Polarizability Measurements at A2/MAMI

Precision Nucleon Structure

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New Vistas in Low-Energy Precision Physics (LEPP)
Kupferbergterrasse Mainz
Mainz, DE

06 April 2016

THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

NOT New Jersey!

Neubraunschweig auf Deutsch. . .

Atlantic Ocean Symmetry Puzzle

Symmetry is explicitly broken by the Gulf Stream. . .

Outline

Non-Perturbative QCD

- Regime where the coupling is too strong and perturbative QCD (pQCD) is not appropriate.
- Very important for a thorough understanding of QCD.
- An understanding of the transition from non-pQCD (confinement) to pQCD (asymptotic freedom) is integral to the overall understanding of QCD.

How do we test QCD in the non-perturbative regime?

High-precision measurements with polarization observables.

Hadron Polarizabilities

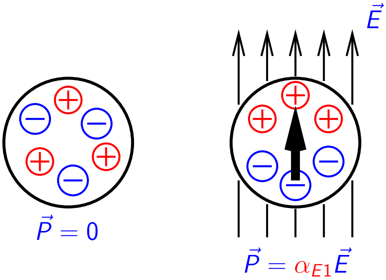
- Fundamental structure constants
- Response of internal structure to external fields
- Fertile meeting ground between theory and experiment
- Best measured via **Compton scattering**, both real and virtual

Theoretical Approaches

- Dispersion Relations (both subtracted and unsubtracted)
- Chiral Perturbation Theory
- Lattice QCD

Scalar Polarizabilities – Conceptual

Electric Dipole Polarizability

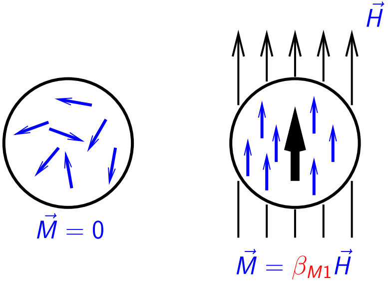


- Apply an electric field to a composite system
- Separation of Charge, or **"Stretchability"**
- Proportionality constant between electric dipole moment and electric field is the electric dipole polarizability, α_{E1}.

Provides information on force holding system together.

Scalar Polarizabilities – Conceptual

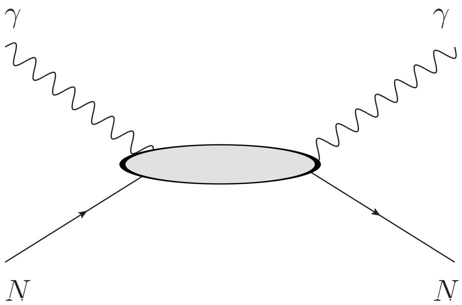
Magnetic Dipole Polarizability



- Apply a magnetic field to a composite system
- Alignment of dipoles or **"Alignability"**
- Proportionality constant between magnetic dipole moment and magnetic field is the magnetic dipole polarizability, β_{M1}.
- Two contributions, paramagnetic and diamagnetic, and they cancel partially, giving $\beta_{M1} < \alpha_{E1}$.

Provides information on force holding system together.

Real Compton Scattering from the Nucleon



Low-energy outgoing photon *plays the role of the applied EM field*.

$\Rightarrow$ Nucleon Response

$\Rightarrow$ **POLARIZABILTIES!**

Global response to internal degrees of freedom.

Real Compton Scattering – Hamiltonian

Expand the Hamiltonian in incident-photon energy.

0th order $\longrightarrow$ charge, mass

1st order $\longrightarrow$ magnetic moment

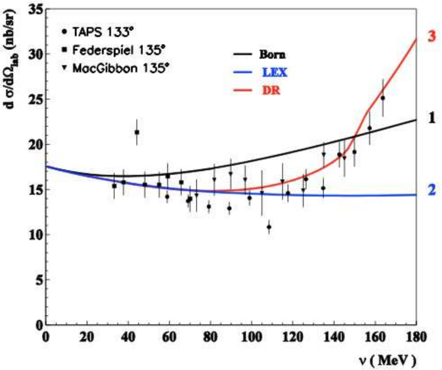
2nd order $\longrightarrow$ **scalar polarizabilities**:

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

3rd order $\longrightarrow$ **spin (or vector) polarizabilities**:

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

Low-Energy Expansion in Proton Compton Scattering



1 Born (anomalous magnetic moment)

2 LEX (polarizabilities at leading order)

3 Dispersion relations (full calculation)

LEX:

$$\frac{d\sigma}{d\Omega}(\nu,\theta) = \frac{d\sigma}{d\Omega}^{Born}(\nu,\theta) - \nu\nu'\left(\frac{\nu'}{\nu}\right)\frac{e^2}{2m}\left[(\alpha_{E1}+\beta_{M1})(1+z)^2 + (\alpha_{E1}-\beta_{M1})(1-z)^2\right]$$

Measure low energies and precise cross sections/asymmetries!

