Probing proton structure
Spin polarisabilities and Compton scattering

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We’re interested in studying the proton polarisabilities:

**Scalar polarisabilities**
- $\alpha$ and $\beta$, describe the response of the protons structure to an electric or magnetic field.
- Previously studied experimentally...

**Spin polarisabilities**
- $\gamma$, describe the response of the protons spin to electric and magnetic fields.
- Very little experimental information exists...
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**Spin polarisabilities**
- $\gamma$, describe the response of the protons spin to electric and magnetic fields.
- Very little experimental information exists...
Polarisabilities of the proton

Polarisabilities can be accessed through Compton scattering:

$$\gamma + p \rightarrow \gamma' + p'$$

Scalar polarisabilities - second order effective Hamiltonian

$$H_{\text{eff}}^{(2)} = -\frac{1}{2} \left( 4\pi \alpha E_1 E^2 + 4\pi \beta M_1 H^2 \right)$$

Spin polarisabilities - third order effective Hamiltonian

$$H_{\text{eff}}^{(3)} = -\frac{1}{2} \left( 4\pi \gamma E_1 E_1 \sigma \cdot \left( E \times \dot{E} \right) + 4\pi \gamma M_1 M_1 \sigma \cdot \left( H \times \dot{H} \right) \right)$$

$$+ \left( 4\pi \gamma M_1 E_2 E_{ij} \sigma_i H_j - 4\pi \gamma E_1 M_2 H_{ij} \sigma_i E_j \right)$$
Understanding proton polarisabilities – scaler terms

proton $\rightarrow$ quark core + positively charged virtual pion cloud
Understanding proton polarisabilities – scaler terms

proton $\rightarrow$ quark core + positively charged virtual pion cloud

\[ p = 4\pi\alpha E_1 E \]

\[ m = 4\pi\beta_{M1} H \]
Understanding proton polarisabilities – scaler terms

\( \alpha_{E1} \) and \( \beta_{M1} \) have been studied previously...

**Static Scaler Polarisabilities**

- **Energy Dependence:**
  \[
  \alpha_{E1} = \alpha_{E1}(\omega) \\
  \beta_{M1} = \beta_{M1}(\omega)
  \]

- **Static terms:**
  \[
  \bar{\alpha}_{E1} = \alpha_{E1}(0) \\
  \bar{\beta}_{M1} = \beta_{M1}(0)
  \]

**Baldin Sum Rule →**

Relates the static scaler polarisabilities to the total photoproduction cross section!

\[
\bar{\alpha}_{E1} + \bar{\beta}_{M1} = \frac{1}{2\pi^2} \int_{\omega_{th}}^{\infty} \frac{\sigma_{tot}(\omega)}{\omega^2} d\omega
\]

Understanding proton polarisabilities – scaler terms

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**Static Scaler Polarisabilities**

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- **Static terms:**
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  \]

**Baldin Sum Rule →**

Relates the static scaler polarisabilities to the total photoproduction cross section!

\[
\bar{\alpha}_{E1} + \bar{\beta}_{M1} = (13.8 \pm 0.4) \times 10^{-4} \text{ fm}^3
\]


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Spin polarisabilities of the proton
Understanding proton polarisabilities – scaler terms

\( \alpha_{E1} \) and \( \beta_{M1} \) have been studied previously...

\[
\bar{\alpha}_{E1} = [12.1 \pm 0.4] \times 10^{-4} \text{ fm}^3
\]

\[
\bar{\beta}_{M1} = [1.6 \pm 0.4] \times 10^{-4} \text{ fm}^3
\]

Understanding proton polarisabilities – scaler terms

$\alpha_{E1}$ and $\beta_{M1}$ have been studied previously...

\[
\bar{\alpha}_{E1} = [11.2 \pm 0.4] \times 10^{-4} \text{ fm}^3
\]

\[
\bar{\beta}_{M1} = [2.5 \pm 0.4] \times 10^{-4} \text{ fm}^3
\]


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Spin polarisabilities of the proton
Review

**Scalar polarisabilities**

Response of the proton’s structure to an electric or magnetic field

\[
H_{\text{eff}}^{(2)} = -\frac{1}{2} \left( 4\pi \alpha E^2 + 4\pi \beta M H^2 \right)
\]

**Spin polarisabilities**

Response of the proton’s spin to an electric or magnetic field

\[
H_{\text{eff}}^{(3)} = -\frac{1}{2} \left( 4\pi \gamma_{E1E1} \sigma \cdot (E \times \dot{E}) + 4\pi \gamma_{M1M1} \sigma \cdot (H \times \dot{H}) \right) \\
+ \left( 4\pi \gamma_{M1E2} E_i \sigma_j H_j - 4\pi \gamma_{E1M2} H_i \sigma_j E_j \right)
\]
Understanding proton polarisabilities – spin terms

