Probing proton structure
Spin polarisabilities and Compton scattering

Cristina Collicott

on behalf of the A2 collaboration at MAMI

HEP2018

Polarisabilities of the proton

We're interested in studying the proton polarisabilities:

Scalar polarisabilities

- α and β, describe the response of the proton's structure to an electric or magnetic field.
- Previously studied experimentally...

Spin polarisabilities

- γ, describe the response of the proton's spin to electric and magnetic fields.
- Very little experimental information exists...

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Scalar polarisabilities

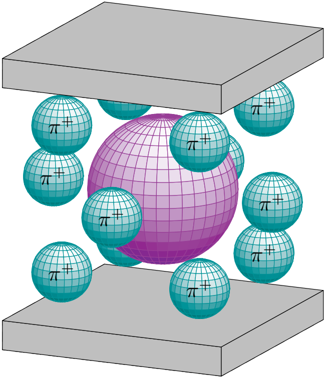
- α and β, describe the response of the proton's structure to an electric or magnetic field.
- Previously studied experimentally... **ongoing experimental studies**

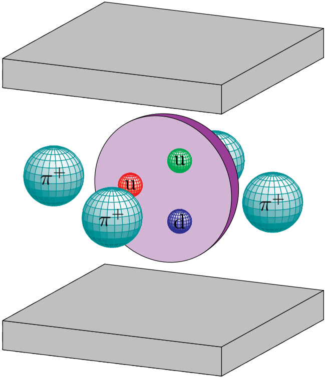
Spin polarisabilities

- γ, describe the response of the proton's spin to electric and magnetic fields.
- **Very little experimental information exists...**

Understanding proton polarisabilities – scaler terms

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

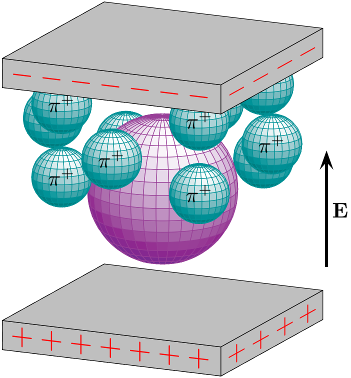


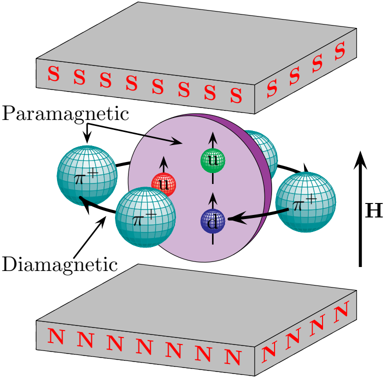


Credit: Phil Martel

Understanding proton polarisabilities – scaler terms

proton → quark core + positively charged virtual pion cloud





$$\mathbf{p} = 4\pi\alpha_{E1}\mathbf{E}$$

$$\mathbf{m} = 4\pi\beta_{M1}\mathbf{H}$$

Polarisabilities of the proton

Polarisabilities can be accessed through Compton scattering:

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

Scalar polarisabilities - second order effective Hamiltonian

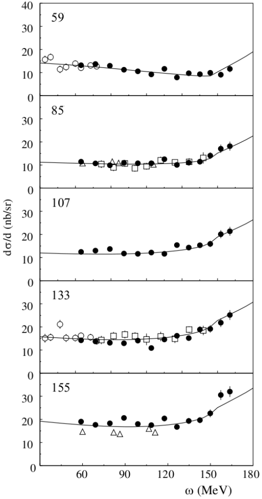
$$H_{eff}^{(2)} = -\frac{1}{2}\left(4\pi\alpha_{E1}\mathbf{E}^2 + 4\pi\beta_{M1}\mathbf{H}^2\right)$$

Spin polarisabilities - third order effective Hamiltonian

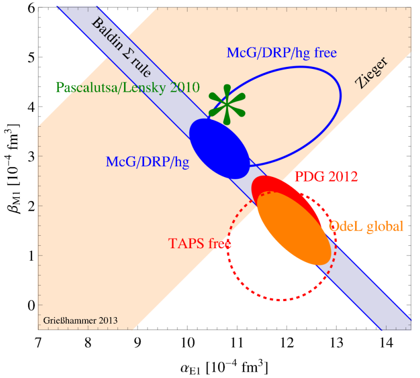
$$H_{eff}^{(3)} = -\frac{1}{2}\left(4\pi\gamma_{E1E1}\boldsymbol{\sigma}\cdot(\mathbf{E}\times\dot{\mathbf{E}}) + 4\pi\gamma_{M1M1}\boldsymbol{\sigma}\cdot(\mathbf{H}\times\dot{\mathbf{H}})\right) + \left(4\pi\gamma_{M1E2}E_{ij}\sigma_i H_j - 4\pi\gamma_{E1M2}H_{ij}\sigma_i E_j\right)$$

