Measuring the Spin-Polarizabilities of the Proton in Polarized Compton Scattering at MAMI-Mainz

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Unpolarized Compton scattering data have been used with great success to measure the electric and magnetic polarizabilities of the proton. However relatively little is known about the spin-polarizabilites of the proton, which parameterize how a polarized photon interacts with the spin of the proton. At $O(\omega^3)$ four spin-polarizabilities γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, and γ_{M1E2} enter the Compton scattering amplitude. The most model independent way to determine the spin-polarizabilities is by measuring Compton scattering asymmetries in the Δ region with circularly polarized photons and a transverse or longitudinally polarized target, Σ_{2x} and Σ_{2z}, and by measuring the in-plane/transverse-plane Compton scattering asymmetry on an unpolarized target with linearly polarized photons, Σ_3. This talk will present new Compton scattering data for Σ_{2x} taken by the A2 Collaboration using the Crystal Ball at Mainz. The incident photon energies ranged from 270 MeV to 2π threshold, and the Compton scattering angles ranged from 50° to 150°. The data are compared with the results of a dispersion theory calculation for Compton scattering, and the sensitivity of the data to the proton spin-polarizabilties are presented.

1. Introduction

Polarizabilities tell us about the response of a system when an external electromagnetic field is applied. At $O(\omega^3)$ nucleon spin-flip operators enter the Compton scattering amplitude, and the constants that multiply the operators are the spin-polarizabilities, given by γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, and γ_{M1E2}, where the multipoles refer to the incident and outgoing photons.

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

In qualitative terms spin polarizabilities tell us about the response of the nucleon spin to the photon polarization. The ``stiffness'' of the spin can be thought of as arising from the nucleons spin interacting with the pion cloud. Polarizabilities can be calculated in dispersion theory, in effective field theories to order $O(\omega^4)$, and in the near future, from lattice calculations. Precision measurements of nucleon polarizabilities are essential in order to extend our knowledge of hadron structure and low-energy QCD.

2. Existing measurements and theoretical predictions

Measurements have been made of two combinations of the spin-polarizabilities. The forward spin-polarizability, γ_0, defined in the multipole basis as

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

has been evaluated using the Gell-Mann, Goldberger, and Thirring sum rule

$$\gamma_0 = \frac{1}{4\pi^2}\int_{m_\pi}^{\infty}\frac{\sigma_{3/2}-\sigma_{1/2}}{\omega^3}d\omega = \left(-1.01\pm.08\pm.10\right)\times10^{-4}\,fm^4$$

where the errors are statistical and systematic. The backward spin-polarizabilty, γ_π, defined in the multipole basis as

$$\gamma_\pi = -\gamma_{E1E1}-\gamma_{E1M2}+\gamma_{M1E2}+\gamma_{M1M1} = \left(-8.0\pm1.8\right)\times10^{-4}\,fm^4$$

has been obtained from a dispersive analysis of unpolarized Compton scattering.

Table 1 presents the results from theory and experiment for the spin-polarizabilities. At present, no data exist for the separated spin-polarizabilities in the multipole basis.

3.Sensitivity of the spin-polarizabilities to Compton scattering asymmetries

The most model independent determination of the proton spin-polarizabilities is through Compton scattering asymmetries in the Δ region. Because the spin-polarizability effect goes at $O(\omega^3)$, energies above pion threshold are needed to amplify the effect. Asymmetries can be measured with incident circularly polarized photons and a transverse or longitudinal polarized target (Σ_{2x}, Σ_{2z}), and through an asymmetry for Compton scattering parallel/perpendicular to the direction of linear polarization (Σ_3). Fig. 1 shows a sensitivity plot of the Σ_{2x} asymmetry (transverse polarized target) when the spin polarizabilities are allowed to vary. Cross sections are calculated using the dispersion theory calculation of Drechsel et al.[1] In the plot on the left,

γ_0 and γ_π are held fixed at their experimental values, γ_{E1E1} is held at the nominal value from Ref. [2] and γ_{M1M1} is allowed to vary from 1.9 to 3.9 in the standard units. For the plot on the right, the same conditions hold, however in this case γ_{M1M1} is held at the nominal value from Ref. [2] and γ_{E1E1} is allowed to vary from -3.3 to -5.3 in the standard units. The width of the bands shows the propagated errors from the uncertainties in the α, β, γ_0 and γ_π. Fig. 1 shows that under conditions where α, β, γ_0 and γ_π are constrained by their experimental values, the Σ_{2x} asymmetry has weak sensitivity to γ_{M1M1}, and good sensitivity to γ_{E1E1}.

