Compton Scattering and Polarizabilities at MAMI

What do they tell us about hadron structure?

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CINP Town Hall Meeting
Edmonton, AB

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SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

NSERC CRSNG

Fundamental Question:

"Can the theory of quark and gluon confinement quantitatively describe the detailed properties of hadrons?"

Perspectives on Subatomic Physics in Canada 2006–2016.

- Theory: QCD describes the strong force in terms of quarks and gluons.
- Nobel Prize in 2004 for **Asymptotic Freedom** in the pQCD regime. . .
- However, in the non-perturbative region, QCD is still unsolved.

One of the top ten challenges for all of physics!

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

High-precision measurements with polarization observables.

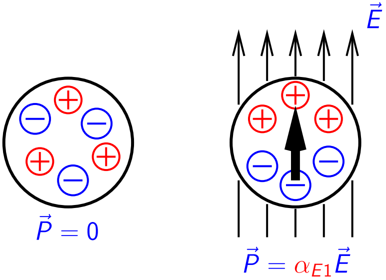
Hadron Polarizabilities

- 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.

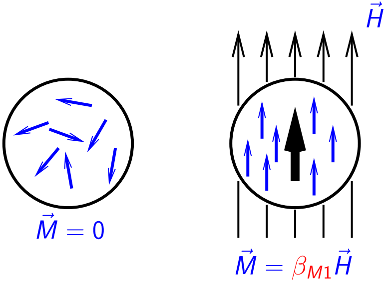
Electric Dipole Polarizability of a Composite System



- 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}.

Use the well-understood EM interaction (QED) to gain information on force holding system together, the strong nuclear force (QCD).

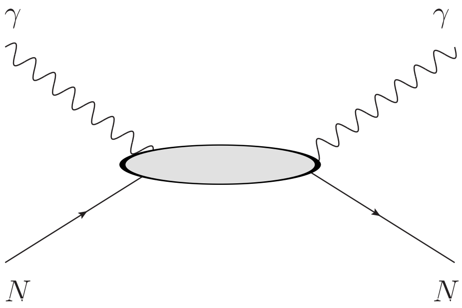
Magnetic Dipole Polarizability of a Composite System



- 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 $\beta_{M1} < \alpha_{E1}$.

Use the well-understood EM interaction (QED) to gain information on force holding system together, the strong nuclear force (QCD).

Real Compton Scattering from the Nucleon



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

$\Rightarrow$ Nucleon Response

$\Rightarrow$ **POLARIZABILITIES!**

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**:

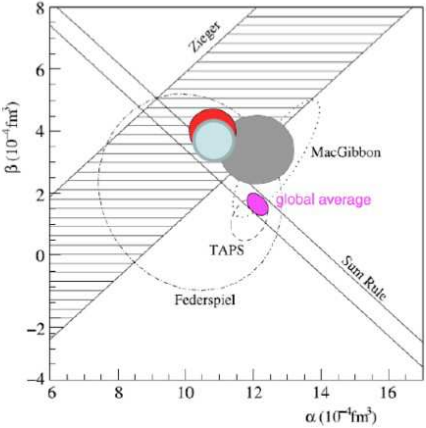
$$H_{\text{eff}}^{(2)} = -4\pi \left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2 \right]$$

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

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

where $E_{ij} = \frac{1}{2}(\nabla_i E_j + \nabla_j E_i)$ and $H_{ij} = \frac{1}{2}(\nabla_i H_j + \nabla_j H_i)$

Scalar Polarizabilities – EFTs vs. DRs

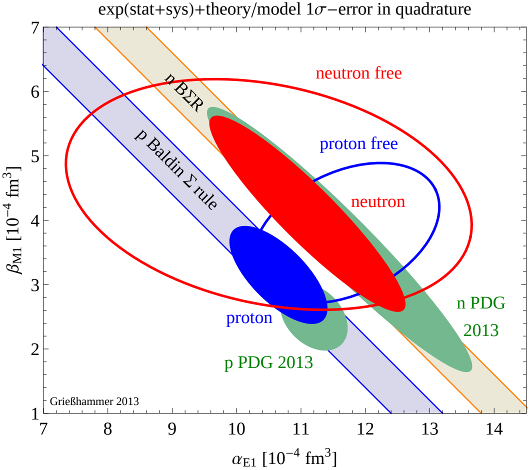


- Old PDG based on DRs
- HBChPT
  Beane et al., NPA **747** (2005)
- BChPT with Δ
  Lensky & Pascalutsa, EPJC **65** (2010)
- Partially Covariant BChPT with Δ
  McGovern et al., EPJA **49**, 12 (2013)

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}:

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

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

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

At low energies ⇒ use beam asymmetry Σ_3 to extract β_{M1}:

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

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.
- Note: each spin polarizability is dominated by a pion-pole contribution. The dispersive (interesting) part is relatively small.

