Proton Spin Polarizabilities with Polarized Compton Scattering

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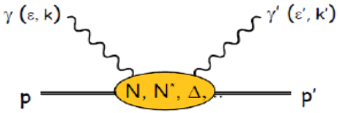
Outline of the talk

1. Nuclear Compton Scattering
   - Scalar Polarizability
     - Electric and Magnetic Scalar Polarizability
   - Spin Polarizability
     - Electric and Magnetic Spin Polarizability
2. Mainz Microtron (MAMI)
   - Experimental data status and results

Nuclear Compton Scattering Equations



$$\gamma(k) + P(p) \rightarrow \gamma(k') + P(p')$$

- Low energy outgoing photon plays a role of an applied EM dipole field
- Internal Structure constants are accessed via Nuclear Compton scattering off a single proton
- Scattering amplitude can be expanded in terms of photon energy

$$H_{eff}^{(0)} = \frac{\left(\vec{p} - e\vec{A}\right)^2}{2m} + e\phi \quad (1)$$

$$H_{eff}^{(1)} = \frac{e(1+\kappa)}{2m}\vec{\sigma}.\vec{H} - \frac{e(1+2\kappa)}{8m^2}\vec{\sigma}.\left[\vec{E}\times\vec{p} - \vec{p}\times\vec{E}\right] \quad (2)$$

How to measure Electric and Magnetic Polarizabilities

- Effective Hamiltonian in second order contains scalar polarizabilities which are the evidence of proton's internal structure

$$H_{eff}^{(2)} = -4\pi \left[\frac{1}{2} \alpha_{E1} \vec{E}^2 + \frac{1}{2} \beta_{M1} \vec{H}^2 \right] \quad (3)$$

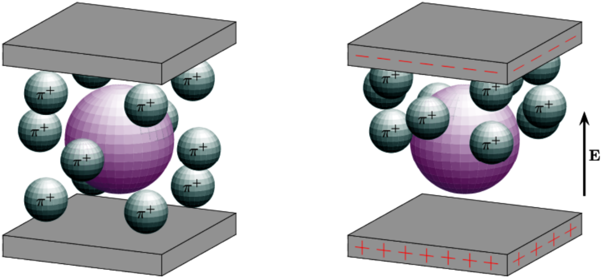
- Where α_{E1} and β_{M1} are measured via unpolarized Compton scattering experiment and represent the internal response of the proton to the applied electric or magnetic field.
- PDG2014 values are:

$$\alpha_{E1} = [11.1 \pm 0.3\,(stat) \mp 0.4\,(syst) \pm 0.3\,(model)] \times 10^{-4} fm^3 \quad (4)$$

$$\beta_{M1} = [2.5 \pm 0.4\,(stat) \pm 0.4\,(syst) \pm 0.4\,(model)] \times 10^{-4} fm^3 \quad (5)$$

Electric Polarizability Visualization

Proton stretched in the direction of Electric field

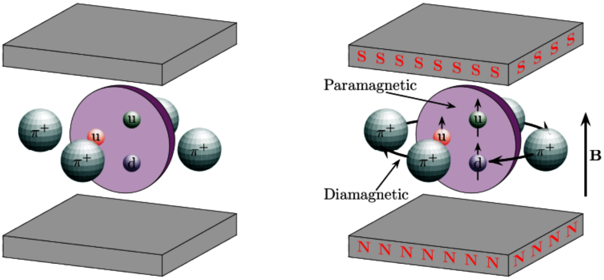


(a) Electric field off (b) Electric field on

- Induced current in the pion cloud separates the positive from negative pions, physically stretching the proton in the direction of the electric field
- α_{E1} can be understood as electric 'stretchability'

