Spin Asymmetries of the Nucleon Experiment
BETA Analysis Update

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Temple University

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     - Lucite Hodoscope
     - Forward Tracker
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Overview

SANE

- 4.7 GeV and 5.9 GeV beam energies
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- Polarized Ammonia Target
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- **Big Electron Telescope Array**
Overview

SANE

- 4.7 GeV and 5.9 GeV beam energies
- Polarized Ammonia Target
- **Big Electron Telescope Array**
- HMS data taken as well for resonance spin structure (Hoyoung Kang) and $G_E/G_M$ (Anusha Liyanage)
Overview

BETA is a unique detector

BETA detector diagram with labels for BigCal, Lucite Hodoscope, Čerenkov, PMTs, Spherical Mirrors, Toroidal Mirrors, Hodoscope, Forward Tracker, Polarized Target, Target Outer, Vacuum Chamber, Superconducting Magnet.
Overview

BETA is a unique detector

- Large solid angle, about 200 msr
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- Open configuration
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BETA is a unique detector

- Large solid angle, about 200 msr
- Open configuration
- No momentum selecting magnet
Polarized Electron Beam: 4.7, 5.9 GeV

Polarized Proton Target: \( \perp, \parallel \)

Ammonia (NH\(_3\)) Polarized via DNP in 5T Magnetic Field
SANE used BETA to detect inclusive electrons with a large acceptance at angles around 40° for energies above about 1 GeV.
BigCal

Two Sections

The upper section from Yerevan Physics Institute used during RCS experiment.
- It consists of $4 \times 4 \times 40 \text{cm}^3$ lead-glass blocks
- They are arranged in a $30 \times 24$ array

Lower section from IHEP in Protvino, Russia.
- It consists of $3.8 \times 3.8 \times 45 \text{cm}^3$ lead-glass blocks
- They are arranged in $32 \times 32$ array

1,744 lead glass blocks total.

Figure: Bigcal lead-glass blocks

Bigcal was previously used in the GEp series of experiments
Gas Čerenkov is from Temple University.

**Design**

- Filled with nitrogen gas at atmosphere.
- Uses 4 spherical and 4 toroidal mirrors to focus light to photomultiplier tubes.
- Used 3 inch quartz window Photonis PMTs for UV transparency.
- Mirror blanks were sent to CERN for special coating for high reflectivity far into the UV.

*Figure: Gas Čerenkov on Hall C floor*
Čerenkov ADCs

- PMT 5
- Spherical mirrors at large scattering angle.

- PMT 4
- Toroidal mirror at small scattering angle.
Lucite Hodoscope

Lucite Hodoscope is from North Carolina A&T State University.

**Design**

- 28 curved Lucite bars with light guides mounted to edges cut at 45°
- PMT with light guide mounted at both ends of each bar.

**Figure:** Lucite Hodoscope in Hall C
Forward Tracker

Forward tracker is from Norfolk State University and University of Regina

Design

- 3 layers of $3mm \times 3mm$ scintillators.
- 1 horizontally segmented layer closest to the target consisting of 72 segments
- 2 vertically segmented layers consisting of 128 segments each
- WLS fibers glued to each bar with fibers connected to Hamamatsu 64-Channel PMTs

Figure: Forward tracker in position between Čerenkov snout and target OVC
Polarized NH₃ Target - UVa Target Group

Target polarization during the experiment by James Maxwell

- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%
The Measured Asymmetry

\[ A_{exp} = \frac{N_+ - N_-}{N_+ + N_-} \]

\[ N_\pm = \frac{n_\pm}{Q\pm L\pm} \]

- \( n_\pm \) is the raw number of counts
- \( Q_\pm \) is the total incident charge
- \( L_\pm \) is the live time for each helicity.