In his closing remarks at MAMI and Beyond in 2009 and again at the SFB1044 Kick-off in September 2012, B. Holstein listed the spin polarizabilities as the **number one** priority.

Spin Polarizabilities – Recent Status

γ	Theory p^4HB	ϵ^3SSE	NNLO	DRs	Kmatrix	Experiment
$E1E1$	-1.4	-5.4	-4.5	-4.3	-5.0	**no data**
$M1M1$	3.3	1.4	3.7	2.9	3.4	**no data**
$E1M2$	0.2	1.0	-0.9	0.0	-1.8	**no data**
$M1E2$	1.8	1.0	2.2	2.1	1.1	**no data**
0	-3.9	2.0	-0.7	-0.7	2.3	$-1.01 \pm 0.08 \pm 0.13$
π	6.3	6.8	11.3	9.3	11.3	$\mathbf{8.0 \pm 1.8}$

Proton spin polarizability predictions and measurements in units of $10^{-4}\,\mathrm{fm}^4$.

The pion-pole contribution has been subtracted.

Note the large absolute error on γ_π.

Asymmetries – D. 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

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

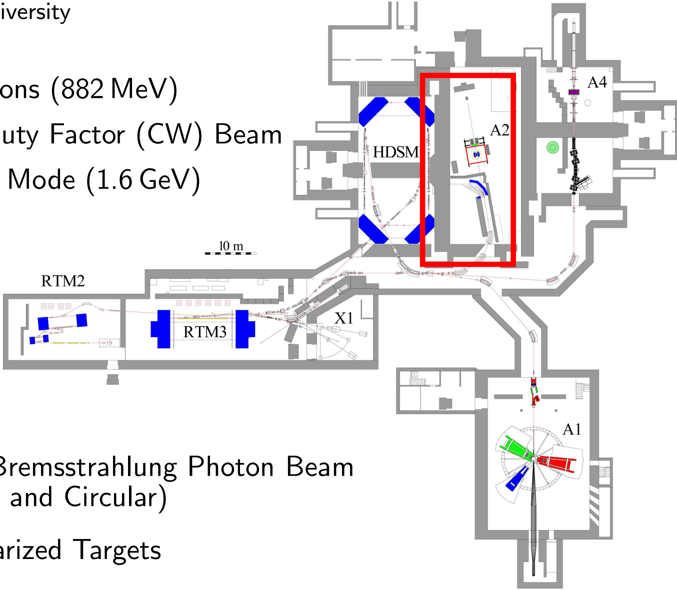
The Mainzer Mikrotron (MAMI)

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

Detector System: CB-TAPS

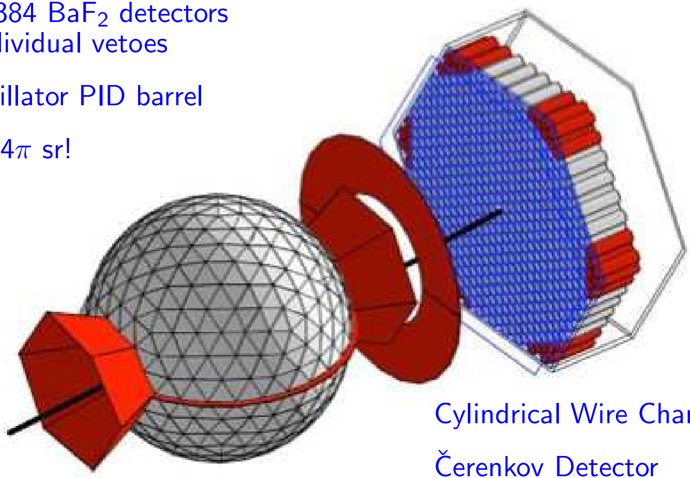
GEANT4 View

CB: 672 NaI detectors

TAPS: 384 BaF_2 detectors
with individual vetoes

24-scintillator PID barrel

96% of 4π sr!



