Measurement of the Neutron Spin Asymmetry $A_{1}^{n}$ using HMS+SHMS at 12 GeV

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- Physics Motivation
  - $A_{1}^{n}$ measurements at JLab 6 GeV in Hall A in 2001
  - Proposal for the $A_{1}^{n}$ measurement with HMS+SHMS
    - Original proposal from 2006
    - Luminosity increase of this update
    - Expected results, beam time request and discussions

- Summary
For most cases, QCD cannot predict the value of structure functions because of their non-perturbative nature.

However, the large x region provides a handful of exceptions:

- $F_2^p/F_2^n$ and d/u
- $A_1^p$, $A_1^n$, or $\Delta u/u$ and $\Delta d/d$

Virtual photon asymmetry:

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1}$$

at large $Q^2$

$$\gamma^2 = \frac{Q^2}{\nu^2} = \frac{4 M^2 x^2}{Q^2}$$

At large $Q^2$, $A_1$ has only weak-dependence on $Q^2$ ($g_1$ and $F_1$ follow the same LO and NLO evolutions, but not in higher orders or higher twists).
Predictions for $A_1$ and $\Delta q/q$ at large $x$

$$|p^\uparrow\rangle = \frac{1}{\sqrt{2}} |u^\uparrow (ud)_{00}\rangle + \frac{1}{\sqrt{18}} |u^\uparrow (ud)_{10}\rangle - \frac{1}{3} |u^\perp (ud)_{11}\rangle$$

$$- \frac{1}{3} |d^\uparrow (uu)_{10}\rangle - \sqrt{\frac{2}{3}} |d^\perp (uu)_{11}\rangle$$

<table>
<thead>
<tr>
<th>Model</th>
<th>$F_2^n/F_2^p$</th>
<th>d/u</th>
<th>$\Delta u/u$</th>
<th>$\Delta d/d$</th>
<th>$A_1^n$</th>
<th>$A_1^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(6) = SU3 flavor + SU2 spin</td>
<td>2/3</td>
<td>1/2</td>
<td>2/3</td>
<td>-1/3</td>
<td>0</td>
<td>5/9</td>
</tr>
<tr>
<td>Valence Quark + Hyperfine</td>
<td>1/4</td>
<td>0</td>
<td>1</td>
<td>-1/3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pQCD + HHC</td>
<td>3/7</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The only place QCD can make absolute predictions for structure functions.
The 6 GeV Hall A Measurement (21 PAC days, 2001)


HHC not valid, quark OAM?

(1) SU(6)
(2) CQM
(3) LSS(BBS)
(4) BBS
(5) Bag Model
(6) Duality
(7) LSS 2001
(8) Statistical Model
(9) Chiral Soliton

(Deuteron data not shown: E143, E155, SMC)
Polarized DIS and Nucleon Spin Structure

H. Avakian, S. Brodsky, A. Deur, F. Yuan,

Figure credit: A. Deur
Polarized DIS and Nucleon Spin Structure

The JLab Hall A data were quoted by the 2007 NSAC long range plan as one of the “most important accomplishments since the 2002 LRP”;

Extensions of these measurements are flag-ship experiments for JLab 11 GeV.
Original Proposal for PAC-30 (Conditionally approved)

- Measured $A_1^n$ in DIS from $^3\bar{He}(\bar{e}, e')$ using

- 12 GeV polarized $e^-$ beam, $P_{beam}=80\%$ (dP/P=1\% Compton, Moller), minimal raster $2 \times 2 \text{mm}^2$

- Polarized $^3\text{He}$ target, SEOP, hybrid pumping, 40cm, 14 atm @ 50°C, $P_{\text{Targ}}=50\%$ (dP/P = 3\%)
  — (6GeV GEn E02-013 has achieved 55% in beam)

- HMS+SHMS to detect $e'$, measure both $A_{\parallel}$ and $A_{\perp}$:

- Total: 1908h (79 days) + Target Installation

- Will reach $\Delta A_1^n=\pm 0.071(\text{stat}) \pm 0.032(\text{syst})$ at $x=0.77$
Improvements on the Polarized 3He Target
1991-2006-2009

Preliminary Target Polarization History
Each Point is an NMR during a Spin Flip
Total 2000+ Flips

Date of year 2008 (During Experiment Transversity)

Spins polarized per second weighted by polarization squared
Improvements on the Polarized 3He Target (2010)

- Will use the same design as GEN-II (11 GeV approved):
  - use of alkali-hybrid mixtures to increase the spin-exchange efficiency;
  - use of narrow-lined high-power diode lasers; \textit{demonstrated}
  - (study of polarimetrics for both 3He and alkali-metal vapor and their densities to improve understanding of the target performance;)
  - use of convection (fast replacement of the polarized gas) to overcome beam and other depolarization effects;
  - metal-based target chamber to resist radiations and avoid cell rupture;

- Will have a postdoc working parttime on the new target in addition to the UVa polarized 3He target group.

