Spin Polarizability of a Proton via Measurement of Nuclear Structure Observable with Polarized Target and Polarized Beam at MAMI

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Nuclear Compton Scattering and polarizabilities

Expand the Hamiltonian in incident- photon energy.

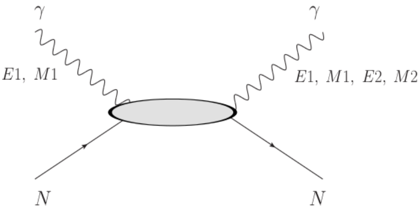
- Second Order → Scalar Polarizabilities

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

- Third Order → Spin Polarizabilities

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

where, $\dot{\vec{E}} = \partial_t \vec{E}$, $\dot{\vec{H}} = \partial_t \vec{H}$, $E_{ij} = \frac{1}{2}(\partial_i E_j + \partial_j E_i)$ and $H_{ij} = \frac{1}{2}(\partial_i H_j + \partial_j H_i)$



quantity	incident γ	scattered γ
α_{E1}	$E1$	$E1$
β_{M1}	$M1$	$M1$
γ_{E1E1}	$E1$	$E1$
γ_{M1M1}	$M1$	$M1$
γ_{M1E2}	$M1$	$E2$
γ_{E1M2}	$E1$	$M2$

Previous Results on Spin Polarizabilities

- Forward spin polarizability (Ahrens et al., PRL**87**, 022003 (2001))

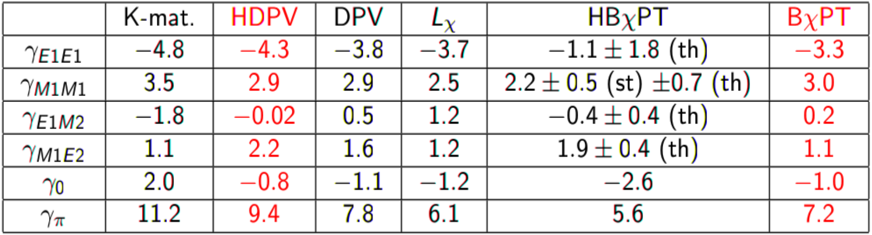
$$\begin{aligned}\gamma_0 &= -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2} \\ &= -\frac{1}{4\pi^2}\int_{\omega_{th}}^{\infty} \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega^3} d\omega, \\ &= (-1.0 \pm 0.08 \pm 0.10) \times 10^{-4} fm^4\end{aligned} \tag{3}$$

- Backward spin polarizability (Schumacher, Prog. Part. Nucl. Phys. **55**, 567 (2005))

$$\begin{aligned}\gamma_\pi^{disp.} &= -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2} \\ &= (8.0 \pm 1.8) \times 10^{-4} fm^4\end{aligned} \tag{4}$$

- Note: $\gamma_\pi^{\pi^0-pole}$ contributes -46.7 $\times 10^{-4} fm^4$.

Proton Spin Polarizability Predictions



	K-mat.	HDPV	DPV	L_χ	HBχPT	BχPT
γ_{E1E1}	-4.8	-4.3	-3.8	-3.7	-1.1 ± 1.8 (th)	-3.3
γ_{M1M1}	3.5	2.9	2.9	2.5	2.2 ± 0.5 (st) ± 0.7 (th)	3.0
γ_{E1M2}	-1.8	-0.02	0.5	1.2	-0.4 ± 0.4 (th)	0.2
γ_{M1E2}	1.1	2.2	1.6	1.2	1.9 ± 0.4 (th)	1.1
γ_0	2.0	-0.8	-1.1	-1.2	-2.6	-1.0
γ_π	11.2	9.4	7.8	6.1	5.6	7.2

- Spin-polarizabilities in units of $10^{-4}\ fm^4$.
- K-mat : **Kmatrix** ⇒ *Kondratyuk et al., PRC 64, 024005 (2001)*
- HDPV , DPV: **Dispersion Relation** ⇒ Holstein et al., PRC **61** 034316 (2000), Drechsel et al., Phys.Rev. **378** 99 (2003), Pasquini et al., PRC **76** 015203 (2007).
- L_χ: **Chiral Lagrangian** ⇒ Gasparyan et al., NP A**866** 79 (2011)
- *HBχPT*, *BχPT*: **Heavy Baryon & Covariant Chiral PT** ⇒ J. A. McGovern et al., Eur. Phys. J.A 49,12 (2013)

Best Way to extract Spin Polarizabilities.

