Probing proton structure
Spin polarisabilities and Compton scattering

Cristina Collicott

on behalf of the A2 collaboration at MAMI

HEP2018
We’re interested in studying the proton polarisabilities:

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

**Spin polarisabilities**
- $\gamma$, describe the response of the proton’s spin to electric and magnetic fields.
- Very little experimental information exists...
We’re interested in studying the proton polarisabilities:

**Scalar polarisabilities**
- $\alpha$ and $\beta$, describe the response of the proton’s structure to an electric or magnetic field.
- Previously studied experimentally... ongoing experimental studies

**Spin polarisabilities**
- $\gamma$, describe the response of the proton’s spin to electric and magnetic fields.
- Very little experimental information exists...
Understanding proton polarisabilities – scaler terms

proton → quark core + positively charged virtual pion cloud
proton → quark core + positively charged virtual pion cloud

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

\[ m = 4\pi\beta M_1 H \]
Polarisabilities of the proton

Polarisabilities can be accessed through Compton scattering:
\[ \gamma + p \rightarrow \gamma' + p' \]

Scalar polarisabilities - second order effective Hamiltonian

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

Spin polarisabilities - third order effective Hamiltonian

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

\( \alpha_{E1} \text{ and } \beta_{M1} \) 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 (HEP 2018)
Two linear combinations have been studied previously...

\[
\gamma_0 = -\bar{\gamma}E_1E_1 - \bar{\gamma}M_1M_1 - \bar{\gamma}E_1M_2 - \bar{\gamma}M_1E_2 \\
\gamma_\pi = -\bar{\gamma}E_1E_1 + \bar{\gamma}M_1M_1 - \bar{\gamma}E_1M_2 + \bar{\gamma}M_1E_2
\]

**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

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

Understanding proton polarisabilities – spin terms

\( E_\gamma = 200 - 800 \text{ MeV} \)

\( E_\gamma = 700 - 1800 \text{ MeV} \)

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


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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 [L’vov, Petrun’kin, Schumacher] applied to data sets

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

Schumacher:

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

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

Understanding proton polarisabilities – spin terms

Theoretical approaches have been applied to the spin polarisabilities:

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

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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 \( 10^{-4} \text{ fm}^4 \).
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
We will perform three unique asymmetry measurements:

\[ \Sigma = \frac{1}{p} \left( \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \right) \]

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

\( \Sigma_{2x} \): 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 (±x, ±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 the sensitivity of $\Sigma_3$ to different $\gamma$ values](image)
What have we accomplished so far?

$\Sigma_{2x}$: Circularly polarized photons, transversely polarized protons

Allowed for the first extraction of $\gamma_{E1E1} \approx -4.7 \times 10^{-4} \text{ fm}^4$
What have we accomplished so far?

$\Sigma_2$: Circularly polarized photons, transversely polarized protons
$\Sigma_3$: Linearly polarized photons, unpolarized protons (LEGS)

Allowed for the first extraction of all four $\gamma$s

\[
\begin{align*}
\gamma_{E1E1} &= -3.5 \pm 1.2 \\
\gamma_{M1M1} &= 3.2 \pm 0.9 \\
\gamma_{E1M2} &= -0.7 \pm 1.2 \\
\gamma_{M1E2} &= 2.0 \pm 0.3
\end{align*}
\]

Published in PRL (2014) *units of $10^{-4}$ fm$^4$*
What have we accomplished so far?

$\Sigma_2$: Circularly polarized photons, transversely polarized protons

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

Allowed for the first extraction of all four $\gamma$s

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What have we accomplished so far?

\( \Sigma_{2z} \): Circularly polarized photons, longitudinally polarized protons
What have we accomplished so far?

\( \Sigma_{2z} \): Circularly polarized photons, longitudinally polarized protons
\( \Sigma_{2x} \): Circularly polarized photons, transversely polarized protons
\( \Sigma_3 \): Linearly polarized photons, unpolarized protons (LEGS)

Dramatic improvement on the uncertainties:

\[ \Delta \gamma_{E1E1} = 1.2 \]
\[ \Delta \gamma_{M1M1} = 0.9 \]
\[ \Delta \gamma_{E1E2} = 1.2 \]
\[ \Delta \gamma_{M1E2} = 0.3 \]
\[ \Delta \gamma_{E1E1} \approx 0.4 \]
\[ \Delta \gamma_{M1M1} \approx 0.4 \]
\[ \Delta \gamma_{E1E2} \approx 0.8 \]
\[ \Delta \gamma_{M1E2} \approx 0.4 \]

Paper is in internal review (ETA: submission in a few weeks)
What have we accomplished so far?

\[ \Sigma_3 : \text{Linearly polarized photons, unpolarized protons (MAMI/LEGS)} \]

Compton Beam Asymmetry: 297.0 \( \pm \) 10.1 MeV
(Dec. 2012)

Compton Beam Asymmetry: 277.1 \( \pm \) 10.1 MeV
(Dec. 2012)

A bit of a mixed result (systematics still being checked...)