4.Measuring Compton scattering asymmetries in the Δ region at MAMI-Mainz

Data were taken using the Crystal Ball and TAPS detectors at Mainz. Fig. 2 shows a schematic view of the detector system. The CB/TAPS system subtends approximately 80% of 4π solid angle, and both the Compton scattered photon and recoil proton are detected. The target was a frozen-spin butanol target, with polarization ~90% and relaxation time ~1000 hours. Details of the experimental setup, data taking, and analysis are given in the Ph.D. thesis of P. Martel[3]. Fig. 3 shows a missing mass spectrum from Martel's analysis where the proton mass peak is clearly visible, as are background events at higher missing mass.

Preliminary experimental asymmetries are presented in Fig. 4 for Σ_{2x}. As demonstrated in Fig. 1, the Σ_{2x} asymmetry has good sensitivity to the γ_{E1E1} spin-polarizability and small sensitivity to γ_{M1M1}, provided that α, β, γ_0 and γ_π are constrained by their experimental values. Based on the position of the asymmetry points on the plot, the statistical errors, and the negligible sensitivity to γ_{M1M1}, we can make a ***preliminary estimate*** for $\gamma_{E1E1} \approx (-4.5 \pm 1) \times 10^{-4}$ fm^4. This value for γ_{E1E1} is in good agreement with dispersion theory calculations.

5.Summary and outlook

The data presented here are the first Compton scattering double-polarization observables on the proton ever measured. The data are sensitive to the γ_{E1E1} spin-polarizability, and can be used to make a preliminary estimate $\gamma_{E1E1} \approx (-4.5 \pm 1) \times 10^{-4}$ fm^4. This estimate will be revised and presented in a future publication, where the effects of finite energy binning and theoretical model dependence will be taken into account.

One of the objectives of the Compton scattering program at Mainz is to measure the four separated spin-polarizabilities of the proton with an accuracy of approximately $\pm 0.5 \times 10^{-4}$ fm^4 through measurements of Σ_{2x}, Σ_{2z}, and Σ_3. In these analyses it will be reasonable to use the experimental constraint on γ_0, because γ_0 is known very well, but not the experimental constraint on γ_π, which is known relatively poorly.

Recently, in late 2012, new Compton scattering data were taken at Mainz with linearly polarized photons and a liquid hydrogen target to measure the Σ_3 asymmetry in the Δ region. Looking towards the future, the frozen-spin target will be reinstalled with longitudinal polarization in summer and fall 2013 and running on Σ_{2z} will commence sometime after that. Over the next

few years we can expect that polarized Compton scattering measurements at Mainz will allow for the determination of all four proton spin-polarizabilities with reasonable accuracy.

	Chiral perturbation theory			Lorentz			Dispersion theory				
	$O(p^3)$	$O(p^4)$	$O(p^4)$	LC3	LC4	SSE	BGLMN	HDPV	KS	DPV	Experiment
γ_{E1E1}	-5.7	-1.4	-1.8	-3.2	-2.8	-5.7	-3.4	-4.3	-5.0	-4.3	-
γ_{M1M1}	-1.1	3.3	2.9	-1.4	-3.1	3.1	2.7	2.9	3.4	2.9	-
γ_{E1M2}	1.1	0.2	.7	.7	.8	.98	0.3	-0.01	-1.8	0	-
γ_{M1E2}	1.1	1.8	1.8	.7	.3	.98	1.9	2.1	1.1	2.1	-
γ_0	4.6	-3.9	-3.6	3.1	4.8	.64	-1.5	-.7	2.3	-.7	-1.01 ±0.08 ±0.10
γ_π	4.6	6.3	5.8	1.8	-.8	8.8	7.7	9.3	11.3	9.3	8.0± 1.8

Table 1. Theory and experiment for the proton spin-polarizabilities. Units are 10^{-4} fm^4. $O(p^n)$ are CPT calculations [4][5][6]. LC3 and LC4 are $O(p^3)$ and $O(p^4)$ Lorentz invariant CPT calculations, respectively [7]. SSE is a calculation in the small-scale-expansion [4]. BGLMN, HDPV, KS, and DPV are dispersion relation calculations [8][2][9][1]. The data for γ_0 and γ_π are from [10] and [11], respectively.

