Spin Asymmetries of the Nucleon Experiment (PR03-109)

Glen Warren
Jefferson Lab
PAC 24
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Outline

- Spin structure
- World's data of $A_{1p}$ and $g_2$
- Method
- Physics
- Systematics, etc...
- Summary
Spin Structure

Deep inelastic lepton scattering data has yielded wealth of knowledge of nucleon structure. Quark distributions inside nucleon are described by four structure functions:

- Structure functions: $F_1, F_2$ - cross section
- Spin Structure Functions: $g_1, g_2$ - polarization observables

In Quark-Parton Model, we can write $F_1$ and $g_1$ in terms of helicity dependent quark distribution functions, $q_i^\pm(x)$:

\[
F_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^+ + q_i^-]
\]

\[
g_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^+ - q_i^-]
\]
\( g_2 \)

\( g_2(x, Q^2) \) does not have as simple an interpretation as \( g_1 \). It can be divided into a twist 2 and a mixed twist term:

\[
g_2 = g_2^{ww} + \overline{g}_2
\]

where \( g_2^{ww} \) depends only on \( g_1 \) (twist 2):

\[
g_2^{ww} = -g_1 + \int_x^1 g_1(y, Q^2) \, y \, dy
\]

\( \overline{g}_2 \) vanishes when all twist-3 (\( d_n \)) matrix elements vanish in Operator Product Expansion (OPE), e.g.

\[
d_2 = 3 \int_0^1 x^2 \overline{g}_2(x, Q^2) \, dx
\]

Thus, \( g_2 \) is interesting for its higher twist contributions.
The spin structure functions $g_1$ and $g_2$ are related to the asymmetries $A_1$ and $A_2$ by:

$$A_1 = \frac{\sigma_{1/2}^T - \sigma_{3/2}^T}{\sigma_{1/2}^T + \sigma_{3/2}^T} = \frac{1}{F_1} (g_1 - \gamma^2 g_2)$$

$$A_2 = \frac{2\sigma_{LT}^T}{\sigma_{1/2}^T + \sigma_{3/2}^T} = \frac{\gamma}{F_1} (g_1 + g_2)$$

Thus $A_1$ and $A_2$ depend on $F_1$, which helps to reduce the $Q^2$ dependence of these asymmetries.

At JLab energies, it is necessary to measure two types of asymmetries to extract $g_1$, $g_2$ or $A_1$, $A_2$ in a model independent manner.
$d_2$

- $d_2$ is a measure of quark-gluon interactions (higher twists).
- Shown to measure response of color electric and magnetic fields to polarization of the nucleon:
  \[ d_2 = \frac{(2x_B + x_E)}{3}. \]
- As a moment, $d_2$ requires both Resonance and DIS data.
- Comparison to Lattice QCD:
  - LQCD can currently calculate moments at $Q^2 = 4$.
  - SANE covers $Q^2$ from 2.5 to 6.5, but has the widest coverage in $x$ around $Q^2 = 4$. 
World's Data at High $x$

- $g_{2}^{ww}$ is twist 2 - from $g_{1}$.
- Spread in $g_{2}$ at $x \sim 0.4$, not clear if due to actual $Q^{2}$ dependence.

- Dominated by NH$_{3}$ experiments.
- CLAS data under analysis.
For JLab Energies, it is necessary to do two asymmetry measurements to extract $A_{1p}$ and $g_2$ in a model independent way.
Extraction

Measure inclusive beam-target asymmetries with polarized electron beam and polarized proton target.

The measured asymmetry is related to $A_1$ and $A_2$ by the target polarization w.r.t. the beam ($\theta_N$):

$$A_{\text{meas}}(\theta_N) = \alpha A_1 \left[ \cos(\theta_N) - \rho \sin(\theta_N) \right] + \beta A_2 \left[ \rho \cos(\theta_N) + \sin(\theta_N) \right]$$

where

$$\alpha = \alpha(E,E',\theta,R)$$
$$\beta = \beta(E,E',\theta,R)$$
$$\rho = \rho(E,E',\theta)$$

By measuring the beam-target asymmetry for two values of $\theta_N$, we can extract $A_1$ and $A_2$.