Understanding proton polarisabilities – scaler terms

α_{E1} and β_{M1} have been studied previously...



$$\bar{\alpha}_{E1} = [11.2 \pm 0.4] \times 10^{-4}\ \text{fm}^3$$
$$\bar{\beta}_{M1} = [\ 2.5 \pm 0.4] \times 10^{-4}\ \text{fm}^3$$



McGovern, Phillips and Grießhammer. Eur. Phys. J. A49, (2013) & PDG

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

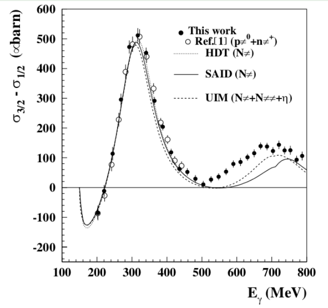
$$\left(\frac{d\sigma}{d\Omega}\right)_{(\theta=0)} = F(M,\kappa,\alpha,\beta) - \frac{e^4\kappa^2\omega^4}{4\pi M}\gamma_0 + \mathcal{O}(\omega^6)$$

Backward spin polarisability

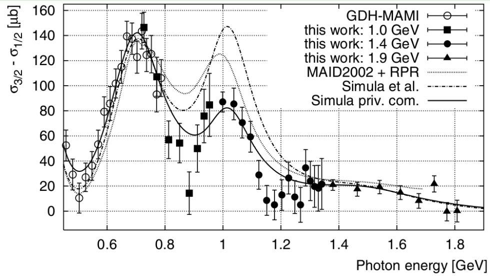
$$\left(\frac{d\sigma}{d\Omega}\right)_{(\theta=\pi)} = F(M,\kappa,\alpha,\beta) - \frac{e^2\omega^2\omega'^2}{4\pi M^2}(\kappa^2+4\kappa+2)\gamma_\pi + \mathcal{O}(\omega^6)$$

Understanding proton polarisabilities – spin terms

$E_\gamma = 200$ - 800 MeV



$E_\gamma = 700$ - 1800 MeV



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

GDH- and A2- collaborations. Phys. Rev. Lett. 87, (2001); GDH collaboration. Phys. Rev. Lett. 91, (2003)

Understanding proton polarisabilities – spin terms

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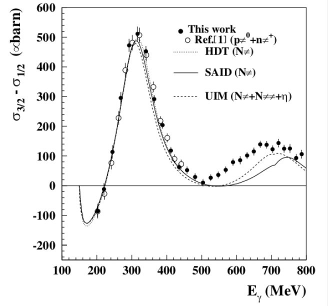

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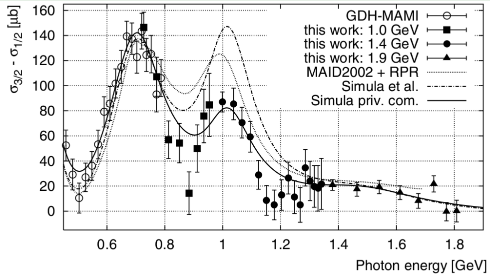
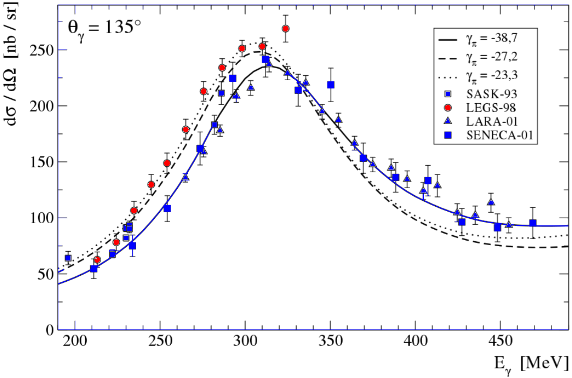


$$\gamma_0 = (-1.00 \pm 0.08_{\,\text{stat.}}) \times 10^{-4}\ \text{fm}^4$$

GDH- and A2- collaborations. Phys. Rev. Lett. 87, (2001); **GDH collaboration. Phys. Rev. Lett. 91, (2003)**

Understanding proton polarisabilities – spin terms

$\gamma_\pi \rightarrow d\sigma/d\Omega$ for Compton scattering at 135°



Data Sets:

- Sask (1993)
- LEGS (1998)
- LARA (2001)
- SENECA (2001)

Dispersive fitting [L′vov, Petrun′kin, Schumacher] applied to data sets

Camen et. al.. Phys. Rev. C65, (2002); L′vov, Petrun′kin, and Schumacher, Phys. Rev. C55, (1997);

Understanding proton polarisabilities – spin terms

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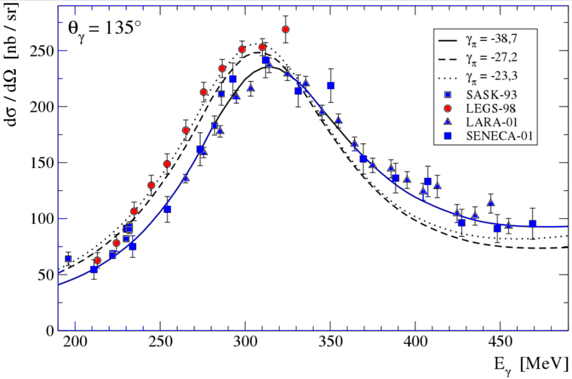

The large backward spin polarisability is dominated by a π^0-pole term, the t-channel emission of a virtual π^0.

