Target Single-Spin Asymmetry
in Quasi-Elastic $^3\text{He} \uparrow (e, e')$ Reaction

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$$A_y = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$

- $A_y \equiv 0$ under $1\gamma$-exchange. $A_y$ is sensitive to the imaginary part of $1\gamma \otimes 2\gamma$.
- Access to the moments of GPDs. $A_y^n$ is particularly sensitive to a special combination of GPD moments due to the small value of $G^n_E$. 
• A non-vanishing $A_y$ has never been observed.

• Quasi-elastic $^3\text{He}^\uparrow(e, e')$ measurement is an easy experiment to perform. Fast target spin-flip is the key to reduce systematic uncertainties, and build-in consistency checks help to control the systematic uncertainties.

• Hadronic Final State Interactions do not generate SSA in the inclusive reaction.
Beyond the Born Approximation

- Has $2\gamma$-exchange effect ever been clearly observed at $Q^2 > 1.0$ GeV$^2$?
- Which observable provides the most significant signature of $2\gamma$-exchange?
- Can we learn anything new on nucleon structure through $2\gamma$-exchange?
A Non-Zero $A_y$ is a Clear Signature of $2\gamma$-Exchange

- Single-Spin Asymmetry $A_y$ is related to the absorptive part of the amplitude.

$$A_y = \frac{2 \text{Im} \left( \sum_{\text{spins}} T_{1\gamma}^* \cdot \text{Abs} T_{2\gamma} \right)}{\sum_{\text{spins}} |T_{1\gamma}|^2}$$

- If $1\gamma$-exchange only, amplitude is real $\Rightarrow A_y \equiv 0$
- $A_y$ needs a helicity flip, linked with $\kappa_N$. $A_y^P > 0$ and $A_y^n < 0$
- $2\gamma$ diagram is T-odd, generates a phase difference, violates “naive-T”.
- $A_y \equiv P_n$ under time-reversal invariance.)
A Non-Vanishing $A_y$ Has Never Been Observed

34 years ago. SLAC $A_y^p$ data.

The last effort in 1968.

- $E_0 = 15.0, 18.0$ GeV.
- $2.4^\circ < \theta_{lab} < 3.2^\circ$
- $(13.5^\circ < \theta_{cm}^e < 19.9^\circ)$.

- Expect $A_y < 1.0\%$ at small $\theta_{cm}^e$ angle.

SLAC, T. Powell et al., PRL 24, 753 (1970)
Target Single-Spin Asymmetry $A_y$ in Elastic $eN \rightarrow e'N$

Under Lorentz, parity and charge conjugation invariance, the $T$-matrix for elastic scattering of two spin-$1/2$ particles can be expanded in terms of six independent Lorentz structures, three of them remain non-zero at the limit of $m_e \rightarrow 0$, the $T$-matrix is:

$$T_{h', \lambda'_N \lambda_N} = \frac{e^2}{Q^2} \tilde{u}(k', h)\gamma_\mu u(k, h)$$

$$\times \tilde{u}(p', \lambda'_N) \left( \tilde{G}_M \gamma^\mu - \tilde{F}_2 \frac{P^\mu}{M} + \tilde{F}_3 \gamma \cdot K \frac{P^\mu}{M^2} \right) u(p, \lambda_N)$$

In the Born approximation, we recover:

$$\tilde{G}_M^{\text{Born}}(\nu, Q^2) = G_M(Q^2),$$
$$\tilde{F}_2^{\text{Born}}(\nu, Q^2) = F_2(Q^2),$$
$$\tilde{F}_3^{\text{Born}}(\nu, Q^2) = 0$$
Separate out the regular Born contributions,

\[
\tilde{G}_M = G_M + \delta \tilde{G}_M \\
\tilde{F}_2 = F_2 + \delta \tilde{F}_2
\]

or use \( \tilde{G}_E = G_E + \delta \tilde{G}_E \) where \( \tilde{G}_E = \tilde{G}_M - (1 + \tau) \tilde{F}_2 \).

The target single-spin asymmetry has two terms:

\[
A_y = \sqrt{\frac{2\varepsilon}{\tau}} \frac{C_B(\varepsilon, Q^2)}{d\sigma} \times \left\{ -G_M \Im \left( \delta \tilde{G}_E + \frac{\nu}{M^2} \tilde{F}_3 \right) + G_E \Im \left( \delta \tilde{G}_M + \left( \frac{2\varepsilon}{1 + \varepsilon} \right) \frac{\nu}{M^2} \tilde{F}_3 \right) \right\}
\]
Separating the hard quark scattering from the soft nucleon structure (Chen, Afanasev, Brodsky, Carlson and Vanderhaeghen, PRL\textbf{93}(2004)122301), in a handbag diagram:

\begin{itemize}
  \item A process of hard quark scattering, including both $1\gamma$ and $2\gamma$.
  \item GPDs describe the soft part of the nucleon structure.
  \item Evaluation of $2\gamma$ box diagram involves \textit{full} nucleon response to doubly virtual Compton scattering.
\end{itemize}

$A_y$ provides a new tool to study nucleon structure, allowing access to the Compton Form Factors.
Y.-C. Chen et al. showed that for $Q^2 > 1$ GeV$^2$, the hard two-photon contributions to $A_y$ can be expressed in terms of moments of GPD's:

$$A_y = \sqrt{\frac{2\varepsilon (1 + \varepsilon)}{\tau}} \frac{C_B(\varepsilon, Q^2)}{d\sigma} \left\{ -G_M \operatorname{Im}(B) + G_E \operatorname{Im}(A) \right\}$$

with

$$A = K \int_{-1}^{1} \frac{dx}{x} \sum_q e_q^2 (H^q + E^q)$$

$$B = K \int_{-1}^{1} \frac{dx}{x} \sum_q e_q^2 (H^q - \tau E^q)$$

where $C_B$ and $K$ are kinematic factors, $H^q$ and $E^q$ are quark GPD's.

