Studies of Compton scattering and nucleon polarizabilities at the upgraded HIγS facility

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HIγS PROGRAM

HUGS_3, June 2009
HI\(\gamma\)S

*Nearly Mono-energetic \(\gamma\)-rays from 2 to 158 MeV*
  • Up to 65 MeV now
  • Up to \(~100\) MeV in 2010
  • Up to 158 MeV by 2012

*\(~100\)% Linearly and Circularly Polarized \(\gamma\)-rays*

*High Beam Intensities*  
*(Ran with \(2\times10^7\) on target at 45 MeV (October, 2008))*
\(\gamma\)-ray Production at HIGS

- **Two modes of operation:**
  - No electron loss \((E_\gamma < 20\text{ MeV})\)
  - Electron loss \((E_\gamma > 20\text{ MeV})\)
The Upgraded HIGS Facility

- RF System with HOM Damping
- 1.2-GeV Booster Injector
### Some typical beam intensities

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>Beam on target ($\Delta E/E = 3%$)</th>
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<tbody>
<tr>
<td>1 - 2</td>
<td>$2 \times 10^7 , \gamma/s$</td>
</tr>
<tr>
<td>8 – 16</td>
<td>$8 \times 10^7$ (total flux of $2 \times 10^9$)</td>
</tr>
<tr>
<td>20 – 45</td>
<td>$8 \times 10^6$</td>
</tr>
<tr>
<td>50 – 95</td>
<td>$4 \times 10^6$ (by 2011)</td>
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The research program at Hi\(\gamma\)S

There is a very broad program of research underway at HiGS. This is expected to take over five years to execute, and will require over 2000 hrs. per year of beam time. The program includes:

- Nuclear Astrophysics
- Few Body Physics
- GDH Sum rule for deuterium and \(^3\)He
- Nuclear Structure studies using NRF
- Compton scattering from nucleons and few body nuclei
- Pion Threshold studies
Study of the fundamental structure of the nucleon:

GOALS:

Use the intense polarized beams at HIγS to obtain precise values of the electric and magnetic polarizabilities of the proton and the neutron.

Perform double polarization experiments to obtain precise values of the spin-polarizabilities of the proton and the neutron.
See: Research Opportunities at the upgraded HIGS Facility, just published in Progress in Particle and Nuclear Physics 62 (2009) 257-303.

The Compton @HIγS Collaboration consists of 32 physicists from 14 Institutions and includes: Averett, Calarco, Feldman, Gao, Kovash, Miskimen, Nathan, Norum, Weller, Whisnant, Wu
The Compton@HIγS Program

1. Use linearly polarized $\gamma$s at $\sim$100 MeV to obtain accurate values for $\alpha$ and $\beta$ of the proton.

2. Perform Compton scattering on the deuteron below 80 MeV to determine the neutron polarizabilities.

3. Use a scintillating polarized proton target and determine the proton spin-polarizabilities with circularly polarized beam at 100 – 140 MeV.

4. Use a polarized $^3$He target and measure elastic scattering to extract neutron spin-polarizabilities using circularly polarized beams.
• **The HINDA Array**
  (HI$_\gamma$S NaI Detector Array)

- NSF/MRI funded project—a high resolution-high acceptance gamma-ray spectrometer consisting of eight 10”x12” NaI detectors in 3” thick segmented NaI shields.

- **The Compton@HI$_\gamma$S Collaboration**
The HINDA Array @ HI$\gamma$S

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First test run using a HINDA detector. Spectrum obtained in 30 minutes (470 counts) with a 45 MeV beam ($2 \times 10^7 \gamma/s$) on a 7.6 cm thick $^{12}$C target.
Proton electric polarizability

Electric polarizability: proton between charged parallel plates

HUGS_3, June 2009
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

† M. Schumacher, Prog. Part. and Nucl. Phys. 55, 567 (2005) and PDG.
Proton magnetic polarizability

Magnetic polarizability: proton between poles of a magnetic field.
Linearly polarized $\gamma$s allow for independent measurements of the electric ($\alpha$) and the magnetic ($\beta$) polarizabilities of the proton. 

