The Nucleon Polarizability Program at MAMI-A2

Garth Huber

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Nucleon Scalar Polarizabilities

- Polarizabilities are fundamental constants that describe the nucleon.
- They limit precision in many areas of physics:
  - In astrophysics, they determine neutron star properties.
  - In atomic physics, they yield an appreciable correction to Lamb shift and hyperfine structure.
  - Uncertainty in scalar polarizability is the largest uncertainty in proton radius extraction from H excitation spectrum.
Proton Scalar Polarizabilities

- Accessed via Compton scattering of Real Photons $\gamma + N \rightarrow \gamma + N$
- 2nd and higher order terms describe polarizabilities and evidence of proton’s internal structure.

$$H_{\text{eff}}^{(2)} = \frac{1}{2} \alpha_{E1} \vec{E}^2 + \frac{1}{2} \beta_{M1} \vec{H}^2$$

Experimental values (PDG2014):

$$\alpha_{E1} = (11.2 \pm 0.4) \times 10^{-4} \, \text{fm}^3 \quad \beta_{M1} = (2.5 \pm 0.4) \times 10^{-4} \, \text{fm}^3$$

Size of $\alpha_{E1}$ measures “stiffness” of system to electric deformation.

- For $^1\text{H}$ atom, expect:

$$\alpha_E^H = \frac{9}{2} a_B^3 = \frac{27}{8\pi} \text{Vol}$$

- But proton data indicate:

$$\alpha_E^p \approx 3 \times 10^{-4} \, \text{Vol}$$

- The proton is very “stiff”, because:

$$\frac{\alpha_E^p}{\alpha_E^H} \approx \frac{E_{\text{bind}}^H}{E_{\text{bind}}^p} \approx \frac{\alpha_{EM}^2}{\alpha_{Str}^2} \approx 10^{-4}$$

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Reanalysis of Compton Data Constraints

- Electric polarizability $\alpha_{E1}$ well constrained by experimental data.
- Magnetic polarizability $\beta_{M1}$ less certain.
- Neutron data are particularly uncertain.

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How to obtain more accurate values of $\alpha_{E1}$, $\beta_{M1}$

- Desire for more precise proton $\beta_{M1}$ has motivated a new generation of experiments.
- Combinations of cross sections with linearly polarized photon beam
  - Leading order contribution from $\alpha$ and $\beta$

\[
\frac{d\sigma^\parallel}{d\Omega} = \frac{d\sigma_{\text{Powell}}^\parallel}{d\Omega} - \frac{e^2}{2\pi m_p} \left( \frac{v'}{v} \right)^2 v u' \left( \alpha_{E1} \cos^2 \theta + \beta_{M1} \cos \theta \right) + O\left( v^3 \right)
\]

\[
\frac{d\sigma^\perp}{d\Omega} = \frac{d\sigma_{\text{Powell}}^\perp}{d\Omega} - \frac{e^2}{2\pi m_p} \left( \frac{v'}{v} \right)^2 v u' \left( \alpha_{E1} + \beta_{M1} \cos \theta \right) + O\left( v^3 \right)
\]

- New work by Krupina & Pascalutsa [PRL 110, 262001 (2013)]
  \(\rightarrow\) At low energies, use beam asymmetry $\Sigma_3$ to extract $\beta_{M1}$

\[
\Sigma_3 \equiv \frac{d\sigma^\perp - d\sigma^\parallel}{d\sigma^\perp + d\sigma^\parallel}
\]

\[
= \Sigma_3^{\text{Born}} - f_3(\theta) \beta_{M1} v^2 + O\left( v^4 \right)
\]

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\( \alpha_{E1}, \beta_{M1} \) from \( \Sigma_3 \) Asymmetry – Sokhoyan, et al.

Only 1/3 of approved data taken so far.

Curves:

\( \chi PT \): Krupina and Pascalutsa, PRL 110, 262001 (2013)

\( HB\chi PT \): J. McGovern, D. Phillips, H. Griesshammer, EPJA 49, 12 (2013)

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Spin Polarizabilities of the Proton

To include spin, next term in Hamiltonian:

$$H_{\text{eff}}^{(3)} = -\frac{1}{2} \left[ \gamma_{E1E1} \vec{\sigma} \cdot \vec{\dot{E}} \times \vec{\dot{E}} + \gamma_{M1M1} \vec{\sigma} \cdot \vec{\dot{H}} \times \vec{\dot{H}} \right. $$

$$+ 2 \gamma_{E1M2} H_{ij} \sigma_i \dot{E}_j - 2 \gamma_{M1E2} E_{ij} \sigma_i H_j \right]$$

involves one field derivative wrt either time or space \( \dot{E} = \partial_t \dot{E} \), \( E_{ij} = \frac{1}{2} \left( \nabla_i \dot{E}_j + \nabla_j \dot{E}_i \right) \)

e.g. \( \gamma_{M1E2} \) excited by electric quadrupole (E2) radiation and decays by magnetic dipole (M1) radiation

• “Stiffness” of proton spin against E.M.-induced deformations relative to the spin axis.
  • Defines the frequency of proton’s spin precession induced by variable E.M. fields.
  • Higher order in incident-photon energy, small effect at lower energies.
• Each spin polarizability is dominated by a pion-pole contribution. → The dispersive (interesting) part is relatively small.