- Most sensitive to $A_1$ for $\theta_N = \theta_q$
  $$A_{\text{meas}} \sim A_\parallel - \text{field } \parallel \text{ beam}$$

- Most sensitive to $A_2$ for $\theta_N \approx 90^\circ$
  $$A_{\text{meas}} \sim A_\perp - \text{field } \perp \text{ beam}$$

Geometry of target magnet prevents 90° measurement, instead we will use 180° and 80°.
Experimental Setup

Target
- UVa NH3 target
- 5 T field

Beamline
- Chicanes
- SEM
- He Bag

Electron Arm
- BETA

Background Studies
- HMS

\[ \theta_N = 180^\circ \]

\[ \theta_{BETA} = 40^\circ \]

\[ \theta_{N} = 80^\circ \]

\[ \theta_{HMS} = 35-45^\circ \]
Two Beam Energies

We propose to take measurements at beam energies of 4.8 and 6.0 GeV because:

• More thorough coverage of kinematics:
  - Study $Q^2$ dependence for constant $x$.
  - Study $x$ dependence for constant $Q^2$.

• Provides limited test of local duality for spin observables. If observed, can significantly extend maximum $x$ for $A_{1p}$. 
Big Electron Telescope Array (BETA)

Designed to be insensitive to backgrounds and have good Particle ID. Target field screens much of low energy background.

Gas-Cerenkov
- Particle Identification
- Minimal knock-on
Big Electron Telescope Array (BETA)

Designed to be insensitive to backgrounds and have good Particle ID. Target field screens much of low energy background.

Gas Cerenkov
- Particle Identification
- Minimal knock-on

Lucite Cerenkov
- Redundant PID
- Tracking
Big Electron Telescope Array (BETA)

Designed to be insensitive to backgrounds and have good Particle ID. Target field screens much of low energy background.

Gas-Cerenkov
- Particle Identification
- Minimal knock-on

Lucite Cerenkov
- Redundant PID
- Tracking

Pb-Glass Calorimeter
- Calorimetry
- Hadron reduction
Physics from SANE

Precision $g_2$

$x, Q^2, W$
Dependence

$A_{1p}$ as $x \to 1$

Spin Duality
Precision Data

\[ x^2 g_{WW} (Q^2 = 5) \]

World

SANE

W < 2 \ W > 2

E = 6.0

E = 4.8

Proposed:

- \( W > 2.0 \)
- \( 1.76 < W < 2.0 \)
- \( 1.48 < W < 1.76 \)
- \( 1.38 < W < 1.58 \)

- E143
- E155
- Hermes

Estimated Systematics

6 GeV

4.8 GeV

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$Q^2$ Dependence

- Spin structure data binned in $x$ and $Q^2$ to demonstrate capabilities of SANE.

- Two beam energies allows for more thorough coverage in $x$ at given $Q^2$. 
Moments ($Q^2$)

- Make connection to Lattice QCD:
  - Lattice calculations at $Q^2 = 4$.
- Study effect of higher twists.

