Measurement of the proton scalar polarizabilities at MAMI

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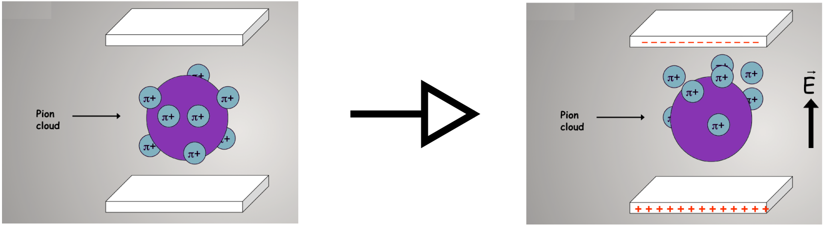
Proton scalar polarizabilities

Main goal

Measurement of the scalar polarizabilities α_{E1} and β_{M1} of the proton,using a linearly polarized photon beam

- Fundamental properties of the nucleon
- Closely related to nucleon internal structure
- Important for nuclear physics, atomic physics, astrophysics, spin polarizabilities measurements, etc.

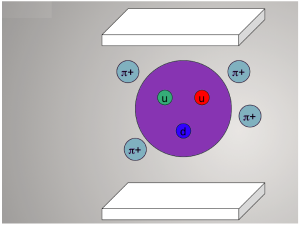
Electric scalar polarizability - α_{E1}

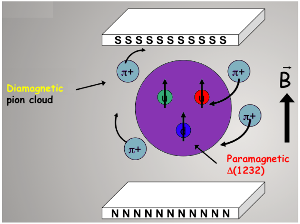


- Electric dipole moment: $\vec{p} = \alpha_{E1}\vec{E}$
- α_{E1}: electric polarizability

- Describes the response of a proton to an applied electric field: "stretchability" of the proton

Magnetic scalar polarizability - β_{M1}

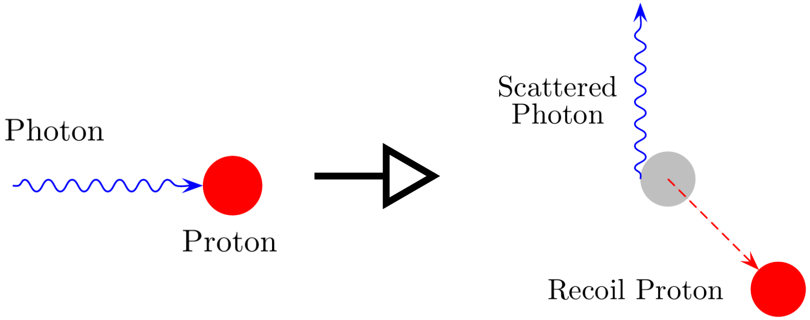




- Magnetic dipole moment: $\vec{m} = \beta_{M1}\vec{H}$
- β_{M1}: magnetic polarizability
- Describes the response of a proton to an applied magnetic field: "alignability" of the proton

Compton scattering

- Internal structure can be accessed via Compton scattering



$$\gamma(\text{k}) + \text{P}(\text{p}) \rightarrow \gamma(\text{k'}) + \text{P}(\text{p'})$$

Compton scattering

Born term

Under the assumption of NO proton internal structure, the effective Hamiltonian can be written in terms of mass, electric charge and anomalous magnetic moment

- Zeroth order: mass and electric charge

$$H_{\text{eff}}^{(0)} = \frac{\vec{\pi}^2}{2m} + e\phi \qquad (\text{where } \vec{\pi} = \vec{p} - e\vec{A})$$

- First order: anomalous magnetic moment

$$H_{\text{eff}}^{(1)} = -\frac{e(1+k)}{2m}\vec{\sigma}\cdot\vec{H} - \frac{e(1+2k)}{8m^2}\vec{\sigma}\cdot\left[\vec{E}\times\vec{\pi} - \vec{\pi}\times\vec{E}\right]$$

Compton scattering

Scalar polarizabilities

Effective Hamiltonian at the second order includes scalar polarizabilities, which are related to the proton internal structure

- Second order: scalar polarizabilities α_{E1} and β_{M1}

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

α_{E1} and β_{M1} quantify the response of the proton to a static applied electric or magnetic field