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# Proton Spin Polarizability Predictions

<table>
<thead>
<tr>
<th></th>
<th>Kmat</th>
<th>HDPV</th>
<th>DPV</th>
<th>$L_\chi$</th>
<th>HB$_\chi$PT</th>
<th>B$_\chi$PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{E1E1}$</td>
<td>-4.8</td>
<td>-4.3</td>
<td>-3.8</td>
<td>-3.7</td>
<td>-1.1±1.8(th)</td>
<td>-3.3</td>
</tr>
<tr>
<td>$\gamma_{M1M1}$</td>
<td>3.5</td>
<td>2.9</td>
<td>2.9</td>
<td>2.5</td>
<td>2.2±0.5(st)±0.7(th)</td>
<td>3.0</td>
</tr>
<tr>
<td>$\gamma_{E1M2}$</td>
<td>-1.8</td>
<td>-0.0</td>
<td>0.5</td>
<td>1.2</td>
<td>-0.4±0.4(th)</td>
<td>0.2</td>
</tr>
<tr>
<td>$\gamma_{M1E2}$</td>
<td>1.1</td>
<td>2.2</td>
<td>1.6</td>
<td>1.2</td>
<td>1.9±0.4(th)</td>
<td>1.1</td>
</tr>
<tr>
<td>$\gamma_0$</td>
<td>2.0</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-2.6</td>
<td>-1.0</td>
</tr>
<tr>
<td>$\gamma_\pi$</td>
<td>11.2</td>
<td>9.4</td>
<td>7.8</td>
<td>6.1</td>
<td>5.6</td>
<td>7.2</td>
</tr>
</tbody>
</table>

**K-matrix:**
Kondratyuk et al., PRC 64, 024005 (2001)

**HDPV, DPV (Dispersion Relation):**
Holstein et al., PRC 61, 034316 (2000)
Pasquini et al., PRC 76, 015203 (2007)

**$L_\chi$ (Chiral Lagrangian):**
Gasparian et al., NP A866, 79 (2011)

**HB$_\chi$PT, B$_\chi$PT (Heavy Baryon & Covariant Chiral PT):**
McGovern et al., EPJ A49, 12 (2013)
Lensky et al, PRC 89, 032202 (2014)
Linear combinations of Spin Polarizabilities

One can extract the spin polarizabilities using knowledge of $\alpha_{E1}, \beta_{M1}$, the linear combinations $\gamma_0, \gamma_\pi$, and Subtracted Dispersion Relations.

Backward Spin Polarizability
(unpolarized Compton scattering)

$$\gamma_\pi = \gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}$$

$$\gamma_\pi = (-38.7 \pm 1.8) \times 10^{-4} \text{ fm}^4$$


Pion pole contributes -46.7
Dispersive part 8.0±1.8 known only to ≈25%.

Forward Spin Polarizability
(polarized beam and target)

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2}$$

$$\gamma_0 = \frac{1}{4\pi^2} \int_{\nu_{thr}}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\nu^3} \, d\nu$$

$$\gamma_0 = -(1.00 \pm 0.08 \pm 0.10) \times 10^{-4} \text{ fm}^4$$

Ahrens et al., PRL87, 022003 (2001)

Known to ≈10%.

Pion pole contribution cancels.
Better way to extract Spin Polarizabilities

- **Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy**
  
  - It is in the Δ resonance region ($E_γ = 200-300$ 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 $E_γ$ and $θ$.
  
  - Measure three asymmetries at different $E_γ$, $θ$.

- **Our plan is to conduct a global analysis:**
  
  - Include constraints from “known” $γ_0$, $γ_π$, $α_{E1}$, $β_{M1}$.
  
  - Extract all four spin polarizabilities independently with small statistical, systematic and model-dependent errors.