- **Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy**
  - It is in the $\triangle$ (1232) resonance region ($E_\gamma = 250 - 350$ 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} and β_{M1}.
  - extract all four spin polarizabilities independently with small statistical, systematic and model-dependent errors.

Double Polarization Asymmetry $\sum_{2z}$

Left helicity state of the beam, target Polarized in +z direction

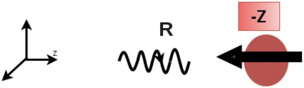
(σ^{L}_{+z}).

Right helicity state of the beam, target Polarized in +z direction

(σ^{R}_{+z}).

Left helicity state of the beam, target Polarized in -z direction

(σ^{L}_{-z}).



Right helicity state of the beam, target Polarized in -z direction

(σ^{R}_{-z}).

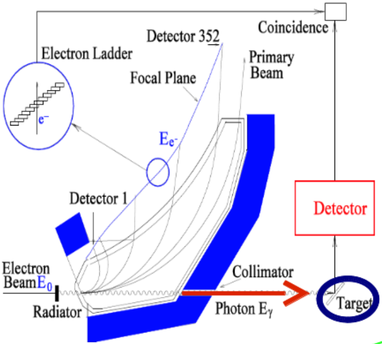
$\sum_{2z}$ in terms of Cross section and Number of events

$$\sum_{2z} = \frac{1}{P_\gamma P_t} \left(\frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} \right), \tag{5}$$

- The degree of target polarization is different for positively and negatively polarized target, so in terms of Number of events the Asymmetry formula is

$$\sum_{2z} = \frac{1}{P_\gamma} \left(\frac{(N^R_{+z} + N^L_{-z}) - (N^L_{+z} + N^R_{-z})}{P_{+z}(N^R_{+z} + N^L_{-z}) + P_{-z}(N^L_{+z} + N^R_{-z})} \right) \tag{6}$$

Experimental Apparatus at MAMI

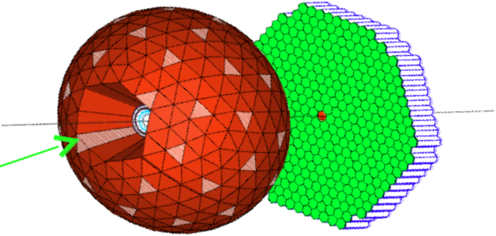


Crystal Ball

- 672 NaI crystals, separate PMT and 94 % solid angle coverage

TAPS

- 366 BaF2, 72 PbWO4 Crystals and 384 Veto Paddles



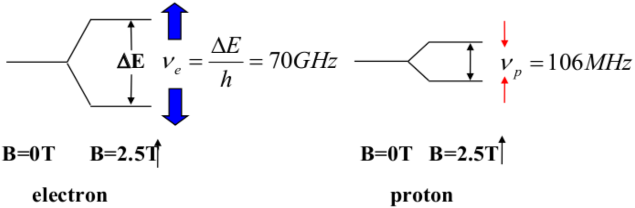
PID

- Cylindrical detectors, 24 thin plastic scintillator strips,Identification of charged particles

MWPC

MWPC between PID and CB for track reconstruction of charged particles

Target Polarization: Dynamic Nuclear Polarization



- Polarizing Mode: Cool target to 0.2 K, use 2.5 Tesla magnet to align electron spins, pump 70 GHz microwaves, causing spin-flips between the electrons and protons.
- Frozen Spin Mode: Cool target to 0.025 K, ‘freezing’ proton spins in place, remove polarizing magnet, energize 0.6 Tesla ‘holding’ coil in the cryostat to maintain the polarization.
- Relaxation times > 1000 hours, Polarizations up to 90%.

