Measuring the Spin-Polarizabilities of the Proton at HI$\gamma$S

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- Nucleon polarizabilities: What are they, and what’s still to be accomplished
- Spin-polarizabilities of the proton
- The experiment in preparation at HIGS
Proton electric and magnetic polarizabilities from real Compton scattering†

\[
\alpha = (12.0 \pm 0.6) \times 10^{-4} \text{fm}^3
\]

\[
\beta = (1.9 \pm 0.6) \times 10^{-4} \text{fm}^3
\]

Some observations...

i. the numbers are small: the proton is very “stiff”

ii. the magnetic polarizability is around 20% of the electric polarizability

Cancellation of positive paramagnetism by negative diamagnetism

The spin-polarizabilities of the nucleon

- At $O(\omega^3)$ four new nucleon structure terms that involve nucleon spin-flip operators enter the RCS expansion.

$$H_{\text{eff}}^{(3),\text{spin}} = -\frac{1}{2} 4\pi \left( \gamma_{E1E1} \bar{\sigma} \cdot \vec{E} \times \dot{\vec{E}} + \gamma_{M1M1} \bar{\sigma} \cdot \vec{B} \times \dot{\vec{B}} - 2 \gamma_{M1E2} E_j \sigma_j H_j + 2 \gamma_{E1M2} H_j \sigma_j E_j \right)$$

- The classical Faraday effect is a spin polarizability effect

- Spin-polarizabilities cause the nucleon spin to precess in rotating electric and magnetic fields
Spin polarizabilities in Virtual Compton Scattering

\[ d^5{\sigma}^{VCS} = d^5{\sigma}^{BH+Born} + q' \Phi \left\{ \nu_1 \left[ P_{LL}(q) - \frac{P_{TT}(q)}{\varepsilon} \right] + \nu_2 P_{LT}(q) \right\} \]

**Contribution of spin polarizabilities in the VCS response functions**

**Graphs showing the contribution of spin polarizabilities in the VCS response functions**
Experiments

The GDH experiments at Mainz and ELSA used the Gell-Mann, Goldberger, and Thirring sum rule to evaluate the forward S.-P. $\gamma_0$

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2}$$

$$\gamma_0 = \frac{1}{4\pi^2} \int_{m_\pi}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\omega^3} d\omega$$

$$\gamma_0 = (-1.01 \pm 0.08 \pm 0.10) \times 10^{-4} \text{ fm}^4$$

Backward spin polarizability from dispersive analysis of backward angle Compton scattering

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2}$$

$$\gamma_\pi = (-38.7 \pm 1.8) \times 10^{-4} \text{ fm}^4$$
## Experiment versus Theory

<table>
<thead>
<tr>
<th></th>
<th>Experiment$^{1,2}$</th>
<th>SSE$^3$</th>
<th>Fixed-(t) DR$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma_0)</td>
<td>(-1.01 \pm 0.08 \pm 0.10)</td>
<td>(.62 \pm -0.25)</td>
<td>(-0.7)</td>
</tr>
<tr>
<td>(\gamma_\pi)</td>
<td>(8.0 \pm 1.8)</td>
<td>(8.86 \pm 0.25)</td>
<td>(9.3)</td>
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</table>

## Theory versus Theory

<table>
<thead>
<tr>
<th></th>
<th>HBCHPT</th>
<th>Fixed-t dispersion analyses</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$O(p^3)$&lt;sup&gt;1&lt;/sup&gt;</td>
<td>$O(p^4)$&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>$\gamma_{E1E1}$</td>
<td>-5.7</td>
<td>-1.8</td>
</tr>
<tr>
<td>$\gamma_{M1M1}$</td>
<td>-1.1</td>
<td>2.9</td>
</tr>
<tr>
<td>$\gamma_{E1M2}$</td>
<td>1.1</td>
<td>.7</td>
</tr>
<tr>
<td>$\gamma_{M1E2}$</td>
<td>1.1</td>
<td>1.8</td>
</tr>
</tbody>
</table>


**Lattice calculations are in progress**
Experiments in progress to measure nucleon spin-polarizabilities in RCS

- **Mainz (J. Ahrens)**
  \[ \vec{\gamma}p \rightarrow \gamma p \] circularly polarized photons, longitudinal and transversely polarized target
  Crystal ball detector, \( \approx 4\pi \) detection
  \( E_\gamma \approx 200 \text{ MeV} \) (large sensitivity to \( \gamma \)'s)
  Possible problem with \( \gamma C \rightarrow \pi^0 C \) and \( \gamma C \rightarrow \gamma C \)

- **HI\( \gamma \)S**
  Compton scattering with polarized beam and target

  \[ \vec{\gamma}p \rightarrow \gamma p \quad \vec{\gamma}^3He \rightarrow \gamma^3He \]
Experimental concept for HI$_\gamma$S:

- $I_\gamma = 10^7$ photons/s, monochromatic $E_\gamma \geq 100$ MeV, 100% circular polarization

- $\approx 800$ hours combined running on longitudinal and transversely polarized target

- HINDA NaI detector array

- Polarized scintillating target, 5 cm long, 80% polarization
GEANT-4 Simulation
Polarized Target
Transverse Coil

