Single Spin Asymmetries (SSA) in n(e,e′) from a vertically polarized $^3$He target.

Nucleon structure studies using two photon exchange

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On behalf of the Jefferson Lab Hall A and polarized $^3$He collaborations

Program Goal: Measure the “vertical” target single spin asymmetry $A_y$ in:

- quasi-elastic $^3$He(e,e′)
- deep-inelastic $^3$He(e,e′)
- quasi-elastic $^3$He(e,e′n)
Born scattering and beyond

• Jefferson Lab physicists' favorite diagram (required for every talk):

Born scattering

• Irritating correction to favorite diagram.
• Suppressed by $\alpha$ relative to Born diagram
Born scattering and beyond

- Dominates unpolarized and most polarized $N(e,e')$ scattering.

- How is it useful?
- Loop integral contains *entire nucleon response*.
- How do we observe this?

\[
\begin{align*}
N(p) & \xrightarrow{l(k)} N(p') \\
& \quad \quad q \\
& \quad \quad l(k') \\
N(p') & \xrightarrow{l(k')} N(p)
\end{align*}
\]

\[
\begin{align*}
N(p) & \xrightarrow{l(k)} N(p') \\
& \quad \quad q_1 \\
& \quad \quad q_2 \\
& \quad \quad l(k') \\
N(p') & \xrightarrow{l(k')} N(p)
\end{align*}
\]
Target Single Spin Asymmetry (SSA)

• Unpolarized $e^-$ beam incident on $^3$He target polarized normal to the electron scattering plane

$$A_y = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

• Note that unpolarized eN scattering and double spin asymmetries (DSA) with beam and target polarization in-plane are dominated by 1-photon exchange. e.g. measurements of $G_e^n, G_M^n, F_1, F_2, g_1, g_2 \quad <----$ (Born approximation)

• However, $A_y=0$ at Born level,
  $\rightarrow$ sensitive to physics at order $\alpha^2$; two-photon exchange.
Two Photon Physics

- Topic 1: Elastic N(e,e’) scattering with two photon exchange:

\[ l(k, h) + N(p, \lambda_N) \rightarrow l(k', h') + N(p', \lambda'_N) \]

\[ T = T_1^\gamma + T_2^\gamma = \frac{e^2}{Q^2} \bar{u}(k', h)\gamma_\mu u(k, h) \times \bar{u}(p', \lambda'_N) \left( \tilde{G}_M \gamma^\mu - \tilde{F}_2 P^\mu + \tilde{F}_3 \frac{\gamma \cdot K P^\mu}{M^2} \right) u(p, \lambda_N) \]

- \( h = \) electron helicity, \( \lambda_N(\lambda'_N) = \) nucleon helicity, \( K = (k+k')/2, \) \( P = (p+p')/2 \)

- The functions \( \tilde{G}_M^{\text{Born}}, \tilde{F}_2^{\text{Born}}, \tilde{F}_3^{\text{Born}} \) are complex and reduce to the usual (real) structure functions and form factors in 1\( \gamma \) exchange:

\[ \tilde{G}_M^{\text{Born}}(\nu, Q^2) = G_M(Q^2) \]
\[ \tilde{F}_2^{\text{Born}}(\nu, Q^2) = F_2(Q^2) \]
\[ \tilde{F}_3^{\text{Born}}(\nu, Q^2) = 0 \]

At low $Q^2$, entire nucleon is involved

At large $Q^2$, assume interaction with a single quark

Loop integral contains entire elastic and inelastic response of nucleon
Elastic form factor data: 2-photon exchange correction at large $Q^2$

- Note that both recoil polarization and Rosenbluth separation measurements of nucleon form factors must be corrected for 2-photon exchange

- Depends on the real part of the interference:

$$\sigma \propto \text{Re}(T_{1\gamma}^* T_{2\gamma})$$

- Elastic contribution well known. Inelastic contribution estimated at large $Q^2$ using e.g. form factors, resonances, moments of GPD’s, ....
Jefferson Lab $G_E^p / G_M^p$

Rosenbluth w/ $2\gamma$ corrections vs. Polarization data


Blunden et al.  
2-photon SSA physics

\[ A_y \propto \frac{\text{Im}(T_{1\gamma} T_{2\gamma}^*)}{|T|^2} \]