Proton – Fit with DRs

Baldin Sum Rule:

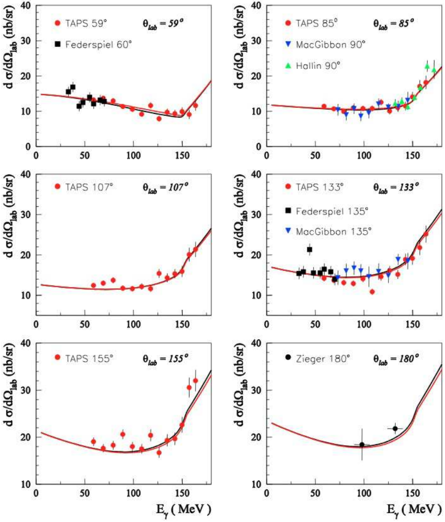
$$\alpha_{E1} + \beta_{M1} = (13.8 \pm 0.4) \times 10^{-4}\,\mathrm{fm}^3$$

Unsubtracted DRs:
Olmos de Leon et al., EPJA **10**, 207 (2001).

$$\alpha_{E1} - \beta_{M1} = (10.5 \pm 0.9) \times 10^{-4}\,\mathrm{fm}^3$$

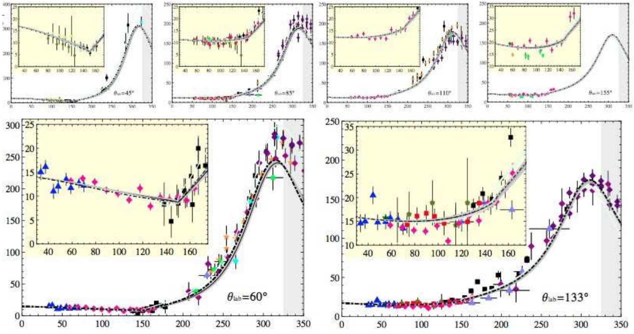
Subtracted DRs:
Drechsel et al., Phys. Rep. 378 (2003).

$$\alpha_{E1} - \beta_{M1} = (11.3 \pm 1.1) \times 10^{-4}\,\mathrm{fm}^3$$



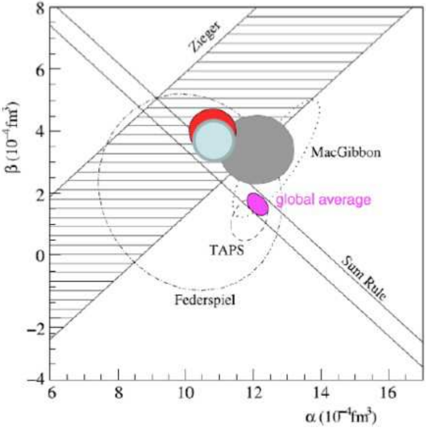
McGovern, Phillips, Grießhammer, EPJA **49**, 12 (2013)

Key Point: Statistically consistent database is used!



NLO + Δ	$\alpha_{E1} = 10.7 \pm 0.4_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.3_{\text{th}}$	$\beta_{M1} = 3.2 \mp 0.4_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.3_{\text{th}}$
NLO + Δ	$\alpha_{E1} = 10.8 \pm 0.7$	$\beta_{M1} = 4.0 \pm 0.7$
δ-expansion, Lensky & Pascalutsa EPJC **65** (2010)		
MAMI/TAPS	$\alpha_{E1} = 12.1 \pm 1.2_{\text{stat/mod}} \pm 0.4_{\Sigma}$	$\beta_{M1} = 1.6 \mp 1.2_{\text{stat/mod}} \pm 0.4_{\Sigma}$

EFTs vs. DRs

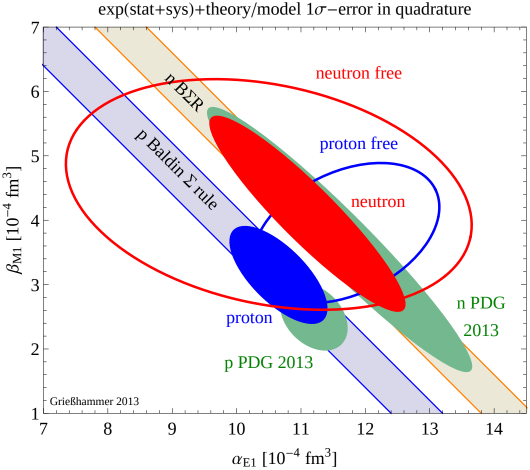


- Old PDG based on DRs
- HBChPT
  Beane et al., NPA **747** (2005)
- BChPT with Δ
  Lensky & Pascalutsa, EPJC **65** (2010)
- Partially Covariant BChPT with Δ
  McGovern et al., EPJA **49**, 12 (2013)

Systematic effect with EFTs consistently higher than DRs!?

New PDG Result and Reanalysis – Proton and Neutron

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



Situation for both the Proton and (especially) the Neutron could be improved. . .

