Nuclear Structure Observables with Polarized Target and Polarized Real Photon Beam at MAMI

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Expand the Compton effective Hamiltonian in incident-photon energy.

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

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

These constants (\(\gamma\)) are spin-dependent polarizabilities, (Meaning: \(\gamma_{M1E2}\) excited by electric quadruple \(E2\) radiation and decays by magnetic dipole \(M1\) radiation).

- Response of the proton spin to an applied electric or magnetic field, ‘stiffness’ of proton spin against E.M. induced deformations relative to the spin axis.
Previous Results on Spin Polarizabilities

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

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

(3)

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

\[
\gamma_{\pi}^{disp.} = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2} \\
= (8.0 \pm 1.8) \times 10^{-4} \text{fm}^4
\]

(4)

- **Note:** \(\gamma_{\pi}^{0-pole}\) 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 $\triangle (1232)$ resonance region ($E_\gamma = 250 - 350$ MeV) where their effect becomes significant.

In this energy region, it is possible to accurately measure polarization asymmetries using a variety of polarized beam and target combinations.

- 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: Conduct a global analysis.

- Include constraints from “known” $\gamma_0$, $\gamma_\pi$, $\alpha_{E1}$ and $\beta_{M1}$.
- Extract all four spin polarizabilities independently with small statistical, systematic and model-dependent errors.
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

$$(\sigma^R_{-z}).$$

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

$$(\sigma^R_{+z}).$$
\[ \sum_{2z} \text{in terms of Cross section and Number of events} \]

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

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

\[ \sum_{2z} = \frac{1}{P_\gamma} \left( \frac{(N^R_{+z} + N^L_{-z}) - (N^L_{+z} + N^R_{-z})}{P_{+z}(N^R_{+z} + N^L_{-z}) + P_{-z}(N^L_{+z} + N^R_{-z})} \right), \quad (6) \]
Experimental Apparatus at MAMI

Crystal Ball
- 672 NaI crystals, separate PMT and 94% solid angle coverage

TAPS
- 366 BaF2, 72 PbWO4 Crystals and 384 Veto Paddles

PID
- Cylindrical detectors, 24 thin plastic scintillator strips, identification of charged particles

MWPC
MWPC between PID and CB for track reconstruction of charged particles
Compton Scattering: Event Selection

- Require ONLY two tracks in the detector: One neutral track and one charged track.
- Require a cut on Coplanarity Angle, $\Delta \phi = |\phi_\gamma - \phi_{\text{recoil}}|$ and an Opening Angle, $\cos(\Omega_{\text{OA}}) = \frac{\vec{p}_{\text{miss}} \cdot \vec{p}_{\text{recoil}}}{|\vec{p}_{\text{miss}}| \times |\vec{p}_{\text{recoil}}|}$.

**Figure:** Left: Make an ‘Opening angle’, requiring that the proton candidate is detected within a cone of its expected angle. Right: Charged particle detection efficiency.
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.
Compton Missing Mass at $E_\gamma = (285 - 305)$ MeV

$$m_{miss} = m_p = \sqrt{(E_{\gamma i} + m_p - E_{\gamma f})^2 - (\vec{P}_{\gamma i} - \vec{P}_{\gamma f})^2}$$ (7)

Comparison of missing mass for incident energy bin $E_\gamma = 285 - 305$ MeV at $\theta = 125 - 140^\circ$

**Figure:** missing mass integration limit. Upper missing mass limit. (Max Limit: Consider missing mass cuts only above the proton mass, analyze $\pi^0$ photoproduction events as if it were Compton events and use them as a reference, asymmetry does not change by more than 4% moving to the right relative to the reference.)
Compton Sigma2z at $E_\gamma = (285 - 305)$ 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 $\gamma_{M1M1}$

Fix $\gamma_{M1M1} = 2.9$, vary $\gamma_{E1E1}$
Compton Sigma2z at $E_\gamma = (265 - 285)$ MeV

Fix $\gamma_{E1E1} = -3.7$, vary $\gamma_{M1M1}$

Fix $\gamma_{M1M1} = 2.9$, vary $\gamma_{E1E1}$
Summary

\[ \sum_{2z} \text{Asymmetry Results:} \]

- Preliminary Results on \( \sum_{2z} \) Asymmetry from 2014 beamtime.

- Working on \( \sum_{2z} \) Asymmetry from 2015 beamtime.

Proton Spin Polarizabilities Status and Future Work:

- Extract proton spin polarizabilities combining the \( \sum_{2z} \) Asymmetry results from 2014 and 2015 beamtime.

- Extract proton spin polarizabilities using the results from the series of all three Compton Scattering experiments (\( \sum_{2x} \), \( \sum_{3} \) and \( \sum_{2z} \)) Asymmetry experiments.

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Back Up Slides
- 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 $\Sigma_{2x}$ 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.
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>
</tr>
<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>
</tr>
<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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<td>$\alpha+\beta$</td>
<td></td>
<td></td>
<td>14.0±0.4</td>
<td>13.8±0.4</td>
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<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)
$\pi^0$ Photoproduction Asymmetry

$E_\gamma = 285 - 305$ MeV

$E_\gamma = 310 - 330$ MeV

**Figure:** $\pi^0$ Asymmetry results (only 2014 beamtime)
Electron Beam Polarization

**Figure:** Electron Beam Polarization for the first round of 2014 butanol beamtime. Average Electron Beam Polarization: 86.63 ± 0.11
Figure: Average Photon Polarization: $68.43 \pm 0.23$ for $E_\gamma = 265 - 285$ MeV, Average Photon Polarization: $72.52 \pm 0.21$ for $E_\gamma = 285 - 305$ MeV and Average Photon Polarization: $76.23 \pm 0.18$ for $E_\gamma = 305 - 325$ MeV
Figure: Average Target Polarization: $62.05 \pm 0.83$ for a butanol target polarized in $+z$ direction, Average Target Polarization: $59.25 \pm 0.88$ for a butanol target polarized in $-z$ direction.