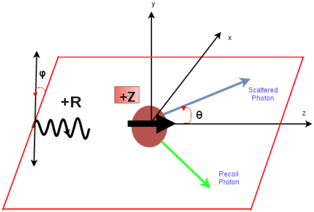
2014 and 2015 beamtime summary

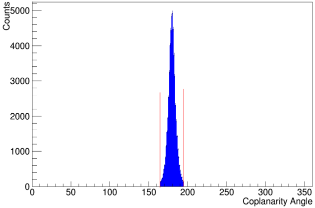
	April 2014	May 2014	June 2015	June 2015
Target Material	Carbon	FS Butanol	FS Butanol	Carbon
Radiator	Moeller	Moeller	Moeller	Moeller
Time (hours)	140	190 + 90	140 + 160	55
Electron Energy (MeV)	450	450	450	450
Beam Current (nA)	7.5	7.5	20	20
Collimator (mm)	2.5	2.5	2.5	2.5
Energy Sum (MeV)	> 40	> 40	> 90	>90
Tagger Channels used	270	270	180	180
Target Polarization	-	62%, 59%	63%, 60%	-
E_γ Polarization	72%	72 %	72 %	72%

- **Positively polarized**, Negatively polarized,

Compton Scattering: Event Selection

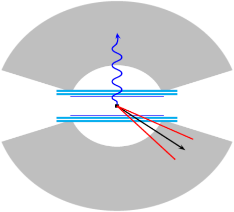
- Require ONLY one **neutral** and one **charged track**.
- Require a cut on Coplanarity Angle, $\Delta\phi = |\phi_{\gamma} - \phi_{recoil}| = 180^{\circ} \pm 15^{\circ}$

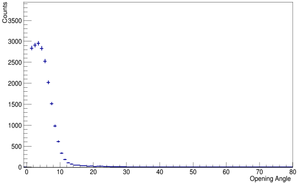




Sharp peak centered at 180° (MC Simulation).

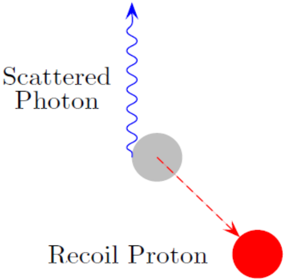
- Opening Angle, $cos(\Omega_{OA}) = \frac{\vec{p}_{miss}\cdot\vec{p}_{recoil}}{|\vec{p}_{miss}|\times|\vec{p}_{recoil}|} = 10^{\circ}$



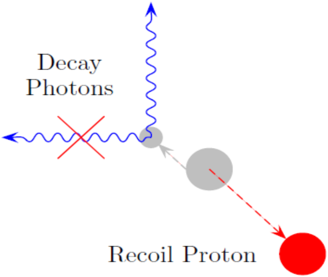


Peak below 10° (MC Simulation).

π^0 Background



Compton Scattering

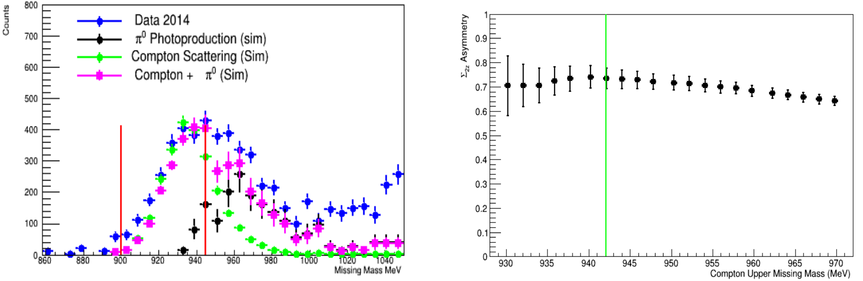


π^0 Photoproduction .

- Provides an excellent reaction for systematic checks and constraints. Due to the large cross-section (and clean reaction signal), π^0 production is an ideal reaction to perform systematic checks

Compton Missing Mass

$$m_{miss} = m_p = \sqrt{\left(E_{\gamma i} + m_p - E_{\gamma f}\right)^2 - \left(\vec{P}_{\gamma i} - \vec{P}_{\gamma f}\right)^2} \tag{7}$$