### Uncertainty in Moments

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<tr>
<th>$Q^2$ Range</th>
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<th>relative</th>
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</thead>
<tbody>
<tr>
<td>$\int x^2 g_1 , dx$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5-3.5</td>
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<td>7.6%</td>
</tr>
<tr>
<td>3.5-4.5</td>
<td>0.0006</td>
<td>4.7%</td>
</tr>
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<td>4.5-5.5</td>
<td>0.0007</td>
<td>5.4%</td>
</tr>
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<td>5.5-6.5</td>
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<td>5.9%</td>
</tr>
<tr>
<td>$\int x^2 g_2 , dx$</td>
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<td></td>
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<tr>
<td>2.5-3.5</td>
<td>0.0013</td>
<td>13.1%</td>
</tr>
<tr>
<td>3.5-4.5</td>
<td>0.0005</td>
<td>5.8%</td>
</tr>
<tr>
<td>4.5-5.5</td>
<td>0.0007</td>
<td>8.1%</td>
</tr>
<tr>
<td>5.5-6.5</td>
<td>0.0007</td>
<td>9.1%</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>absolute</th>
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</thead>
<tbody>
<tr>
<td>World</td>
<td>2-18</td>
<td>0.0006</td>
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<tr>
<td>$d_2$</td>
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<td>2.5-4.5</td>
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<td>4.5-6.5</td>
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<td>45%</td>
</tr>
<tr>
<td>World</td>
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<td>0.0017</td>
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Edelmann et al., hep-ph/9909524
Test of Spin Duality

• HERMES observes spin duality in $A_1^p$ with resonant region data of $\delta A/A \sim 0.3$ (Phys. Rev. Lett., 2003).

• Two beam energies of SANE will permit limited test of spin duality.

• SANE will be able to do better than $\delta A/A \sim 0.1$.

• Transverse measurements of SANE in Resonance region allow for model independent test.
Extrapolated $A_1^p$ data using $\alpha x^8 (1 + \gamma x^2)$. Fit to:

- World's Data.

![Graph showing data points and curves representing the fit to the world's data.](image)
Extrapolated $A_1^p$ data using $\alpha x^8(1+\gamma x^2)$. Fit to:

- World's Data.
- World + Estimated EG1b:
  - EG1b improves uncertainty w.r.t World data by 30%.
$A_1^p$ as $x \to 1$

Extrapolated $A_1^p$ data using $\alpha x^8(1+\gamma x^2)$. Fit to:

- World's Data.
- World + Estimated EG1b:
  - EG1b improves uncertainty w.r.t World data by 30%.
- World + Estimated EG1b + Projected SANE:
  - SANE improves uncertainty w.r.t World+EG1b by 20%.
Extrapolated $A_1^p$ data using $\alpha x^8 (1 + \gamma x^2)$. Fit to:

- World's Data.
- World + Estimated EG1b:
  - EG1b improves uncertainty w.r.t World data by 30%.
- World + Estimated EG1b + Projected SANE:
  - SANE improves uncertainty w.r.t World+EG1b by 20%.
- If demonstrate spin duality, can improve extrapolation significantly.
Beam Line Background Studies

CEBAF Hall C End Station
Cut plane at y = 0.001 m
Beam Line Background Studies

Conducted preliminary beam line background studies using simulation package of Pavel Degtiarenko.

- **Parallel field:** no problems with BETA at 40°.
- **Transverse field:** a large fraction of electrons escape pathologically into BETA:
  - expect at most 200 kHz/PMT for Gas Cerenkov.
  - Pileup, trigger rates, detector rates all remain manageable.
  - These numbers are conservative... will probably have a reduction of at least 2 in Cerenkov rates.
## Estimated Systematics for 6 GeV

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<thead>
<tr>
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<th>A1p</th>
<th>g2</th>
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<tr>
<td>Radiative Corrections</td>
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<tr>
<td>Dilution Factor</td>
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<td></td>
</tr>
<tr>
<td>Target Polarization</td>
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</tr>
<tr>
<td>Beam Polarization</td>
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<tr>
<td>Nitrogen Correction</td>
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<table>
<thead>
<tr>
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<th>$x=0.6$</th>
<th>$x=0.3$</th>
<th>$x=0.6$</th>
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<td>1.2%</td>
<td>1.5%</td>
<td>1.3%</td>
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<tr>
<td></td>
<td>0.4%</td>
<td>0.5%</td>
<td>2.7%</td>
<td>4.5%</td>
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<tr>
<td></td>
<td>1.0%</td>
<td>1.0%</td>
<td>3.7%</td>
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<tr>
<td>Background</td>
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<td>2.3%</td>
<td>4.0%</td>
<td>4.1%</td>
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<tr>
<td></td>
<td>3.3%</td>
<td>3.3%</td>
<td>4.6%</td>
<td>4.7%</td>
</tr>
<tr>
<td>Total</td>
<td>4.2%</td>
<td>4.0%</td>
<td>6.8%</td>
<td>6.7%</td>
</tr>
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</table>
## Beam Time request

