Spin Polarizability of a Proton via Measurement of Double Polarization Asymmetry $\sum_{2z}$

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Nuclear Compton Scattering and polarizabilities

\[ H(2)_{\text{eff}} = -\frac{4}{\pi} \left[ \frac{1}{2} \alpha E_{1\rightarrow E_{2}} + \frac{1}{2} \beta M_{1\rightarrow H_{2}} \right] \]

\[ H(3)_{\text{eff}} = -\frac{4}{\pi} \left[ \frac{1}{2} \gamma E_{1}E_{1\rightarrow \sigma.} (\sigma.\leftrightarrow E_{2}E_{2}) + \frac{1}{2} \gamma M_{1}M_{1\rightarrow \sigma.} (\sigma.\leftrightarrow H_{2}H_{2}) - \gamma M_{1}E_{2}E_{ij} \sigma_{i}H_{j} + \gamma E_{1}M_{2}H_{ij} \sigma_{i}E_{j} \right] \]

where,
\[ \dot{E}_{\rightarrow E} = \frac{\partial}{\partial t} \dot{H}_{\rightarrow H} = \frac{\partial}{\partial t} \]
\[ E_{ij} = \frac{1}{2} \left( \frac{\partial}{\partial i} E_{j} + \frac{\partial}{\partial j} E_{i} \right) \]
\[ H_{ij} = \frac{1}{2} \left( \frac{\partial}{\partial i} H_{j} + \frac{\partial}{\partial j} H_{i} \right) \]
Nuclear Compton Scattering and polarizabilities

Second Order → Scalar Polarizabilities

\[ H_{\text{eff}}^{(2)} = -4\pi \left[ \frac{1}{2} \alpha_{E1} \vec{E}^2 + \frac{1}{2} \beta_{M1} \vec{H}^2 \right] \] (1)
Nuclear Compton Scattering and polarizabilities

\[ H_{\text{eff}}^{(2)} = -4\pi \left[ \frac{1}{2} \alpha_{E1} \vec{E}^2 + \frac{1}{2} \beta_{M1} \vec{H}^2 \right] \]  

\[ H_{\text{eff}}^{(3)} = -4\pi \left[ \frac{1}{2} \gamma_{E1E1} \vec{\sigma} \cdot (\vec{E} \times \vec{E}) + \frac{1}{2} \gamma_{M1M1} \vec{\sigma} \cdot (\vec{H} \times \vec{H}) - \gamma_{M1E2} E_i \sigma_i H_j + \gamma_{E1M2} H_i \sigma_i E_j \right] \]

where, \( \vec{E} = \partial_t \vec{E} \), \( \vec{H} = \partial_t \vec{H} \), \( E_{ij} = \frac{1}{2} (\partial_i E_j + \partial_j E_i) \) and \( H_{ij} = \frac{1}{2} (\partial_i H_j + \partial_j H_i) \)
Previous Results on Spin Polarizabilities

- Forward spin polarizability (Ahrens et al., PRL 87, 022003 (2001))

\[
\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2}
\]

\[
= -\frac{1}{4\pi^2} \int_{\omega_{th}}^{\infty} \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega^3} \, d\omega,
\]

\[
= (-1.0 \pm 0.08 \pm 0.10) \times 10^{-4} \text{fm}^4
\]

- Backward spin polarizability (Schumacher, Prog. Part. Nucl. Phys. 55, 567 (2005))

\[
\gamma_{\text{disp}} = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2}
\]

\[
= (8.0 \pm 1.8) \times 10^{-4} \text{fm}^4
\]

Note: \(\gamma_{\pi0} - \text{pole} \pi\) contributes \(-46.7 \times 10^{-4} \text{fm}^4\).
Previous Results on Spin Polarizabilities

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  \[ \gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2} \]
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  \[ = (-1.0 \pm 0.08 \pm 0.10) \times 10^{-4} \text{ fm}^4 \]  
  \[ (3) \]

- **Backward spin polarizability**  
  \[ \gamma_{\pi}^{\text{disp.}} = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2} \]
  \[ = (8.0 \pm 1.8) \times 10^{-4} \text{ fm}^4 \]  
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- **Note:** \( \gamma_{\pi}^{\pi^0 - \text{pole}} \) contributes \(-46.7 \times 10^{-4} \text{ fm}^4\).
Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy.