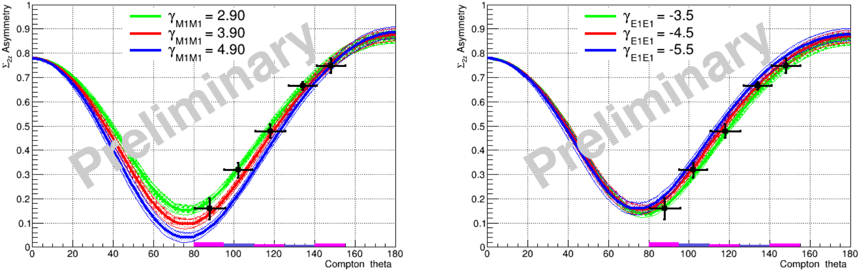
Missing Mass at E_γ = (285 - 305) MeV

Compton $\sum_{2z}$ Asymmetry versus upper missing mass

Figure: Results from 2014 beamtime at $\theta_\gamma = 125 - 140^\circ$.

Compton $\sum_{2z}$ Asymmetry at E_γ = (285 - 305) MeV

- Curves are from DR calculation of Pasquini et al., making use of constraints on γ_0, γ_π, $\alpha_{E1} + \beta_{M1}$ and $\alpha_{E1} - \beta_{M1}$ to vary by their experimental errors.

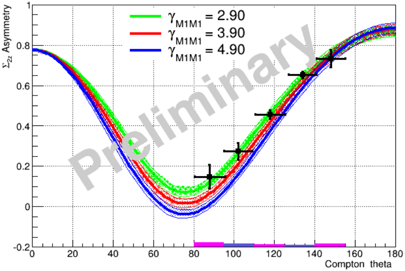


Fix $\gamma_{E1E1} = -3.7$, vary γ_{M1M1}

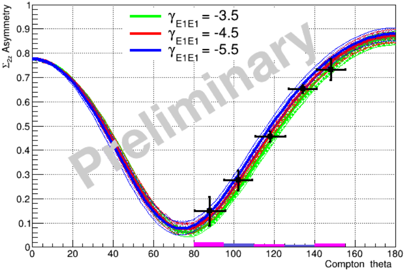
Fix $\gamma_{M1M1} = 2.9$, vary γ_{E1E1}

Figure: Error band represents the systematic error

Compton $\sum_{2z}$ Asymmetry at E_γ = (265 - 285) MeV



Fix $\gamma_{E1E1} = -3.7$, vary γ_{M1M1}



Fix $\gamma_{M1M1} = 2.9$, vary γ_{E1E1}

Proton Spin Polarizabilities Status and Future Work

- Extract proton spin polarizabilities using the results from the series of all three Asymmetry experiments ($\sum_{2x}$, $\sum_3$ and $\sum_{2z}$).
- Finalize the systematic errors and prepare a draft paper.
- Graduate in summer 2017.

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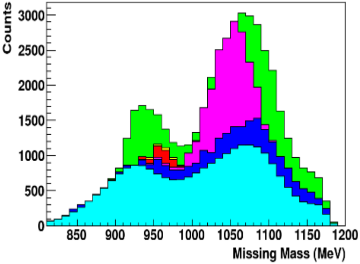
NSERC CRSNG

CINP ICPN Canadian Institute of Nuclear Physics Institut canadien de physique nucléaire

NSERC Grant: SAPPJ-2015-00023

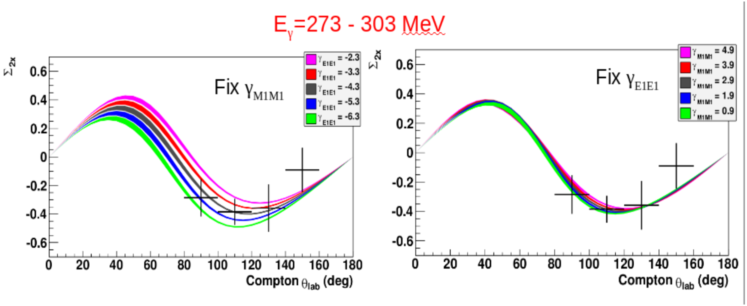
Thank You

$\sum_{2x}$ Martel, et al.