Cylindrical Wire Chamber

Čerenkov Detector

Detector System: CB-TAPS

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

Standard A2 Equipment was used:

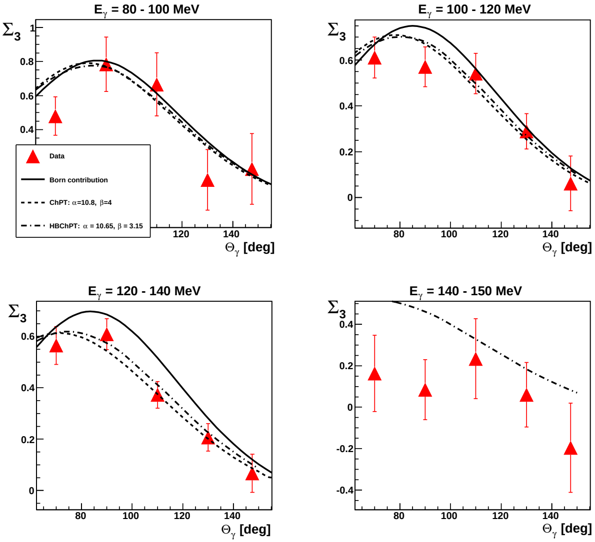
- MAMI electrons
- Glasgow-Mainz Tagger
- CB-TAPS detector system
- Cryogenic Targets

Run Parameter	Σ_{2x}/Σ_{2z}	Σ_3 and α_{E1}, β_{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

Asymmetries – Experimental Challenges

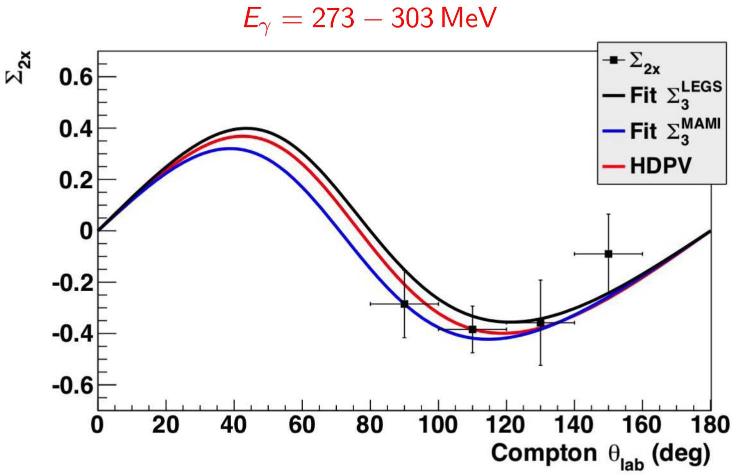
- Small Compton scattering cross sections.
- Large backgrounds:
  - π^0 photoproduction cross section is about *100 times* that of Compton scattering.
  - Coherent and incoherent reactions off of C, O, and He for butanol.
- A source of polarized protons is not easy to come by (or to operate).
- In Δ-region, proton tracks are required to suppress backgrounds, but energy losses in the LH_2 target, frozen-spin cryostat, and CB-TAPS are considerable.
- Under certain conditions, π^0 photoproduction can mimic Compton scattering. . .

α_{E1}, β_{M1}: Preliminary Asymmetries – Sokhoyan & Downie



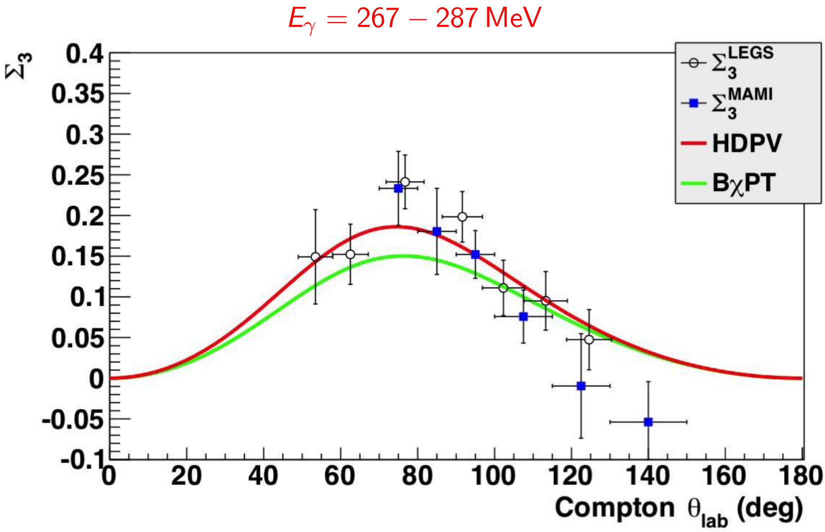
More data are need.