Two linear combinations have been studied previously...

\[ \gamma_0 = -\bar{\gamma}_{E1E1} - \bar{\gamma}_{M1M1} - \bar{\gamma}_{E1M2} - \bar{\gamma}_{M1E2} \]
\[ \gamma_\pi = -\bar{\gamma}_{E1E1} + \bar{\gamma}_{M1M1} - \bar{\gamma}_{E1M2} + \bar{\gamma}_{M1E2} \]

Forward spin polarisability

\[
\left( \frac{d\sigma}{d\Omega} \right)_{(\theta=0)} = F(M, \kappa, \alpha, \beta) - \frac{e^4 \kappa^2 \omega^4}{4\pi M} \gamma_0 + O(\omega^6)
\]

Backward spin polarisability

\[
\left( \frac{d\sigma}{d\Omega} \right)_{(\theta=\pi)} = F(M, \kappa, \alpha, \beta) - \frac{e^2 \omega^2 \omega'^2}{4\pi M^2} (\kappa^2 + 4\kappa + 2) \gamma_\pi + O(\omega^6)
\]
Understanding proton polarisabilities – spin terms

\[ E_\gamma = 200 - 800 \text{ MeV} \]

\[ E_\gamma = 700 - 1800 \text{ MeV} \]

\[ \gamma_0 = - \frac{1}{4\pi^2} \int_{\omega_{th}}^{\infty} \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega^3} d\omega \]

Understanding proton polarisabilities – spin terms

$E\gamma = 200 - 800$ MeV

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

Understanding proton polarisabilities – spin terms

\[ \gamma_\pi \rightarrow d\sigma/d\Omega \text{ for Compton scattering at } 135^\circ \]

Data Sets:
- Sask (1993)
- LEGS (1998)
- LARA (2001)
- SENECA (2001)

Dispersive fitting [P'lov, Petrun'kin, Schumacher] applied to data sets

Understanding proton polarisabilities – spin terms

\[ \gamma_\pi \rightarrow d\sigma/d\Omega \text{ for Compton scattering at 135}^\circ \]

Data Sets:
- Sask (1993)
- LEGS (1998)
- LARA (2001)
- SENECA (2001)

\[ \gamma_\pi = (−38.7) \text{ or } (−23.3) \times 10^{-4} \text{ fm}^4 \]

Understanding proton polarisabilities – spin terms

\[ \gamma_\pi \rightarrow d\sigma/d\Omega \text{ for Compton scattering at } 135^\circ \]

Data Sets:
- Sask (1993)
- LEGS (1998)
- LARA (2001)
- SENECA (2001)

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

Understanding proton polarisabilities – spin terms

The large backward spin polarisability is dominated by a $\pi^0$-pole term, the t-channel emission of a virtual $\pi^0$.

Schumacher:

$$\gamma_{\pi^0} = -46.7$$

$$\gamma_{\pi} - \gamma_{\pi^0}\text{-pole} = (8.0 \pm 1.8) \times 10^{-4} \text{ fm}^4$$

Understanding proton polarisabilities – spin terms

Theoretical approaches have been applied to the spin polarisabilities:

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

<table>
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<td>(\bar{\gamma}_{M1M1})</td>
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<td>0.4</td>
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<td>-1.1</td>
<td>-1.0</td>
<td>-1.00(0.08)</td>
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* For comparison: \(\gamma_{\pi}\) from LEGS (without \(\pi\)-pole) is +23.4

All polarisabilities are given in units of \(10^{-4}\) fm\(^4\).
Understanding proton polarisabilities – spin terms

Theoretical approaches have been applied to the spin polarisabilities:

\[
\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{M1E2} - \gamma_{E1M2} \\
\gamma_\pi = -\gamma_{E1E1} + \gamma_{M1M1} + \gamma_{M1E2} - \gamma_{E1M2}
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* For comparison: $\gamma_\pi$ from LEGS (without $\pi$-pole) is +23.4

All polarisabilities are given in units of $10^{-4}$ fm$^4$. 
We will perform three unique asymmetry measurements:

\[
\Sigma = \frac{1}{p} \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}
\]

\(\Sigma_{2x}\): Circularly polarized photons, longitudinally polarized protons

\(\Sigma_{2z}\): Circularly polarized photons, transversely polarized protons

\(\Sigma_3\): Linearly polarized photons, unpolarized protons

Each asymmetry quantifies the change in scattering behaviour due to a **change in polarization orientation**:

- Circularly polarized photons: Helicity flip
- Polarized protons: Flip in polarization axis \((\pm x, \pm z)\)
- Linearly polarized photons: Perpendicular polarisation planes
Moving from asymmetries to polarisabilities...