Schumacher:

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

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

Camen et. al.. Phys. Rev. C65, (2002); L′vov, Petrun′kin, and Schumacher, Phys. Rev. C55, (1997);

Understanding proton polarisabilities – spin terms

Theoretical approaches have been applied to the **spin polarisabilities**:

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

	HDPV	DPV	$\mathcal{O}(p^4)_a$	$\mathcal{O}(p^4)_b$	$\mathcal{O}(\epsilon^3)$	BχPT	Exp.
$\bar{\gamma}_{E1E1}$	-4.3	-3.8	-5.4	1.3	-1.9	-3.3	No data
$\bar{\gamma}_{M1M1}$	2.9	2.9	1.4	3.3	0.4	3.0	No data
$\bar{\gamma}_{E1M2}$	-0.02	0.5	1.0	0.2	0.7	0.2	No data
$\bar{\gamma}_{M1E2}$	2.2	1.6	1.0	1.8	1.9	1.1	No data
γ_0	-0.8	-1.1	1.9	-3.9	-1.1	-1.0	-1.00(0.08)
γ_π	9.4	7.8	6.8	6.1	3.5	7.2	8.0(1.8) *

* For comparison: γ_π from LEGS (without π-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: γ_π from LEGS (without π-pole) is $+23.4$

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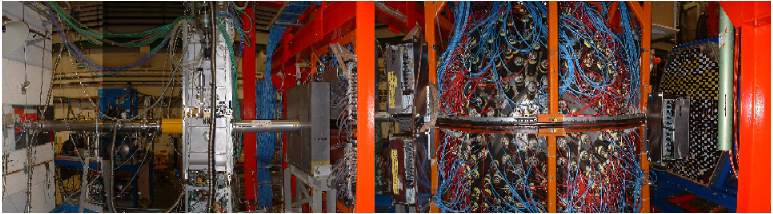
A2-MAMI tagged photon facility

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

Experiment Effort at MAMI

We will perform three unique asymmetry measurements:

$$\Sigma = \frac{1}{p}\,\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Σ_{2z}: Circularly polarized photons, longitudinally polarized protons
Σ_{2x}: Circularly polarized photons, transversely polarized protons
Σ_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...

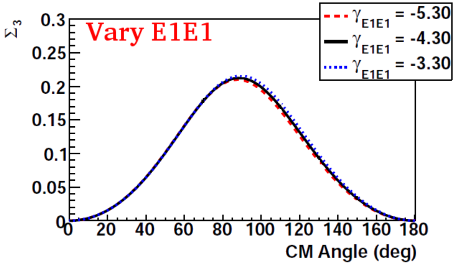
Each Σ has a unique sensitivity to the spin polarisabilities:

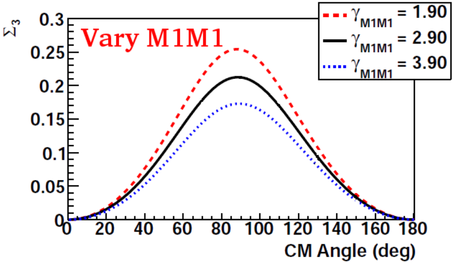
Global Analysis

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

Constraints

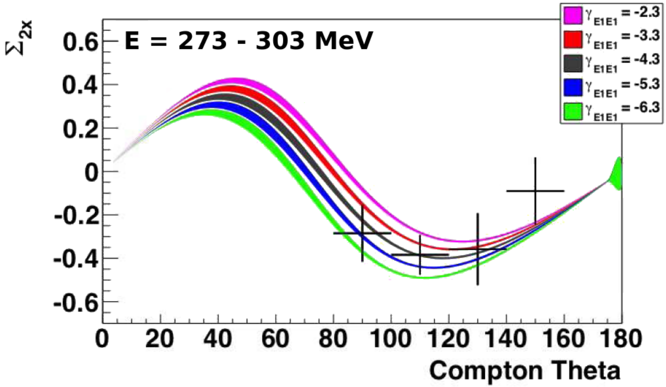
We will use the scalar polarisabilities (α and β) as well as the backward and forward polarisabilities (γ_0 and γ_π) to constrain our fit.





What have we accomplished so far?