(Leonard Maximon, PRC39, 347 (1989))

Present values ($x$ 10⁻⁴ fm³)

$\alpha = 12.0 \pm 1.1$ (stat + sys) $\pm$ 0.5 (th); $\beta = 1.9 \pm 0.8$ (stat + sys) +/− 0.5 (th)

\[
\frac{d\sigma_{\perp}}{d\Omega}|_{\theta=90} - \frac{d\sigma_{\perp}^{pt}}{d\Omega}|_{\theta=90} = -K\alpha
\]

\[
\cos^2\theta \left( \frac{d\sigma_{\perp}}{d\Omega} - \frac{d\sigma_{\perp}^{pt}}{d\Omega} \right) - \left( \frac{d\sigma_{\parallel}}{d\Omega} - \frac{d\sigma_{\parallel}^{pt}}{d\Omega} \right) = K\beta \cos\theta \sin^2\theta
\]

where $K = 2\left( \frac{e^2}{Mc^2} \right) \left( \frac{\omega'}{\omega} \right)^2 \omega \omega'$
Comments

Explicit expressions for the *point values* of the cross section for polarizations perpendicular and parallel to the scattering plane are given by Maximon for a point proton with charge, spin and magnetic moment.

Measurements at $90^\circ$ with the detectors perpendicular to the plane of polarization of the beam will provide a direct determination of $\alpha$, independent of $\beta$.

The results of Maximon only include the polarizabilities at order $(\omega/M)^2$. If contributions of order $(\omega/M)^4$ are significant, they will show up as a deviation in the measured value of the cross section in a $90^0$ detector parallel to the plane of polarization wrt. the point value.
Linearity Polarized $\gamma$ on Proton (100 MeV)

- $d\sigma_{\perp}$
- $d\sigma_{\parallel}^{PT}$
- $d\sigma_{\parallel}$
- $d\sigma_{\parallel}^{PT}$

Cross Section (nb/sr)

Photon Scattering Angle (deg)
• Determination of the electric and magnetic polarizabilities of the proton using 100% linearly polarized gammas@HIGs – a ~300 hr experiment with a beam intensity of $5 \times 10^7$ γ/s will yield ~5% errors on $\alpha$ (now~15%) and $\beta$ (now~40%).
Compton scattering from the deuteron—
determining the neutron polarizabilities

This determines the isoscalar polarizabilities $\alpha_N$ and $\beta_N$,
which lead to the neutron polarizabilities using the known
values of the proton.

Data to date:

Saskatoon, $E_\gamma = 95$ MeV D. L. Hornidge et al. PRL 84, 2334(2000)
Lund, $E_\gamma = 60$ MeV M. Lundinet et al, PRL 90 (2003) 192501
Compton Scattering from the deuteron below 100 MeV

Measurements yield the isoscalar polarizabilities:
\[ \alpha_E^s = \frac{1}{2}(\alpha_E^p + \alpha_E^n) \] and \[ \beta_M^s = \frac{1}{2}(\beta_M^p + \beta_M^n) \]

Hildebrandt, Griesshammer and Hemmert have used Chiral Effective Field Theory with explicit \( \Delta(1232) \) degrees of freedom within the Small Scale Expansion up to leading-one loop order and calculated this process up to 100 MeV.

(nucl-th/0512063)

Their results have resolved a “long standing” problem, obtaining consistent fits to the data, especially the 94.2 MeV data.

(Dissertation project of Seth Henshaw (Duke))
A global fit to all existing $\gamma d$ data using the Baldin sum rule. The results are

$$\alpha_E^s = (11.3 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (Baldin)}) \times 10^{-4} \text{ fm}^3$$

$$\beta_M^s = (3.2 \pm 0.7 \text{ (stat)} \pm 0.6 \text{ (Baldin)}) \times 10^{-4} \text{ fm}^3$$

which indicates, by comparing to the proton values, that the $n$ and $p$ polarizabilities are essentially the same within experimental errors.

Figure 18: Results from a global fit of $\alpha_E^s$ to all existing elastic $\gamma d$ data, using the chiral wave function [35]. $\beta_M^s$ is fixed via the Baldin sum rule, Eq. (4.3). The grey bands are derived from our statistical errors.
Compton on the deuteron @ HiγS

The *HINDA spectrometer* and a liquid *scintillating target* will be used in these experiments.

Angular distributions will be measured in 10 MeV steps between 30 and 80 MeV. **We expect to obtain 1.5% statistics in each of 8 detectors at 6 energies in ~300 hours.** The absolute cross section will be determined to an accuracy of ~7%.

