Compton Scattering and the Nucleon Polarizabilities

Precision Hadron Structure at MAMI

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Outline

• Hadron Polarizability Motivation
• Proton - scalar and spin pols
• Neutron - scalar pols
• Summary and Outlook
Non-Perturbative QCD

• Regime where coupling is too strong and perturbative QCD (pQCD) is not appropriate.

• Very important for a thorough understanding of QCD.

• An understanding of the transition region 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 of polarization observables.

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

- **Theoretical Approaches:**
  - Dispersion Relations
  - 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, $\alpha_{E1}$.

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, $\beta_{M1}$.
- Two contributions, paramagnetic and diamagnetic, and they cancel partially, giving $\beta_{M1} < \alpha_{E1}$.

Provides information on force holding system together.
How about subatomic particles?

- We obviously can’t just put a proton between the plates of a capacitor or the poles of a magnet and measure its deformation. What to do?

- The answer of course is **Compton scattering**!

- What kind of fields can we get from from a high-energy photon?

- Naively, for a 100-MeV photon:

  \[ E = \frac{V}{d} \]

  \[ \approx \frac{100 \text{ MV}}{10^{-15} \text{ m}} \]

  \[ \approx 10^{23} \text{ V/m} \]

  **A HUGE field!**
Real Compton Scattering from the Nucleon

- The outgoing photon plays the role of the applied EM field.
- Nucleon Response.
- POLARIZABILITIES!
- Global response to the internal degrees of freedom.
Compton Scattering - Hamiltonian

Expand the Hamiltonian in incident-photon energy.

0th order $\rightarrow$ charge, mass

1st order $\rightarrow$ magnetic moment

2nd order $\rightarrow$ scalar polarizabilities:

$$H_{\text{eff}}^{(2)} = -4\pi \left[ \frac{1}{2} \alpha_{E_1} \vec{E}^2 + \frac{1}{2} \beta_{M_1} \vec{H}^2 \right]$$

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

$$H_{\text{eff}}^{(3)} = -4\pi \left[ \frac{1}{2} \gamma_{E_1E_1} \vec{\sigma} \cdot \left( \vec{E} \times \dot{\vec{E}} \right) + \frac{1}{2} \gamma_{M_1M_1} \vec{\sigma} \cdot \left( \vec{H} \times \dot{\vec{H}} \right) \\
- \gamma_{M_1E_2} E_{ij} \sigma_i H_j + \gamma_{E_1M_2} H_{ij} \sigma_i E_j \right]$$
Low-Energy Expansion - LEX

How do you extract polarizabilities from Compton scattering data?

Ideally, you use low energies and measure very precise cross sections and asymmetries.

**LEX:**

\[
\frac{d\sigma}{d\Omega}(\nu, \theta) = \frac{d\sigma}{d\Omega}^{\text{Born}}(\nu, \theta)
\]

\[
- \nu\nu' \left( \frac{\nu'}{\nu} \right) \frac{e^2}{2m} \left[ (\alpha_{E1} + \beta_{M1})(1 + z^2)(\alpha_{E1} - \beta_{M1})(1 - z^2) \right]
\]

with \( z = \cos \theta \)

Measure low energies and precise cross sections/asymmetries!
Comparison of DRs with EFTs

Fit to UNPOLARIZED cross section $\rightarrow$ sensitivity to $\alpha_{E1} - \beta_{M1}$ and $\alpha_{E1} + \beta_{M1}$

- **Particle Data Group (PDG)** [analysis based on DRs]
- **Heavy Baryon ChPT** [Beane, Malheiro, McGovern, Phillips, van Kolck, NPA747 (2005)]
- **Baryon ChPT with $\Delta$** [Lensky and Pascalutsa, EPJC65 (2010)]
- **Partially Covariant Baryon ChPT with $\Delta$** [McGovern, Phillips, Griesshammer, EPJA49 (2013)]
Proton and Neutron

exp(stat+sys)+theory/model $1\sigma$–error in quadrature

$\beta_{M1}$ [$10^{-4}$ fm$^3$]

$\alpha_{E1}$ [$10^{-4}$ fm$^3$]

neutron free

p Baldin $\Sigma$ rule

n BER

proton free

neutron

proton

n PDG 2013

p PDG 2013

Grießhammer 2013

MPG, EPJA49

12 (2013)
Nucleon Scalar Polarizabilities

Take aways:

• Still lots of work to do.

• Especially for the neutron.

