Proton Spin Polarizabilities with Polarized Compton Scattering at MAMI

Dilli Paudyal
University of Regina, Regina, SK, S4S 0A2, Canada
Supervisor: Dr. Garth Huber
Nuclear Compton Scattering and Polarizabilities

- Polarizabilities are very low energy fundamental structure constants and Nuclear Compton scattering off a single proton is used to access these Internal structure constants of a nucleon.

\[ \gamma(k) + P(p) \rightarrow \gamma(k') + P(p') \]

- Low energy outgoing photon plays a role of an applied EM dipole field

\[ H^{(0)}_{\text{eff}} = \left( \frac{1}{2m} \gamma - e \vec{A} \right)^2 + e\phi \]  \hspace{1cm} (1)

\[ H^{(1)}_{\text{eff}} = \frac{e}{2m} (1 + \kappa) \gamma \vec{\sigma} \cdot \vec{H} - \frac{e}{8m^2} (1 + 2\kappa) \gamma \vec{\sigma} \cdot \left[ \vec{E} \times \vec{p} - \vec{p} \times \vec{E} \right] \]  \hspace{1cm} (2)
**What are Spin Polarizabilities**

- Effective Hamiltonian in second order contains scalar polarizabilities ($\alpha_{E1}$ and $\beta_{M1}$) which are the evidence of proton’s internal structure

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

  \[ (3) \]

- The third order effective Hamiltonian term in the expansion:

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

  \[ (4) \]

- These constants ($\gamma$) are spin (or vector) polarizabilities (e.g. $\gamma_{M1E2}$ excited by electric quadrupole $E2$ radiation and decays by magnetic dipole $M1$ radiation).

- They describe the 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.
What do we know about Spin Polarizabilities

\[
\begin{align*}
\gamma_{E1E1} & = -4.8 \pm 0.4 \times 10^{-4} \text{ fm}^4 \\
\gamma_{M1M1} & = 3.5 \pm 0.2 \times 10^{-4} \text{ fm}^4 \\
\gamma_{E1M2} & = -1.8 \pm 0.02 \times 10^{-4} \text{ fm}^4 \\
\gamma_{M1E2} & = 1.1 \pm 0.2 \times 10^{-4} \text{ fm}^4 \\
\gamma_0 & = -1.0 \pm 0.08 \times 10^{-4} \text{ fm}^4 \\
\gamma_\pi & = 11.2 \pm 0.4 \times 10^{-4} \text{ fm}^4
\end{align*}
\]

<table>
<thead>
<tr>
<th>$\gamma_{E1E1}$</th>
<th>$\gamma_{M1M1}$</th>
<th>$\gamma_{E1M2}$</th>
<th>$\gamma_{M1E2}$</th>
<th>$\gamma_0$</th>
<th>$\gamma_\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-4.8$</td>
<td>$3.5$</td>
<td>$-1.8$</td>
<td>$1.1$</td>
<td>$2.0$</td>
<td>$11.2$</td>
</tr>
<tr>
<td>$-4.3$</td>
<td>$2.9$</td>
<td>$-0.02$</td>
<td>$2.2$</td>
<td>$-0.8$</td>
<td>$9.4$</td>
</tr>
<tr>
<td>$-3.8$</td>
<td>$2.9$</td>
<td>$0.5$</td>
<td>$1.6$</td>
<td>$-1.1$</td>
<td>$7.8$</td>
</tr>
<tr>
<td>$-3.7$</td>
<td>$2.5$</td>
<td>$1.2$</td>
<td>$1.2$</td>
<td>$-1.2$</td>
<td>$6.1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$2.2 \pm 0.5$</td>
<td>$1.9 \pm 0.4$</td>
<td>$5.6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\pm 0.7$</td>
<td>$\pm 0.4$</td>
<td>$7.2$</td>
</tr>
</tbody>
</table>

\[
\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2} = (-1.0 \pm 0.08) \times 10^{-4} \text{ fm}^4 \tag{5}
\]

\[
\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2} = (-8.0 \pm 1.8) \times 10^{-4} \text{ fm}^4 \tag{6}
\]

- Spin-polarizabilities in units of $10^{-4}$ fm$^4$.
Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy

- It is in the $\triangle$ (1232) resonance region ($E_\gamma = 200 - 300$ 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

- The various asymmetries respond differently to the individual spin polarizabilities at different $E$ and $\theta$.
- Measure three asymmetries at different $E$, $\theta$.