- \textbf{Goal: 60-cm long, 12 amg, up to 60\textmu A beam with 60\% polarization}

- Overall, provide a factor of 8 improvement in luminosity!
  - allow the use of less beam time to achieve higher precision (now set statistical uncertainty $\sim$ systematic at $x=0.77$)
  - added resonance measurements (with little extra beam time)
Improvements on the Polarized 3He Target (2010)
Kinematics

Production (DIS and resonance)

<table>
<thead>
<tr>
<th>Kine</th>
<th>$E_b$ (GeV)</th>
<th>$E_p$ (GeV)</th>
<th>$\theta$ (°)</th>
<th>$(e,e')$ rate (Hz)</th>
<th>$\pi^-/e^-$</th>
<th>$e^+/e^-$</th>
<th>$x$ ($Q^2$, in GeV$^2$) (W, in GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 HMS</td>
<td>11.0</td>
<td>5.70</td>
<td>12.5</td>
<td>2300.75</td>
<td>&lt; 0.5</td>
<td>&lt; 0.1%</td>
<td>0.25-0.35 (2.78-3.17) (2.6-3.0)</td>
</tr>
<tr>
<td>2 HMS</td>
<td>11.0</td>
<td>6.80</td>
<td>12.5</td>
<td>1768.35</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1%</td>
<td>0.35-0.55 (3.26-3.78) (2.0-2.6)</td>
</tr>
<tr>
<td>3 HMS</td>
<td>11.0</td>
<td>2.82</td>
<td>30.0</td>
<td>5.03</td>
<td>&lt; 7.0</td>
<td>&lt; 0.9%</td>
<td>0.50-0.60 (7.84-8.87) (2.6-3.0)</td>
</tr>
<tr>
<td>4 HMS</td>
<td>11.0</td>
<td>3.50</td>
<td>30.0</td>
<td>0.94</td>
<td>&lt; 1.6</td>
<td>&lt; 0.1%</td>
<td>0.65-0.77 (9.59-10.54) (2.0-2.5)</td>
</tr>
<tr>
<td>5 HMS</td>
<td>11.0</td>
<td>7.50</td>
<td>12.5</td>
<td>598.43</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1%</td>
<td>0.45-0.55 (3.59-3.78) (2.0-2.3)</td>
</tr>
<tr>
<td>A SHMS</td>
<td>11.0</td>
<td>5.80</td>
<td>12.5</td>
<td>2817.72</td>
<td>&lt; 0.6</td>
<td>&lt; 0.1%</td>
<td>0.25-0.55 (2.71-3.77) (2.0-3.0)</td>
</tr>
<tr>
<td>B SHMS</td>
<td>11.0</td>
<td>3.00</td>
<td>30.0</td>
<td>9.61</td>
<td>&lt; 9.4</td>
<td>&lt; 1.4%</td>
<td>0.45-0.77 (7.52-10.54) (2.0-3.2)</td>
</tr>
<tr>
<td>C SHMS</td>
<td>11.0</td>
<td>2.25</td>
<td>30.0</td>
<td>28.20</td>
<td>&lt; 42.3</td>
<td>&lt; 10.1%</td>
<td>0.35-0.55 (5.94-8.21) (2.8-3.5)</td>
</tr>
<tr>
<td>D SHMS</td>
<td>11.0</td>
<td>7.50</td>
<td>12.5</td>
<td>857.47</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1%</td>
<td>0.40-0.55 (3.40-3.78) (2.0-2.4)</td>
</tr>
</tbody>
</table>

Resonances

| Kine  | $E_b$ (GeV) | $E_p$ (GeV) | $\theta$ (°) | elastic x-sec (nb/sr) | elastic rate (Hz) | Asymmetry | $A_{||}$ = 0.0589 | $A_{\perp}$ ~ a few % | Time (hours) |
|-------|-------------|-------------|--------------|-----------------------|-------------------|-----------|------------------|---------------------|---------------|
| 5 HMS | 11.0        | 7.50        | 12.5         | 666.78                | –                 | –         | 0.55-0.83 (3.84-4.26) (1.3-2.0) |
| D SHMS| 11.0       | 7.50        | 12.5         | 440.74                | –                 | –         | 0.55-0.89 (3.84-4.36) (1.2-2.0) |