### Production

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Beamtime (h)</th>
<th>Yield (in)</th>
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</thead>
<tbody>
<tr>
<td>6.0</td>
<td>180</td>
<td>100</td>
</tr>
<tr>
<td>6.0</td>
<td>80</td>
<td>200</td>
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<tr>
<td>4.8</td>
<td>180</td>
<td>70</td>
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<tr>
<td>4.8</td>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td>2.4</td>
<td>-</td>
<td>10</td>
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</table>

### Systematics

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Packing Fraction</td>
<td>20</td>
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<tr>
<td>Mollers</td>
<td>21</td>
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</table>

**Total beam time**: 551 (23 d)

### Overhead

<table>
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<td>Anneals</td>
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<tr>
<td>Energy Change</td>
<td>48</td>
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<tr>
<td>Target Rotation</td>
<td>48</td>
</tr>
<tr>
<td>Stick Changes</td>
<td>48</td>
</tr>
</tbody>
</table>

**Total Overhead**: 206 (9 d)

**Requested Time**: 654 (27 d)
Collaboration


Jefferson Lab


University of Virginia

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Yerevan Physics Institute, Armenia

Spin Structure Physics

→ JLab, Temple, UVa, W&M

Detectors

→ Yerevan, LA Tech, JLab

Calorimeter

→ Protvino

Target

→ JLab, UVa
Summary

SANE: Spin Asymmetries of the Nucleon Experiment

Physics:
- Precision measurement of fundamental quantity, $g_2$, in practically unmeasured region; complements CLAS.
- $Q^2$ study of third moments.
- $d_2$ measurement equivalent of $\frac{1}{2}$ of current uncertainty.
- Kinematics in realm of Lattice QCD calculations.
- Physics spin-offs:
  - Limited test of local duality,
  - Data to aid in extrapolation of $A_{1p}$ to $x=1$.

BETA

- Designed to handle high rates of low energy background.
- Multi-purpose device: SANE, Flavor Decomposition, GPDs, Transversity (hint, hint) ...
  - similar technique could be used at 12 GeV
Background Rates

- Dominated by charge-symmetric processes, mostly $\pi^0 \rightarrow \gamma e^+ e^-$.  
- Measure ratio of rates in HMS.  
- Measure ratio of asymmetries using events with $\gamma$, $\gamma \gamma$ and $e^+ e^-$ in BETA and use CLAS data.  
- Hadron backgrounds measured by ignoring Gas Cerenkov in trigger.  
- Reduce Positron Rates by increasing energy threshold.
Shielding of BETA

CEBAF Hall C End Station
Cut plane at y = 0 m
Beam Line Background Studies

As a result of background in transverse mode:

- Increase online CAL threshold to 900 MeV to bring trigger rate < 1kHz. No impact on physics.
- Slightly increased pileup: 0.8% above 10 MeV, but 0.01% above 50 MeV.
- Increased accidentals between gas Cerenkov and CAL: < 5%, but uncertainty in correction will be < 0.5% of true rate.

These numbers are conservative... will probably have a reduction of at least 2 in Cerenkov rates.
Pileup In Calorimeter

Closely examined pileup in Calorimeter:

- Considered 9 block cluster with 100 ns time window.
- Eliminated events in which there was an identifiable and separate second cluster.
- Included beam line pileup.
- Total pileup is above 10 MeV is 1.3%, above 50 MeV is 0.25%.