Σ_{2x}: Results – Martel & Miskimen



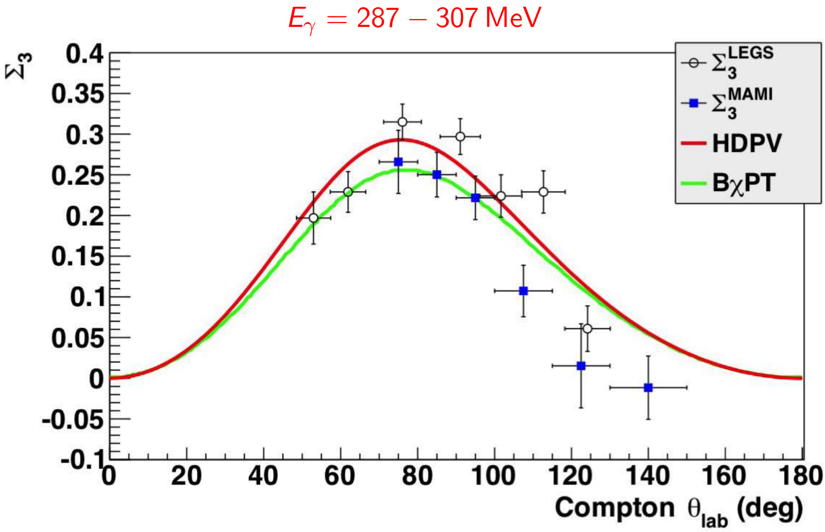
The recent (MAMI) and older (LEGS) Σ_3 measurements along with two theoretical curves using their preferred polarizabilities.

$\boldsymbol{\Sigma_3}$: Results – Collicott



The recent (MAMI) and older (LEGS) Σ_3 measurements along with two theoretical curves using their preferred polarizabilities.

Σ_3: Results – Collicott



The recent (MAMI) and older (LEGS) Σ_3 measurements along with two theoretical curves using their preferred polarizabilities.

Fitting

Dispersion relation fitted to Σ_{2x} along with either Σ_3^{MAMI} or Σ_3^{LEGS} – G. Blanpied *et al.*, PRC 64, 025203 (2001)

	Σ_{2x} and Σ_3^{LEGS}	Σ_{2x} and Σ_3^{MAMI}
$\bar{\gamma}_{E1E1}$	-3.5 $\pm$ 1.2	-5.0 $\pm$ 1.5
$\bar{\gamma}_{M1M1}$	3.16 $\pm$ 0.85	3.13 $\pm$ 0.88
$\bar{\gamma}_{E1M2}$	-0.7 $\pm$ 1.2	1.7 $\pm$ 1.7
$\bar{\gamma}_{M1E2}$	1.99 $\pm$ 0.29	1.26 $\pm$ 0.43
γ_0	-1.03 $\pm$ 0.18	-1.00 $\pm$ 0.18
γ_π	9.3 $\pm$ 1.6	7.8 $\pm$ 1.8
$\bar{\alpha} + \bar{\beta}$	14.0 $\pm$ 0.4	13.8 $\pm$ 0.4
$\bar{\alpha} - \bar{\beta}$	7.4 $\pm$ 0.9	6.6 $\pm$ 1.7
χ^2/dof	1.05	1.25

Scalar polarizabilities in units of $10^{-4}\,\mathrm{fm}^3$
Spin polarizabilities in units of $10^{-4}\,\mathrm{fm}^4$

Spin Polarizabilities – New Results

γ	Theory					Experiment
	p^4HB	ϵ^3SSE	NNLO	DRs	Kmatrix	
$E1E1$	-1.4	-5.4	-4.5	-4.3	-5.0	$\mathbf{-5.0 \pm 1.5}$
$M1M1$	3.3	1.4	3.7	2.9	3.4	$\mathbf{3.13 \pm 0.88}$
$E1M2$	0.2	1.0	-0.9	0.0	-1.8	$\mathbf{1.7 \pm 1.7}$
$M1E2$	1.8	1.0	2.2	2.1	1.1	$\mathbf{1.26 \pm 0.43}$
0	-3.9	2.0	-0.7	-0.7	2.3	-1.00 ± 0.18
π	6.3	6.8	11.3	9.3	11.3	7.8 ± 1.8