Scalar Polarizabilities – Direct Measurement

Linearly Polarized Beam

Different dxs combinations are dependent only on α_{E1} or β_{M1}:

$$\frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = f_1(\text{Born}) - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\alpha_{E1}(1 - z^2) + O(\nu^3)$$

$$\frac{z^2 d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = f_2(\text{Born}) - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\beta_{M1}z(z^2 - 1) + O(\nu^3)$$

Recent work by Krupina and Pascalutsa [PRL **110**, 262001 (2013)]

At low energies $\Rightarrow$ use beam asymmetry Σ_3 to extract β_{M1}:

$$\begin{aligned}\Sigma_3 &\equiv \frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\sigma^{\perp} + d\sigma^{\parallel}} \\ &= \Sigma_3^{\text{NB}} - f_3(\theta)\beta_{M1}\nu^2 + \mathcal{O}(\nu^4).\end{aligned}$$

Spin Polarizabilities of the Proton

- Nucleon has 4 spin or vector polarizabilities:

$$\gamma_{E1E1} \qquad \gamma_{M1M1} \qquad \gamma_{M1E2} \qquad \gamma_{E1M2}$$

- Similar to scalar polarizabilities (α_{E1} and β_{M1}), but higher in order.
- Intimately connected to the nucleon's spin structure. **Fundamental structure constants!**
- Higher order in incident-photon energy, small effect at lower energies.
- Need theoretical help in extracting values.

Predicted Values

	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-matrix: calculation from Kondratyuk et al., PRC **64**, 024005 (2001)
- HDPV, DPV: dispersion relation calculations, Holstein et al., PRC **61**, 034316 (2000) and Pasquini et al., PRC **76**, 015203 (2007), Drechsel et al., PR **378**, 99 (2003)
- L_χ: chiral lagrangian calculation, Gasparyan et al., NPA **866**, 79 (2011)
- HBχPT and BχPT are heavy baryon and covariant, respectively, ChPT calculations, McGovern et al., EPJA **49**, 12 (2013), Lensky et al., PRC **89**, 032202 (2014)

Sensitivity to Spin Polarizabilities

#	asymmetry	polarization beam	polarization target	E_γ range (MeV)	spin polarizability
1	$\mathbf{\Sigma_{2z}}$	circular	longitudinal	200–300	**both**
2	$\mathbf{\Sigma_{2x}}$		transverse	200–300	$\boldsymbol{\gamma_{E1E1}}$
3	$\mathbf{\Sigma_{3}}$	linear	none	200-300	$\boldsymbol{\gamma_{M1M1}}$
4	Σ_{3y}		transverse	200-300	γ_{E1E1}
5	Σ_{1z}		longitudinal	200–300	both
6	Σ_{1x}		transverse	150–250	both

Analysis based on Pasquini et al., PRC **76** 015203 (2007).

Asymmetries – Babusci et al., PRC **58** 1013 (1998)

1. Beam: circular
   Target: longitudinal

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

2. Beam: circular
   Target: transverse

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

3. Beam: linear, $\parallel$ and $\perp$ to scattering plane
   Target: unpolarized

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

Spin Polarizability Extraction

Use γ_0, γ_π, α_{E1}, and β_{M1} along with the three asymmetries.

The various asymmetries respond differently to the individual spin polarizabilities at different energies and angles.

We will conduct an in-depth global analysis, and should be able to extract **all four spin polarizabilities independently** with small statistical, systematic, and model-dependent errors!

See next talk by R. Miskimen.

Mainz S2 Subproject: RCS Experimental Status

Important part of CRC1044.

Experiment	Status	
$\boldsymbol{\Sigma_{2x}}$	February 2011	$\surd$
$\boldsymbol{\Sigma_{3}}$	December 2012	$\surd$
$\boldsymbol{\alpha_{E1}, \beta_{M1}}$	June 2013	$\surd$
$\boldsymbol{\Sigma_{2z}}$	2014/2015	$\surd$

More data will be taken on $\boldsymbol{\alpha_{E1}, \beta_{M1}}$ at low energy.

NOTE: Complementary measurements planned for HIGS!

High-flux, monoenergetic beam, with $\approx \mathbf{100\%}$ polarization.

Experimental Set-Up for $\Sigma_{2x}/\Sigma_{2z}/\Sigma_3$ and α_{E1}, β_{M1}

Standard A2 Equipment is required:

- MAMI electrons
- Glasgow-Mainz Tagger
- CB-TAPS detector system
- Cryogenic Targets

