr>
</tbody>
</table>

Instantons!
N. Kochelev, hep-ph/9711226

~0
SUMMARY

- In most approaches $A_1^n$ large and positive as $x$ becomes large ($x > 0.3$)
- At present all data are consistent with $A_1^n(x) \leq 0$
- If $A_1^n$ stays negative the constituent quark picture is in jeopardy! New degrees of freedom might need to be considered, for example, Instantons??

This has been an important question for 25 years!

Experiment is believed to be possible with

- An intense polarized $\vec{e}$ beam
- A dense polarized $^3\vec{He}$ target
- A beam energy $E > 6\ GeV$, a MAD spectrometer, etc...

CEBAF at 11GeV is by far the best facility to measure $A_1^n$ at high $x$
Proposed Measurements

Measure $A_{\parallel}^{3\text{He}}$ & $A_{\perp}^{3\text{He}}$

- 3 incident energies: $E_i = 6.6, 8.8$ and $11 \text{GeV}$
- 3 scattering angles: $\theta = 35^\circ, 27^\circ$ and $25^\circ$
- 3 MAD momentum settings covering the range:
  
  \[
  0.1 < x < 0.75 \\
  2.0 < Q^2 < 10 \text{ GeV}^2 \\
  W^2 \geq 4 \text{ GeV}^2
  \]

- Perform radiative corrections on $A_{\parallel}^{3\text{He}}$ & $A_{\perp}^{3\text{He}}$

- Determine
  
  $A_1^{3\text{He}} = (A_{\parallel}/D - \eta A_{\perp}/d)/(1+\eta\zeta)$

- Correct for nuclear effects to extract
  
  $A_1^n(x,Q^2)$
Uniqueness of CEBAF

• Depolarization factor typically about 0.7 compared to 0.3 in most experiments performed at the high energy facilities ($A_1 \approx A_{\parallel}/D$).

• Scattered electrons detected at large angle lead to high $x$, high $Q^2$ and low scattered energy ($E' < 6$ GeV). A large acceptance spectrometer like MAD matches the kinematics efficiently.

• High beam and target polarizations and high beam current provide for a good polarized luminosity.

• Target reconstruction reduces entrance and exit windows background thus, dilution of the asymmetry.
Kinematic Coverage for an $A_1^n$ measurement using MAD

- $E = 11$ GeV = 25°
- $E = 8.8$ GeV = 27°
- $E = 6.6$ GeV = 35°
Comparison of some relevant parameters between CERN, HERA, SLAC and CEBAF. Note the difference in the D factor and size of the x bin.

<table>
<thead>
<tr>
<th>Expt. Name</th>
<th>$E_i$ (GeV)</th>
<th>$E'$ (GeV)</th>
<th>$\theta$ (deg)</th>
<th>$x$ bin</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>D</th>
<th>$P_{e,\mu}$</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERMES</td>
<td>35</td>
<td>17.0</td>
<td>5.2</td>
<td>0.6-0.7</td>
<td>9.1</td>
<td>0.22</td>
<td>0.50</td>
<td>0.05</td>
</tr>
<tr>
<td>SLAC E142</td>
<td>23</td>
<td>16.5</td>
<td>7.0</td>
<td>0.4-0.6</td>
<td>5.2</td>
<td>0.27</td>
<td>0.35</td>
<td>7.0</td>
</tr>
<tr>
<td>SLAC E143</td>
<td>29</td>
<td>25.5</td>
<td>7.0</td>
<td>0.6-0.7</td>
<td>9.1</td>
<td>0.29</td>
<td>0.84</td>
<td>0.3</td>
</tr>
<tr>
<td>SMC</td>
<td>190</td>
<td>161</td>
<td>1.8</td>
<td>0.4-0.7</td>
<td>29.5</td>
<td>0.14</td>
<td>0.80</td>
<td>0.005</td>
</tr>
<tr>
<td>CEBAF</td>
<td>11</td>
<td>4.4</td>
<td>25</td>
<td>0.7-0.75</td>
<td>10</td>
<td>0.67</td>
<td>0.80</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Target Polarization: 40%

HRS Spectrometer

Pb-glass

To Beam Dump

Drift Chambers

Cerenkov Scintillators

Preshower

Moller Polarimeter

Laser hut

Beam Polarization: 80%

Beam Current: 15 microA

Hall A Floor Configuration with MAD

HRS Spectrometer

Scintillators

Shower Counter Pb-glass

Cerenkov

Drift Chambers
Jlab Hall A polarized $^3$He Target

- NMR and EPR techniques for polarization monitoring.
- Elastic scattering for current induced depolarization.
- Target used successfully in E94-010 and E95-001.
- Target length will be 25 cm.
Run Number