These measurements will *determine the neutron polarizabilities to an accuracy of ~10%.*
COMPTON ON d WITH A SCINTILLATING TARGET

Vertical axis: number of photons detected
Horizontal axis: Missing energy (binding energy)
Courtesy of Rory Miskimen
The ratio of $\sigma(45)$ to $\sigma(150)$, for example, is insensitive to the values of $\alpha_N$, but varies with $\beta_N$. 
Compton on the deuteron @ HIγS

This will determine $\beta_n$ to better than +/- 1.0 x 10^{-4} \text{fm}^3 in just 100 hrs at 60 MeV.

(plot below varies $\beta_N$ by +/- 1.0 x 10^{-4} \text{fm}^3) from “theoretical” value)
Spin polarizabilities.

- They tell us about the response of the spin of the nucleon to the polarization of the photons. The stiffness of the spin can be thought of as arising from the nucleon’s spin interacting with the pion cloud.

- Measuring these requires circularly polarized beams and polarized targets – ideally suited to HIγS.

- Polarized protons will be provided by our frozen-spin target. A polarized $^3$He target will be used to obtain the neutron spin-polarizabilities.
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.

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

- A rotating electric field will induce a precession of the proton spin around the direction of the polarized photon, with a rate proportional to the spin-polarizability.
Circularly polarized photons moving in the z-direction incident on a proton initially polarized in the x-direction.

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Experiments

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

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

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

$$\gamma_0 = (-1.00 \pm 0.08 \pm 0.10) \times 10^{-4} \text{ fm}^4$$

Backward spin polarizability from dispersive analysis of backward angle Compton scattering

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

$$\gamma_\pi = (-38.7 \pm 1.8) \times 10^{-4} \text{ fm}^4$$
Alternative notation

Also denote the four spin polarizabilities as
\[ \gamma_1 \gamma_2 \gamma_3 \gamma_4 \]
\[ \gamma_{E1E1} = -\gamma_1 - \gamma_3 \]
\[ \gamma_{M1M1} = \gamma_4 \]
\[ \gamma_{E1M2} = \gamma_3 \]
\[ \gamma_{M1E2} = \gamma_2 + \gamma_4 \]
Proton spin-polarizabilities will be measured using a scintillating frozen-spin polarized target

Rory Miskimen et al., U. Mass.
Simulations have been performed. A working prototype is under construction.

The initial experiment will run near 100 MeV.
HIγS Frozen Spin Polarized Target (HIFROST)

- Butanol
- Polarization ~ 80 %
- Polarizing Field ~ 2.5 T
- Holding Field ~ 0.6 T
• APD or SSPM

• Transparent shell

• Polarized scintillating disks 5 mm thick, BC-490 doped with Tempo

• Overall light transport efficiency $\approx 2\%$

HUGS_3, June 2009
Results of a simulation using the scintillating Butanol target and a HINDA detector (performed by Rory Miskimen).

\(\text{Missing Energy} = E_{\text{beam}} - E_{\text{NaI}} - E_{\text{target}}\)
The first experiment will determine $\gamma_{E_1E_1}$ by measuring $\Sigma_{2x}$ using a transverse polarized target and 8 HINDA detectors near 90° at 100 MeV. Find little sensitivity to $\gamma_{M1M1}$ and use $\gamma_0$ and $\gamma_\pi$ to fix the other two. Anticipated uncertainty in $\gamma_{E1E1}$ is $\sim 1.0 \times 10^{-4}$ fm$^4$. 

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Four HINDA detectors will be located clustered around 90° in the horizontal plane on both the right and left sides of the beam.
Count rate calculations and projections


Target thickness: $2.6 \times 10^{23}$ p/cm$^2$ ; 80% polarization
Beam intensity: $1 \times 10^7 \gamma$/s @ 120 MeV
The HINDA array with dets. 75 cm from the target
Running time: 200 hrs. longitudinal, 200 hrs. transverse

Spin pols. were fit to pseudo-data using theoretical model of Hildebrandt to generate the uncertainties.
Running at 120 MeV with both transverse and longitudinal targets will produce ~5% results for the dipole spin polarizabilities in ~400 hours of beam time (200 hrs. transverse polarization and 200 hrs. longitudinal).

Total beam time for proton measurement: 400 hrs

100 hrs for each target spin orientation

Theory curves: Hildebrandt, Griesshammer, Hemmer

• Nucl-th/0308054

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Experiments are being developed by Dr. Haiyan Gao at Duke/HI\(_\gamma\)S to measure the spin-polarizabilities of the neutron.

Haiyan Gao has built a high pressure spin-polarized \(^3\)He target. Target thickness is about 10\(^{22}\) atoms/cm\(^2\) with a length of 40 cm. Polarizations of ~40% have been achieved.