Elastic $e^-^3$He(Ⅱ) and $\Delta(1232)$ (Ⅰ) at low $Q^2$ to check $P_{b\perp}$ and beam helicity:

10$^4$:1 π rejection is needed, not a problem for HMS or HRS (using both a cherenkov and a lead glass counter).
From $^3$He to Neutron

- S, S', D, Δ isobar in $^3$He wavefunction: \[ A_1^n = \frac{F_2^\text{3He}}{P_n F_2^n (1 + \frac{0.056}{P_n})} \left[ A_1^\text{3He} - 2 \frac{F_2^p}{F_2^\text{3He} P_p A_1^p} \left( 1 - \frac{0.014}{2 P_p} \right) \right] \]

- Other Inputs for DIS nuclear corrections:
  - $F_2^p, F_2^D$ – NMC fits and MRST/CTEQ
  - $P_n = 0.86^{+0.036}_{-0.020}, P_p = -0.028^{+0.009}_{-0.004}$
    - Uncertainty on Pp expected to reduce by factor of 4 from Hall A Ax and Az measurements;
  - $R(x,Q^2)$ – R1998, \text{PLB 452, 194 (1999)}
  - $A_1^p$ – from fit to world data (at large x also consistent with CLAS12 expected results) \text{PRC 70, 065207 (2004)}
  - For resonances, will use the most up-to-date method: \text{PRC 79, 035205 (2009)}
    - Will also extract $F_{1,2}$ from data (~5%) to use in the correction.
# Projected $A_1^n$ Uncertainties

## DIS

<table>
<thead>
<tr>
<th>$x$</th>
<th>$\Delta A_1^n$ (stat.)</th>
<th>$\Delta A_1^n$ (stat.)</th>
<th>$\Delta A_1^n$ (stat.)</th>
<th>$\Delta A_1^n$ (syst.)</th>
<th>$\Delta A_1^n$ (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low $Q^2$</td>
<td>high $Q^2$</td>
<td>two $Q^2$ combined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>0.0022</td>
<td>–</td>
<td>0.0022</td>
<td>0.0054</td>
<td>0.0059</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0020</td>
<td>–</td>
<td>0.0020</td>
<td>0.0063</td>
<td>0.0066</td>
</tr>
<tr>
<td>0.35</td>
<td>0.0025</td>
<td>0.0109</td>
<td>0.0024</td>
<td>0.0074</td>
<td>0.0078</td>
</tr>
<tr>
<td>0.40</td>
<td>0.0030</td>
<td>0.0084</td>
<td>0.0028</td>
<td>0.0089</td>
<td>0.0093</td>
</tr>
<tr>
<td>0.45</td>
<td>0.0029</td>
<td>0.0106</td>
<td>0.0028</td>
<td>0.0105</td>
<td>0.0109</td>
</tr>
<tr>
<td>0.50</td>
<td>0.0033</td>
<td>0.0081</td>
<td>0.0031</td>
<td>0.0124</td>
<td>0.0127</td>
</tr>
<tr>
<td>0.55</td>
<td>–</td>
<td>0.0069</td>
<td>0.0047</td>
<td>0.0145</td>
<td>0.0152</td>
</tr>
<tr>
<td>0.60</td>
<td>–</td>
<td>0.0092</td>
<td>0.0092</td>
<td>0.0168</td>
<td>0.0192</td>
</tr>
<tr>
<td>0.65</td>
<td>–</td>
<td>0.0105</td>
<td>0.0105</td>
<td>0.0197</td>
<td>0.0223</td>
</tr>
<tr>
<td>0.71</td>
<td>–</td>
<td>0.0143</td>
<td>0.0143</td>
<td>0.0246</td>
<td>0.0285</td>
</tr>
<tr>
<td>0.77</td>
<td>–</td>
<td>0.0288</td>
<td>0.0288</td>
<td>0.0340</td>
<td>0.0446</td>
</tr>
</tbody>
</table>