Parallel kinematics

Perpendicular kinematics
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\[ A = \frac{A_{exp}}{fP_B P_T} \]

where \( P_B \) and \( P_T \) are the beam and target polarizations.
Dilution factor

Packing Fraction
- PF obtained from HMS using F1F209 cross-section model.
- PF determines how much of target-cell volume is ammonia vs He.
- Roughly 60 percent

Dilution
- Takes into account scattering from unpolarized material in target.
- Need to know target geometry and material.
- Yields from model are normalized to data from C target of known thickness.
- Function of $x$ and $W$

$$f(x, W) = \frac{N_p \sigma_p(x, W)}{N_p \sigma_p + \sum_i N_i \sigma_i(x, W)}$$
Uncorrected Asymmetries

$A_{180}^\ast, E=4.7\text{GeV}$

$A_{180}^\ast, E=5.9\text{GeV}$

$A_{80}^\ast, E=4.7\text{GeV}$

$A_{80}^\ast, E=5.9\text{GeV}$
Pair Symmetric Background Corrections

Electroproduction

- Model production cross sections (using Wiser’s fits)
- Run monte carlo to get $R = \frac{N_{pair}^{e^+}}{N_{total}^{e^-}}$
- Pion asymmetry from previous SLAC experiments (analysis by Oscar Rondon)

Photoproduction

$$A_{corr}^{bg} = \left( \frac{1}{1 - 2R} \right) A_{raw} - \left( \frac{2RA_{pair}}{1 - 2R} \right)$$

$$= \frac{1}{f_{bg}} A_{raw} - C_{bg}$$
Background Corrections

\[ R(e^+/e^-) \]

\[ \frac{1}{f_{bg}} \]

\[ N_{\text{pair}} \text{ and } N_{\text{dis}} \]

\[ C_{bg} \]

SANE Q^2=2.2 GeV^2
SANE Q^2=3.0 GeV^2
SANE Q^2=4.1 GeV^2
SANE Q^2=5.5 GeV^2

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Radiative Corrections

New Radiative Correction Code

Unpolarized formalism of Mo and Tsai \cite{2}

Includes internal and external radiative corrections.

Polarized formalism of Akushevich, et.al.

Written in C++ (part of InSANE)

Check and re-checked against existing codes (RADCOR and POLRAD)

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\textsuperscript{a} Akushevich, et.al.POLRAD 2.0 Manual\cite{1}

\textsuperscript{b} I.V.Akushevich and N.M.Shumeiko, J. Phys. G20(1994)513.

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Formalism Differences

- Polarized formalism treats *only internal* RCs
- External RCs calculated using beam depolarization term
- Unpolarized formalism does internal and external RCs

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\[\text{E'} \text{ (GeV)} \quad 0.6 \quad 0.8 \quad 1.0 \quad 1.2 \quad 1.4 \quad 1.6 \quad 1.8 \quad 2.0 \quad 2.2 \text{ (nb/GeV/sr)}\]

\[\Omega \quad dE'd \quad \sigma \quad d\theta \]

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Elastic Radiative Tail Subtraction

Elastic

- **Largest** radiative correction
- Treated with polarization following Akushevich, et.al.
- Correction depends on accurate calculation of radiated inelastic cross section

\[
A_{corr}^{el} = \frac{A_{corr}^{bg}}{f_{el}} - C_{el}
\]

\[
\frac{1}{f_{el}} = \frac{\Sigma T}{\Sigma in} \quad \quad C_{el} = \frac{\Delta_{el}}{\Sigma in}
\]

\[
\Sigma x = \sigma_{x}^{+} + \sigma_{x}^{-}
\]

\[
\Delta x = \sigma_{x}^{+} - \sigma_{x}^{-}
\]
Radiated cross sections and asymmetries

\[ A_{180}^p, \ E=5.9 \text{ GeV} \]

\[ \sigma_{180}, \ E=5.9 \text{ GeV} \]

\[ A_{80}^p, \ E=5.9 \text{ GeV} \]

\[ \sigma_{80}, \ E=5.9 \text{ GeV} \]
Motivating Physics

Direct access to the polarized structure functions can be obtained utilizing the following

$$A_∥ = D(A_1 - \xi A_2)$$

$$A_⊥ = d(A_2 - \xi A_1)$$

$$A_1 = g_1 - (4M^2x_2/Q^2)g_2$$

$$A_2 = 2Mx_2\sqrt{Q^2}g_1 + g_2$$

Direct access to twist-3 processes through using transverse target.