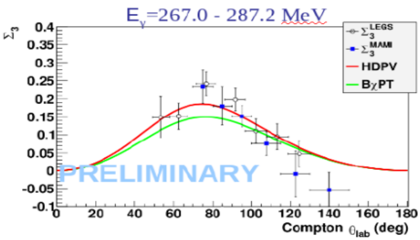
- MM distribution for $E_\gamma = 273 - 303$ MeV, $\theta_{\gamma'} = 100 - 120$ degree.
- Background contributions to MM: accidental coincidences , carbon/cryostat contributions (blue), reconstructed π_0. background where one decay γ escapes setup in: TAPS downstream hole and CB upstream hole.
- Right: Fully-subtracted MM spectrum with simulated Compton peak and conservative MM <940 MeV cut is applied to exclude neutral pion production

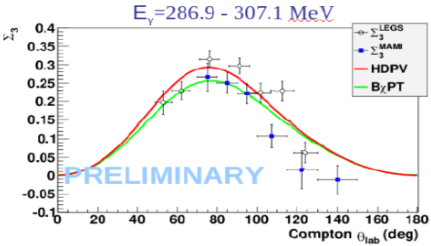
$\sum_{2x}$ Martel, et al.

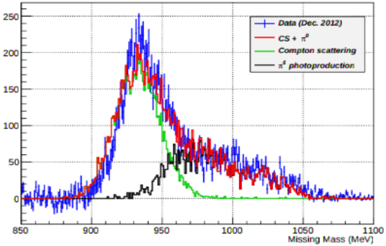


- New results. Physical Review Letters 114, 112501 (2015), arXiv:1408.1576 [nucl-ex]
- Measurement of a $\sum_{2x}$ asymmetry on the nucleon. Curves are from DR calculation of Pasquini et al., making use of constraints on γ_0, γ_π,$\alpha_{E1} + \beta_{M1}$, $\alpha_{E1} - \beta_{M1}$ (allowed to vary within experimental errors).
- Checks were done with $B\chi PT$ calculation of Lensky and Pascalutsa

$\sum_3$ Collicot, et al.



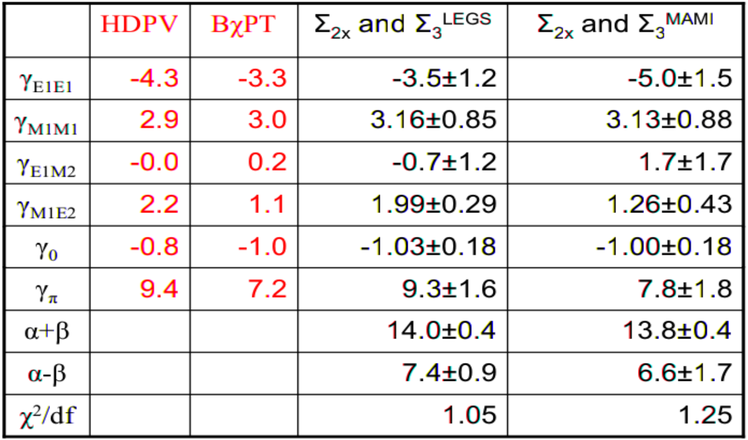




- **New MAMI and Older LEGS measurements along with two theoretical curves using their preferred polarizabilities**

- **Simulation of neutral pion photoproduction in Liquid hydrogen target matches background of the distribution quite well**

Frame Preliminary Combined Spin Polarizabilities



	HDPV	BχPT	Σ_{2x} and Σ_3^{LEGS}	Σ_{2x} and Σ_3^{MAMI}
γ_{E1E1}	-4.3	-3.3	-3.5±1.2	-5.0±1.5
γ_{M1M1}	2.9	3.0	3.16±0.85	3.13±0.88
γ_{E1M2}	-0.0	0.2	-0.7±1.2	1.7±1.7
γ_{M1E2}	2.2	1.1	1.99±0.29	1.26±0.43
γ_0	-0.8	-1.0	-1.03±0.18	-1.00±0.18
γ_π	9.4	7.2	9.3±1.6	7.8±1.8
$\alpha+\beta$			14.0±0.4	13.8±0.4
$\alpha-\beta$			7.4±0.9	6.6±1.7
χ^2/df			1.05	1.25

- Dispersion relation fits to $\sum_{2x}$ along with either $\sum_3^{MAMI}$ or $\sum_3^{LEGS}$
- (Note: Pion pole contribution has been subtracted)