- Third order: spin polarizabilities γ_{E1E1}, γ_{M1M1}, γ_{M1E2} and γ_{E1M2}

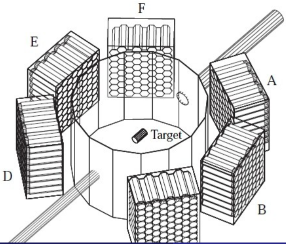
$$H_{\text{eff}}^{(3)} = -4\pi \Big[\frac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \frac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j \Big]$$

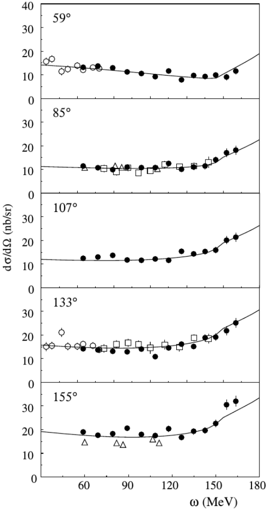
Existing data

- Highest statistics published data:

  V. Olmos de Leon et al. Eur. Phys. J. A 10, 207-2015 (2001)

- 200 hours of Compton scattering
- $E_{beam} = 180$ MeV
- $E_\gamma = 55 - 165$ MeV, $\theta_\gamma = 59^\circ - 155^\circ$
- 1/3 acceptance of CB system





Triangles: P.S. Baranov et al.(1974)
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Open circles: F.J. Federspiel et al.(1991)
Squares B.E. MacGibbon et al.(1995)
Curve: R.A. Arndt et al.(1996)

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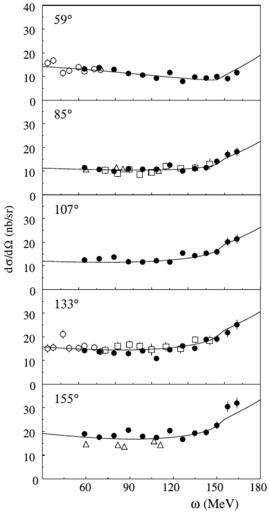
	with Baldin	without Baldin
α_{E1}	12.1 ± 1.08	11.9 ± 1.39
β_{E1}	1.6 ± 0.89	1.2 ± 0.76



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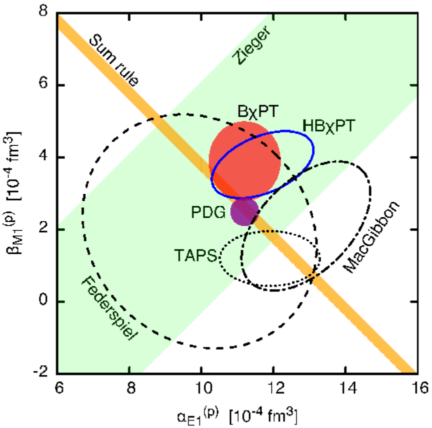


PDG (2012) values:

$$\alpha_{E1} = (12.0 \pm 0.6)\, 10^{-4}\ \text{fm}^3$$
$$\beta_{M1} = (1.9 \pm 0.5)\, 10^{-4}\ \text{fm}^3$$

New PDG (2013) values:

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

Significant change between reviews without new experimental data
$\Rightarrow$ New high quality data needed!

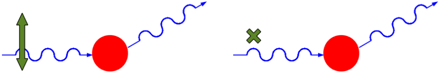
At low energy (and in certain phase-space regions) Σ_3 is mainly dependent on β_{M1}

Krupina and Pascalutsa, PRL 110, 262001 (2013)

Asymmetries

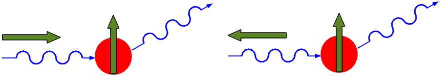
- Linearly polarized beam & unpolarized target

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



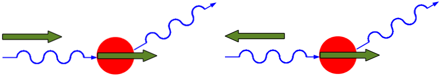
- Circularly polarized beam & transversely polarized target

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^R_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}}$$