Deviations of $g_{p2}$ from $g_{WW2} = \int x^0 dy y g_1(y) − g_1 x^0$ as $x \to 1$
Motivating Physics

Direct access to the polarized structure functions can be obtained utilizing the following

\[ A_\parallel = D(A_1 - \xi A_2) \]
\[ A_\perp = d(A_2 - \xi A_1) \]
\[ A_1 = \frac{g_1 - (4M^2x^2/Q^2)g_2}{F_1} \]
\[ A_2 = \frac{2Mx g_1 + g_2}{\sqrt{Q^2} F_1} \]
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- Direct access to twist-3 processes through using transverse target.
- Deviations of \( g_2^p \) from

\[ g_2^{WW} = \int_x^1 \frac{dy}{y} g_1(y) - g_1 \]
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- Direct access to twist-3 processes through using transverse target.
- Deviations of \( g_2^p \) from \( g_{WW}^2 \):

\[ g_{WW}^2 = \int_x^1 \frac{dy}{y} g_1(y) - g_1 \]

- Twist-3 matrix element \( d_2^p \)
- \( A_1^p \) as \( x \to 1 \)
A twist-3 sum rule

Using the Operator Product Expansion for the non-local operators showing up in the S matrix, one can arrive at the infinite set of sum rules below. For \( n \geq 3 \) and \( n \) odd, we have

\[
\int_0^1 dx x^{n-1}\left\{g_1 + \frac{n}{n-1}g_2\right\} = \frac{1}{2} \sum_i \delta_i d_{n-1}^i E_{2,i}^n(Q^2, g)
\]  

(1)

For \( n = 3 \)

\[
\int_0^1 x^2\{2g_1 + 3g_2\} dx = d_2
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(2)
A twist-3 sum rule

Using the Operator Product Expansion for the non-local operators showing up in the S matrix, one can arrive a the infinite set of sum rules below. For $n \geq 3$ and $n$ odd, we have

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For $n = 3$

$$\int_0^1 x^2 \{2g_1 + 3g_2\} dx = d_2$$ \hspace{1cm} (2)$$

Interpretations of $d_2$

- Color Polarizabilities (X.Ji)
- Average Color Lorentz force (M.Burkardt)
Quark-gluon Correlations

M. Burkardt

\[ d_2 = 3 \int x^2 \bar{g}_2(x) dx = \frac{1}{2 M P^2} \langle P, S | \bar{q}(0) g G^+(0) \gamma^+ q(0) | P, S \rangle \]

but with \( \vec{v} = -c \hat{z} \)

\[ \sqrt{2} G^+ = -E^y + B^x = -(\vec{E} + \vec{v} \times \vec{B})^y \]

\[ d_2 \Rightarrow \text{average color Lorentz force} \text{ acting on quark moving backwards} \]

(since we are in inf. mom. frame) the \text{instant after being struck by the virtual photon}. \( \langle F^y \rangle = -2 M^2 d_2 \)
$x^2 g_1^p$ and $x^2 g_2^p$

Models are showing $g_2^{WW}$. 
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Far valence domain: $x > 0.5$

- $A_1^p$ as $x \to 1$

![Graph showing $A_1^p$ vs. $x$ with various data points and models indicated on the x- and y-axes. The graph includes data from SLAC_E143, SLAC_E155, SMC, HERMES, and CLAS-E93009 W>2.1, with comparisons to PQCD, NJL, and DSE models. The SU(6) model is nearly ruled out by $F_n^2/F_p^2$ data.]
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- $A_1^p$ as $x \to 1$
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.
Far valence domain: $x > 0.5$