Absorptive part=Imaginary contribution


For inclusive scattering \( N(e,e') \), \( A_y^{\text{Born}} = 0 \)


When we allow 2-photon exchange, the leading contribution is from \( 1\gamma + 2\gamma \) interference

- Calculable at large \( Q^2 \) using moments of GPD’s.
- Measurement of \( A_y \) at large \( Q^2 \) provides new constraint on GPD’s
Existing $A_y$ Data

- SLAC Proton Data for $A_y$ (solid) and $P_n$ (open); expected $A_y^p < 1\%$


- NIKHEF QE $^3\text{He}(e, e')$ at $Q^2 = 0.1 \text{ GeV}^2$ gave $A_y = -1.0 \pm 5.4\%$.

  M. C. Harvey, Ph.D. thesis, Hampton University, 2001

- Precision measurements of $A_y$ do not exist! A non-zero $A_y$ never measured!
Experimental Design

- Use two symmetric spectrometers for singles electron detection. Jefferson Lab Hall A HRS spectrometers.
- Vertically polarized \(^3\text{He}\) target.
- Measurements at \(Q^2=0.1, 0.5\) and \(1.0\) GeV\(^2\)
  - Test GPD calculation
  - Study \(Q^2\) dependence
  - Parton to hadron transition
Hall A polarized $^3$He target

- Effective polarized neutron target
- Spin Exchange Optical Pumping (SEOP) technology
- 5:1 ratio of K:Rb for high efficiency optical pumping and spin exchange.
- Spectrally narrowed diode lasers
- With 15uA beam, $<P_{\text{targ}}>$~65%
- Luminosity $L \sim 10^{36}$ /cm$^2$/s
New record for polarization at this luminosity

6/22/10
Preliminary results

- Next two slides will show $A_y$ for $^3\text{He}$
- Preliminary results with target polarization and nitrogen dilution corrections applied.
- No radiative corrections applied
- $^3\text{He}$ to neutron correction needed
- Systematic uncertainties not finished
Preliminary $^3$He results at $Q^2=0.5$ and 1.0 GeV$^2$

$Q^2 = 0.5$ GeV$^2$

- $(1.34 \pm 0.20) \times 10^{-3}$

$Q^2 = 1.0$ GeV$^2$

- $(1.60 \pm 0.22) \times 10^{-3}$

- $(1.34 \pm 0.20) \times 10^{-3}$

- $(1.60 \pm 0.22) \times 10^{-3}$

- $A_y^{^3}$He $\sim$ - 0.17% at $Q^2=1$ GeV$^2$, $A_y^{^3}$He $\sim$ - 0.14% at $Q^2=0.5$ GeV$^2$,

- Data at $Q^2=0.1$ GeV$^2$ being analyzed. *Seems to show little $Q^2$ dependence.*
Topic 2: What about $A_y$ for n(e,e′) in DIS?

- The formalism remains the same:
  $A_y=0$ for 1-photon exchange

- For DIS, one assumes that the scattering is dominated by two photon exchange with a single quark.

- This was measured in Hall A during the transversity experiment, using the BigBite Spectrometer in singles mode.

- Joe Katich–W&M graduate thesis student
n(e,e′) prediction for DIS

- In a simple quark model, $A_y = 0$ for two-photon exchange due to helicity conservation at the quark level.


- The SSA should change by two orders of magnitude from DIS to QE kinematics.

- Allows one to study the “transition” from hadron-like to parton-like behavior.
Kinematics

Measure $^3$He(e,e') SSA using BB and LHRs in singles mode.