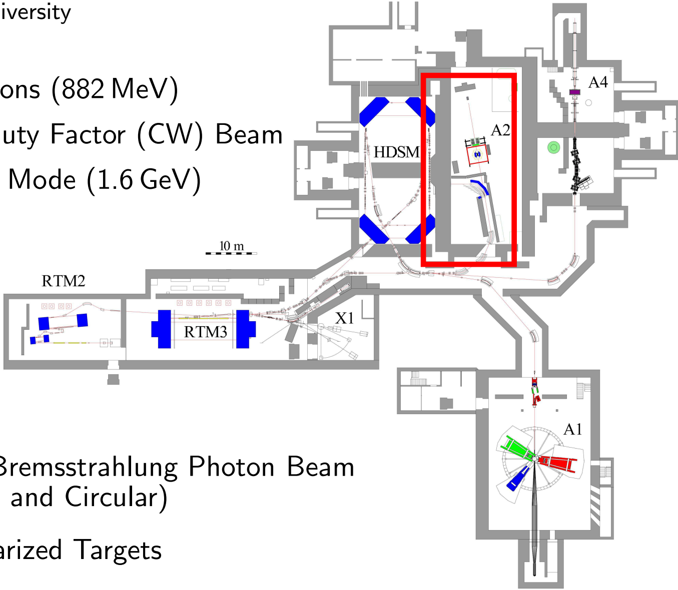
Run Parameter	$\boldsymbol{\Sigma_{2x}/\Sigma_{2z}}$	$\boldsymbol{\Sigma_3}$ and $\boldsymbol{\alpha_{E1}, \beta_{M1}}$
Electron Beam Energy	450 MeV	883 MeV
Target	butanol	LH_2
Radiator	Copper	Diamond
Tagged Energy Range	100 – 400 MeV	100 – 400 MeV
Channel Energy Resolution	1 MeV	2 MeV
Beam Polarization	circular	linear
Target Polarization	transverse/longitudinal	none

Johannes Gutenberg University
Mainz, Germany

3 Race-Track Microtrons (882 MeV)

High-Quality 100% Duty Factor (CW) Beam

HDSM in Production Mode (1.6 GeV)

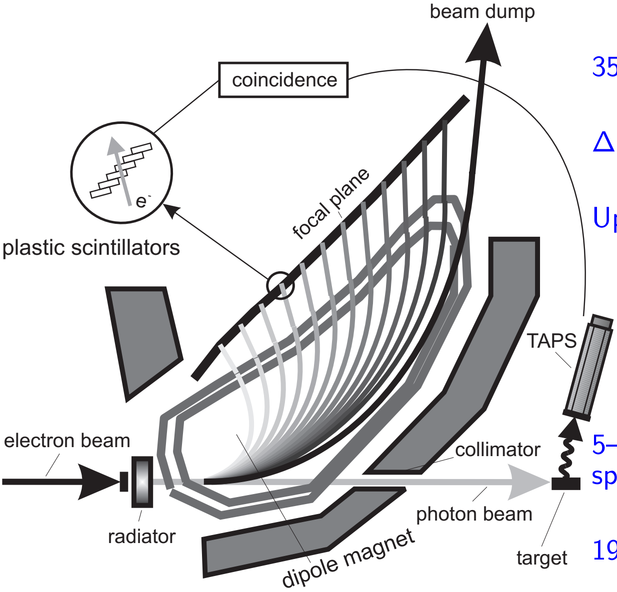


A2 Collaboration:

High-Flux, Tagged, Bremsstrahlung Photon Beam
(Unpolarized, Linear, and Circular)