Σ_{2x}: Circularly polarized photons, transversely polarized protons



Allowed for the first extraction of $\gamma_{E1E1} \approx$ -4.7 $\times$ 10^{-4} fm^4

What have we accomplished so far?

Σ_{2x}: Circularly polarized photons, transversely polarized protons
Σ_3 : Linearly polarized photons, unpolarized protons (LEGS)

Allowed for the first extraction of all four γs

$$\begin{aligned} \gamma_{E1E1} &= -3.5 \pm 1.2 \\ \gamma_{M1M1} &= 3.2 \pm 0.9 \\ \gamma_{E1M2} &= -0.7 \pm 1.2 \\ \gamma_{M1E2} &= 2.0 \pm 0.3 \end{aligned}$$

Published in PRL *(2014)*

*units of 10^{-4} fm^4

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Allowed for the first extraction of all four γs

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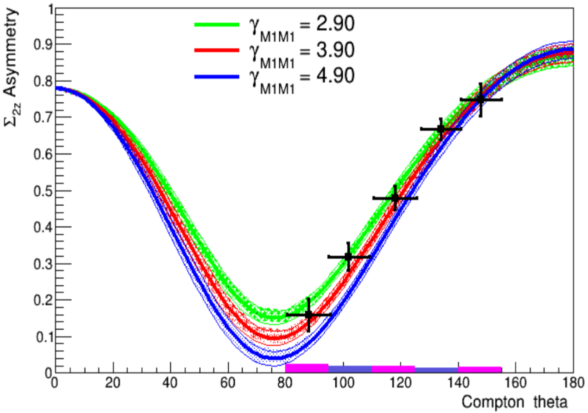
$\bar{\gamma}_{M1M1}$	2.9	1.4	3.3	0.4	3.0	**3.2 $\pm$ 0.9**
$\bar{\gamma}_{E1M2}$	-0.02	1.0	0.2	0.7	0.2	**-0.7 $\pm$ 1.2**
$\bar{\gamma}_{M1E2}$	2.2	1.0	1.8	1.9	1.1	**2.0 $\pm$ 0.3**

What have we accomplished so far?

Σ_{2z}: Circularly polarized photons, longitudinally polarized protons



What have we accomplished so far?

Σ_{2z}: Circularly polarized photons, longitudinally polarized protons
Σ_{2x}: Circularly polarized photons, transversely polarized protons
Σ_3 : Linearly polarized photons, unpolarized protons (LEGS)

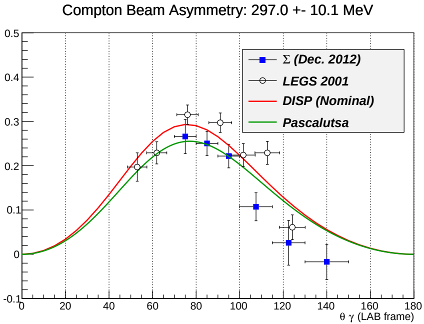
Dramatic improvement on the uncertainties:

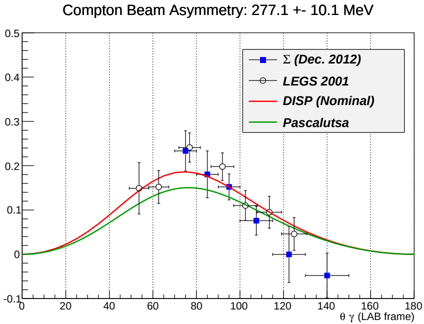
$\Delta\ \gamma_{E1E1} = 1.2$	$\Delta\ \gamma_{E1E1} \approx 0.4$
$\Delta\ \gamma_{M1M1} = 0.9$	$\Delta\ \gamma_{M1M1} \approx 0.4$
$\Delta\ \gamma_{E1M2} = 1.2$	$\Delta\ \gamma_{E1M2} \approx 0.8$
$\Delta\ \gamma_{M1E2} = 0.3$	$\Delta\ \gamma_{M1E2} \approx 0.4$

Paper is in internal review (ETA: submission in a few weeks)

What have we accomplished so far?

Σ_3 : Linearly polarized photons, unpolarized protons (MAMI/LEGS)





A bit of a mixed result (systematics still being checked...)
New (higher statistics) measurement in the spring!

Full extraction plan

Σ_{2z}: Circularly polarized photons, longitudinally polarized protons
Σ_{2x}: Circularly polarized photons, transversely polarized protons
Σ_3 : Linearly polarized photons, unpolarized protons (LEGS/MAMI)

$$\downarrow$$

Extraction of γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, and γ_{M1E2}

ETA: final paper before end of 2018

Summary

New experimental data:

- First measurement of Σ_{2x} for Compton scattering
- First measurement of Σ_{2z} for Compton scattering

First measurement of the proton spin polarisabilities:

	HDPV	$\mathcal{O}(p^4)_a$	$\mathcal{O}(p^4)_b$	$\mathcal{O}(\epsilon^3)$	BχPT	Experiment
$\bar{\gamma}_{E1E1}$	-4.3	-5.4	1.3	-1.9	-3.3	**-3.5 $\pm$ 1.2**
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$\bar{\gamma}_{M1E2}$	2.2	1.0	1.8	1.9	1.1	**2.0 $\pm$ 0.3**

Upcoming results with improved uncertainties!