It is in the $\Delta$ (1232) resonance region ($E_\gamma = 250 - 350$ MeV) where their effect becomes significant.
Best Way to extract Spin Polarizabilities.

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- In this energy region, it is possible to accurately measure polarization asymmetries using a variety of polarized beam and target combinations
  - The various asymmetries respond differently to the individual spin polarizabilities at different $E_\gamma$ and $\theta$.
  - Measure three asymmetries at different $E_\gamma$, $\theta$. 

Our plan is to conduct a global analysis:
- include constraints from "known" $\gamma_0$, $\gamma_\pi$, $\alpha_{E_1}$ and $\beta_{M_1}$.
- extract all four spin polarizabilities independently with small statistical, systematic and model-dependent errors.
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Double Polarization Asymmetry $\sum_{2z}$

Left helicity state of the beam, target Polarized in $+z$ direction ($\sigma^L_{+z}$).

Right helicity state of the beam, target Polarized in $-z$ direction ($\sigma^R_{-z}$).
Double Polarization Asymmetry $\sum_{2z}$

Left helicity state of the beam, target Polarized in $+z$ direction ($\sigma^{L}_{+z}$).

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Right helicity state of the beam, target Polarized in $-z$ direction ($\sigma^R_{-z}$).
\[ \sum_{2z} \text{ in terms of Cross section and Number of events} \]

\[ \sum_{2z} = \frac{1}{P_\gamma P_t} \left( \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} \right), \quad (5) \]

- The degree of target polarization is different for positively and negatively polarized target, so in terms of Number of events the Asymmetry formula is

\[ \sum_{2z} = \frac{1}{P_\gamma} \left( \frac{(N^R_{+z} + N^L_{-z}) - (N^L_{+z} + N^R_{-z})}{P_\gamma (N^R_{+z} + N^L_{-z}) + P_\gamma (N^L_{+z} + N^R_{-z})} \right) \quad (6) \]
# 2014 and 2015 beamtime summary

<table>
<thead>
<tr>
<th></th>
<th>April 2014</th>
<th>May 2014</th>
<th>June 2015</th>
<th>June 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Material</strong></td>
<td>Carbon</td>
<td>FS Butanol</td>
<td>FS Butanol</td>
<td>Carbon</td>
</tr>
<tr>
<td><strong>Radiator</strong></td>
<td>Moeller</td>
<td>Moeller</td>
<td>Moeller</td>
<td>Moeller</td>
</tr>
<tr>
<td><strong>Time (hours)</strong></td>
<td>140</td>
<td>190 + 90</td>
<td>140 + 160</td>
<td>55</td>
</tr>
<tr>
<td><strong>Electron Energy (MeV)</strong></td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
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<tr>
<td><strong>Beam Current (nA)</strong></td>
<td>7.5</td>
<td>7.5</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Collimator (mm)</strong></td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Energy Sum (MeV)</strong></td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 90</td>
<td>&gt; 90</td>
</tr>
<tr>
<td><strong>Tagger Channels used</strong></td>
<td>270</td>
<td>270</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td><strong>Target Polarization</strong></td>
<td>-</td>
<td>62%, 59%</td>
<td>63%, 60%</td>
<td>-</td>
</tr>
<tr>
<td>$E_\gamma$ Polarization</td>
<td>72%</td>
<td>72%</td>
<td>72%</td>
<td>72%</td>
</tr>
</tbody>
</table>

- **Positively polarized**, **Negatively polarized**.

- **Note**: Problem with PID ADC (2014), MWPC CH1 High Voltage off (2015), no multiplicity and no TAPS trigger.
Compton Scattering: Event Selection

- Require ONLY one neutral and one charged track.

- Require a cut on Coplanarity Angle,
  \[ \Delta \phi = |\phi_\gamma - \phi_{\text{recoil}}| = 180^\circ \pm 15^\circ \]
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Event Selection: Accidentals - Prompt versus Random

Tagger - Neutral Time without Random Cut
Event Selection: Accidentals - Prompt versus Random

Tagger - Neutral Time without Random Cut

Tagger - Neutral Time with cut on Random
Event Selection: Accidentals - Prompt versus Random

Tagger - Neutral Time without Random Cut

Tagger - Neutral Time with cut on Random

Prompt only
Event Selection: Accidentals - Prompt versus Random

Tagger - Neutral Time without Random Cut

Tagger - Neutral Time with cut on Random

Prompt only

Zoomed in on the Prompt
Event Selection contd ........