OD=Ø4cm
Length=20cm
\( \vec{\gamma} p \rightarrow \gamma p \) longitudinal polarized target, 110 MeV

Projected errors for 200 hours running

Sensitivity to \( \gamma \)'s
Transverse polarized target, 110 MeV

Projected errors for 200 hours running

Sensitivity to γ's
\( \vec{\gamma}p \rightarrow \gamma p \) transverse polarized target, 130 MeV

**Transverse Target Pol.**
- +X
- +X no spin pol.
- -X
- -X no spin pol.

Projected errors for 200 hours running

Sensitivity to \( \gamma \)'s
Projected Uncertainties: 800 hours @ 100 MeV

<table>
<thead>
<tr>
<th>S.-P.</th>
<th>Value* (10^{-4} fm^3)</th>
<th>Fitting error Δγ †</th>
<th>Δγ/γ</th>
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<tbody>
<tr>
<td>$\gamma_{E1E1}$</td>
<td>-4.3</td>
<td>.21</td>
<td>5 %</td>
</tr>
<tr>
<td>$\gamma_{M1M1}$</td>
<td>2.9</td>
<td>.16</td>
<td>6 %</td>
</tr>
<tr>
<td>$\gamma_{E1M2}$</td>
<td>-.01</td>
<td>.25</td>
<td>2500 %</td>
</tr>
<tr>
<td>$\gamma_{M1E2}$</td>
<td>2.1</td>
<td>.25</td>
<td>12 %</td>
</tr>
</tbody>
</table>

† Statistical errors only, no systematic

* B. Pasquini
Scintillating polarized target

- Coherent Compton scattering from complex nuclei in butanol \((C_4H_{10}O)\) is orders of magnitude larger than the proton Compton scattering

  Tag Compton events on proton by observing scintillation light from recoil protons

- Eliminate backgrounds in the NaI detectors by timing cut
Light capture with wavelength shifting fibers

APD or SSPM

Transparent shell

- Polarized scintillating disks 5 mm thick, BC-490 doped with Tempo
- BCF-92 blue to green wavelength shifting fiber, 1 mm square, double clad, wrapped around clear shell, 7% capture efficiency

Overall light transport efficiency ≈ 2%
Trues:Accidentals = 35:1
Cryogenic capable photo-detectors for the polarized target

1. Hamamatsu Si-APD (commercially available)
2. SS-PMT from Radiation Monitoring Devices operating in proportional mode
   - Phase I SBIR proposal approved and completed
   - Phase II SBIR proposal submitted. If approved, this SBIR will provide experiment-ready detectors for HIγS.
Quantum Efficiency of Hamamatsu Si-APD

Gain $\approx \times 200$
Solid-State Photomultipliers

- Array of photodiodes readout in parallel.
- Each diode has a binary response to single photons.
- The response to each diode is associated with a large gain, providing good signal to noise.
- Radiation Monitoring Devices, Inc. has built these devices using CMOS technology, which allows integrated circuits on the same silicon die.
Low temperature performance of the RMD SS-PMT

 QE \approx 30\%

 Gain = 10^3 \text{ to } 10^4
Target material: the problems

Use dynamic nuclear polarization with chemical doping to polarize the target. There are problems,

1. the paramagnetic dopant must survive the process of making the target
2. the target should be reasonably efficient for producing scintillation light
3. the target should be reasonably transparent to blue scintillation light

If we can do all that, then we still must obtain high proton polarization, \( \approx 80\% \).

Tools for testing target materials include:

- Electron Polarization Resonance (EPR) for counting paramagnetic centers in target material (Paul Lahti, UMass Chemistry)
- Helium dilution refrigerator, high field magnet, RF, and NMR system for polarizing target samples. (Don Candela, UMass Physics)
Polarized-Scintillating Target: Possible materials

1. PSI technique
   - Dissolve polystyrene scintillator in toluene
   - Dope the scintillator mixture with a paramagnetic doping agent, tempo, at \(2 \times 10^{19}\) p.c.’s/cc
   - Pour out thin films of the scintillator mixture and let the toluene evaporate
   - Press the thin films together to form scintillating blocks several mm thick

2. Dope a castable polyethylene scintillator resin, BC-490, with tempo and use a peroxide setting agent to harden the scintillator.

3. Prepare a liquid scintillator doped with tempo, then freeze it in liquid nitrogen
   - Xylene mixed with \(\approx 1\%\) PPO and \(\approx 0.05\%\) POPOP
   - Mineral oil based liquid scintillator, e.g. BC-517S
   - BC-490 polyethylene scintillator resin
Summary:

• Spin-polarizabilities parameterize the long distance spin-structure of the nucleon, in the limit where π’s and Δ’s are the relevant degrees of freedom. The pion cloud is one of the key ingredients in deciphering the proton “spin crisis”.

• There exist no measurements of individual nucleon spin-polarizabilities

• Can measure the polarizabilities at HIGS with an uncertainty of $\approx 0.2 \times 10^{-4} \text{ fm}^4$. This will be sufficient to test and differentiate between theoretical models.
$\vec{\gamma}p \rightarrow \gamma p$ *longitudinal* polarized target, 130 MeV

Projected errors for 200 hours running

Sensitivity to $\gamma$'s