Supplementary

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 (BχPT)

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

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

Global fit with Σ_{2x}, Σ_{2z} and Σ_3...

Moving from asymmetries to polarisabilities...

Each Σ has a unique sensitivity to the spin polarisabilities:

Global Analysis

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

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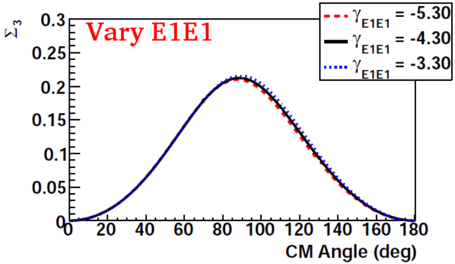
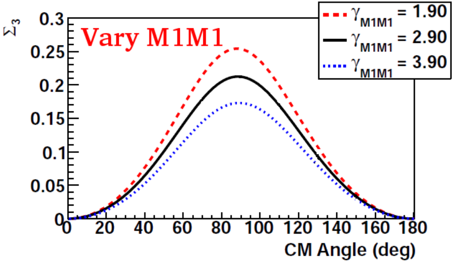
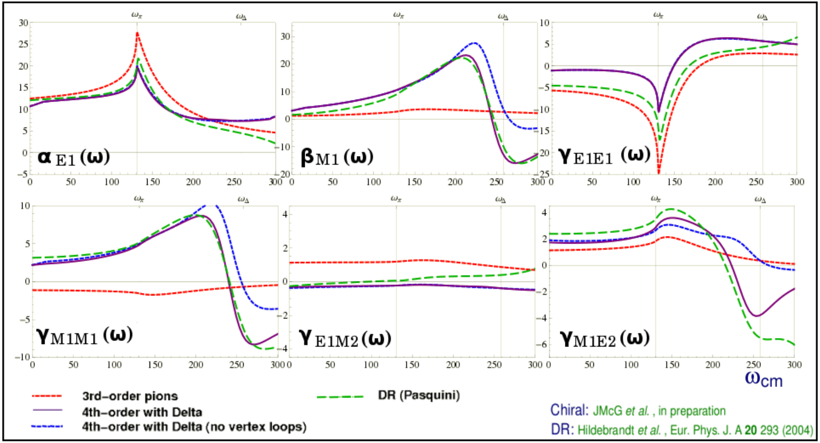




Energy dependence: Static polarisabilities

Energy dependent!

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

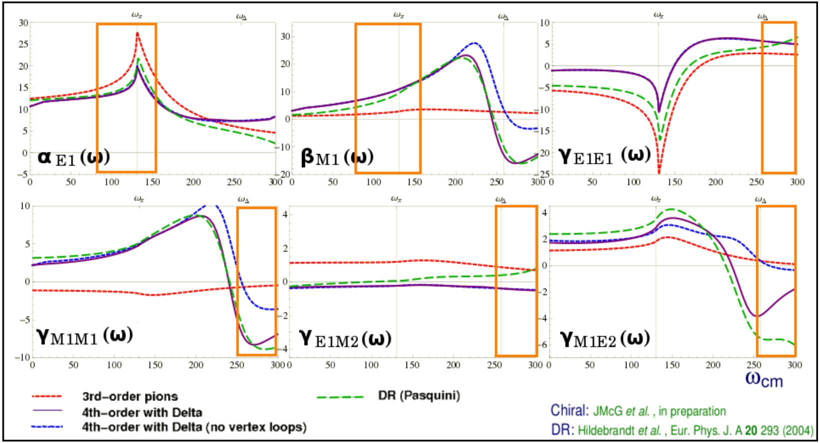


CREDIT: Judith McGovern

Energy dependence: Static polarisabilities

Energy dependent!