Polarized and Unpolarized Targets

Incident Photon Beam – Glasgow-Mainz Photon Tagger



352 channels

$\Delta E = 4\,\text{MeV}$ at 1.6 GeV

Up to $\sim 10^8 \gamma/\text{s}$

Refurbished to work at 1.6 GeV

5–94% of Bremsstrahlung spectrum

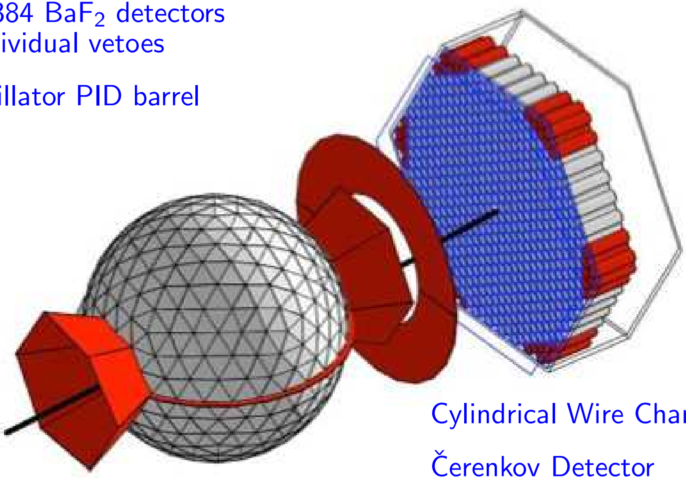
191-channel microscope

Detector System: CB-TAPS

CB: 672 NaI detectors

TAPS: 384 BaF_2 detectors
with individual vetoes

24-scintillator PID barrel

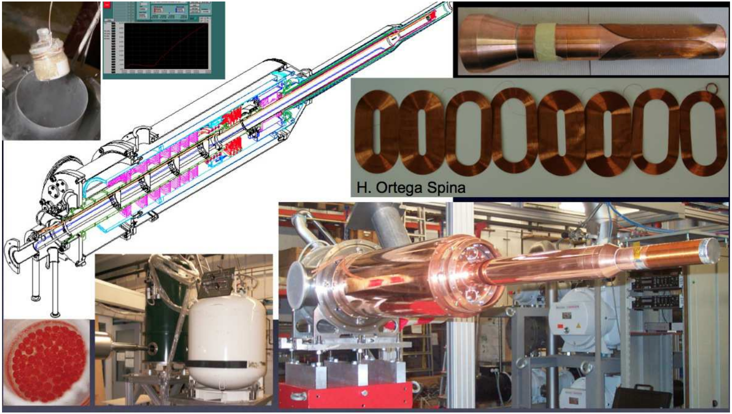


Cylindrical Wire Chamber

Čerenkov Detector

Detector System: CB-TAPS

Polarized Target



Dynamical Nucleon Polarization
Target material is butanol, $C_4H_{10}O$
Dilution cryostat with bath of liquid $^3He/^4He$, $T < 30\,\mathrm{mK}$
$P_p \approx 90\%$ with a relaxation time of $\tau > 1000$ hours.

Asymmetries – Experimental Challenges

- Small Compton scattering cross sections.
- Large backgrounds:
  - π^0 photoproduction cross section is about 100 times that of Compton scattering.
  - 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 LH_2 target, frozen-spin cryostat, and CB-TAPS are considerable.

α_{E1}, β_{M1} Results

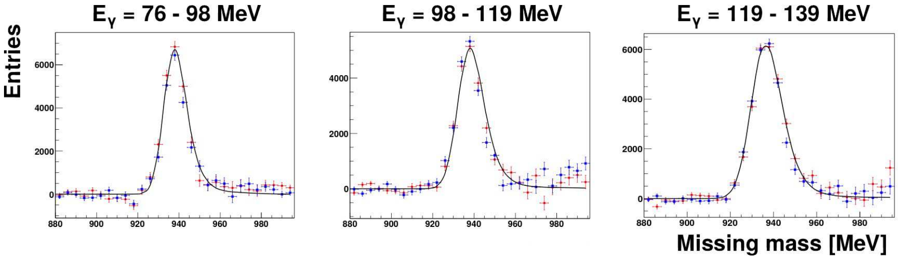
Work of E. Mornacchi and V. Sokhoyan

Low-energy Compton scattering.

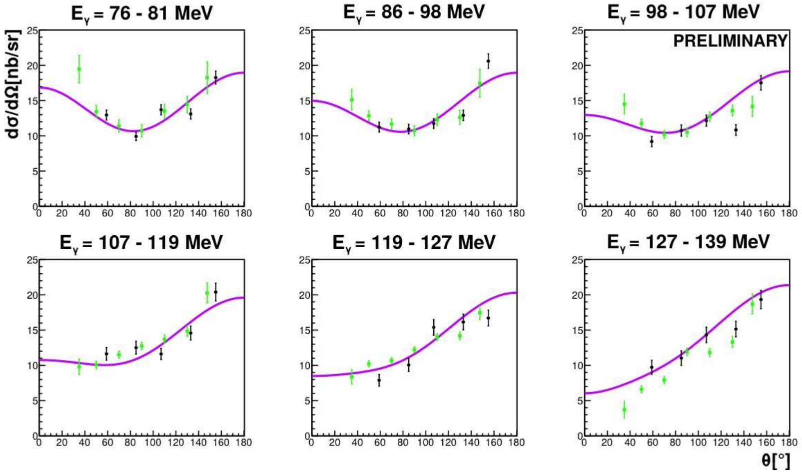
Linearly polarized beam, liquid hydrogen target.

High-statistics cross sections, $d\sigma/d\Omega$, and beam asymmetry, Σ_3.

Most important data are below pion threshold.



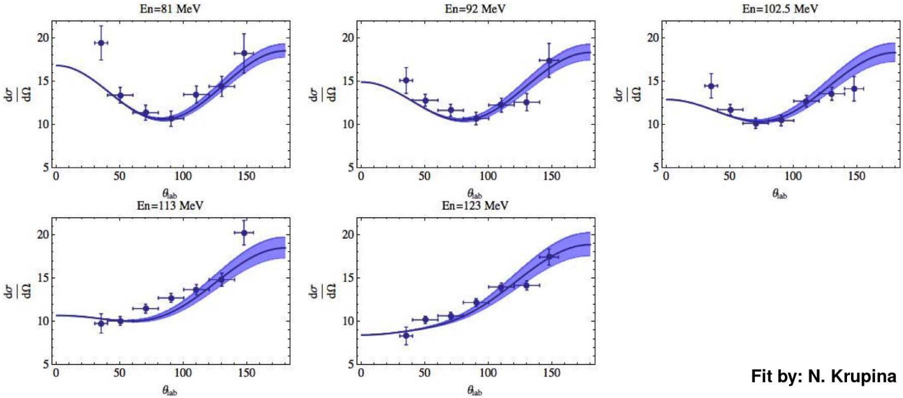
α_{E1}, β_{M1} Results – Cross Sections with DR



Our data along with older TAPS data [Olmos de Leon et al., EPJA **10** 207 (2001)].