- For a free polarized neutron, with $G_E^n \approx 0$, $A_y^n$ provides clear access to GPD moments.
Proton has approx. equal and opposite contributions from $G_E^p$ and $G_M^p$.

Neutron dominated by $G_M^n$ term $\implies$ Sensitive to one GPD moment only.

Neutron asymmetry $A_y^n \approx -1.7\%$ at $\theta_{cm} \approx 60^\circ$
Constraining GPD’s

- \( H^q(x, 0, 0) = q(x) \) – use world data; \( E^q \) not as well constrained.
- Moments of GPD’s are related to nucleon structure functions,
  \[
  F_1^q(t) = \int_{-1}^{1} dx \ H^q(x, 0, t), \quad F_2^q(t) = \int_{-1}^{1} dx \ E^q(x, 0, t)
  \]
- World form factor data don’t constrain sea quark contribution (assume symmetric sea).
- Though GPD’s models fit world form factor data reasonably well, there are still contributions which are relatively unconstrained.
- The quark contribution to the nucleon angular momentum, \( J^q \), is related to a different moment of \( H^q \) and \( E^q \), but \( J^q \) not well constrained.
  \[
  J^q = \frac{1}{2} \int_{-1}^{1} dx \ x \ [H^q(x, 0, 0) + E^q(x, 0, 0)]
  \]
Experiment E05-015: Quasi-Elastic $^3\text{He}^\uparrow (e, e')$

Goal: to clearly establish a non-zero $A_y^n$ at $Q^2 = 0.5, 1.0$ (and 2.3) GeV$^2$.

- Low $Q^2$ points (8 days approved) to clearly establish a non-vanishing $A_y^n$.
- $Q^2 = 2.3$ GeV$^2$ (later, for 17 days), to access GPD moments.
Experiment E05-015 $^3\text{He}^{\uparrow}(e, e')$: A Very Simple Setup

two independent measurements at the same time

- Two identical spectrometers for two independent $(e, e')$ measurements.
- $A_y \propto \vec{S}_T \cdot (\vec{e} \times \vec{e'}) \Rightarrow A_y (\text{left spectrometer}) = -A_y (\text{right spectrometer})$. 

![Diagram of the experimental setup]
## Kinematics, Rates and Beam Time

<table>
<thead>
<tr>
<th>$E_0$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$E'$ (GeV)</th>
<th>$\theta_e$ (deg)</th>
<th>$\theta_{e\text{cm}}$ (deg)</th>
<th>$e^-$ rate (10$^6$/day)</th>
<th>Time (days)</th>
<th>$\delta A_y^n$ ($\times 10^{-3}$)</th>
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<td>3.30</td>
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<td>2.26</td>
<td>4.30</td>
<td>17.80</td>
<td>58.4</td>
<td>2.3</td>
<td>17</td>
<td>2.5</td>
</tr>
</tbody>
</table>

- Assume $P_{\text{target}} = 0.42$, $I_{\text{beam}} = 15$ $\mu$A.
A Vertically Polarized $^3$He Target

Side view.

- Fast target spin reversal to reduce systematic uncertainties in SSA.

View toward the beam.
Hadronic Final State Interactions: No Contribution to $A_y$

- $^3\text{He}^\uparrow(\epsilon, \epsilon')$ inclusive reaction, final hadrons are not detected.
- When all hadronic final states are summed over, FSI does not contribute to SSA.
Systematic Uncertainties: \( (\delta A_y)_{sys} / A_y \leq 15\% \)

Runs between target spin ↑ and ↓ only differ by the target laser polarization
\( \Rightarrow \delta (\mathcal{L}_\uparrow / \mathcal{L}_\downarrow)_{sys} \) dominates \( (\delta A_y)_{sys} \).

Build-in consistency checks to beat down systematics: \( A^n_y(\text{left}) = -A^n_y(\text{right}) \)

- Physics asymmetries flip sign, target unrelated systematics don’t.
- The same number \( \mathcal{L}_\uparrow / \mathcal{L}_\downarrow \) in \( A^n_y(\text{left}) \) becomes \( \mathcal{L}_\downarrow / \mathcal{L}_\uparrow \) in \( A^n_y(\text{right}) \).

Contamination of non-quasi-elastic events is small and can be corrected.

\( P_T \) drifts is a second order effect.
Summary

- A non-vanishing $A_y$ is a clear signature of $2\gamma$-exchange effect.
  - sensitive to $\text{Im}(1\gamma \otimes 2\gamma)$, access to double-virtual Compton scattering amplitudes and GPD moments.
  - Contributions from elastic intermediate state is well-known.

JLab Hall A E05-015 will provide:

- The first observation of a non-vanishing $A_y$.
- A new observable in the study of GPD, $A^n_y$ access to one special combination of GPD moments.

On the technical side: rather easy for $^3\text{He}^\uparrow(e, e')$
Discussions

- We would also like to measure $A_y$ in elastic $ep \rightarrow ep$ reaction.
  - more directly related to the $G_E/G_M$ issue.
  - however, technical issues related to the polarized proton target make the experiment rather difficult.

In the long term future, if we manage to flip the target spin fast enough such that systematic uncertainties in $A_y$ can be controlled to $10^{-6}$ level:

- $A_y$ in resonance production, deep-inelastic scattering and elastic scattering on nuclei.
- Measure $A_y$ with both electron and positron beam.
- Address small terms in the cross sections that violate Parity and/or Time-reversal.

On the technical side: fast target spin flip is the key to the future.