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

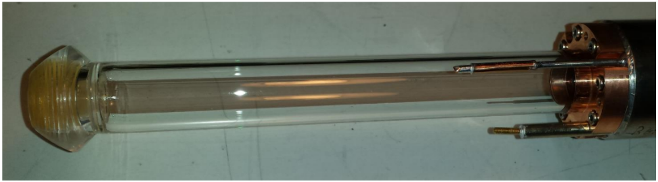


CREDIT: Judith McGovern

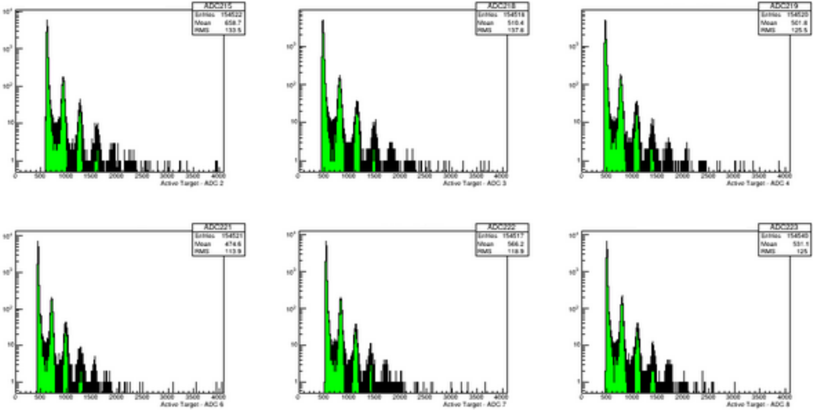
Outlook – new experiments

Move into the low-energy regime!

- Active polarised proton target
- Target material scintillates
- Allows (low energy) measurement of double polarisation observables



APPT results



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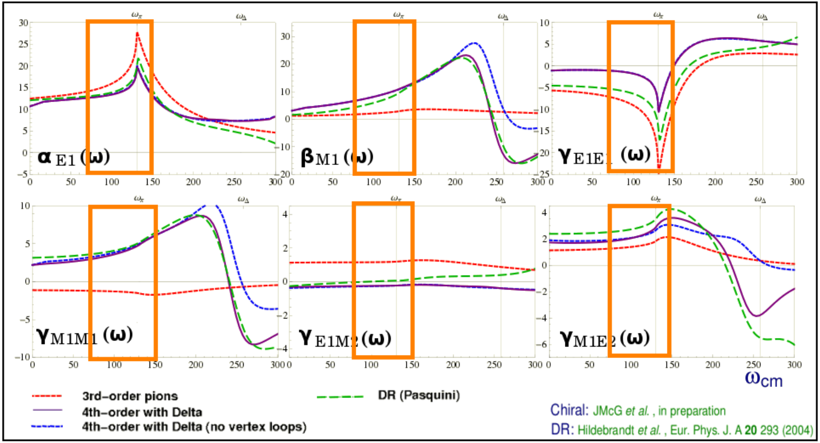


CREDIT: Judith McGovern

New experiments for scaler terms

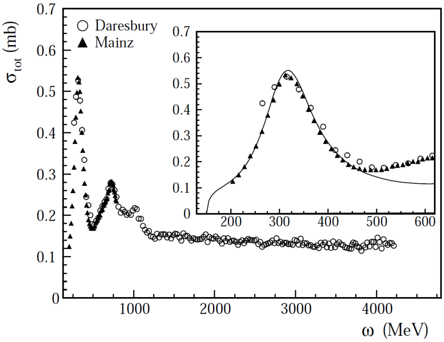
α_{E1} and β_{M1} have been studied previously...

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!



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

V. Olmos de Leon et al., Eur. Phys. J. A10, 207 (2001)

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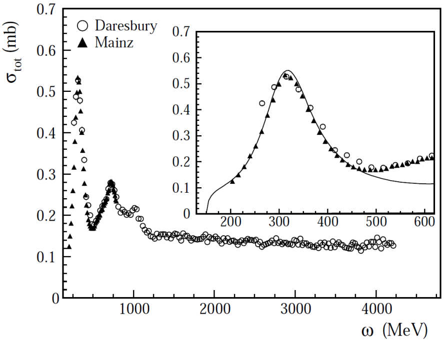

$$\bar{\alpha}_{E1} + \bar{\beta}_{M1} = (13.8 \pm 0.4) \times 10^{-4}\ \text{fm}^3$$

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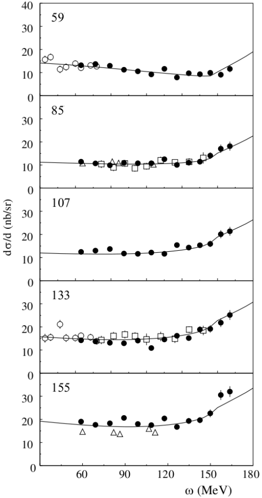
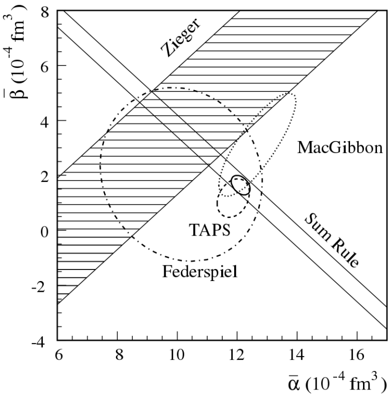