Our plan is to 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.
Three Polarization Asymmetry Experiment at A2

Circularly polarized beam, longitudinally polarized target

\[ \sum_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}} \]

\[ \sum_{2z} \text{ is sensitive to } \gamma_{M1M1} \]

Circularly polarized beam, transversely polarized target

\[ \sum_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}} \]

\[ \sum_{2x} \text{ is sensitive to } \gamma_{E1E1} \]
Linearly polarized ($\parallel$ and $\perp$ to scattering plane) beam, unpolarized target

\[ \sum_3 = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp} \]

- $\sum_{2z}$ is sensitive to $\gamma M_1 M_1$

Experimental data:

- **Transverse Target** ($\sum_{2x}$): Sep 2010, Feb 2011 - 500 hrs (P. Martel)
- **Unpolarized Target** ($\sum_3$): Dec 2012- 150 hrs (C. Collicot)
- **Longitudinal Target** ($\sum_{2z}$): D. Paudyal (University of Regina) and A. Rajabi (University of Massachusetts)
  - First round of data in 2014 with Butanol (320 hours) and Carbon Target (180 hrs)
  - Second round of data in 2015 with Butanol (310 hours) and Carbon Target (60) hrs
  - Worked as a run coordinator for two weeks during 2015 beam time.
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
Calibration of first round of carbon and butanol target data has been completed.

Tagging Efficiency and target polarization check has been competed.

Experimental Challenges

- Small Compton scattering cross sections.
- Coherent and incoherent reactions off of C, O, and He.
- A source of polarized protons is not easy to come by (or to operate).
- In \( \Delta \)-region, proton tracks are required to suppress backgrounds, but energy losses in the frozen-spin cryostat, and CB-TAPS are considerable.

What to do ???

- \( \pi^0 \) photo-production cross section is about 100 times that of Compton scattering, work on \( \pi_0 \) photo-production Asymmetry.
Compton Scattering $\gamma + P \rightarrow \gamma + P$

- Dominant Background for Compton Scattering Experiments

$\pi^0$ Production as a Systematic Check

- Provides an excellent reaction for systematic checks and constraints. Due to the large $\sigma$ (and clean reaction signal), $\pi^0$ production is an ideal reaction to perform systematic checks.
MM distribution for $E_\gamma = 273-303$ MeV, $\theta_\gamma' = 100-120$ degree (green)

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

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

First measurement of a double-spin Compton scattering asymmetry on the nucleon. Curves are from DR calculation of Pasquini et al., making use of constraints on \( \gamma_0, \gamma_\pi, \alpha_{E_1} + \beta_{M_1}, \alpha_{E_1} - \beta_{M_1} \) (allowed to vary within experimental errors). Checks were done with \( B\chi PT \) calculation of Lensky & 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
<table>
<thead>
<tr>
<th></th>
<th>HDPV</th>
<th>BχPT</th>
<th>$\Sigma_{2x}$ and $\Sigma_{3}^{\text{LEGS}}$</th>
<th>$\Sigma_{2x}$ and $\Sigma_{3}^{\text{MAMI}}$</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>
</tr>
<tr>
<td>$\alpha+\beta$</td>
<td></td>
<td></td>
<td>14.0±0.4</td>
<td>13.8±0.4</td>
</tr>
<tr>
<td>$\alpha-\beta$</td>
<td></td>
<td></td>
<td>7.4±0.9</td>
<td>6.6±1.7</td>
</tr>
<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 $\Sigma_{3}^{\text{MAMI}}$ or $\Sigma_{3}^{\text{LEGS}}$ (Note: Pion pole contribution has been subtracted)
To get a rough idea of the sensitivities, use a basis of $\gamma_{E1E1}$, $\gamma_{M1M1}$, $\gamma_0$ and $\gamma_\pi$. Produce event rates for nominal values of the SPs, using a dispersion theory calculation.

Hold either $\gamma_{E1E1}$ or $\gamma_{M1M1}$ fixed, and perturb the other by a fixed amount and allow $\gamma_0$, $\gamma_\pi$, $\alpha_{E1}$ and $\beta_{M1}$ to vary by their experimental errors.

The bands represent the spread about these values by varying $\gamma_0$, $\gamma_\pi$, $\alpha_{E1}$ and $\beta_{M1}$ by their errors.
• $\Sigma_{2x}$ has been measured for the first time and published in recent PRL.

• To further reduce the $\Sigma_{2x}$ error bars, we have planned to acquire more data in January/February 2016.
  
  • $\Sigma_3$ data analysis has been completed and planned for publication.

• Planned to finish data analysis and have Compton double polarization asymmetries results $\Sigma_{2z}$ before the end of 2016.

• Extract proton spin polarizabilities combining the $\Sigma_{2z}$ results from first round of $\Sigma_{2z}$ data taken in 2014 and second round of data taken in 2015.
Back Up slides

Carbon Target

Frozen Butanol
- 2 cm long and 2 cm diameter

\[ H - C - C - C - C - O - H \]
\[ H - H - H - H - H \]
• **DNP**: Cool target to 0.2 K, use 2.5 Tesla magnet to align electron spins, pump 70 GHz microwaves, causing spin-flips between the electrons and protons.

• Cool target to 0.025 K, ‘freezing’ proton spins in place, remove polarizing magnet, energize 0.6 Tesla ‘holding’ coil in the cryostat to maintain the polarization, Relaxation times > 1000 hours, Polarizations up to 90%.
\( \pi^0 \) Beam Asymmetry: 288.3 \pm 3.9 MeV