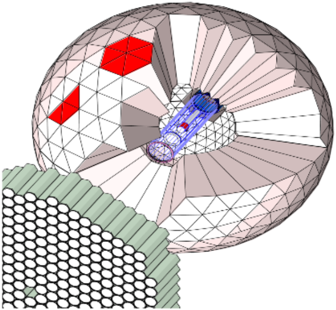

Proton Spin Polarizabilities with Polarized Compton Scattering at MAMI

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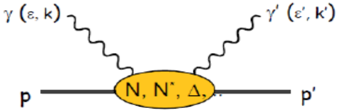
Nuclear Compton Scattering and Polarizabilities

- Polarizabilities are very low energy fundamental structure constants and Nuclear Compton scattering off a single proton is used to access these Internal structure constants of a nucleon.



- $\gamma(k) + P(p) \rightarrow \gamma(k') + P(p')$
- Low energy outgoing photon plays a role of an applied EM dipole field

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

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

What are Spin Polarizabilities

- Effective Hamiltonian in second order contains scalar polarizabilities (α_{E1} and β_{M1}) which are the evidence of proton's internal structure

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

- The third order effective Hamiltonian term in the expansion:

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

- These constants (γ) are spin (or vector) polarizabilities (e.g. γ_{M1E2} excited by electric quadrupole $E2$ radiation and decays by magnetic dipole $M1$ radiation.
- They describe the response of the proton spin to an applied electric or magnetic field, 'stiffness ' of proton spin against E.M. induced deformations relative to the spin axis.

What do we know about Spin Polarizabilities

	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

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2} = (-1.0 \pm 0.08) \times 10^{-4} fm^4 \quad (5)$$

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2} = (-8.0 \pm 1.8) \times 10^{-4} fm^4 \quad (6)$$

- Spin-polarizabilities in units of 10^{-4} fm^4.
- **K-matrix:** *Kondratyuk et al., PRC 64, 024005 (2001)* **, HDPV and 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* **and** *BχPT* **(Heavy Baryon & Covariant Chiral PT)** : *J. A. McGovern et al., Eur. Phys. J.* ***A 49****, 12 (2013).*

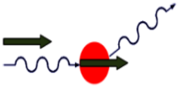
Best Way to extract Spin Polarizabilities

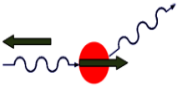
- **Spin polarizabilities appear in the effective interaction Hamiltonian at third order in photon energy**
  - It is in the $\triangle$ (1232) resonance region ($E_\gamma = 200 - 300$ MeV) where their effect becomes significant.
- **In this energy region, it is possible to accurately measure polarization 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.

Three Polarization Asymmetry Experiment at A2

Circularly polarized beam, longitudinally polarized target

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

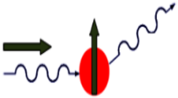


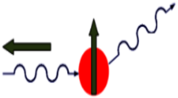


- $\sum_{2z}$ is sensitive to γ_{M1M1}

Circularly polarized beam, transversely polarized target

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



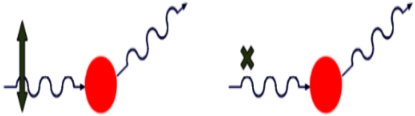


- $\sum_{2x}$ is sensitive to γ_{E1E1}

Polarization Asymmetry (contd..)

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

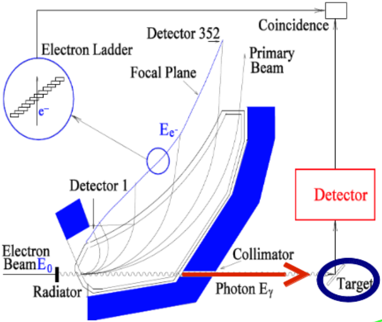
$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$



- $\sum_{2z}$ is sensitive to γ_{M1M1}

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

- Transverse Target($\sum_{2x}$): Sep 2010, Feb 2011 - 500 hrs (P. Martel)
- Unpolarized Target($\sum_3$): Dec 2012- 150 hrs (C. Collicot)
- **Longitudinal Target ($\sum_{2z}$)**: D. Paudyal (University of Regina) and A. Rajabi (University of Massachusetts)
  - First round of data in 2014 with Butanol (320 hours) and Carbon Target (180 hrs)
  - Second round of data in 2015 with Butanol (310 hours) and Carbon Target (60) hrs
  - Worked as a run coordinator for two weeks during 2015 beam time.