E=5.89 GeV

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Check for False Asymmetries: Luminosity Asymmetry

- Entries: 387
- Mean: 22.55
- RMS: 285.8
- $\chi^2 / \text{ndf}$: 30.41 / 16
- Constant: $62.07 \pm 4.28$
- Mean: $38.29 \pm 12.15$
- Sigma: $229.2 \pm 10.1$

ppm
Backgrounds

• **BigBite:** Pair produced $e^+ / e^-$ pairs from $\pi^0$ decay.
  – Measure using positive polarity
  – 50% contamination in lowest momentum bin
  – 1% in largest momentum bin
  – Largest systematic uncertainty

• **BigBite:** $\pi^-$ in $e^-/+$ spectrum. No Cherenkov detector. EM pre-shower and shower calorimeter

• **LHRS spectrometer,** virtually background free.
  – Good PID
  – Highest momentum = negligible pair-electron contamination
Final pi- Contamination

**T1**

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**T6**

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$A_y$ for $^3\text{He}$ versus $Q^2$

**Preliminary results**

$$A_y^{^3\text{He}} \sim 1-5 \times 10^{-3}, \text{ not zero??}$$

**Expected uncertainties only**

SLAC proton

Statistical and systematic uncertainties included
HERMES proton DIS data

$A_y$ vs. $Q^2$

- BigBite
- LHRS

Topic 3: SSA in quasi-elastic $^3$He(e,e’n)

- Detect recoil neutron during QE scattering.

- Christ-Lee theorem doesn’t apply for semi-inclusive scattering. $A_y$ not necessarily zero.

- Sensitive to final state interactions

- PWIA predicts $A_y=0$

- Unpublished NIKHEF result shows $A_y=50\%$

- Precise laboratory for studying $^3$He wavefunction
• Measured $A_y \sim 50\%$ !!!

• $Q^2 = 0.2$ GeV$^2$

Golak et al., non-relativistic Fadeev

Laget, Nagorney, 3-body partial wave analysis

PWIA

Note: Golak calculation was used to extract $G_e^n$ from deuteron and $^3$He data.
Hall A Neutron Detector (HAND)

- Detect coincidence between RHRS and HAND

\[ Q^2 \text{ (GeV)}^2 \]
Summary

• First measurements of the inclusive target SSA using vertically polarized $^3$He in QE, DIS scattering.

• Measured QE $A_y^{3\text{He}} \sim -0.14$, 0.17% for $Q^2=0.5$, 1.0 GeV$^2$

• Measured DIS $A_y^{3\text{He}} \sim -0.14$, 0.17% for $Q^2=0.5$, 1.0 GeV$^2$

• First DIS results for $A_y \sim 1-5 \times 10^{-3}$ for $^3$He at $Q^2=1.0-3.0$ GeV$^2$.
  • Statistical precision comparable to HERMES proton results.

• Precision results for SSA in $^3$He(e,e’n).

• Theoretical calculations needed.

• Measurements at high $Q^2$ possible with Jefferson Lab 12 GeV upgrade.
Connection with (GPDs) (con't)


\[ A_y = \sqrt{\frac{2\varepsilon (1 + \varepsilon)}{\tau}} \frac{1}{\sigma_R} \left\{ -G_M \text{Im}(B) + G_E \text{Im}(A) \right\} \]

\[ A = \int_{-1}^{1} \frac{dx}{x} \tilde{K} \sum_q e_q^2 \left[ H^q(x, 0, t) + E^q(x, 0, t) \right] \]

\[ B = \int_{-1}^{1} \frac{dx}{x} \tilde{K}' \sum_q e_q^2 \left[ H^q(x, 0, t) - \tau E^q(x, 0, t) \right] \]

- \( H^q \) and \( E^q \) are GPD's for quarks of flavor \( q \).
- \( \tilde{K} \) and \( \tilde{K}' \) contain the contributions from the hard scattering amplitudes.
- \( \text{Im}(A) \) and \( \text{Im}(B) \) are non-zero through \( 2\gamma \) contribution in \( \tilde{K} \) and \( \tilde{K}' \).
- Measuring neutron \( A_y \) provides new constraint on specific GPD moment.
S, S’, D, Δ-isobar contributions to $^3$He wavefunction

$$A_y^n = \frac{F_2^{^3\text{He}}}{P_n F_2^n (1 + \frac{0.056}{P_n})} \left[ A_y^{^3\text{He}} - 2 \frac{F_2^p}{F_2^{^3\text{He}}} P_p A_y^p \left(1 - \frac{0.014}{2P_p}\right) \right]$$

$$P_n = 0.86^{+0.036}_{-0.020}, \quad P_p = -0.028^{+0.009}_{-0.004}$$