DR: Pasquini, Drechsel, and Vanderhaeghen, PRC **76**, 015203 (2007)

α_{E1}, β_{M1} Results – Cross Sections with ChPT Fit

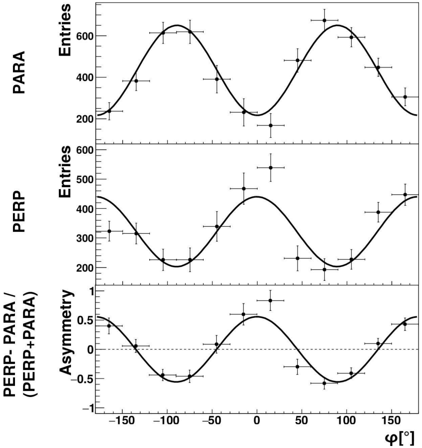


Fit by: N. Krupina

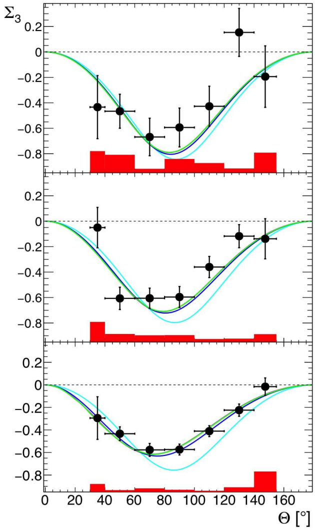
Including 20% systematic error and constrained with Baldin sum rule leads to: $\beta_{M1} = 2.8 \pm 1.3 \times 10^{-4}\ \text{fm}^3$ (fit by: N. Krupina)

ϕ-distributions for PERP and PARA polarization orientations.

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



α_{E1}, β_{M1} Results – Asymmetries



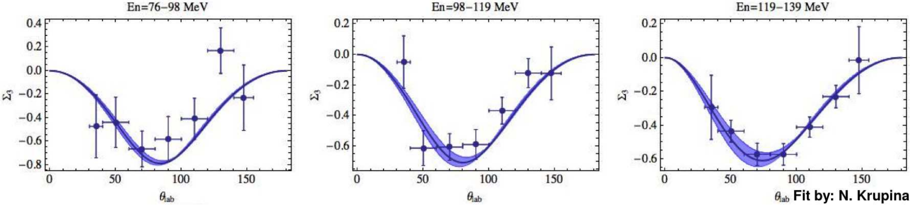
Data are at three energies: 76 – 98 MeV, 98 – 119 MeV, and 119 – 139 MeV.

Systematic errors in red.

Curves:

- Born contribution
- BChPT: Krupina and Pascalutsa, PRL **110**, 262001 (2013)
- HBChPT: McGovern et al., EPJA **49**, 12 (2013)

α_{E1}, β_{M1} Results – Asymmetries with ChPT Fit



Including 20% systematic error and constrained with Baldin sum rule leads to: $\beta_{M1} = 1.2 \pm 2.6 \times 10^{-4}\,\mathrm{fm}^3$ (fit by: N. Krupina)

Combined fit gives $\beta_{M1} = 2.5 \pm 1.2 \times 10^{-4}\,\mathrm{fm}^3$

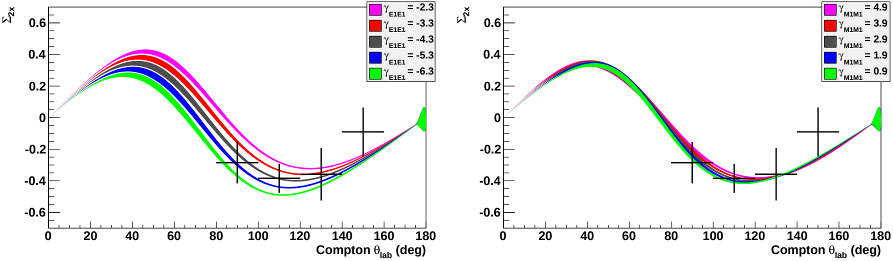
α_{E1}, β_{M1} Outlook

New measurement planned:

- Tagger upgrade (increase photon flux by a factor of 4)
- Improved running conditions, including more stable polarization
- Increased statistics, reduced systematic errors

Use a simultaneous fit to unpolarized cross sections and beam asymmetry to achieve precision on β_{M1} comparable to the current PDG value!