Magnetic Polarizability Visualization

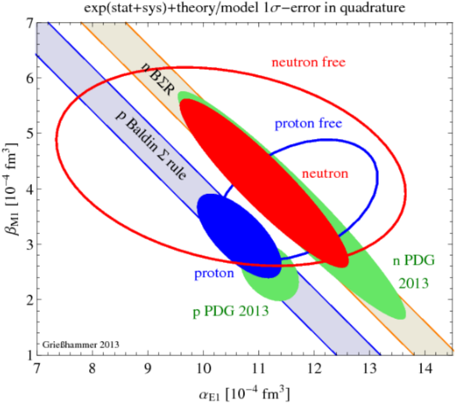
Proton aligned in magnetic field



- Induced current in the cloud creates a diamagnetic moment which opposes the paramegnetic moment of the constituent quarks
- β_{M1} can be understood as magnetic 'alignability'

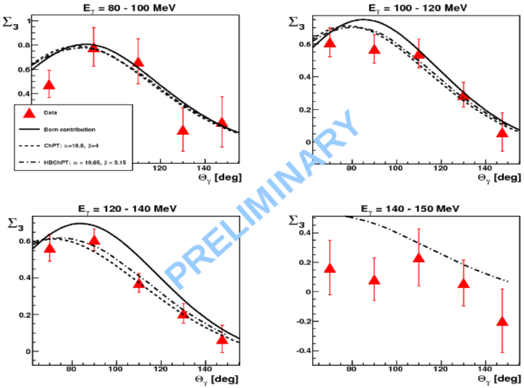
Reanalysis of Compton Data Constraints

McGovern, Phillips, Griesshammer
EPJA **49**, 12 (2013)



- Electric polarizability α_{E1} well constrained by experimental data.
- Magnetic polarizability β_{M1} less certain
- Neutron data are particularly uncertain.

α_{E1} and β_{M1} from Σ_3 Asymmetry- Sokhoyan, et al.



- Only 1/3 of approved data taken so far.
- Curves:
  - χPT: Krupina and Pascalutsa, PRL 110, 262001 (2013)
  - $HB\chi PT$: J. McGovern, D. Phillips, H. Griesshammer, EPJA 49, 12 (2013)

Spin Polarizabilities

- The third order effective Hamiltonian term in the expansion:

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

- These constants (γ) are spin (or vector) polarizabilities which describe the response of the proton spin to an applied electric or magnetic field.
- To date, these have not been individually determined. However, two linear combinations of them have been.

Forward and Backward Polarizabilities

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2} \quad (6)$$

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2} \quad (7)$$

Model Prediction of Spin Polarizabilities

	Kmat	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	-0.0	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

- **K-matrix:** *Kondratyuk et al., PRC 64, 024005 (2001)*
- **HDPV, DPV (Dispersion Relation):** *Holstein et al., PRC 61, 034316 (2000) Drechsel et al., Phys.Rep. 378, 99 (2003) Pasquini et al., PRC 76, 015203 (2007)*
- L_χ **(Chiral Lagrangian):** *Gasparyan et al., NP A866, 79 (2011)*
- *HBχPT*, *BχPT* **(Heavy Baryon & Covariant Chiral PT)**: *McGovern et al., EPJ A49, 12 (2013) Lensky et al, PRC 89, 032202 (2014)*

Better way to extract Spin Polarizabilities

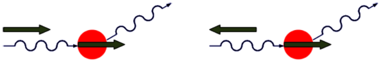
- **Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy**
  - It is in the $\triangle$ resonance region ($E_\gamma = 200 - 300$ MeV) where their effect becomes significant.
- **In this energy region, it is possible to accurately measure polarization asymmetries using a variety of polarized beam and target combinations**
  - The various asymmetries respond differently to the individual spin polarizabilities at different E and θ.
  - Measure three asymmetries at different E, 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.