Each $\Sigma$ has a unique sensitivity to the spin polarisabilities:

**Global Analysis**

We can perform a global analysis (global $\chi^2$ fitting) combining all asymmetry measurements to extract the spin polarisabilities.

**Constraints**

We will use the scalar polarisabilities ($\alpha$ and $\beta$) as well as the backward and forward polarisabilities ($\gamma_0$ and $\gamma_\pi$) to constrain our fit.

![Graph showing sensitivity of $\Sigma_3$ to $\gamma_{E1E1}$ and $\gamma_{M1M1}$]
A2-MAMI tagged photon facility

We can complete this experiment with the A2 Collaboration at the MAMI tagged photon facility (Mainz, Germany):

Why A2-MAMI?

- Polarized photon beams (linear/circular)
- Proton targets (unpolarized/polarized)
- Detector system ideally suited to study Compton scattering
Σ₂ₓ - September 2010 (Martel)

Σ₂ₓ Data were analyzed by Dr. Phil Martel (advisor Dr. Miskimen).

Figures

Σ₂ₓ asymmetry results are shown (Eₜ = 272.73 → 303.32 MeV) along with the Pasquini dispersion relation asymmetries for varied γ₁₁₁ (top) and γ₁₁₁ (bottom).

Conclusions

Σ₂ₓ is most sensitive to γ₁₁₁.

A first estimate of γ₁₁₁ can be extracted:

γ₁₁₁ = (-4.5 ± 1.5) × 10⁻⁴ fm⁴
**Σ₃ - December 2012**

**Figures**

**Left:** Σ₃ (265-305 MeV) was measured. LEGS 2001 data is also shown.

**Right:** Missing mass (compared to MC simulation).
Extracting the spin polarisabilities

Fitting method

Pasquini disp. relation (HDPV) or Pascalutsa EFT (BχPT)

\[
\begin{align*}
\bar{\alpha} + \bar{\beta} &= (13.8 \pm 0.4) \times 10^{-4} \text{ fm}^3 \\
\bar{\alpha} - \bar{\beta} &= (7.6 \pm 1.7) \times 10^{-4} \text{ fm}^3 \\
\gamma_0 &= (-1.00 \pm 0.18) \times 10^{-4} \text{ fm}^4 \\
\gamma_\pi &= (8.0 \pm 1.8) \times 10^{-4} \text{ fm}^4
\end{align*}
\]

Vary \( \bar{\alpha}, \bar{\beta} \) and \( \bar{\gamma}_{E1E1}, \bar{\gamma}_{M1M1}, \bar{\gamma}_{E1M2}, \bar{\gamma}_{M1E2} \)

Ideally we would have all three asymmetry measurements (global fit) but we can already try with just \( \Sigma_{2x} \) and \( \Sigma_3 \)…
Recent Results

\[
\bar{\gamma}_{E1E1} = (-5.15 \pm 1.12) \quad \bar{\gamma}_{E1M2} = (1.76 \pm 1.32)
\]

\[
\bar{\gamma}_{E1E1} = (-3.98 \pm 0.95) \quad \bar{\gamma}_{E1M2} = (0.20 \pm 1.17)
\]
Recent Results

\[ \tilde{\gamma}_{E1E1} = (3.07 \pm 0.50) \]
\[ \tilde{\gamma}_{E1E1} = (2.76 \pm 0.52) \]

\[ \tilde{\gamma}_{E1M2} = (1.32 \pm 0.52) \]
\[ \tilde{\gamma}_{E1M2} = (2.03 \pm 0.56) \]
New extraction of the proton’s spin polarisabilities (DR)

\[
\begin{align*}
\bar{\gamma}_{E_1E_1} &= (-5.15 \pm 1.12) \times 10^{-4} \text{ fm}^4 \\
\bar{\gamma}_{M_1M_1} &= (3.07 \pm 0.50) \times 10^{-4} \text{ fm}^4 \\
\bar{\gamma}_{E_1M_2} &= (1.76 \pm 1.32) \times 10^{-4} \text{ fm}^4 \\
\bar{\gamma}_{M_1E_2} &= (1.32 \pm 0.52) \times 10^{-4} \text{ fm}^4
\end{align*}
\]

Once $\Sigma_{2z}$ measurement is complete:
- a global fit to all three data sets can be completed
- final extraction of the proton’s spin polarisabilities!

Continued work: model dependence studies!
New extraction of the proton’s spin polarisabilities (DR)

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Continued work: model dependence studies!
Thanks

Special thanks to: (A2 collaboration)
A. Sarty, D. Hornidge, P. Martel, E.J Downie, R. Miskimen
Energy dependence: Static polarisabilities

Energy dependent!
... we’re interested in the static polarisabilities ($\omega = 0$)

CREDIT: Judith McGovern

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Spin polarisabilities of the proton
Energy dependence: Static polarisabilities

Energy dependent!