% Polarization

E94-010  He Target Polarization
From $^3$He to the Neutron

- Extract an effective $\tilde{A}_1^n$
  - Wave function includes S, S’ and D waves.
  - Fermi motion not included.
  - Binding effects not included

$$\tilde{A}_1^n = \frac{1}{f_n \rho_n} (A_1^3He - 2 f_p \rho_p A_1^p)$$

where

$$f_{p(n)} = \frac{F_2^n}{F_2}$$

$$\rho_p = -2\Delta' = -2.7 \pm 0.3\%$$

$$\rho_n = 1 - 2\Delta = 87 \pm 2\%$$

$$\Delta = (\rho_{S'} + 2 \rho_D)/3$$

$$\rho_{S'} = 1.55 \pm 2\%$$

$$\Delta' = (\rho_D - \rho_{S'})/6$$

$$\rho_D = 9.1 \pm 0.9\%$$

Very good approximation according to

C. Cioffi Degli Atti, S. Scopetta, E. Pace and G. Salme *University of Perugia report DFUPG 75/92.*


W. Melnitchouk et al., Private communication
Residual of Nuclear corrections to extract the Neutron from $^3$He

W. Melnitchouk et al., private communication
Rates and Times for parallel and perpendicular measurements which optimize the statistical uncertainty on $A_{1}^{n}$

$E_i = 11$ GeV \hspace{1cm} $\theta = 25^0$

| $E'$ (GeV) | $x$ | $Q^2$ (GeV)$^2$ | $W$ (GeV) | D | $A_{1}^{3He}$ | $\Delta A_{1}^{3He}$ | $A_{2}^{3He}$ | $\Delta A_{2}^{3He}$ | Rate (Hz) | time$_{||}$ (Hours) | time$_{\perp}$ (Hours) |
|-----------|-----|----------------|----------|---|---------------|-----------------|--------------|-----------------|------------|-----------------|-----------------|
| 4.40      | .732| 9.07           | 2.05     | 0.67| 0.072         | 0.0046          | 0.0330       | 0.0159          | 1.26       | 540             | 22              |
| 3.98      | .623| 8.20           | 2.42     | 0.71| 0.050         | 0.0041          | 0.0205       | 0.0155          | 2.69       | 252             | 10              |
| 3.60      | .534| 7.42           | 2.71     | 0.75| 0.036         | 0.0036          | 0.0132       | 0.0153          | 4.21       | 161             | 6               |
| 3.26      | .463| 6.72           | 2.95     | 0.78| 0.022         | 0.0033          | 0.0075       | 0.0152          | 5.56       | 122             | 4.9             |
| 2.95      | .403| 6.08           | 3.15     | 0.81| 0.010         | 0.0030          | 0.0031       | 0.0152          | 6.66       | 102             | 4.1             |
| 2.67      | .352| 5.50           | 3.32     | 0.83| 0.000         | 0.0028          | -0.0001      | 0.0153          | 7.47       | 91              | 3.6             |
| 2.40      | .307| 4.95           | 3.47     | 0.86| -0.009        | 0.0027          | -0.0024      | 0.0154          | 8.06       | 84              | 3.3             |
| 2.20      | .275| 4.53           | 3.59     | 0.87| -0.015        | 0.0026          | -0.0037      | 0.0156          | 8.38       | 81              | 3.2             |
| 2.00      | .244| 4.12           | 3.69     | 0.89| -0.020        | 0.0025          | -0.0045      | 0.0159          | 8.58       | 79              | 3.2             |
| 1.35      | .154| 2.78           | 4.03     | 0.93| -0.028        | 0.0022          | -0.0049      | 0.0175          | 8.56       | 79              | 3.2             |
| 1.20      | .135| 2.47           | 4.10     | 0.94| -0.028        | 0.0022          | -0.0046      | 0.0182          | 8.41       | 81              | 3.2             |
| 1.10      | .122| 2.27           | 4.15     | 0.95| -0.028        | 0.0022          | -0.0043      | 0.0187          | 8.28       | 82              | 3.3             |

Each color represents one momentum setting for MAD

$E' = 4.05$ GeV Each momentum bin in the table corresponds to:

$E' = 3.00$ GeV $\Delta \Theta = +/- 35$ mrd
$E' = 2.20$ GeV $\Delta \Phi = +/- 150$ mrd
$E' = 1.25$ GeV $\delta p/p = +/- 5\%$
### Total uncertainty of the neutron asymmetry $A_n^1$ extracted from that of $^3$He