Beam-target Assymetry

Three different Compton scattering experiments at A2:

Circularly polarized beam, longitudinaly polarized target

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



Circularly polarized beam, transversly polarized target

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

Beam Assymetry

Linearly polarized($\parallel$ *and* $\perp$ to scattering plane) beam , unpolarized target

$\sum_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$

$\sum_{2x}$, $\sum_3$ and $\sum_{2z}$ data analysis status

- Transverse Target($\sum_{2x}$): Sep 2010, Feb 2011 - 500 hours (P. Martel)
- Unpolarized Target($\sum_3$): Dec 2012- 150 hours (C. Collicot)
- **Longitudinal Target ($\sum_{2z}$)**:First round of data: Butanol (320 hours) and Carbon Target (180) hours
- Carbon Target calibration completed and working on butanol target calibration (D. Paudyal)

Crystall Ball experiment at MAMI

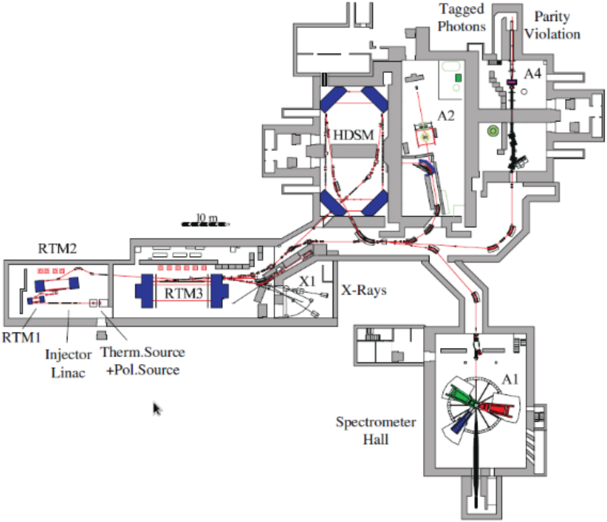
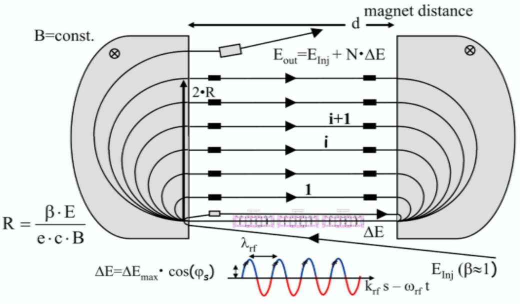


Figure : Floor Plan of MAMI

RaceTrack Microtron(RTM)



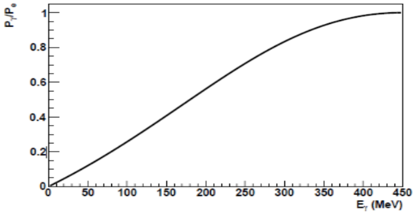
$$\triangle E = \frac{ec^2 B}{2\pi\vartheta_f}$$

- Linear accelerator (linac) sends electron beam into dipole magnet.
- Magnetic field bends the beam into one of many exit lines.
- Second dipole magnet bends the beam back into the linac.
- Finally, 'kicker' magnet ejects the beam from the microtron, Note: 2.45 GHz Klystron frequency

RTM Output

	Injector	RTM1	RTM2	RTM3	HDSM
inject. energy	611 keV	3.97 MeV	14.86 MeV	180 MeV	855 MeV
extr. energy	3.97 MeV	14.86 MeV	180 MeV	855 MeV	1508 MeV
σE	1.2 keV	1.2 keV	2.8 keV	13 keV	110 keV
# of turns	—	18	51	90	43
magn. field	—	0.1026 T	0.5550 T	1.2842 T	1.53-0.95 T
magn. weight	—	4.2 t	92.3 t	911.6 t	1030 t
linac length	4.93 m	0.80 m	3.55 m	8.87 m	8.57/10.10 m

Polarized Photon Beam

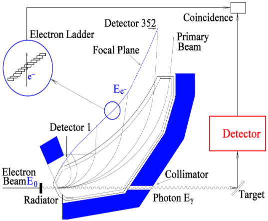


$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_{2_e} - 4E_\gamma E_e + 3E_{2_\gamma}}$$

- A high energy electron can produce Bremsstrahlung ('braking radiation') photons when slowed down by a material.
- If the electron beam is longitudinally polarized, it produces a circularly polarized photon beam through a helicity transfer.
- Pe measured with a Mott polarimeter before the RTMs.
- Circular beam helicity can be flipped by alternating the electron beam polarization (about 1 Hz).