... but we can’t measure at $\omega = 0$ (so we need theorists!)

CREDIT: Judith McGovern
Extraction with LEGS2001?

Forward/Backward polarisability constraint
Extraction with LEGS2001?

MAMI --- BχPT
MAMI --- HDPV

Forward/Backward polarisability constraint
Extraction with LEGS2001?

- Forward/Backward polarisability constraint

**LEGs --- BχPT**

**LEGs --- HDPV**
Extraction with LEGS2001?

Forward/Backward polarisability constraint

M1E2

MAMI --- BχPT
MAMI --- HDPV

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Spin polarisabilities of the proton
MAMI electron accelerator

Cascade of RTM

- **RTM 1**
  - 18 turns
  - 15.3 MeV

- **RTM 2**
  - 51 turns
  - 185.9 MeV

- **RTM 3**
  - 90 turns
  - 883.1 MeV
MAMI electron accelerator

Cascade of RTM
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**HDSM** - not used
- 1.6 GeV
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MAMI electrons are incident upon a radiator → bremsstrahlung

“Photon Tagging”

If we measure the energy of the electron after bremsstrahlung, we can infer the energy of the photon:

\[ k = E_o - E \]

Note:

\[ E_o \approx \text{monoenergetic} \]

(\[ \Delta E_o = 0.0002E_o \])
Polarized photon beams

MAMI electrons are incident upon a radiator → bremsstrahlung

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\( (\Delta E_o = 0.0002E_o) \)

Glasgow-Mainz Tagger

353 plastic scintillators
Polarized photon beams are produced via Bremsstrahlung

Circularly polarized beams
Polarized electrons, incident upon a radiator (copper), will produce circularly polarized bremsstrahlung photons.

Linearly polarized beams
Electrons, incident upon a crystalline radiator (diamond), will produce linearly polarized bremsstrahlung photons.
Polarized photon beams are incident upon a proton target

Polarized Proton Target
- 2 cm Butanol Target
- Transverse/longitudinal pol. greater than 90%

Unpolarized Proton Target
- Liquid Hydrogen Target
- 2 cm, 5 cm, and 10 cm target cells
**Detectors**

**Advantages**
- Huge angular coverage
- Excellent $\gamma$ reconstruction

**Ideally suited for Compton scattering experiments**

**Crystal Ball System**
- CB (672 NaI detectors), MWPC, PID
- Angular coverage: ($\theta = 20^\circ \rightarrow 160^\circ$)

**TAPS System**
- TAPS (384 BaF$_2$ and 72 PbWO$_4$ detectors), Veto Wall
- Covers the forward angles missed by the CB ($\theta \rightarrow 20^\circ$)
Suppose we include an intermediate state, A, in the CS interaction.

\[ \gamma + p \rightarrow A \rightarrow \gamma' + p' \]

Let’s keep our example: \( \gamma_{M1E2} \)

- Assume \( p \) and \( p' \) are ground state protons \( \rightarrow J^\pi = \frac{1}{2}^+ \)
- Incident photon (E2) has \( L^\pi = 2^+ \)
- Scattered photon (M1) has \( L^\pi = 1^+ \)

What restrictions does this place on the state A?

- Parity conservation: \( \pi_A \) must be +
- Angular Momentum conservation: \( J_A = \frac{3}{2} \)

\( \rightarrow A \) must have \( J^\pi_A = \frac{3}{2}^+ \).
Understanding proton polarisabilities – spin terms

What could $A$ be to satisfy $J_A^\pi = \frac{3}{2}^+$?

- $\pi_A = +$ requires $A$ have $L = 0, 2, \ldots$ (even)
- The spin of $A$ must satisfy $|L - S| \leq J \leq |L + S|$
- $L = 0 \rightarrow S = \frac{3}{2} \rightarrow$ Ground state $\Delta^+$
- $L = 2 \rightarrow S = \frac{1}{2}, \frac{3}{2} \rightarrow$ D-state proton/$\Delta^+$

Excitation of the ground state $\Delta^+$ (uud) $\rightarrow$ spin flip transition

$$\gamma(2^+) + p(\frac{1}{2}^+) \rightarrow \Delta^+ (\frac{3}{2}^+) \rightarrow \gamma'(1^+) + p'(\frac{1}{2}^+)$$
Supplementary materials - 297, 90-100

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Spin polarisabilities of the proton

Supplementary materials - 297, 90-100

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Spin polarisabilities of the proton
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Data (Dec. 2012)  CS + $\pi^0$  Compton scattering  $\pi^0$ photoproduction