- $A^p_1$ as $x \rightarrow 1$
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.
- Many predictions from models

![Graph showing $A^p_1$ versus $x$ with various models and data points plotted.](image-url)
Far valence domain: $x > 0.5$

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- Distinct predictions for most models. SU(6) nearly ruled out by $F_2^m/F_2^p$ data.
- SANE data cut off around $x \approx 0.55$ to exclude resonance region.
- SANE data goes out to $x \approx 0.8$ so stay tuned!
Conclusion

What did we learn during SANE

Open configuration can work.

Be careful with magnets.

Understanding background is very important.

Tracking detectors are challenging (maybe gems would have been better?)

Analysis nearly complete!

Vary models used in RCs to estimate its contribution to the systematic error.

Determine lowest $E'$ cut w.r.t. background to get lowest possible $x$.

Finalize systematic errors

Fits to SSFs and calculate moments.

Calculate $d\sigma/dp$ matrix element

Also leading twist ($a_0$) and possibly twist-4 ($f_4$) matrix elements.
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Thank You!
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[1] Akushevich, I., Ilyichev, A., Shumeiko, N., Soroko, A., and Tolkachev, A.
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[2] Mo, L. W., and Tsai, Y.-S.
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$A_{90}$ from $A_{180}$ and $A_{80}$

\[ A_1 = \left( \frac{1}{1 + \eta \zeta} \right) \left[ A_{180} \left( \frac{1 + \cot(\alpha) \chi}{D} \right) + A_\alpha \left( \frac{\csc(\alpha) \chi}{D} \right) \right] \]

and

\[ A_2 = \left( \frac{1}{1 + \eta \zeta} \right) \left[ A_{180} \left( \frac{\zeta - \cot(\alpha) \chi / \eta}{D} \right) + A_\alpha \left( \frac{\zeta - \cot(\alpha) \chi / \eta}{D(\cos(\alpha) - \sin(\alpha) \cos^2(\phi) \chi)} \right) \right] \]

where

\[ D = \frac{E - \epsilon E'}{E(1 + \epsilon R)}, \]

\[ \eta = \frac{\epsilon \sqrt{Q^2}}{E - \epsilon E'}, \]

\[ \zeta = \frac{1 + \epsilon}{2\epsilon}, \]

\[ \chi = \frac{E' \sin(\theta) \sec(\phi)}{E - E' \cos(\theta)}, \]

\[ R = \frac{W_2}{W_1} \left( 1 + \frac{\nu^2}{Q^2} \right) - 1 = \frac{F_2}{2x F_1} \left( 1 + \frac{4M^2 x^2}{Q^2} \right) - 1 \]

\[ A_{90} = \frac{A_\alpha + \cos \alpha A_{180}}{\sin \alpha} \]
Pair Symmetric Background

- At low $x$ there is a large pair symmetric background.
Pair Symmetric Background

- At low $x$ there is a large pair symmetric background.
- Take ratio of double track Čerenkov to single track events as a measurement of pair background.

![JLAB Positron Data](image-url)
Internal Inelastic Radiative Tail

\[ \frac{d\sigma}{dE' d\Omega} \] (nb/GeV/sr)

\( \theta_{\text{target}} = 0 \)
\( \theta_e = 40 \)
\( E = 5.89 \text{GeV} \)

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Internal Elastic Radiative Tail

$\frac{d\sigma}{dE'd\Omega}$

$E' (GeV)$

$\Omega$

$\sigma$

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1.0$ $1.2$

$E=5.90 GeV$

$\theta_0 = 45$

$\theta_\alpha = 0$

$\theta_\text{target} = 0$

$E=20.00 GeV$

$\theta_0 = 5$

$\theta_\alpha = 0$

$\theta_\text{target} = 0$
Dilution

![Graph showing dilution data]

Run: 72425
Dilutions: 2.220, 3.000, 4.066, 5.490

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