Pileup is not a problem.
## Rates in BETA

### Gas Cerenkov (> 20 MeV)

<table>
<thead>
<tr>
<th>E</th>
<th>e±</th>
<th>π±</th>
<th>Trig</th>
</tr>
</thead>
<tbody>
<tr>
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<td>28.1</td>
<td>242.0</td>
<td>30.5</td>
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<tr>
<td>4.8</td>
<td>1590.0</td>
<td>223.0</td>
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<tr>
<td>6.0</td>
<td>25.3</td>
<td>255.0</td>
<td>27.9</td>
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<tr>
<td>6.0</td>
<td>1510.0</td>
<td>236.0</td>
<td>1512.4</td>
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</table>

### Calorimeter (> 900 MeV)

<table>
<thead>
<tr>
<th>E</th>
<th>e±</th>
<th>π±</th>
<th>π0+N</th>
<th>Trig</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8</td>
<td>0.3</td>
<td>1.0</td>
<td>7.2</td>
<td>8.5</td>
</tr>
<tr>
<td>4.8</td>
<td>0.3</td>
<td>1.0</td>
<td>7.1</td>
<td>8.4</td>
</tr>
<tr>
<td>6.0</td>
<td>0.3</td>
<td>1.1</td>
<td>8.1</td>
<td>9.5</td>
</tr>
<tr>
<td>6.0</td>
<td>0.3</td>
<td>1.2</td>
<td>8.0</td>
<td>9.4</td>
</tr>
</tbody>
</table>

### BETA Trigger Rates

<table>
<thead>
<tr>
<th>E</th>
<th>True</th>
<th>Accd</th>
<th>offline A/T</th>
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<tbody>
<tr>
<td>4.8</td>
<td>0.31</td>
<td>0.03</td>
<td>0.0%</td>
</tr>
<tr>
<td>4.8</td>
<td>0.31</td>
<td>1.34</td>
<td>0.6%</td>
</tr>
<tr>
<td>6.0</td>
<td>0.31</td>
<td>0.03</td>
<td>0.0%</td>
</tr>
<tr>
<td>6.0</td>
<td>0.31</td>
<td>1.43</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
Third Moment of $g_1$
Third Moment of $g_2$
Integrals for $d_2$
Systematics

Calorimeter Gains:

- Calibrated by measuring $\pi^0$ mass from double $\gamma$ events. Cross checked with proton elastics (using HMS in coincidence).
- Monitored through Lucite light system, punch-through pions and cosmics.

Background:

- Dominated by charge-symmetric processes, mostly $\pi^0 \rightarrow \gamma e^+ e^-$. 
- Measure ratio of rates in HMS; measure ratio of asymmetries using events with $\gamma$, $\gamma\gamma$ and $e^+ e^-$ in BETA and use CLAS data.
- Hadron backgrounds measured by ignoring Gas Cerenkov in trigger.
Why High $x$?

$x = Q^2 / 2 M \nu$

- Examine predictions of $x \to 1$ of $A_{1p}$ of pQCD and SU(6) models:
  - SU(6) symmetric $A_{1p} \to 5/9$,
  - SU(6) broken and pQCD predicts $A_{1p} \to 1$, but different reasons.

- Higher twist effects become more significant at higher $x$.
- Region in which sea quarks play only minor role.
- Understanding higher order moments to compare to Lattice QCD and QCD predictions.
- Existing data at large $x$ is limited compared to lower $x$ region. Region is“ statistically challenged”. 