References

[1] D. Drechsel, B. Pasquini, M. Vanderhaeghen, Phys. Rep. 378, 015204 (2003).

[2] B. Holstein, D. Drechsel, B. Pasquini, M. Vanderhaeghen, Phys. Rev. C 61, 034316 (2000).

[3] P. Martel, PhD thesis, University of Massachusetts, 2012.

[4] T.R. Hemmert, B.R. Holstein, J. Kambor, and G. Knochlein, Phys. Rev. D 57, 5746 (1998)

[5] V. Vijaya Kumar, J. McGovern, M. Birse, Phys. Lett B 479, 167 (2000).

[6] G. Gellas, T. Hemmert, Ulf-G. Meißner, Phys. Rev. Lett 86, 14 (2001)

[7] D. Djukanovic, PhD thesis, Johannes Gutenberg Universitat Mainz, Germany, June 2008.

[8] D. Babusci, G. Giordano, A. L'vov, G. Matone, A. Hathan, Phys. Rev. C 58, 1003 (1998).

[9] S. Kondratyuk, O. Scholten, Phys. Rev. C 64, 024005 (2001).

[10] GDH and A2 collaborations, Phys. Rev. Lett. 87,2 (2001); H. Dutz, et al., Phys. Rev. Lett 91, 19 (2003).