- Opening Angle, \( \cos(\Omega_{OA}) = \frac{\vec{p}_{\text{miss}} \cdot \vec{p}_{\text{recoil}}}{|\vec{p}_{\text{miss}}| \times |\vec{p}_{\text{recoil}}|} = 10^\circ \)
Opening Angle, \( \cos(\Omega_{OA}) = \frac{\vec{p}_{\text{miss}} \cdot \vec{p}_{\text{recoil}}}{|\vec{p}_{\text{miss}}| \times |\vec{p}_{\text{recoil}}|} = 10^\circ \)
Dominant Background

Butanol Target \((C_4H_9OH)\)

- Compton Scattering off H
- Coherent scattering off C (or O)
- Incoherent scattering off C (or O)
- Pion photoproduction off H
- Coherent pion off C (or O)
- Incoherent pion off C (or O)

Density of carbon target is chosen to match the number of non-hydrogen nucleons in the Butanol target so we can directly subtract data taken on a carbon.
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π⁰ Background

Compton Scattering

Scattered Photon

Recoil Proton
Provides an excellent reaction for systematic checks and constraints. Due to the large cross-section (and clean reaction signal), $\pi^0$ production is an ideal reaction to perform systematic checks.
Background as a systematic check

Carbon is scaled by a base scaling factor.

Carbon is scaled by a corrected scaling factor.
$\pi^0$ Background as a systematic check

Carbon is scaled by a base scaling factor.

Ratio of Yield of butanol to carbon target (only base scaling factor).
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Ratio of Yield of butanol to carbon target (only base scaling factor).

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Subtracted Missing Mass compared with simulation.
Corrected scaling factor and $\pi^0 \sum_{2z}$ Asymmetry

Corrected carbon scaling factor 265 - 285 MeV
Corrected scaling factor and $\pi^0 \sum_{2z}$ Asymmetry

Corrected carbon scaling factor 265 - 285 MeV

Corrected carbon scaling factor 285 - 305 MeV.
Corrected scaling factor and $\pi^0 \sum_{2z}$ Asymmetry

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Tagged photon energy 265 - 285 MeV.

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Compton Missing Mass

\[ m_{\text{miss}} = m_p = \sqrt{(E_{\gamma i} + m_p - E_{\gamma f})^2 - (\vec{P}_{\gamma i} - \vec{P}_{\gamma f})^2} \]  

(7)

Missing Mass at \( E_\gamma = (285 - 305) \) MeV
Compton Missing Mass

\[ m_{\text{miss}} = m_p = \sqrt{(E_{\gamma i} + m_p - E_{\gamma f})^2 - (P_{\gamma i} - P_{\gamma f})^2} \] (7)

Missing Mass at \( E_\gamma = (285 - 305) \text{ MeV} \)

Compton \( \sum_{2z} \) Asymmetry versus upper missing mass at \( \theta_\gamma = 125 - 140^\circ \).
Compton $\sum_{2z}$ Asymmetry at $E_\gamma = (265 - 285)$ MeV

Curves are from DR calculation of Pasquini et al., making use of constraints on $\gamma_0$, $\gamma_{\pi}$, $\alpha_{E1} + \beta_{M1}$ and $\alpha_{E1} - \beta_{M1}$ to vary by their experimental errors.

Fix $\gamma_{E1E1} = -3.7$, vary $\gamma_{M1M1}$ (2014 beamtime)

Fix $\gamma_{E1E1} = -3.7$, vary $\gamma_{M1M1}$ (2015 beamtime)
Compton $\sum_{2z}$ Asymmetry at $E_\gamma = (265 - 285)$ MeV

Fix $\gamma_{M1M1} = 2.9$, vary $\gamma_{E1E1}$ (2014 beamtime)

Fix $\gamma_{M1M1} = 2.9$, vary $\gamma_{E1E1}$ (2015 beamtime)
Final $\Sigma_{2z}$ Asymmetry at $E_\gamma = (265 - 285)$ MeV

Figure: Fix $\gamma_{E1E1} = -3.7$, vary $\gamma_{M1M1}$ (2014 and 2015 combined)
Final $\sum_{2z}$ Asymmetry at $E_\gamma = (265 - 285)$ MeV