$E_\gamma = 273 - 303\,\text{MeV}$



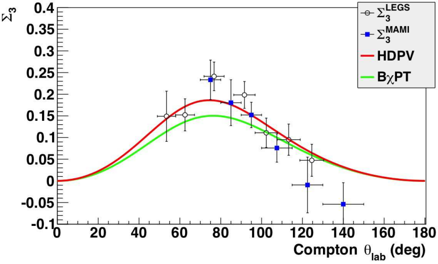
- First measurement of a double-polarized Compton scattering asymmetry on the nucleon, Σ_{2x}.
- Curves are from DR calculation of Pasquini et al.
- Data have sensitivity to the γ_{E1E1} spin-polarizability, with a preliminary estimate of

$$\boxed{\gamma_{E1E1} = (-4.5 \pm 1.5) \times 10^{-4}\ \text{fm}^4}$$

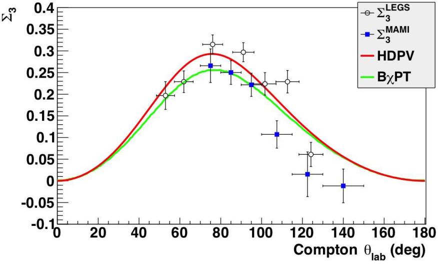
Σ_3 Results

PhD work of C. Collicott

$E_\gamma = 267 - 282\,\text{MeV}$



$E_\gamma = 286 - 307\,\text{MeV}$



- Recent data (MAMI) and older data (LEGS) are shown along with Dispersion Relation (HDPV) and ChPT (BχPT) predictions.
- Fits have been done. See the upcoming talk by R. Miskimen!

Σ_{2z} Results

- PhD work of both D. Paudyal (Regina) and A. Rajabi (UMass).
- Data have been taken.
- Analysis is ongoing.
- See upcoming talk by R. Miskimen.

The "Other" Nucleon – The Neutron

Situation is considerably worse than for the proton:

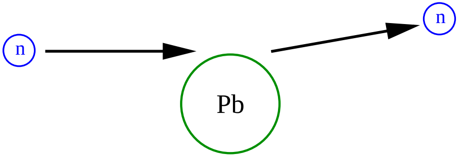
- No free neutron target.
- Neutron is uncharged.
- Small data set!

Techniques:

- Low-energy neutron scattering.
- Elastic Compton scattering from deuterium.
- QF Compton scattering from deuterium.
- Compton scattering from heavier nuclei.

Nuclear Effects are NOT negligible!

Low-Energy Neutron Scattering



Scatter neutrons in the Coulomb field of a heavy nucleus, i.e. Pb.

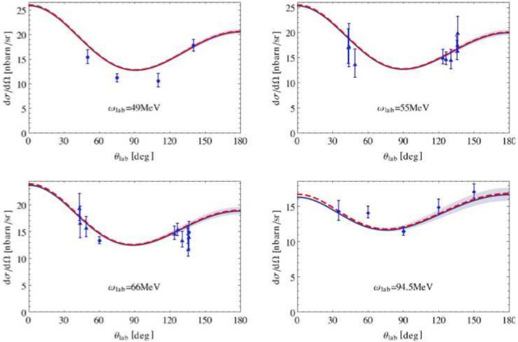
For $k < 100\,\text{keV} \Rightarrow \sigma_s(k) = \sigma_s(0) + ak + bk^2 + \mathcal{O}(k^4)$
where a depends **ONLY** on α^n_{E1}.

Results:

Data	α_{E1} (10^{-4} fm^3)
Schmiedmayer et al.	$12.0 \pm 1.5 \pm 2.0$
Koester et al.	0 ± 5
Enik et al. reanalysis	$7 - 19$

Unsatisfactory situation.

Elastic Compton from Deuterium



Interference between proton and neutron increases sensitivity.

Higher cross section.

Nuclear effects are much bigger than one might naively expect!

Amount of data pretty sparse compared to the proton. . .

Estimates of scalar polarizabilities from an NLO analysis of Grießhammer et al.:

$$\alpha^n_{E1} = 11.1 \pm 1.8_{\text{stat}} \pm 0.4_{\Sigma} \pm 0.8_{\text{th}} \qquad \beta^n_{M1} = 4.1 \mp 1.8_{\text{stat}} \pm 0.4_{\Sigma} \pm 0.8_{\text{th}}$$

Big error bars! $\Rightarrow$ Planned measurements at HIGS at 65 MeV and 100 MeV.

QF Compton from Neutron in Deuterium

$d(\gamma,\gamma' n)p$

In certain kinematic regions, proton acts like a spectator and scattering is done primarily from the neutron.

Model dependence and nuclear effects should be minimized, but higher energies mean more model dependence.

Measurements at both Saskatoon and Mainz.

Analysis of M. Schumacher, PPNP **55**, 567 (2005), using theory of Levchuk & L'vov, NPA **674**, 449 (2000):

$$\alpha^n_{E1} = 12.5 \pm 1.8_{\text{stat}} \pm 1.1_{\text{mod}} \qquad \beta^n_{M1} = 2.7 \mp 1.8_{\text{stat}} \pm 1.1_{\text{mod}}$$

Suggested results from same using weighted average of Coulomb, Elastic, and QF:

$$\alpha^n_{E1} = 12.5 \pm 1.7 \qquad \beta^n_{M1} = 2.7 \mp 1.8$$

Error on β^n_{M1} still very large!