• EFTs give consistently higher values than DRs for $\beta_{M1}$
Use polarization observables below pion threshold

**Linearly Polarized Beam**

Different dxs combinations are dependent only on $\alpha_{E1}$ or $\beta_{M1}$:

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

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

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

At low energies $\Rightarrow$ use beam asymmetry $\Sigma_3$ to extract $\beta_{M1}$:

\[
\Sigma_3 \equiv \frac{d\sigma^\perp - d\sigma^\parallel}{d\sigma^\perp + d\sigma^\parallel} = \Sigma_3^{NB} - f_3(\theta) \beta_{M1} \nu^2 + O(\nu^4).
\]
Spin Polarizabilities of the Proton

• Nucleon has four vector or spin polarizabilities:

\[ \gamma_{E1E1} \quad \gamma_{M1M1} \quad \gamma_{M1E2} \quad \gamma_{E1M1} \]

• Similar to the scalar polarizabilities but higher in order.
• Intimately connected to the nucleon’s spin structure. **Fundamental Structure Constants!**
• Higher order in incident-photon energy, so they have a smaller effect at lower energies.
• Need theoretical help in extracting values from data.
# Spin Polarizabilities - Pre-2015 Status

<table>
<thead>
<tr>
<th></th>
<th>K-mat.</th>
<th>HDPV</th>
<th>DPV</th>
<th>$L_\chi$</th>
<th>HB(\chi)PT</th>
<th>B(\chi)PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{E1E1}$</td>
<td>$-4.8$</td>
<td>$-4.3$</td>
<td>$-3.8$</td>
<td>$-3.7$</td>
<td>$-1.1 \pm 1.8$ (th)</td>
<td>$-3.3$</td>
</tr>
<tr>
<td>$\gamma_{M1M1}$</td>
<td>$3.5$</td>
<td>$2.9$</td>
<td>$2.9$</td>
<td>$2.5$</td>
<td>$2.2 \pm 0.5$ (st) $\pm 0.7$ (th)</td>
<td>$3.0$</td>
</tr>
<tr>
<td>$\gamma_{E1M2}$</td>
<td>$-1.8$</td>
<td>$-0.02$</td>
<td>$0.5$</td>
<td>$1.2$</td>
<td>$-0.4 \pm 0.4$ (th)</td>
<td>$0.2$</td>
</tr>
<tr>
<td>$\gamma_{M1E2}$</td>
<td>$1.1$</td>
<td>$2.2$</td>
<td>$1.6$</td>
<td>$1.2$</td>
<td>$1.9 \pm 0.4$ (th)</td>
<td>$1.1$</td>
</tr>
<tr>
<td>$\gamma_0$</td>
<td>$2.0$</td>
<td>$-0.8$</td>
<td>$-1.1$</td>
<td>$-1.2$</td>
<td>$-2.6$</td>
<td>$-1.0$</td>
</tr>
<tr>
<td>$\gamma_\pi$</td>
<td>$11.2$</td>
<td>$9.4$</td>
<td>$7.8$</td>
<td>$6.1$</td>
<td>$5.6$</td>
<td>$7.2$</td>
</tr>
</tbody>
</table>

- Spin polarizabilities in units of $10^{-4}$ fm$^4$
- K-matrix: calculation from Kondratyuk et al., PRC 64, 024005 (2001)
- $L_\chi$: chiral lagrangian calculation, Gasparyan et al., NPA 866, 79 (2011)
- HB\(\chi\)PT and B\(\chi\)PT are heavy baryon and covariant, respectively, ChPT calculations, McGovern et al., EPJA 49, 12 (2013), Lensky et al., PRC 89, 032202 (2014)
How to measure the spin pols?

• Use **Compton scattering**.

• Requires polarization degrees of freedom.

• Small effect at low energies, so we need higher energies, into the $\Delta$ region.

• We have chosen three asymmetries, $\Sigma_{2x}$, $\Sigma_{2z}$, and $\Sigma_3$, that we can use to help obtain the spin polarizabilities of the proton.
Spin Polarizability Extraction

Use $\gamma_0$, $\gamma_\pi$, $\alpha_{E1}$, and $\beta_{M1}$ 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!
Institut für Kernphysik

On the Johannes Gutenberg University Campus. Student population of c. 35k.

7 collaborations: two beam-related (B1, B2), four experimental (A1, A2, A4, X1) and Theory.

Approximately 200 staff members.
Plan view of the MAMI Accelerator
MAMI - Schematic

- Maximum energy 1604 MeV.
- 100% duty cycle (CW).
- Current up to 100 μA.
- Electron polarization 85%.
Real Photons - Glasgow Photon Tagger

- Detects post-bremsstrahlung electron, $E_Y = E_e - E_{e'}$
- 352 channels.
- $\approx 5-95\%$ of spectrum tagged.
- Energy resolution 1-4 MeV
- Tagger microscope
- Circularly polarized photons
- Linearly polarized photons
- Timing coincidence between detected electron and reaction product in detectors.
Reaction Targets

- \textbf{LH}_2/\textbf{LD}_2: unpolarized protons/deuterons
- Liquid $^4\text{He}/^3\text{He}$
- Frozen Spin: polarized protons/deuterons
- Solid Targets: C, Pb, and many more...
- Gas target: polarized $^3\text{He}$
- Active Polarized Proton target
- High-Pressure Active Helium target
Total # of Signals:

- 672 NaI(Tl) in CB
- 24 plastics in PID
- 320 strips in MWPC
- 480 wires in MWPC
- 384 BaF$_2$ in TAPS
- 384 plastics in TAPS veto
- (352 in Tagger)

Gives:

- Energy
- Time
- Position
- Particle Type
# Experimental Status

Important part of CRC1044.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>$\Sigma_{2x}$</td>
<td>February 2011</td>
</tr>
<tr>
<td>$\Sigma_3$</td>
<td>December 2012</td>
</tr>
<tr>
<td>$\Sigma_{2z}$</td>
<td>2014/2015</td>
</tr>
<tr>
<td>$\alpha_{E1}, \beta_{M1}$</td>
<td>June 2013, 2017/2018</td>
</tr>
</tbody>
</table>

**NOTE:** Complementary measurements planned for HIGS!

High-flux, monoenergetic beam, with $\approx 100\%$ polarization.
Pilot Experiment to Measure Proton $\alpha_{E_1}, \beta_{M_1}$

Work of E. Mornacchi and V. Sokhoyan

Low-energy Compton scattering, $\vec{\gamma}p \rightarrow \gamma p$.

Linearly polarized beam, (unpolarized) liquid hydrogen target.

High-statistics cross sections, $d\sigma/d\Omega$, and beam asymmetry, $\Sigma_3$.

Most important data are below pion threshold.
\( \alpha_{E1}, \beta_{M1} \) 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)
New A2 Measurement of $\vec{\gamma}p \rightarrow \gamma p$

- **Ph.D. work of Edoardo Mornacchi.**
- Data taken in 2017/2018. Similar set up to pilot measurement.
- LH$_2$ target, CB-TAPS setup, coherent Bremsstrahlung photon beam
- **Upgraded tagger, improved systematic errors:**
  - higher $\gamma$-flux with better flux monitoring
  - improved linpol peak stability
  - improved background subtraction
- $1.2 \times 10^6$ events, an improvement of $\times 6$ compared to the pilot measurement.
- Approximately $\times 10$ the statistics of the previous world best measurement with TAPS (also A2!) [OdL et al., EPJA 10 207 (2001)], which makes up of about 50% of the existing world data.
New A2 Measurement of $\vec{\gamma}p \rightarrow \gamma p$

$E_\gamma = 120 - 140$ MeV

Mornacchi Ph.D.
New A2 Measurement of $\vec{\gamma}p \rightarrow \gamma p$

Mornacchi Ph.D.
\( \alpha_{E1}, \beta_{M1} \) Outlook

- Finish data analysis
- Use a simultaneous fit to unpolarized cross sections AND asymmetries to achieve precision on \( \beta_{M1} \) comparable to that of the current PDG value!
\[ \frac{\Sigma_{2\chi}}{\Sigma_{2\chi}} \] Asymmetries - Experimental Challenges

- A source or polarized protons is not easy to come by (nor to operate).
- Small Compton scattering cross sections
- Large background cross sections
  - \( \pi^0 \) photoproduction cross section is about 100 times larger than that for Compton scattering
  - Coherent and incoherent reactions of C, O, and He
- Proton tracks are required to suppress backgrounds, but energy losses in the frozen-spin cryostat (and CB-TAPS) are considerable.
**Results $\Sigma_{2x}$ - Martel et al., PRL 114 12501 (2015)**

$E_\gamma = 273 - 303$ MeV

- First measurement of a double-polarized Compton scattering asymmetry on the nucleon.
- Curves are from the DR calculation of Pasquini et al.
- Data resulted in the first extraction of the proton’s spin pols in the multipole basis:

  \[
  \begin{align*}
  \gamma_{E1E1} &= -3.5 \pm 1.2 \\
  \gamma_{M1M1} &= 3.16 \pm 0.85 \\
  \gamma_{E1M2} &= -0.7 \pm 1.2 \\
  \gamma_{M1E2} &= 1.99 \pm 0.29
  \end{align*}
  \]
$\sum_3$ 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 ($B_\chi PT$) predictions.
- Fits have been done.
\[ \sum_{2z} \]

Results

- PhD work of both D. Paudyal (Regina) and A. Rajabi (UMass).
- Data have been taken and analysis is done.
- There were some background issues, but we are more or less ready to publish.
- Do global fit, extract spin polarizabilities.
The “Other” Nucleon - The Neutron

The situation is considerably worse for the neutron:

- 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!
Elastic Compton Scattering from $^3$He


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 in the next year.
The New Active Target

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

8th December 2015

Active Target 3,4He, J.R.M. Annand
Outlook

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

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 Edoardo Mornacchi and Vahe Sokhoyan for slides and input.*