Figure: Fix $\gamma_{M1M1} = 2.9$, vary $\gamma_{E1E1}$ (2014 and 2015 combined)
Compton $\sum_{2z}$ Asymmetry at $E_\gamma = (285 - 305)$ MeV

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**Figure:** Fix $\gamma_{E1E1} = -3.7$, vary $\gamma_{M1M1}$ (2014 and 2015 combined)
Final $\sum_{2z}$ Asymmetry at $E_\gamma = (285 - 305)$ MeV

Figure: Fix $\gamma_{M1M1} = 2.9$, vary $\gamma_{E1E1}$ (2014 and 2015 combined)
Proton Spin Polarizabilities Status and Future Work

- Finalize proton spin polarizabilities from 2014 and 2015 beamtime.

- Finalize the systematic errors.

- Finalize $\sum_{2z}$ Asymmetry at $E_\gamma = (310 - 330)$ MeV from 2014 and 2015 beamtime.
Thank You
MM distribution for $E_\gamma = 273 - 303$ MeV, $\theta_\gamma = 100 - 120$ degree.

Background contributions to MM: accidental coincidences, carbon/cryostat contributions (blue), reconstructed $\pi_0$. background where one decay $\gamma$ escapes setup in: TAPS downstream hole and CB upstream hole.

Right: Fully-subtracted MM spectrum with simulated Compton peak and conservative MM <940 MeV cut is applied to exclude neutral pion production,

Measurement of a $\sum_{2x}$ asymmetry on the nucleon. Curves are from DR calculation of Pasquini et al., making use of constraints on $\gamma_0, \gamma_\pi, \alpha_{E1} + \beta_{M1}, \alpha_{E1} - \beta_{M1}$ (allowed to vary within experimental errors).

Checks were done with $B_\chi PT$ calculation of Lensky and Pascalutsa.
\[ \sum_3 \text{Collicot, et al.} \]

\[ E_y = 267.0 - 287.2 \text{ MeV} \quad \text{and} \quad E_y = 286.9 - 307.1 \text{ MeV} \]

- New MAMI and Older LEGS measurements along with two theoretical curves using their preferred polarizabilities

- Simulation of neutral pion photoproduction in Liquid hydrogen target matches background of the distribution quite well
Frame Preliminary Combined Spin Polarizabilities

<table>
<thead>
<tr>
<th></th>
<th>HDPV</th>
<th>BχPT</th>
<th>$\Sigma_{2x}$ and $\Sigma_3^{LEGS}$</th>
<th>$\Sigma_{2x}$ and $\Sigma_3^{MAMI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{E1E1}$</td>
<td>-4.3</td>
<td>-3.3</td>
<td>-3.5±1.2</td>
<td>-5.0±1.5</td>
</tr>
<tr>
<td>$\gamma_{M1M1}$</td>
<td>2.9</td>
<td>3.0</td>
<td>3.16±0.85</td>
<td>3.13±0.88</td>
</tr>
<tr>
<td>$\gamma_{E1M2}$</td>
<td>-0.0</td>
<td>0.2</td>
<td>-0.7±1.2</td>
<td>1.7±1.7</td>
</tr>
<tr>
<td>$\gamma_{M1E2}$</td>
<td>2.2</td>
<td>1.1</td>
<td>1.99±0.29</td>
<td>1.26±0.43</td>
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<tr>
<td>$\gamma_0$</td>
<td>-0.8</td>
<td>-1.0</td>
<td>-1.03±0.18</td>
<td>-1.00±0.18</td>
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<tr>
<td>$\gamma_{\pi}$</td>
<td>9.4</td>
<td>7.2</td>
<td>9.3±1.6</td>
<td>7.8±1.8</td>
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<tr>
<td>$\alpha+\beta$</td>
<td></td>
<td></td>
<td>14.0±0.4</td>
<td>13.8±0.4</td>
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<tr>
<td>$\alpha-\beta$</td>
<td></td>
<td></td>
<td>7.4±0.9</td>
<td>6.6±1.7</td>
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<tr>
<td>$\chi^2/df$</td>
<td></td>
<td></td>
<td>1.05</td>
<td>1.25</td>
</tr>
</tbody>
</table>

- Dispersion relation fits to $\Sigma_{2x}$ along with either $\Sigma_3^{MAMI}$ or $\Sigma_3^{LEGS}$
- (Note: Pion pole contribution has been subtracted)