Gas Cerenkov

$N_2$ Gas
- Reduced knock-on's
- At STP, pion threshold is 5.8 GeV/c

Point-to-Point focusing
- Easy alignment of mirrors
- Further reduction of background

PMTs
- 8 Mirrors and PMTs
- Baffled
- Apply tight electron cuts
- Expected 17-20 photoelectrons

\(\delta\)-Ray Probability versus Kinetic Energy

\begin{itemize}
\item $N_2$: Threshold = 21.6 MeV
\item $CO_2$: Threshold = 18.5 MeV
\end{itemize}

\begin{align*}
\text{Probability} & = 10^{-2} \\
\text{Hadron Kinetic Energy (GeV)} & \text{pions} \\
& \text{protons}
\end{align*}
UVa Polarized Target

- Dynamic Nuclear Polarization
- 5 T Field
  - can steer beam
  - affect optics of scattered electrons
- 1 K evaporative refrigerator
- Composite target: N+H+He
  - asymmetry is diluted by unpolarized materials
- Measure target polarization
  - calibration: thermal equilibrium
  - monitoring: NMR
BETA

Tracking Resolutions
Angle 2°
Vertex 10 cm

Reconstruction Resolutions
Angle 3-17 mrad
Momentum 45-70 MeV

Particle Rejection
Pions >1000
Protons >10000
Acceptance: $E = 6.0, \theta_N = 180$
## BigBite and BETA

|                | BigBite                                      | BETA                           |
|----------------|----------------------------------------------|--------------------------------
| **Solid Angle**| ~75 msr                                      | 207 msr                        |
| **Detector Package** | Calorimeter Gas Cerenkov wire chambers (2) | Calorimeter Gas Cerenkov Lucite Cerenkov |
| **Dispersion**  | Open Dipole                                  | None                           |
| **Advantages**  | Better Resolution                            | Built for high rates           |
| **Disadvantages** | Interaction of fringe field with target field |                                |
Technical Comments, part I

1) Overhead has been included in the beam time request including time to calibrate the new "BETA" detector proposed. Additional survey time for beam line chicane changes has not been included, but may occur in conjunction with target anneals etc.

Adjust and survey time of the chicane is included in the target rotation time.

2) This is a large installation experiment, albeit a standard one requiring the polarized target and associated beam I chicane. Installation time has not been included, and is estimated to be 2-3 months. Deinstallation is estimated to be one month.

3) Strong technical support is assumed from the JLab Target Group for the installation, calibration, and operation of the polarized target. We do note that this may be alleviated by the strong involvement on this proposal by the UVa group.
Technical Comments, part II

4) Compared to the Gep-III calorimeter, this experiment adds the requirement of gain monitoring. The plans outlined in this proposal can be accommodate into the present designs for this calorimeter. The detector package is further augmented by a gas cerenkov and a lucite detector for particle identification. The experiment relies on the rejection of pions using the gas cerenkov. The required rejection factor is aggressive, but seems achievable at the cost of some electron inefficiency.

Excellent pion rejection is a matter of good design and quality control. It is not a matter of new invention. For the x>1 analysis, John Arrington found a 500:1 rejection in the HMS Cerenkov. He was able to predict this level of rejection using the same analytic expressions and figures as in our proposal. Considering the amount of material in front of the HMS gas Cerenkov, there is nothing controversial about our goal of 1000:1. Even at 500:1, the experiment still works.

5) New equipment required for this experiment would consist of a Lucite detector and a gas cerenkov, with some 60 PMT's total with associated infrastructure (cables, electronics), a pulsed laser for gain monitoring a cerenkov gas system, and likely additional TDC's. All are straightforward.
6) The experiment takes advantage of the magnetic field, used to polarize the target, to eliminate background from low-energy charged particles. A realistic Monte Carlo is used to estimate these backgrounds.

7) The experiment will require a low current dump in the Hall for the non-parallel field measurements. This technique has before been used for the E93-026 experiment.

8) Electronics for the BETA device will be almost entirely in the Hall. Experience with this, and whether a shield house is needed, will come from the Gep-III E01-109 experiment.

9) The HMS is used both to detect protons from elastic scattering and to measure positron rates following charge-symmetric processes.

10) Since HMS is not used all the time, and both beam energies and target configurations seem compatible with PR03-111, part of this experiment may run concurrent with PR03-111, assuming a second independent DAQ system.