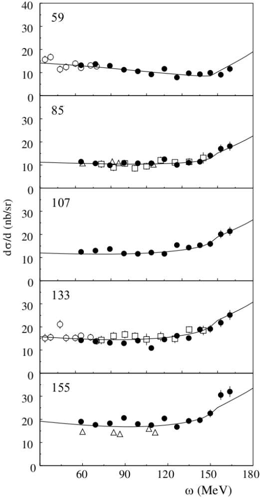
$$\bar{\alpha}_{E1} = [12.1 \pm 0.4] \times 10^{-4}\ \text{fm}^3$$
$$\bar{\beta}_{M1} = [\ 1.6 \pm 0.4] \times 10^{-4}\ \text{fm}^3$$



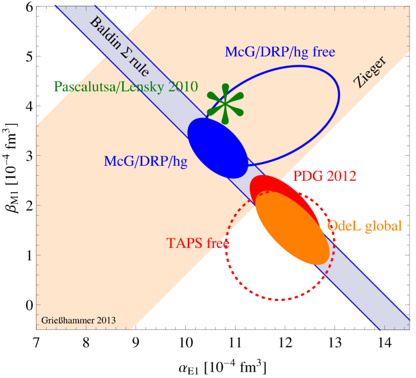
V. Olmos de Leon et al., Eur. Phys. J. A10, 207 (2001)

New experiments for scaler terms

α_{E1} and β_{M1} have been studied previously...

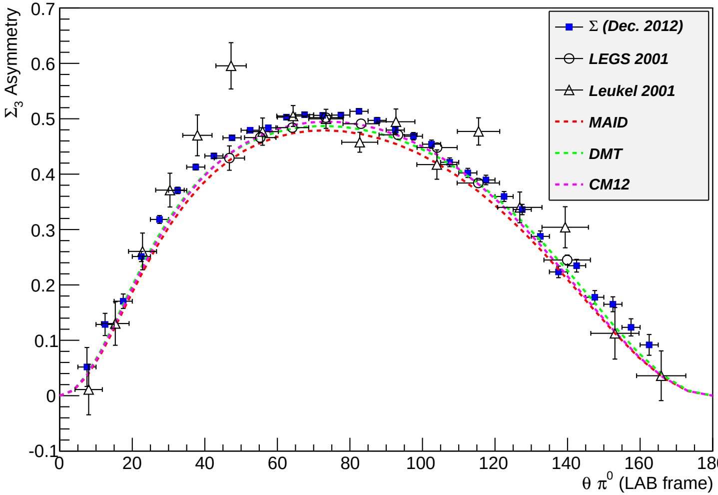


$$\bar{\alpha}_{E1} = [11.2 \pm 0.4] \times 10^{-4}\ \text{fm}^3$$
$$\bar{\beta}_{M1} = [\ 2.5 \pm 0.4] \times 10^{-4}\ \text{fm}^3$$

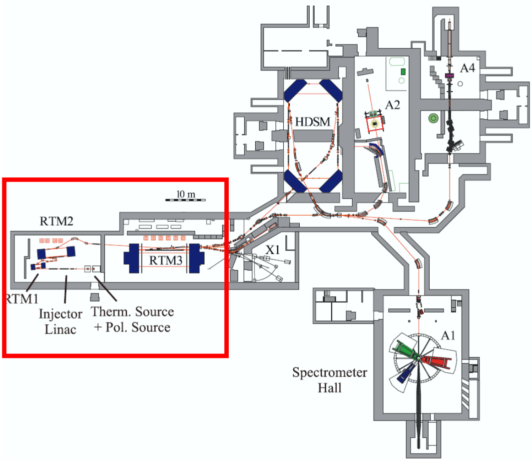


McGovern, Phillips and Grießhammer. Eur. Phys. J. A49, (2013) & PDG

Σ_3 results



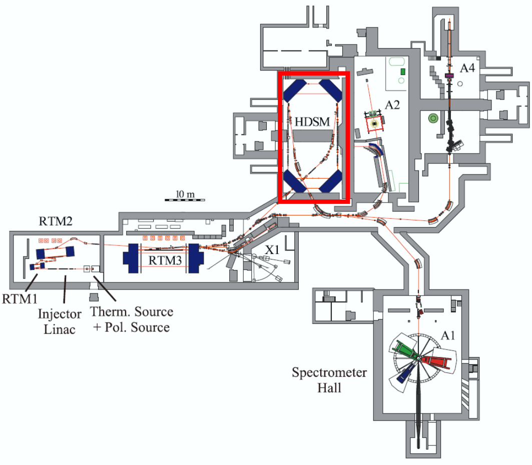
MAMI electron accelerator



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



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HDSM - not used

- 1.6 GeV

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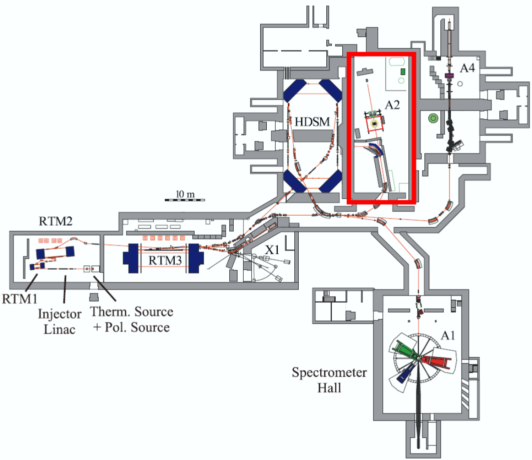