## Resonance

<table>
<thead>
<tr>
<th>$x$</th>
<th>$\Delta A_1^n$ (stat.)</th>
<th>$\Delta A_1^n$ (syst.)</th>
<th>$\Delta A_1^n$ (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55</td>
<td>0.0072</td>
<td>0.0145</td>
<td>0.0162</td>
</tr>
<tr>
<td>0.60</td>
<td>0.0061</td>
<td>0.0169</td>
<td>0.0180</td>
</tr>
<tr>
<td>0.65</td>
<td>0.0074</td>
<td>0.0197</td>
<td>0.0210</td>
</tr>
<tr>
<td>0.71</td>
<td>0.0095</td>
<td>0.0242</td>
<td>0.0260</td>
</tr>
<tr>
<td>0.77</td>
<td>0.0138</td>
<td>0.0323</td>
<td>0.0352</td>
</tr>
<tr>
<td>0.83</td>
<td>0.0302</td>
<td>0.0530</td>
<td>0.0610</td>
</tr>
<tr>
<td>0.89</td>
<td>0.0593</td>
<td>0.1003</td>
<td>0.1165</td>
</tr>
</tbody>
</table>
Expected Results

- HMS+SHMS, DIS, 636 hours
- HMS+SHMS, RES, 48 hours
- SLAC E142
- SLAC E154
- HERMES
- JLab Hall A E99117

\[ Q^2 \]

\[ \Delta A_1 \]
Expected Results

- Combined results from Hall C (neutron) and B (proton) 11 GeV experiments
Beam Time Request

- **Production:** 684 hours

Table 5: Beam time for DIS (636 hours) and resonance (48 hours) measurements. We have reduced the beam time by 45% compared to our original proposal.

<table>
<thead>
<tr>
<th>Kine</th>
<th>$E_b$ (GeV)</th>
<th>$\theta$ (°)</th>
<th>$E_p$ (GeV)</th>
<th>$e^-$ production (hours)</th>
<th>$e^+$ prod. (hours)</th>
<th>Tot. Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11.0</td>
<td>HMS</td>
<td>12.5</td>
<td>5.70</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>11.0</td>
<td>HMS</td>
<td>12.5</td>
<td>6.80</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>11.0</td>
<td>HMS</td>
<td>30.0</td>
<td>2.82</td>
<td>59</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>11.0</td>
<td>HMS</td>
<td>30.0</td>
<td>3.50</td>
<td>539</td>
<td>540</td>
</tr>
<tr>
<td>A</td>
<td>11.0</td>
<td>SHMS</td>
<td>12.5</td>
<td>5.80</td>
<td>36</td>
<td>36</td>
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<tr>
<td>B</td>
<td>11.0</td>
<td>SHMS</td>
<td>30.0</td>
<td>3.00</td>
<td>493</td>
<td>500</td>
</tr>
<tr>
<td>C</td>
<td>11.0</td>
<td>SHMS</td>
<td>30.0</td>
<td>2.25</td>
<td>91</td>
<td>100</td>
</tr>
<tr>
<td>Resonances</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>11.0</td>
<td>HMS</td>
<td>12.5</td>
<td>7.50</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>D</td>
<td>11.0</td>
<td>SHMS</td>
<td>12.5</td>
<td>7.50</td>
<td>48</td>
<td>48</td>
</tr>
</tbody>
</table>

- **Commissioning:** 3 days if not including the target, longer if include target.
- **Elastic:** $\Delta(1232)$; Reference Cell ($N_2$, pressure curve and empty cell run)
- **Configuration changes; Beam pass change;**
- **Moller; Target polarimetry;**

**Total:** 843h (35 days) + **Target Installation**, ~45% of our 2006 request
Answer to some (major) TAC comments

- Heating of the target cell
  - The 11 GeV beam with the new cell geometry will cause about 20W of heat deposit, ~6 times higher than current design.
  - However, heating should not be a problem because of the use of metal chamber and frame (allow conduction), and the rapid replacement of the polarized gas in the target chamber.
  - Like all 6 GeV experiments, a 4He cooling jet will be used to bring the temperature further down. Raster must be used, minimal size 2x2mm².
  - Full calculation is underway nevertheless.

- Effect of the spectrometer magnet fringe field
  - Will use compensation coils to “offset” any field gradient from the spectrometers. Have experience with Hall A septum and BigBite spectrometers.
A combination of the Hall A and C measurement will allow the study of the $Q^2$-dependence of $A_{1n}$ up to $x=0.71$. The use of HMS+SHMS (close spectrometers) will allow clean measurements of $A_{1n}$ with less systematics than open spectrometers. As a result, reliable and fast online and/or offline data analysis will be possible, allowing fast turn-around of physics results.

Even if BigBite works for 11 GeV, it will be limited by systematics (first by background and PID, secondly by nuclear corrections). And the physics of $A_{1n}$ at large $x$ is important enough that it's worth more than one measurement.