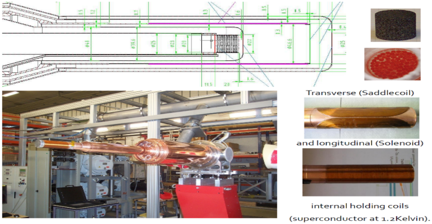
A2 Photon Tagging System

$$E_\gamma = E_e - E_{tagging}$$



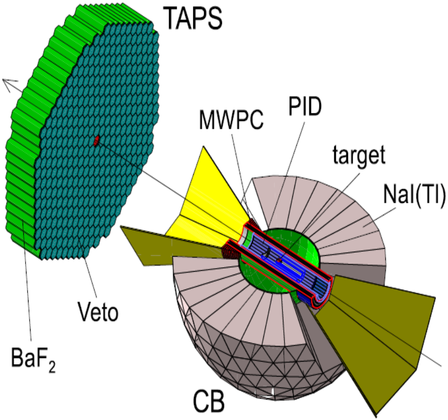
- Electron beam strikes the radiator foil (Moeller or diamond) producing Bremsstrahlung photon beam.
- Residual electrons path are bent in a magnetic dipole spectrometer magnet.
- Array of 353 focal plane detector determines the electron energy and tags the photon energy by energy conservation

Frozen Spin Butanol Target



- Longitudinally/Transversely polarized frozen spin target utilizing Dynamic Nuclear Polarization(DNP).
- Cool target to 0.2 Kelvin, use 2.5 Tesla magnet to align electron spins, pump 70 GHz microwaves (just above, or below, the electron Spin Resonance frequency), causing spin-flips between the electrons and protons.
- Cool target to 0.025 Kelvin, '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,

Detector System:CB-TAPS



Detector System:CB-TAPS Contd..

Crystall Ball(CB)

- 672 NaI Crystals, each crystal equipped with separate PMT and 93% solid angle coverage.
- $21^\circ < \theta < 159^\circ$ and Energy resolution $\approx 3\%$ θ resolution $\approx 2.5^0$

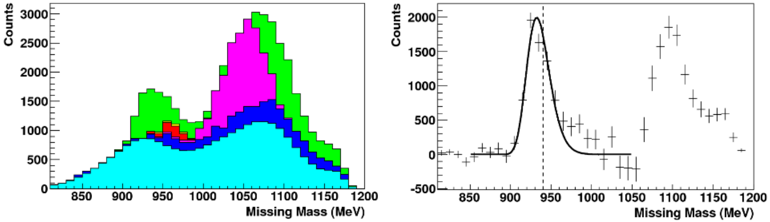
Particle Identification Detector (PID)

- Cylindrical detectors 24 thin plastic scintillator strips,
- $\Delta E/E$ identification of charged particles

Multiwire Proportional Chambers

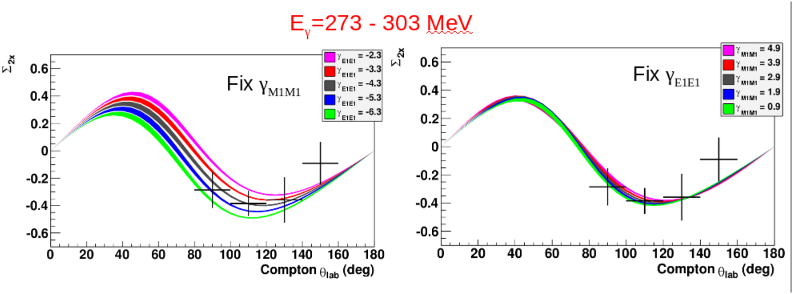
- 2 MWPC between PID and CB
- 480 wires, 320 stripes
- Track reconstruction for charged particles

Σ_{2x} – Martel, et al.