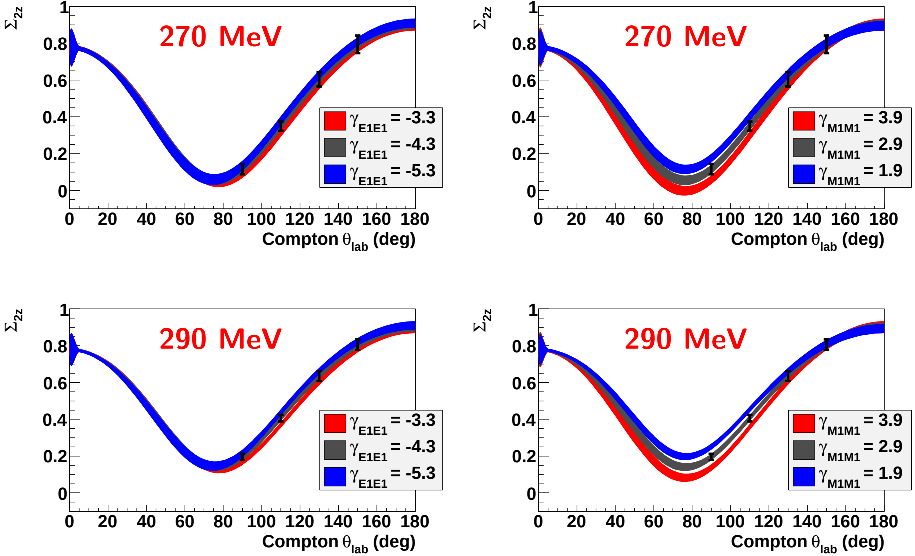
Proton spin polarizability predictions and measurements in units of $10^{-4}\,\text{fm}^4$.

The pion-pole contribution has been subtracted.

The errors could still be improved...

Σ_{2z} – Estimated Experimental Precision

Vary γ_{E1E1} Vary γ_{M1M1}



Proton RCS Summary

Important part of the CRC1044 in Mainz.

Experiment	Status	
$\mathbf{\Sigma_{2x}}$	February 2011	$\surd$
$\mathbf{\Sigma_3}$	December 2012	$\surd$
$\alpha_{\mathbf{E1}}, \beta_{\mathbf{M1}}$	June 2013	$\surd$
$\mathbf{\Sigma_{2z}}$	May 2014	$\surd$

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!

Baldin sum-rule constraint also employed:

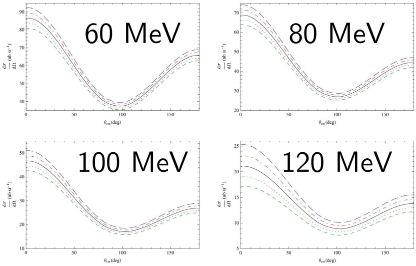
$$\alpha^n_{E1} + \beta^n_{M1} = \frac{1}{4\pi^2} \int_{\nu_0}^{\infty} d\nu \frac{\sigma_{abs}}{\nu^2} = (15.2 \pm 0.4) \times 10^{-4}\,\mathrm{fm}^3$$

M.I. Levchuk and A.I. L'vov, NPA **674**, 449 (2000).

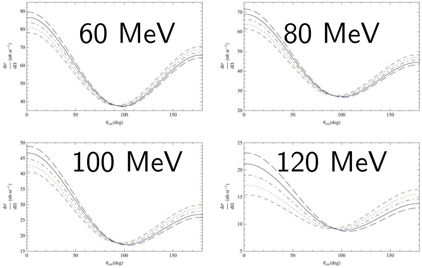
ChPT for ^{3}He$(\gamma,\gamma)^3$He

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

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



Sensitivity $\alpha^{\mathbf{n}}_{\mathbf{E1}}$



Sensitivity $\beta^{\mathbf{n}}_{\mathbf{M1}}$

Theory is promising, but still needs some work...
Proposal A2-01-2013 for ^{3}He$(\gamma,\gamma)^3$He
Given a rating of A by the PAC!

Hadron Polarizabilities – What do they tell us?

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.

Polarizabilities – Outlook and Plans

1. Finish analysis and publish Σ_3, α_{E1}, β_{M1}, and Σ_{2z} results.
2. Complete global extraction of the proton spin polarizabilities.
3. Continue development of an active polarized target. Polarizable scintillators have been developed at UMass.
4. Active, high-pressure helium target for approved neutron polarizability experiments.
5. Can we use deuterated butanol in the Frozen Spin Target for neutron spin polarizabilities? *Feasibility studies are upcoming.*
6. Timelike VCS measurements.

HQP in the Last 5 Years

1. 3 PDFs
2. 3 Graduate students
3. 22 Undergraduates