New (higher statistics) measurement in the spring!
Full extraction plan

\[\Sigma_{2z}:\] Circularly polarized photons, longitudinally polarized protons
\[\Sigma_{2x}:\] Circularly polarized photons, transversely polarized protons
\[\Sigma_3:\] Linearly polarized photons, unpolarized protons (LEGS/MAMI)

\[\downarrow\]

Extraction of \(\gamma_{E1E1}, \gamma_{M1M1}, \gamma_{E1M2},\) and \(\gamma_{M1E2}\)

ETA: final paper before end of 2018
Summary

New experimental data:
- First measurement of $\Sigma_{2x}$ for Compton scattering
- First measurement of $\Sigma_{2z}$ for Compton scattering

First measurement of the proton spin polarisabilities:

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Upcoming results with improved uncertainties!
Some topics:
- Fitting routines
- Energy/Theory dependence
- The low energy regime for spin polarisabilities
- New experiments for scaler polarisabilities at MAMI
Extracting the spin polarisabilities

Fitting method

Pasquini disp. relation (HDPV) or Pascalutsa EFT ($B\chi$PT)

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

Vary $\bar{\alpha}$, $\bar{\beta}$ and $\tilde{\gamma}_{E1E1}$, $\tilde{\gamma}_{M1M1}$, $\tilde{\gamma}_{E1M2}$, $\tilde{\gamma}_{M1E2}$

Global fit with $\Sigma_{2x}$, $\Sigma_{2z}$ and $\Sigma_3$...
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.
Energy dependence: Static polarisabilities

Energy dependent!

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

CREDIT: Judith McGovern

Chiral: JMcG et al., in preparation
Energy dependence: Static polarisabilities

Energy dependent!

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

CREDIT: Judith McGovern
Move into the low-energy regime!

- Active polarised proton target
- Target material scintillates
- Allows (low energy) measurement of double polarisation observables
APPT results
Move into the low-energy regime!

CREDIT: Judith McGovern
New experiments for 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!

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

New experiments for scalar terms

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

**Static Scalar 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 scalar polarisabilities to the total photoproduction cross section!

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

New experiments for scaler terms

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

\[ \bar{\alpha}_{E1} = [12.1 \pm 0.4] \times 10^{-4} \text{ fm}^3 \]
\[ \bar{\beta}_{M1} = [1.6 \pm 0.4] \times 10^{-4} \text{ fm}^3 \]

New experiments for scalar terms

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

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

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

\[ \Sigma_3 \] results

![Graph showing \( \Sigma_3 \) asymmetry vs. \( \theta \) in the LAB frame]

- Blue squares: \( \Sigma \) (Dec. 2012)
- Open circles: LEGS 2001
- Triangles: Leukel 2001
- Red dashed line: MAID
- Green dashed line: DMT
- Pink dashed line: CM12

\( \theta \) in the LAB frame ranges from 0 to 180 degrees.

Data points and error bars represent experimental measurements, with theoretical curves overlaid for comparison.
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

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Spin polarisabilities of the proton (HEP 2018)
MAMI electron accelerator

Cascade of RTM
- RTM 1
  - 18 turns
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HDSM - not used
- 1.6 GeV
Cascade of RTM

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**HDSM** - not used

- 1.6 GeV
Polarized photon beams

MAMI electrons are incident upon a radiator \(\rightarrow\) 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

“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:

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

\[ (\Delta E_o = 0.0002E_o) \]

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

Ideal 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 \( J_A^\pi = \frac{3}{2}^+ \).
Understanding proton polarisabilities – spin terms

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

- $\pi_A = +$ 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

$$\gamma(2^+) + p\left(\frac{1}{2}^+\right) \rightarrow \Delta^+\left(\frac{3}{2}^+\right) \rightarrow \gamma'(1^+) + p'\left(\frac{1}{2}^+\right)$$