Effect of the reduced target thickness is offset by the increased sensitivity in the observables.

Polarized target reference:
K. Kramer et al., NIM A \textbf{582}, 318 (2007)
Target polarization \( \sim 40\% \)
Target thickness \( \sim 10^{22} \) nuclei/cm\(^2\)

**Polarized \(^3\)He Target**

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• Present proposed experiments

ChPT calculations by Choudury, Nogga and Phillips make extraction of spin-polarizabilities possible from elastic scattering data.

With a gamma intensity of $2 \times 10^7$/sec at 114 MeV and the target and detector system just described, a 2000 hour experiment will give neutron spin polarizabilities with errors of about $+/- 0.5 \times 10^{-4}$ fm$^4$. 

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\[
\begin{align*}
\Delta_z &= \left( \frac{d\sigma}{d\Omega} \right)_{\uparrow\uparrow} - \left( \frac{d\sigma}{d\Omega} \right)_{\uparrow\downarrow} \\
\Delta_x &= \left( \frac{d\sigma}{d\Omega} \right)_{\uparrow\rightarrow} - \left( \frac{d\sigma}{d\Omega} \right)_{\uparrow\leftarrow}
\end{align*}
\]
$\Delta x \ vs \ cm \ angle \ at \ 120 \ MeV$

Choudury, Nogga and Phillips,
Projected HIγS measurements on Nucleon Spin Polarizabilities (all × 10⁻⁴ fm⁴)—Theoretical values are from Gellas, Hemmert and Meissner PRL 85 (2

<table>
<thead>
<tr>
<th>Proton HIγS projected uncertainties</th>
<th>Neutron HIγS projected uncertainties</th>
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<tbody>
<tr>
<td>( \gamma^p_1 = 1.1 ) ± 0.10</td>
<td>( \gamma^n_1 = 3.7 ) ± 0.43</td>
</tr>
<tr>
<td>( \gamma^p_2 = -1.5 ) ± 0.36</td>
<td>( \gamma^n_2 = -0.1 ) ± 0.03</td>
</tr>
<tr>
<td>( \gamma^p_3 = 0.2 ) ± 0.24</td>
<td>( \gamma^n_3 = 0.4 )</td>
</tr>
<tr>
<td>( \gamma^p_4 = 3.3 ) ± 0.17</td>
<td>( \gamma^n_4 = 2.3 ) ± 0.57</td>
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Summary:

• Measuring the spin-polarizabilities of the nucleon is an important next step. These are fundamental structure constants of the nucleons. The beam, targets, and detectors are now available for these experiments.

• Spin-polarizabilities represent the spin-response functions of the nucleon in a regime where pions and Δ's, not quarks and gluons, are the relevant degrees of freedom.

• Can measure the polarizabilities at HIGS with a precision of from 0.2 to 0.4 × 10^{-4} \text{ fm}^4 , which is sufficient to test and differentiate between theoretical models. Full Lattice QCD calculations are imminent.
Spin Polarizabilities from Lattice QCD

**Quenched Lattice QCD results**

\( m_\pi \simeq 500 \text{ MeV} \)

\( \alpha_{elec} \)

\( \beta_{mag} \)

J. Christensen et al.
PRD73 (2006) 100 configurations
PRD72 (2005) 150 configurations

(see also E. Shintani et al. hep-lat/0611032)

Measure mass shift in background field:

eg: magnetic polarizability

\[ \delta m = m(B) - m(0) = -\vec{\mu} \cdot \vec{B} - \frac{1}{2} \beta_{mag} B^2 + \ldots \]

Can also determine neutron (and proton) spin polarizabilities from lattice QCD with varying external field

W. Detmold, B. C. Tiburzi, A. Walker-Loud
PRD73 (2006)

- **Exploratory, quenched calculation at** \( m_\pi \simeq 500 \text{ MeV} \) **possible today.** Precision similar to that of electromagnetic polarizabilities, \( \alpha_{elec}, \beta_{mag} \)

- **First full QCD calculation of all isovector electromagnetic and spin polarizabilities possible with moderate computational resources:** 1-2 year time frame.

- **Complete calculation will require significant computational investment:**
  - Need studies on multiple volumes and lattice spacings
  - For isoscalar polarizabilities, need new gauge configurations with EM fields (expensive but also useful for other EM lattice studies)

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Spin-exchange optical pumping