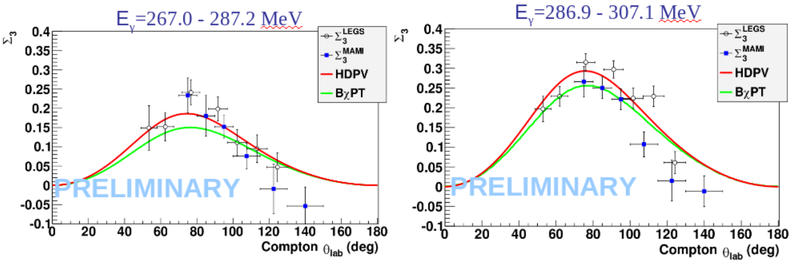
- **Background contributions to MM:** accidental coincidences, carbon/cryostat contributions, reconstructed π_0 background where one decay γ escapes setup in: TAPS downstream hole and CB upstream hole
- **Fully-subtracted MM spectrum**: conservative MM <940 MeV integration limit , simulated Compton peak

Σ_{2x} – Martel, et al.



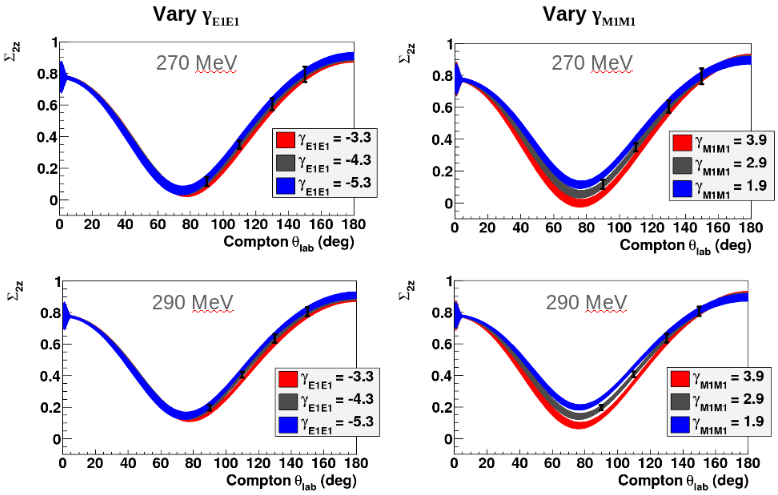
- **New results!** Physical Review Letters 114, 112501 (2015), arXiv:1408.1576 [nucl-ex]
- **First measurement of a double-spin Compton scattering asymmetry on the nucleon.** Curves are from DR calculation of Pasquini et al., making use of constraints on " γ_0, γ_π, $\alpha_{E1} + \beta_{M1}$. $\alpha_{E1}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

Σ_{2x} – Collicot, et al.



- New MAMI and older LEGS Σ_3 measurements along with the two theoretical curves using their prefered polarizabilities

Σ_{2z} – Estimated Experimental Precision (D. Paudyal)



D. Paudyal

Summary:

- **Polarizabilities are an important tool for testing QCD via χPT and DRs in the non-perturbative regime.**
- **Σ_{2x} has been measured for the first time.**
  - **Published in recent PRL.**
  - **Plans to acquire more data but not yet scheduled.**
  - **Σ_3 data analysis has been completed and planed for publication.**
  - **Plan to acquire more low energy data for α_{E1} and β_{M1} in 2016.**
- **My Thesis Work: First round of Σ_{2z} data taken, Another round of data is scheduled from June 23 - July 20, 2015.**
  - Heading back to Mainz, Germany and have committed to work as a run coordinator.