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Asymmetries with Linearly Polarized $\gamma$

- $\phi = 0$ and unpolarized target $\rightarrow \Sigma_3$
- $\phi = 0$ and transversely polarized target in the y direction $\rightarrow \Sigma_{3y}$
- $\phi = 45^\circ$ and longitudinally pol. target $\rightarrow \Sigma_{1z}$
- $\phi = 45^\circ$ and transv. pol. target in the x direction $\rightarrow \Sigma_{1x}$

$$\Sigma_3 = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp}$$

Asymmetry is measured with linearly polarized photons, parallel and perpendicular to the scattering plane, and unpolarized target.
Double Spin Asymmetries w/ Circularly Polarized $\gamma$

- **Longitudinal asymmetry**

$$\Sigma_{2z} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\uparrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\downarrow}}{Sum} \quad h=\pm1$$

- **Transverse asymmetry**

$$\Sigma_{2x} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\rightarrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\leftarrow}}{Sum} \quad h=\pm1$$

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## Sensitivity to Spin Polarizabilities

<table>
<thead>
<tr>
<th>Polarization Asymmetry</th>
<th>Beam</th>
<th>Target</th>
<th>Eγ Range (MeV)</th>
<th>Spin Polarizability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Σ2z</td>
<td>Circular</td>
<td>Longitudinal</td>
<td>200-300</td>
<td>γM1M1</td>
</tr>
<tr>
<td>Σ2x</td>
<td>Transverse</td>
<td>200-300</td>
<td>γE1E1</td>
<td></td>
</tr>
<tr>
<td>Σ3</td>
<td>Linear</td>
<td>None</td>
<td>200-300</td>
<td>γM1M1</td>
</tr>
<tr>
<td>Σ3y</td>
<td>Transverse</td>
<td>200-300</td>
<td>γE1E1</td>
<td></td>
</tr>
<tr>
<td>Σ1z</td>
<td>Longitudinal</td>
<td>200-300</td>
<td>Both</td>
<td></td>
</tr>
<tr>
<td>Σ1x</td>
<td>Transverse</td>
<td>150-250</td>
<td>Both</td>
<td></td>
</tr>
</tbody>
</table>
1. Production and energy measurement of Bremsstrahlung photons

2. Determination of the degree of polarization of the electron beam (Moeller Polarimeter);
Circularly pol. photons

\[ A = \frac{N^+ - N^-}{N^+ + N^-} = a\vec{p}_t \cdot \vec{p}_b \cos(z) \]

3. Coherent production of linearly polarized photons on a diamond radiator

"Vacoflux" Foil  
\[ p_t = (8.1 \pm 0.2)\% \]

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Frozen Spin Butanol Target

DNP at 200 mK and 2.5 T with 70 GHz microwaves. Frozen spin target (25 mKelvin, 0.6 T). Secondary particles punch through holding coil. $P^{\text{max}} \tau > 90\%, \tau > 1000\text{h}$
4π photon Spectrometer @ MAMI

**TAPS:**
- 366 BaF₂, 72 PbWO₄ elements
- 384 Veto paddles
- Max. kin. energy:
  - π⁺⁻ : 180 MeV
  - K⁺⁻ : 280 MeV
  - P : 360 MeV

**Crystal Ball:**
- 672 NaI detectors
- Max. kin. energy:
  - μ⁺⁻ : 233MeV
  - π⁺⁻ : 240 MeV
  - K⁺⁻ : 341 MeV
  - P : 425 MeV

**Vertex detector:**
- 2 Cylindr. MWPCs
- 480 wires, 320stripes

**PID detector:**
- 24 thin plastic detectors

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Setup in the A2 – Tagger Hall

Movable Crystal Ball
4π-Photon Detector

Cryostat

Movable 2.5 Tesla Polarizing Magnet


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Asymmetries – Experimental Challenges

- Small Compton scattering cross sections.
- Large backgrounds:
  - $\pi^0$ photoproduction cross section is about 100 times that of Compton scattering.
  - Coherent and incoherent reactions of C, O, He in polarized target.

- In $\Delta$–region, proton tracks can be used to suppress backgrounds,
  - but energy losses in the LH$_2$ target, frozen-spin cryostat, and CB-TAPS are considerable.

- Under certain conditions, $\pi^0$ photoproduction can mimic Compton scattering.
\( \Sigma_{2x} \) – Martel, et al.

\[ E_\gamma = 273 \text{ - } 303 \text{ MeV and } \theta_\gamma = 100 \text{ - } 120^\circ \]

**Background contributions to MM:**
- accidental coincidences
- carbon/cryostat contributions
- reconstructed \( \pi^0 \) background where one decay \( \gamma \) escapes setup in:
  - TAPS downstream hole
  - CB upstream hole

**Fully-subtracted MM spectrum:**
- conservative MM<940 MeV integration limit
- simulated Compton peak

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New results!