Doubts exist about theory...

ChPT for ^{3}He$(\gamma, \gamma)^3$He

Relatively new idea for extraction of scalar polarizabilities for the neutron.

Shukla, Nogga, and Phillips, NPA **819**, 98 (2009).

Theory is promising, but still needs some work to extend it to higher energies. . .

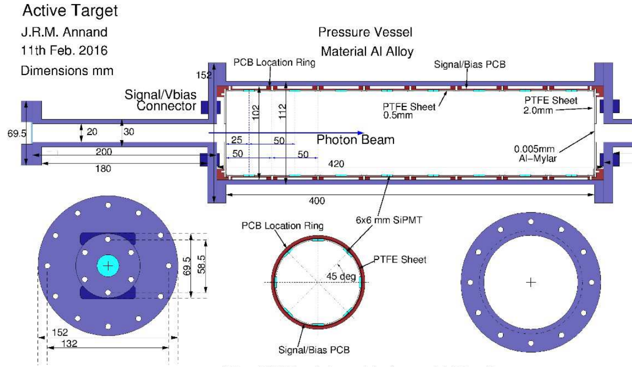
Proposal A2-01-2013 using a high-pressure active helium target (both ^{3}He and ^{4}He).

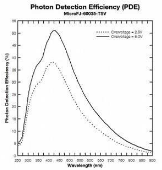
Given a rating of A by the PAC!

Will hopefully run at the end of this year.

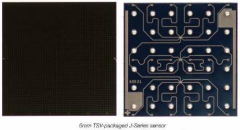
High-pressure, Active He Target

The New Active Target





8 rings of SiPMT, each ring consisting 8 groups of 4 6x6mm tiles.
Total number of SiPMT 8x8x4 = 256.
Readout in groups of 16, each group connected to an op–amp.
16 signal outputs
2 vias–voltage inputs

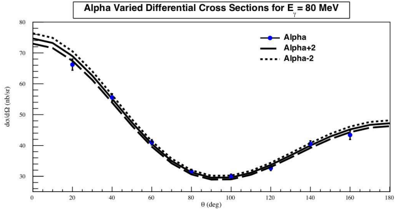


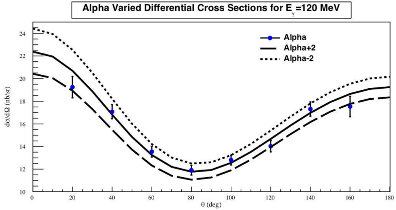
6 x 6mm J-Series SiPMT

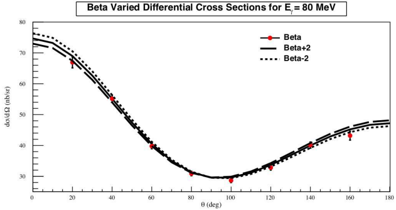
- Al pressure vessel, no welds
- Reuse Be outer windows from original Active Target
- PTFE sheet covers printed circuit board, windows cut for SiPMT

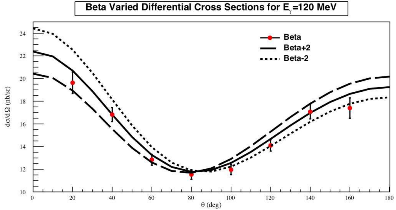
Rate Estimates and Sensitivity Study

Work done by MTA honours student Meg Morris.









$\boldsymbol{E_\gamma = 80\,\mathrm{MeV}}$ $\boldsymbol{E_\gamma = 120\,\mathrm{MeV}}$

$\boxed{\delta\alpha^n_{E1} \approx \delta\beta^n_{M1} \approx 1.0 \times 10^{-4}\ \mathrm{fm}^3}$ compared to $1.8 \times 10^{-4}\ \mathrm{fm}^3$!

Polarizabilities – Outlook and Plans

1. Publish high-energy $\boldsymbol{\Sigma_3}$ results.
2. Finish analysis and publish $\boldsymbol{\Sigma_{2z}}$ results.
3. Complete global fit and extraction of the proton spin polarizabilities.
4. Take more data on $\boldsymbol{\alpha_{E1}, \beta_{M1}}$.
5. Complementary measurements at HIGS on the proton and deuteron.
6. An active polarized target is being developed, and we plan to use it for improved measurements of the asymmetries.
7. Active, high-pressure Helium target for approved neutron polarizability experiment at MAMI.

Polarizabilities

1. Important tool for *testing* QCD via ChPT & DRs in the non-perturbative regime.
2. Both theory and experiment are very active at the moment.
3. We can expect lots of new results in the near future.

Special thanks to Judith McGovern, Phil Martel, Edoardo Mornacchi, Harald Grießhammer, and Cristina Collicott.