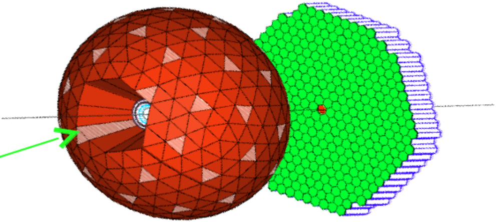


Crystal Ball

- 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

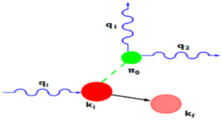
Σ_{2z} Data Analysis Status and Experimental challenges

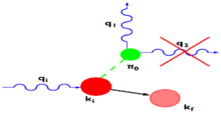
- Calibration of first round of carbon and butanol target data has been completed
- **Tagging Efficiency and target polarization check has been competed**
- Σ_{2z}– **Experimental Challenges**
  - Small Compton scattering cross sections.
  - Coherent and incoherent reactions off of C, O, and He.
  - A source of polarized protons is not easy to come by (or to operate)
  - In Δ-region, proton tracks are required to suppress backgrounds, but energy losses in the frozen-spin cryostat, and CB-TAPS are considerable.
- What to do ???
  - π^0 photo-production cross section is about 100 times that of Compton scattering, work on π_0 photo-production Asymmetry.

π^0 Production - Background Reaction

Compton Scattering $\gamma + P \rightarrow \gamma + P$

- Dominant Background for Compton Scattering Experiments

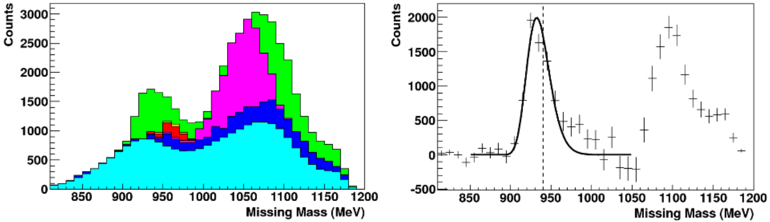




π^0 Production as a Systematic Check

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

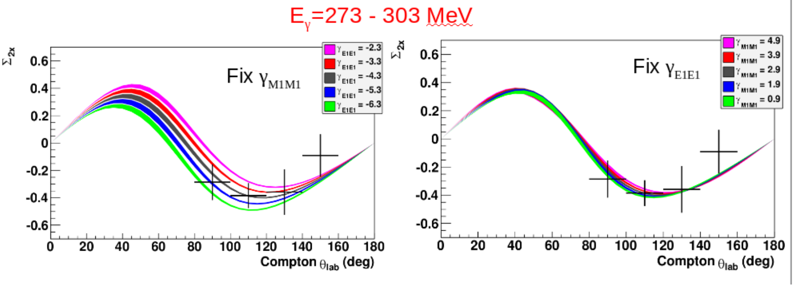
Σ_{2x} – Martel, et al.



- MM distribution for E_γ =273-303 MeV, $\theta_{\gamma'=100-120}$ degree (green)
- **Background contributions to MM:** accidental coincidences, (cyan) carbon/cryostat contributions (blue), reconstructed π_0 background where one decay γ escapes setup in: TAPS downstream hole (red) and CB upstream hole(magenta)
- **Right: Fully-subtracted MM spectrum with** simulated Compton peak and conservative

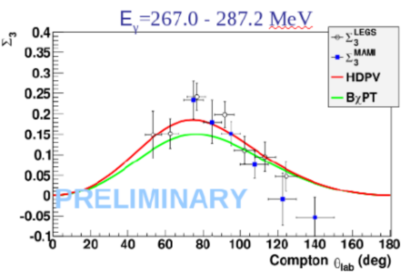
  MM <940 MeV cut is applied to exclude neutral pion production,

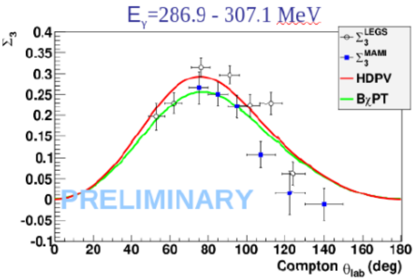
Σ_{2x} – Martel, et al.