$E_\gamma = 273 - 303$ MeV

- 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 $\alpha_{E1} + \beta_{M1}$, $\alpha_{E1} - \beta_{M1}$, $\gamma_0$, $\gamma_\pi$ (allowed to vary within experimental errors).
- Checks were done with B$\chi$PT calculation of Lensky & Pascalutsa.

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Simulation of $\pi^0$ photoproduction in LH$_2$ target matches background of the distribution quite well.

New (MAMI) and older (LEGs) $\Sigma_3$ measurements along with two theoretical curves using their preferred polarizabilities.

$E_\gamma$ = 267.0 - 287.2 MeV

$E_\gamma$ = 286.9 - 307.1 MeV

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LEGs = Blanpied et al., PRC 64, 025203 (2001)
PRELIMINARY - Combined Spin Polarizability Analysis

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

<table>
<thead>
<tr>
<th></th>
<th>HDPV</th>
<th>B$\chi$PT</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>14.0±0.4</td>
<td>13.8±0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha-\beta$</td>
<td>7.4±0.9</td>
<td>6.6±1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi^2$/df</td>
<td>1.05</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Spin polarizabilities in units of $10^{-4}$ fm$^4$.
Scalar polarizabilities $10^{-4}$ fm$^3$.

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Effect of $\Sigma_3$ Data on $\Sigma_{2x}$ Fits - PRELIMINARY

1) Dispersion Relation Calcs w/ fitted polarizability values
Fit with $\Sigma_3^{\text{LEGS}} \rightarrow \text{HDPV}$. Fit with $\Sigma_3^{\text{MAMI}} \rightarrow \text{B}_\gamma\text{PT}$. 

![Image](image1.png)

$E_\gamma = 267.0 - 287.2$ MeV

![Image](image2.png)

$E_\gamma = 286.9 - 307.1$ MeV

2) Look at $\Sigma_{2x}$ with different $\Sigma_3$ fits 
→ Clearly shows importance of the $\Sigma_3$ constraint.
→ Planned $\Sigma_{2x}$ data will further constrain spin polarizabilities.

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$\Sigma_{2z}$ – Estimated Experimental Precision

**Vary $\gamma_{E1E1}$**

- **270 MeV**
  - $\gamma_{E1E1} = -3.3$
  - $\gamma_{E1E1} = -4.3$
  - $\gamma_{E1E1} = -5.3$

- **290 MeV**
  - $\gamma_{E1E1} = -3.3$
  - $\gamma_{E1E1} = -4.3$
  - $\gamma_{E1E1} = -5.3$

**Vary $\gamma_{M1M1}$**

- **270 MeV**
  - $\gamma_{M1M1} = 3.9$
  - $\gamma_{M1M1} = 2.9$
  - $\gamma_{M1M1} = 1.9$

- **290 MeV**
  - $\gamma_{M1M1} = 3.9$
  - $\gamma_{M1M1} = 2.9$
  - $\gamma_{M1M1} = 1.9$

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Neutron Scalar Polarizabilities

In certain kinematic regions, proton acts like a spectator and scattering is done from neutron.

- A relatively new idea is to use $^3\text{He}$ instead of $^2\text{H}$ target:
  - $\chi$PT calcs by Shukla, Nogga, Phillips [NP A819, 98 (2009)]
  - $\alpha_{nE1}^n$, $\beta_{nM1}^n$ determined from fit to Angular distributions vs. Energy

![Graphs showing angular distributions for $\gamma + ^3\text{He} \rightarrow \gamma + ^3\text{He}$ and $\gamma + ^4\text{He} \rightarrow \gamma + ^4\text{He}$](image)

J. Annand et al. working on high-pressure active He gas scintillator target.
- Proposal A2-01-2013 for $^3\text{He}(\gamma,\gamma)^3\text{He}$ given `A` rating by PAC.
- Expected good separation of backgrounds from target windows and $\pi^0$ production.

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Summary

Polarizabilities are an important tool for testing QCD via $\chi$PT and DRs in the non-perturbative regime.

- $\Sigma_{2x}$ has been measured for the first time.
  - Published in recent PRL.
  - Plans to acquire more data but not yet scheduled.
- $\Sigma_3$ data taken to supplement existing data.
  - Higher energy analysis for spin polarizability finished.
  - Plan to acquire more low energy data for $\alpha_{E1}$, $\beta_{M1}$ in 2016.
- $\Sigma_{2z}$ data partly taken, more scheduled for July 2015.

- Future:
  - Improvements in simulation to remove $\pi^0$ backgrounds would allow less restrictive MM cut to be used, increase statistics.
  - Plan to combine results with ongoing $\alpha_{E1}$, $\beta_{M1}$ studies.
  - Implement active target to expand kinematic range.
  - Extend measurements to neutron.