- Circularly polarized beam & longitudinally polarized target

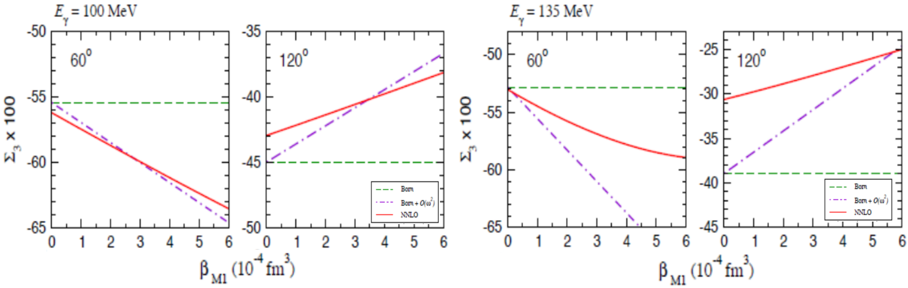
$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^z_{+z}}$$



Beam asymmetry Σ_3 and measurement of β_{M1}

At low energy, β_{M1} can be extracted from the beam asymmetry Σ_3 using a linearly polarized photon beam and an unpolarized proton target:

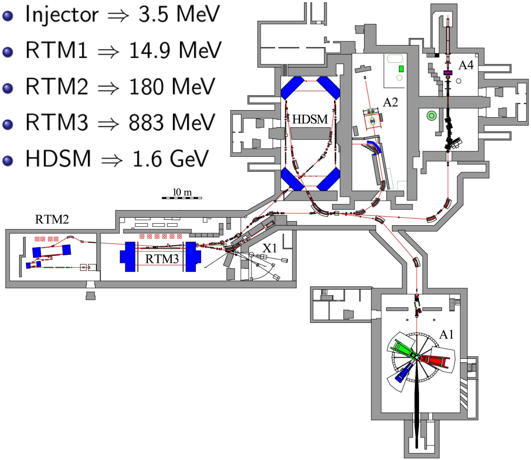
$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 cos(2\phi)\right] \text{ where } \boldsymbol{\Sigma_3 = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}}$$



Krupina and Pascalutsa, PRL 110, 262001 (2013)

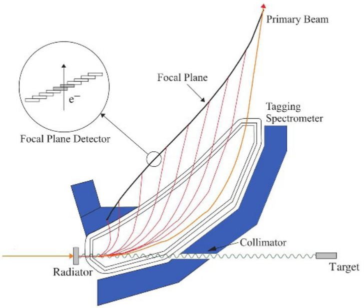
Experimental setup

- Injector ⇒ 3.5 MeV
- RTM1 ⇒ 14.9 MeV
- RTM2 ⇒ 180 MeV
- RTM3 ⇒ 883 MeV
- HDSM ⇒ 1.6 GeV



High intensity beam of linearly polarized tagged photons:

$$E_\gamma = E_0 - E_{e^-}$$



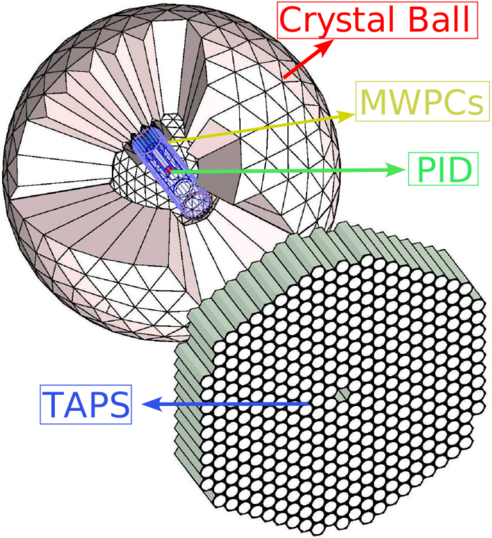
Experimental setup

Crystal Ball

- 672 NaI(Tl) crystals
- Particle Identification Detector (PID): 24 scintillator paddles
- 2 Multiwire Proportional Chambers (MWPCs)

TAPS

- 366 BaF_2 and 72 $PbWO_4$ crystals
- 384 veto paddles



Analysis conditions

$\Rightarrow$ The beam asymmetry Σ_3 is an alternative way to extract β_{M1}:

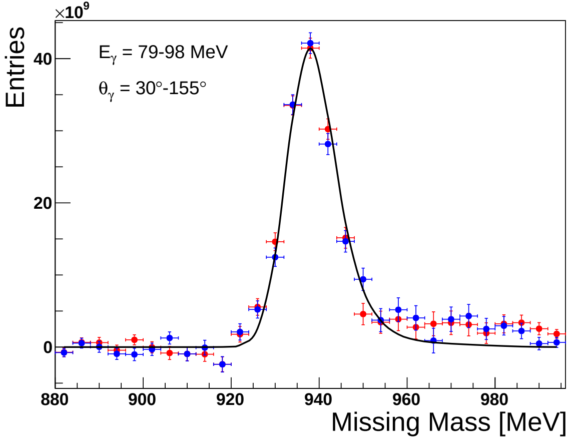
$$\Sigma_3 = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$$

$\Rightarrow$ We selected Compton scattering $\vec{\gamma}p \rightarrow \gamma(p)$ events:

- $E_{\gamma_{beam}} = 79 - 139$ MeV
- $\theta_{\gamma_{out}} = 30^\circ - 155^\circ$
- Events with 1 γ in the final state
- Random background subtraction
- Subtraction of empty target contribution
- Missing mass cut

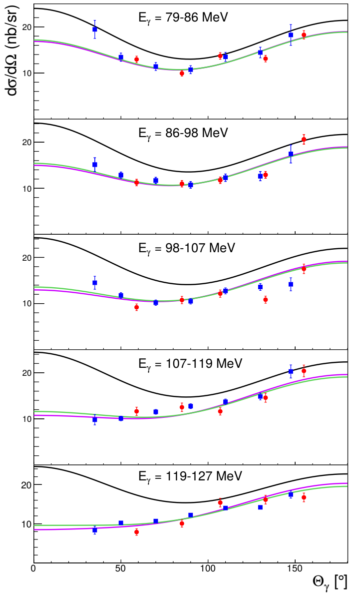
$\Rightarrow$ More than 200,000 Compton scattering events

Example of missing mass distribution



Good agreement between PARA, PERP and Monte carlo simulation
⇒ Low background dataset

Unpolarized cross-section



- **New DATA**
- **V. Olmos de Leon et al., EPJ A 10 (2001)**
- **Born contribution**
- **N. Krupina and V. Pascalutsa, PRL 110, 262001 (2013)**
- **B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76 (2007)**

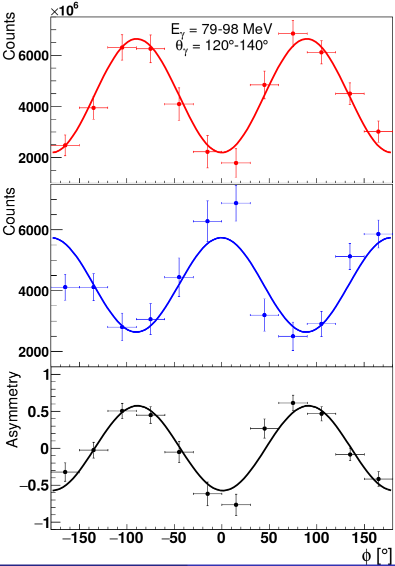
- Agreement with Olmos et al.
- Compatible (or better) statistics in the new data
- Significant deviation from Born contribution
- Extension of the angular coverage in the forward direction

Example of ϕ distribution

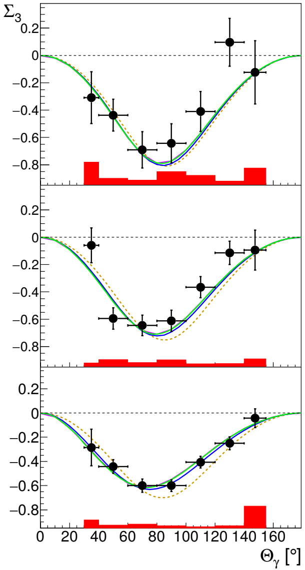
ϕ distribution for PARA and PERP data

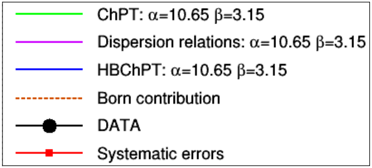
$\cos(2\phi)$ modulation clearly seen

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 cos(2\phi)\right]$$



Σ_3 results





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B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76 (2007)

J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)

Fit on our Σ_3 results using Baldin sum rule constrain gives

BChPT framework:

$\beta_{M1} = (2.8^{+2.3}_{-2.1})\ 10^{-4}\ \text{fm}^3$

HBChPT framework:

$\beta_{M1} = (3.7^{+2.5}_{-2.3})\ 10^{-4}\ \text{fm}^3$

New experiment @ MAMI

- **Proposed experiment: 600 hours of Compton scattering on proton:**

→ Measurement of the beam asymmetry Σ_3 and unpolarized cross-section

→ 10 cm LH_2 target and a polarized photon beam with $E_{e^-} = 883$ MeV

- **Improvement in statistics:**

	Diamond (both sets)		Copper radiator	
Experiment	Full target	Empty target	Full target	Empty target
Pilot	116 h	110 h	42 h	39 h
Proposed	500 h	70 h	30 h	-

- Tagger upgrade → improvement in rate ∼5 times

⇒ Decrease of the statistical error ∼3.5 times

- **Improvement in systematics:**

→ Stable linear polarization with the new setup

→ Improvement in tagger performance

→ Continuous tagging efficiency monitor with pair spectrometer

⇒ Smaller systematic errors

Achieved and expected precision

BChPT fits from P. Martel

Experiment	Compton ev.		Error from ChPT fit (10^{-4} fm^3)					
			With Baldin			Without Baldin		
			Σ_3	$\frac{d\sigma}{d\omega}$	$\Sigma_3, \frac{d\sigma}{d\omega}$	Σ_3	$\frac{d\sigma}{d\omega}$	$\Sigma_3, \frac{d\sigma}{d\omega}$
Pilot	$\approx$ 200000	$\Delta\alpha_{E1}$	2.5	1.3	1.1	3.8	1.4	1.3
		$\Delta\beta_{E1}$				2.5	1.7	1.4
Proposed	$\approx$ 4000000	$\Delta\alpha_{E1}$	0.7	0.4	0.3	1.1	0.4	0.4
		$\Delta\beta_{E1}$				0.7	0.5	0.4

$\Rightarrow$ Highest statistic data set: Olmos et al. ($\sim$ 50% of the existing data):

	with Baldin	without Baldin
α_{E1}	12.1 ± 1.08	11.9 ± 1.39
β_{E1}	1.6 ± 0.89	1.2 ± 0.76

$\Rightarrow$ Word data errors (without double counting):

α_{E1}	0.76	β_{E1}	0.69

$\Rightarrow$ **Precision improved compared to the existing data based on a single measurement!**

Summary and outlook

- **Successful pilot experiment!**

→ Low background data set in the range 79 – 139 MeV
→ First measurement of the beam asymmetry Σ_3 below pion threshold
→ Alternative extraction of β_{M1} using ChPT and HBChPT frameworks
→ Preliminary measurement of the unpolarized cross-section in agreement with theoretical calculations and existing data

- **Proposed experiment:**

→ New measurement of the proton scalar polarizabilities with an unprecedently high precision
→ Simultaneous measurement of the unpolarized cross-section and beam asymmetry
→ Increased of the statistics and reduced of the systematic effects

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THANK YOU FOR YOUR ATTENTION!

BACKUP

Analysis conditions

⇒ The best way to extract β is the beam asymmetry Σ_3:

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

⇒ We selected Compton scattering $\vec{\gamma}\mathrm{p} \rightarrow \gamma(\mathrm{p})$ events:

- $E_{\gamma_{beam}} = 79 - 139$ MeV
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⇒ More than 200,000 Compton scattering events

Measurement of α and β

$$\Sigma_3 = \Sigma_3^{(\mathrm{B})} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2}\beta_{M1} + O(\omega^4), \qquad (6)$$

where $\Sigma_3^{(\mathrm{B})}$ is the pure Born contribution, while

$$\omega = \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \qquad (7)$$

are the photon energy and scattering angle in the Breit (brick-wall) reference frame. In fact, to this order in the LEX the formula is valid for ω and θ being the energy and angle in the lab or center-of-mass frame.

Proton scalar polarizabilities

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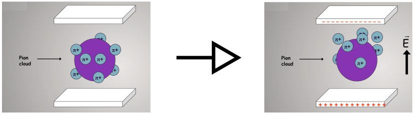

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