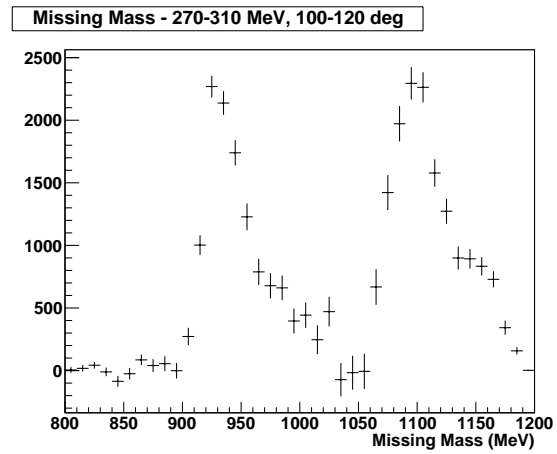
[11] M. Camen et al., Phys. Rev. C 65, 0302202 (2002); M. Schumacher, Prog. Part. Nucl. Phys. 55, 567 (2005); B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rev. C 76, 015203 (2007).
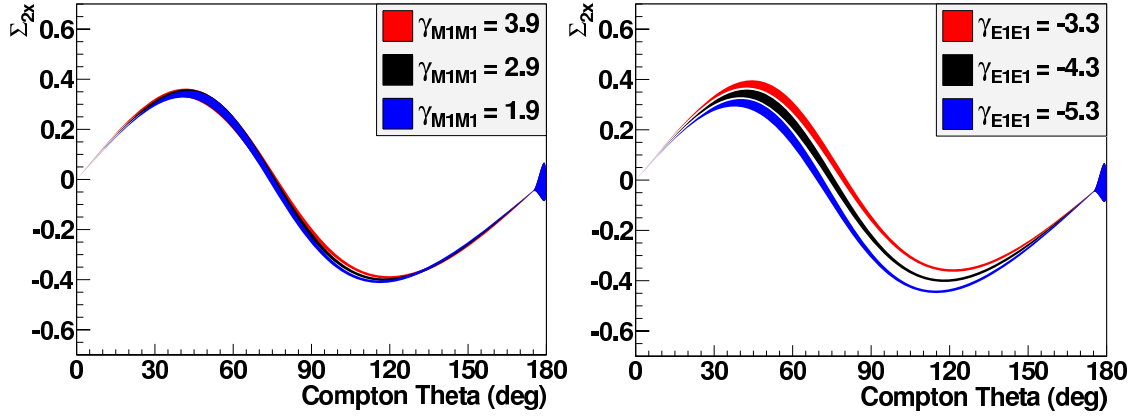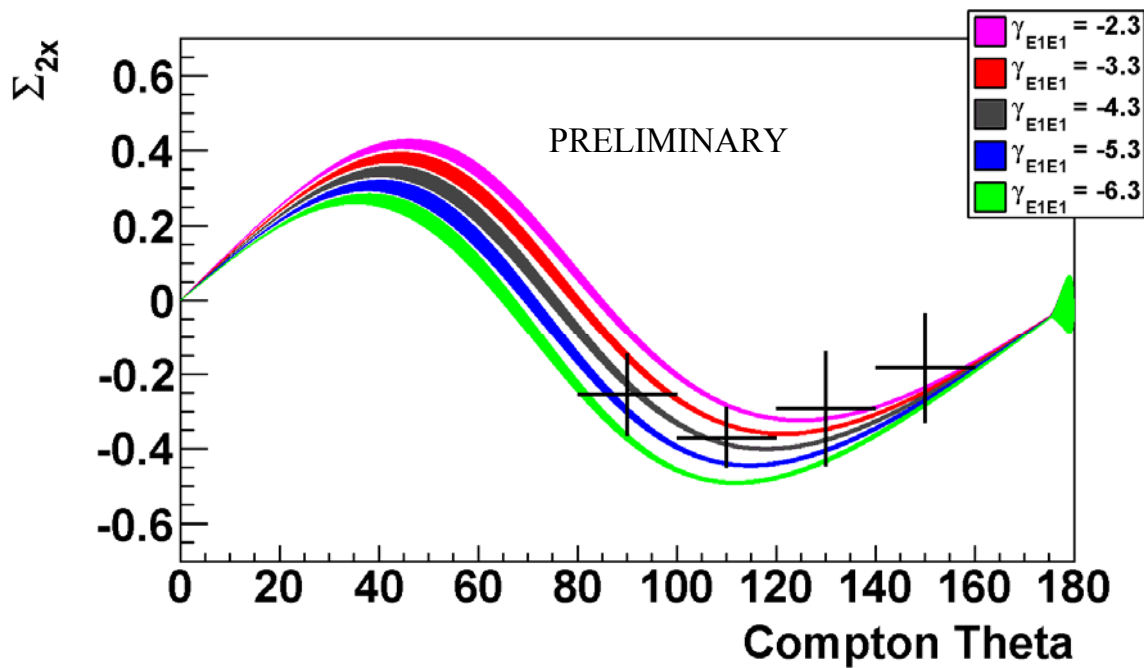
Fig. 1. Left plot, sensitivity to γ_{M1M1} (see text for details). Right plot, sensitivity to γ_{E1E1}. The incident photon energy is 290 MeV.
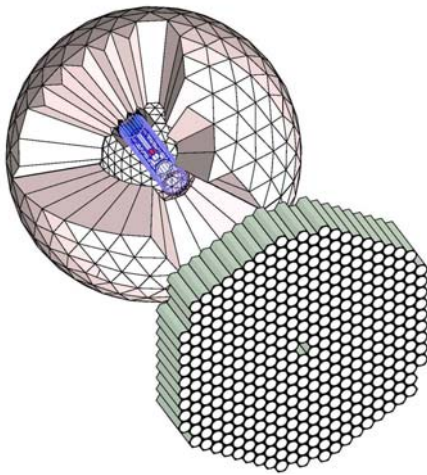
Fig. 2. Diagram of the Crystal Ball and TAPS detectors.

Fig. 3. Missing mass spectrum over incident energies 270 to 310 MeV, and scattering angles 100° to 120°. The vertical axis is counts, the horizontal MeV.

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Fig. 4. Preliminary experimental asymmetries. The bands are calculations for different values of γ_{E1E1}.