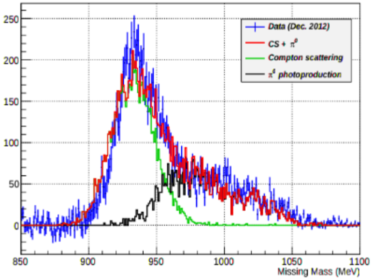


- **New results!** Physical Review Letters 114, 112501 (2015), arXiv:1408.1576 [nucl-ex]
- **First measurement of a double-spin Compton scattering asymmetry on the nucleon.** Curves are from DR calculation of Pasquini et al., making use of constraints on " γ_0, γ_π, $\alpha_{E1} + \beta_{M1}$. $\alpha_{E1}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

Σ_3 – Collicot, et al.







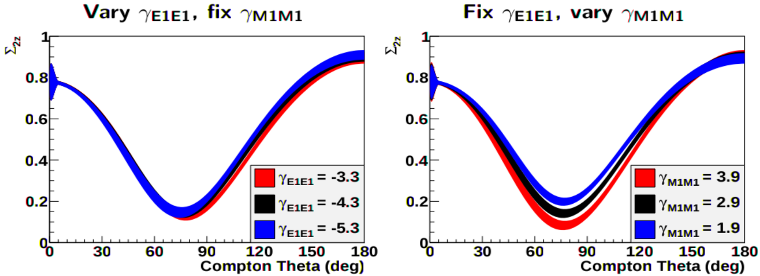
- **New MAMI and Older LEGS measurements along with two theoretical curves using their preferred polarizabilities**
- **Simulation of neutral pion photoproduction in Liquid hydrogen target matches background of the distribution quite well**

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 Σ_{2x} along with either $\sum_3^{MAMI}$ or $\sum_3^{LEGS}$ (Note: Pion pole contribution has been subtracted)**

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



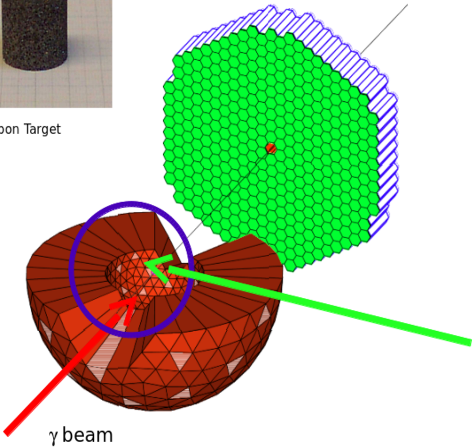
- To get a rough idea of the sensitivities, use a basis of γ_{E1E1}, γ_{M1M1}, γ_0 and γ_π, Produce event rates for nominal values of the SPs, using a dispersion theory calculation.
- Hold either γ_{E1E1} or γ_{M1M1} fixed, and perturb the other by a fixed amount and allow γ_0, γ_π, α_{E1} and β_{M1} to vary by their experimental errors.
- **The bands represent the spread about theese values by varying** γ_0, γ_π, α_{E1} and $\beta_{M1}$by their errors.

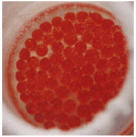
Summary

- Σ_{2x} has been measured for the first time and published in recent PRL.
- To further reduce the Σ_{2x} error bars, we have planned to acquire more data in January/February 2016.
  - Σ_3 data analysis has been completed and planed for publication.
- Planned to finish data analysis and have Compton double polarization asymmetries results Σ_{2z} before the end of 2016.
- Extract proton spin polarizabilities combining the Σ_{2z}results from first round of Σ_{2z} data taken in 2014 and second round of data taken in 2015

Back Up slides

Carbon Target



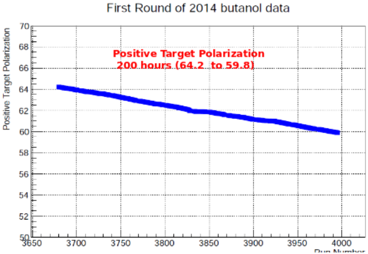


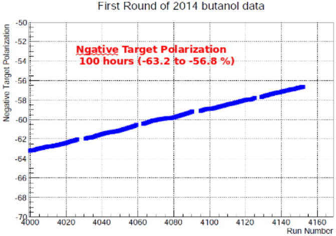
Frozen Butanol

- 2 cm long and 2 cm diameter

```
   H   H   H   H
H – C – C – C – C – O – H
   H   H   H   H
```

Back Up slides





- **DNP**: 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.
- 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%.

Back Up slides