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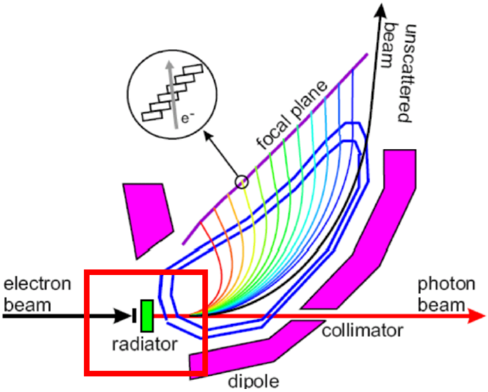
Polarized photon beams

MAMI electrons are incident upon a radiator $\rightarrow$ bremsstrahlung



Glasgow-Mainz Tagger
353 plastic scintillators

"Photon Tagging"

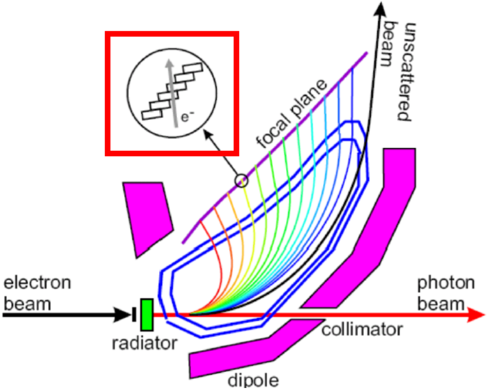
If we measure the energy of the electron after bremsstrahlung, we can infer the energy of the photon:

$$k = E_o - E$$

Note:
$E_o \approx$ monoenergetic
$(\Delta E_o = 0.0002 E_o)$

Polarized photon beams

MAMI electrons are incident upon a radiator → bremsstrahlung



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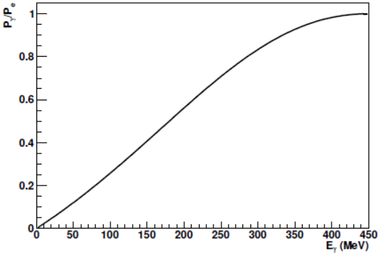
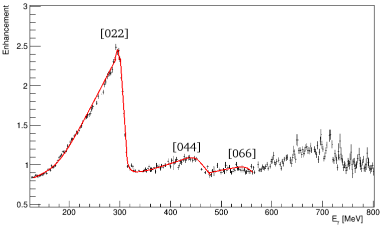
Polarized photon beams

Polarized photon beams are produced via Bremsstrahlung





Circularly polarized beams

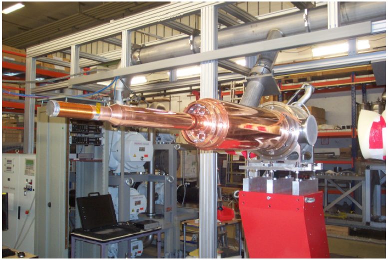
Polarized electrons, incident upon a radiator (copper), will produce circularly polarized bremsstrahlung photons.

Linearly polarized beams

Electrons, incident upon a crystalline radiator (diamond), will produce linearly polarized bremsstrahlung photons.

Proton Targets

Polarized photon beams are incident upon a proton target



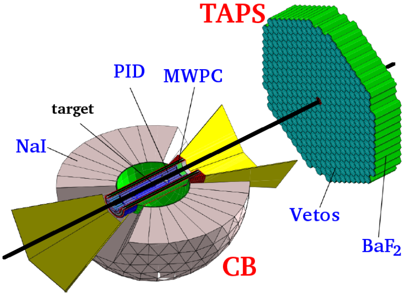
Polarized Proton Target

- 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 γ 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 ($\theta \rightarrow 20^\circ$)

Understanding proton polarisabilities – spin terms

Suppose we include an intermediate state, A, in the CS interaction.

$$\gamma + \text{p} \rightarrow \text{A} \rightarrow \gamma' + \text{p}'$$

Let's keep our example: γ_{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: π_A must be $+$
- Angular Momentum conservation: $\text{J}_A = \frac{3}{2}$

$\rightarrow$ A must have $J_A^{\pi} = \frac{3}{2}^{+}$.

Understanding proton polarisabilities – spin terms

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

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

Excitation of the ground state Δ^+ (uud) → spin flip transition

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