<table>
<thead>
<tr>
<th>$E'$ (GeV)</th>
<th>$x$</th>
<th>$Q^2$ (GeV)$^2$</th>
<th>$W$ (GeV)</th>
<th>$D$</th>
<th>$A_{3He}^1$</th>
<th>$\Delta A_{3He}^1$ (stat.)</th>
<th>$\Delta A_{3He}^1$ (syst.)</th>
<th>$\Delta A_{3He}^1$ (total)</th>
<th>$A_n^1$</th>
<th>$\Delta A_n^1$ (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.40</td>
<td>.732</td>
<td>9.07</td>
<td>2.05</td>
<td>0.67</td>
<td>0.072</td>
<td>0.0046</td>
<td>0.0042</td>
<td>0.0062</td>
<td>0.561</td>
<td>0.048</td>
</tr>
<tr>
<td>3.98</td>
<td>.623</td>
<td>8.20</td>
<td>2.42</td>
<td>0.71</td>
<td>0.050</td>
<td>0.0041</td>
<td>0.0029</td>
<td>0.0050</td>
<td>0.415</td>
<td>0.040</td>
</tr>
<tr>
<td>3.60</td>
<td>.534</td>
<td>7.42</td>
<td>2.71</td>
<td>0.75</td>
<td>0.036</td>
<td>0.0036</td>
<td>0.0021</td>
<td>0.0042</td>
<td>0.294</td>
<td>0.033</td>
</tr>
<tr>
<td>3.26</td>
<td>.463</td>
<td>6.72</td>
<td>2.95</td>
<td>0.78</td>
<td>0.022</td>
<td>0.0033</td>
<td>0.0013</td>
<td>0.0035</td>
<td>0.196</td>
<td>0.028</td>
</tr>
<tr>
<td>2.95</td>
<td>.403</td>
<td>6.08</td>
<td>3.15</td>
<td>0.81</td>
<td>0.010</td>
<td>0.0030</td>
<td>0.0058</td>
<td>0.0031</td>
<td>0.115</td>
<td>0.024</td>
</tr>
<tr>
<td>2.67</td>
<td>.352</td>
<td>5.50</td>
<td>3.32</td>
<td>0.83</td>
<td>0.000</td>
<td>0.0028</td>
<td>0.0021</td>
<td>0.0028</td>
<td>0.053</td>
<td>0.022</td>
</tr>
<tr>
<td>2.40</td>
<td>.307</td>
<td>4.95</td>
<td>3.47</td>
<td>0.86</td>
<td>-0.009</td>
<td>0.0027</td>
<td>0.0005</td>
<td>0.0027</td>
<td>0.002</td>
<td>0.020</td>
</tr>
<tr>
<td>2.20</td>
<td>.275</td>
<td>4.53</td>
<td>3.59</td>
<td>0.87</td>
<td>-0.015</td>
<td>0.0026</td>
<td>0.0009</td>
<td>0.0027</td>
<td>-0.028</td>
<td>0.019</td>
</tr>
<tr>
<td>2.00</td>
<td>.244</td>
<td>4.12</td>
<td>3.69</td>
<td>0.89</td>
<td>-0.020</td>
<td>0.0025</td>
<td>0.0012</td>
<td>0.0027</td>
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<td>0.018</td>
</tr>
<tr>
<td>1.35</td>
<td>.154</td>
<td>2.78</td>
<td>4.03</td>
<td>0.93</td>
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<td>0.95</td>
<td>-0.028</td>
<td>0.0022</td>
<td>0.0016</td>
<td>0.0027</td>
<td>-0.094</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Each color corresponds to a different momentum setting of the MAD spectrometer.

- $E' = 4.05$ GeV
- $E' = 3.00$ GeV
- $E' = 2.20$ GeV
- $E' = 1.25$ GeV
$10^{-0.4} 10^{-0.2} 0 10^{0.2} 10^{0.4} 10^{0.6} 10^{0.8} 1$

$TJNAF$ at $11$ GeV, $15\mu$A

SLAC E142 ($^3$He)

SLAC E143 ($^2$D)

SLAC E154 ($^3$He)

Hermes ($^3$He)

SMC ($^2$D)

$Isgur$

$(LSS)_{BBS}$

$2 \leq Q^2 \leq 10$ (GeV/c)$^2$

$x_{Bjorken}$
Conclusion

• Precision measurement of the deep inelastic asymmetry $A_{n_1}$ in the region $0.10 \leq x < 0.75$ and $2 \leq Q^2 \leq 10 \text{ GeV}^2$

• 865 hours of beam on target for the 11 GeV beam energy measurement.

• A period of 2 months of beam on target should allow us to measure all energies incident beam energies leading to a $Q^2$ dependence and a $W^2$ dependence investigation.

• CEBAF at 11 GeV is the best place to perform this measurement. Further observables of great interest can be obtained at the same time. An example $d_2^n$, a quark-gluon correlation matrix element.
MEASURING $g_2^n$ AT 11 GeV

- $g_2$ is one of the few clean places to measure higher twist effects which provide direct information about quark-gluon interactions.

- The leading twist contribution can be cleanly subtracted away using $g_1$ data.

$$g_2(x, Q^2) = -\frac{F_1(x, Q^2)}{D'} \frac{\nu}{2E \sin \theta} \left[ \sin \theta A_{\parallel} - \frac{E + E' \cos \theta}{E'} A_{\perp} \right]$$

$$d_2^n(Q^2) = 2 \int_0^1 x^2 \left[ g_1^n(x, Q^2) + \frac{3}{2} g_2^n(x, Q^2) \right] dx$$

- $d_2^n$ is a twist-3 matrix element which is uniquely sensitive to quark-gluon correlations and can be related to the color electric and magnetic polarizabilities in the nucleon.

$$d_2 = (2\chi_B + \chi_E)/3$$

- This integral is dominated by the high-$x$ region and is well-suited to JLab at 11 GeV.

- Can improve error on $d_2^n$ by a factor of 10 in less than 1000 hours.
SLAC E155x preliminary results

Jlab 11 GeV expected errors