Comparison with the Hall A BigBite Experiment

Hall A: uses the BigBite spectrometer, will provide DIS data up to $x=0.71$ with a 8.8 GeV beam, with slightly smaller uncertainties than this proposal. Hall A: can be done as soon as the accelerator is ready. But it is unknown yet whether it will work for 11 GeV; Cherenkov did not work for the inclusive measurement of Transversity, and barely worked for $d_2n$. Lot of effort will be needed for PID background: not only $\pi$, but also $\pi_0$ and $e^+e^-$. 

Assuming no significant systematic uncertainties really need this point to tell which works better: pQCD(+OAM) or CQM
Comparison with the Hall A BigBite Experiment

- Hall A: uses the BigBite spectrometer, will provide DIS data up to $x=0.71$ with a 8.8 GeV beam, with slightly smaller uncertainties than this proposal.
- Hall A: can be done as soon as the accelerator is ready. But it is unknown yet whether the open-geometry BigBite will work for 11 GeV;
  - BigBite Cherenkov did not work for the inclusive measurement of Transversity, and barely worked for $d2n$. Lot of effort will be needed for PID and background (not only $\pi^-$, but also $\pi^0$ and $e^+e^-$).
- Even if BigBite works for 11 GeV, it will be limited by systematics (first by background and PID, secondly by nuclear corrections). And
  - The physics of $A_1^n$ at large $x$ is important enough that it's worth more than one measurement;
  - A combination of the Hall A and C measurement will allow the study of the $Q^2$-dependence of $A_1^n$ up to $x=0.71$.
  - The use of HMS+SHMS (close spectrometers) will allow clean measurements of $A_1^n$ with less systematics than open spectrometers. As a result, reliable and fast online and/or offline data analysis will be possible, allowing fast turn-out of physics results.
Summary

Will measure $A_1^n$ up to $x=0.77$ in DIS, **test of CQM vs pQCD and the role of quark OAM**;

Will combine with CLAS12 proton data to extract $\Delta q/q$; provide further tests of models and theories;

Wide $Q^2$ coverage allows the study of $Q^2$-dependence up to $x=0.55$;

Requires: pol3He target in Hall C + SHMS + HMS w/ 10^4:1 $\pi$ rejection;

Compare to the 2006 version: Added resonance data to test quark-hadron duality; **Recent development in the target allows significant reduction of the beam time and increased physics outcome.**

Beam time request: 35 days total (not including target commissioning)

Compare to the Hall A BigBite proposal; Can reach higher $x$ than Hall A; Use of HMS/SHMS spectrometers allows clean studies of $A_1^n$ and fast and reliable/easier data analysis;
Building on the foundation of the recent past, nuclear science is focused on three broad but highly related research frontiers: (1) QCD and its implications and predictions for the state of matter in the early universe, quark confinement, the role of gluons, and the structure of the proton and neutron; (2) the structure of atomic nuclei and nuclear astrophysics, which addresses the origin of the elements, the structure and limits of nuclei, and the evolution of the cosmos; and (3) developing a New Standard Model of nature’s fundamental interactions, and understanding its implications for the origin of matter and the properties of neutrinos and nuclei.
Extra slides
Expected Results

![Graph showing expected results with data points labeled by number and symbols for HMS and SHMS categories. The x-axis represents $x_{Bi}$ and the y-axis represents $Q^2 (\text{GeV}/c)^2$. The graph includes markers for different experiments and statistical error bars.](image-url)
Expected Results on $Q^2$ dependence of $A_1^n$

Higher twist contribution to $g_1^n(x,Q^2)$ can be described by

\[
\left[ \frac{g_1(x,Q^2)}{F_1(x,Q^2)} \right]_{\text{exp}} = \frac{g_1(x,Q^2)_{LT} + h_1(x)/Q^2}{F_1(x,Q^2)_{\text{exp}}}
\]

Figure credit: the LSS group
These are using Hall A 2006 projected results.
Summary

Significant improvement over our 2006 proposal thanks to the development in polarized 3He target

Spins polarized per second weighted by polarization squared
Heating of the target cell

For previous experiments (cell made of GE180 glass), a heating test was done in Hall C in 1997. Results show:

- a $^4$He cooling jet was needed to cool the scattering chamber, temperature in situ was measured near the window, temperature at the center of the window was estimated to $<100\,^\circ\text{C}$ with the cooling jet, but much higher if without.

- window temperature rises linearly with beam current, but not so dependent on the raster size.
Why Large $x$?

- At large $x$, valence quarks dominate, easier to model;
- Less contribution from q-qbar sea and gluons — a relatively clean region to study the nucleon structure;
- To understand the nucleon spin, high $x$ is a good place to start with.