Probing the Nuclear and Nucleon Spin Structure at the Upgraded HI$\vec{\gamma}$S Facility

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Sample of experiments at the *Upgraded* High Intensity γ-Ray Source (HIγS) aimed at studying the spin structure

- Determination of the Gerasimov-Drell-Hearn (GDH) Sum Rule for Deuteron (2.25 - 140 MeV) and ^{3}He
- A Compton scattering program to study the *electromagnetic* and *spin* polarizabilities of the nucleon (50 - 120 MeV)

What is GDH Sum Rule ?

Start with Compton scattering amplitude with $f(\omega)$ and $g(\omega)$ amplitudes:

$$
\begin{aligned}
f(\omega) &= \frac{-e^2}{4\pi m} + (\alpha + \beta)\omega^2 + O(\omega^4) \\
g(\omega) &= \frac{-e^2\kappa^2}{8\pi m^2}\omega + \gamma\omega^3 + O(\omega^5) \\
I^{GDH} &= \int_{\omega_{th}}^{\infty} (\sigma_P(\omega) - \sigma_A(\omega))\frac{d\omega}{\omega} \\
&= 4\pi^2 e^2 \frac{\kappa^2}{M^2} S \;, \qquad (1)
\end{aligned}
$$

Ground State Static Property $\longrightarrow$ Dynamical Structure of the Target

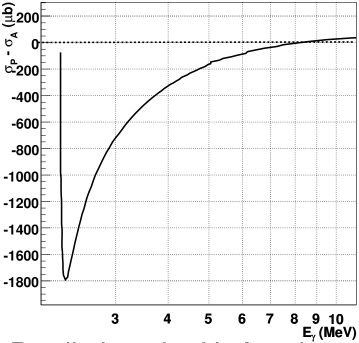
GDH sum rule determination is a test of many fundamental assumptions. The consistancy of the GDH sum rule can be used to search for new Physics

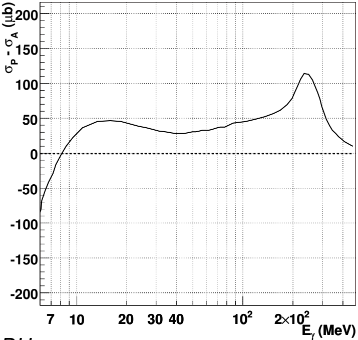
GDH Integral for Deuteron

The D has a small anomalous magnetic moment (κ_d = -0.143 [1]).

$$
\begin{aligned}
I_D^{GDH} &= 0.652\mu b && (2)\\
I_D^{GDH} &= \int_{\omega_{th}}^{\omega_\pi} GDH_D + \int_{\omega_\pi}^{\infty} GDH_D && (3)\\
I_D^{GDH} &= \int_{\omega_{th}}^{\omega_\pi} GDH_D + \int_{\omega_\pi}^{\infty} GDH_p + \int_{\omega_\pi}^{\infty} GDH_n\\
I_D^{GDH} &= \int_{\omega_{th}}^{\omega_\pi} GDH_D + 204\mu b + 232\mu b\\
\int_{\omega_{th}}^{\omega_\pi} GDH_D &\sim -436\mu b
\end{aligned}
$$

[1] P. Mohr and B. Taylor, Rev. of Mod. Phys., 72, 351 (2000)





Predictions by H. Arenhövel [2] for I_D^{GDH}. Contributions of various channels to the finite GDH Integral[3] gives an I_D^{GDH} of 27 μb.

[2] Phys. Lett. B407, 1-7 (1997)

[3] AFS, PRL 93, 202301 (2004)

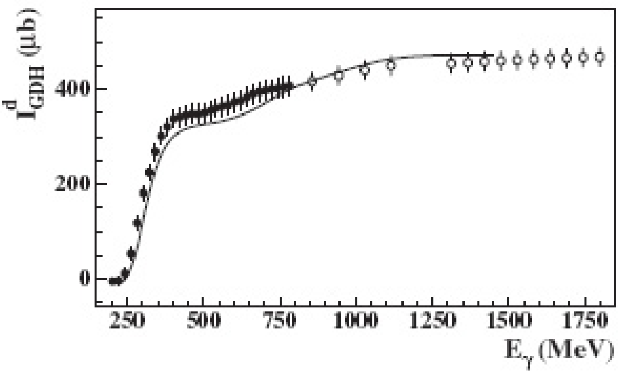
Global Efforts on the GDH_D

$$\int_{\omega_{th}}^{\omega_\pi} GDH_D \longrightarrow \text{HI}\gamma\text{S}$$

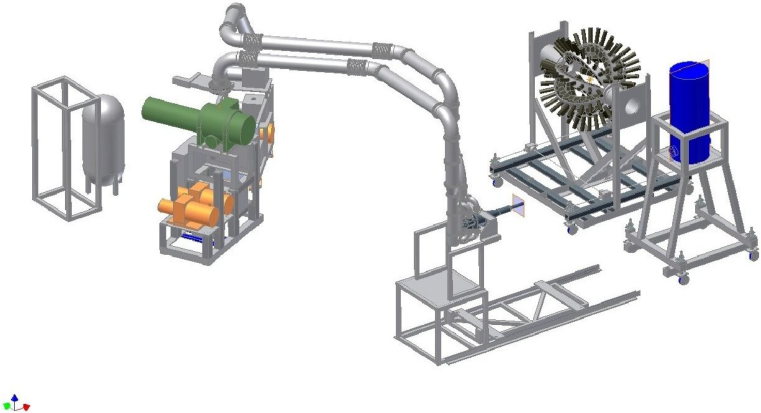
$$\int_{\omega_\pi}^{\infty} GDH_D \longrightarrow \text{LEGS, Mainz, Bonn}$$

At High Intensity γ-ray Source (HIγS) we will begin to measure the part of the GDH_D below the pion production threshold using Polarized Frozen Spin Target (HIFROST), Blowfish neutron detector array, and circularly polarized γ-rays in 2008.

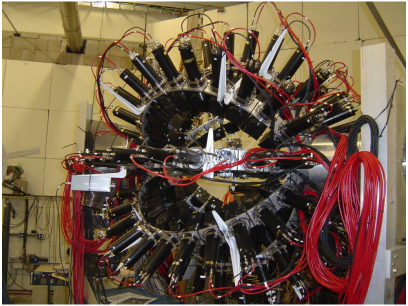
I_D^{GDH} Above Pion Production Threshold[4]



[4] J. Ahrens *et al.* Phys. Rev. Lett. 97, 202303 (2006)



Blowfish : 88-cell neutron detector array, 25 % of 4π coverage
HIFROST : 10 cm long target, T = 50 mK, Polarization $\sim$ 80 %



Meanwhile ...

$$\sigma_P - \sigma_A = \frac{\pi\lambda^2}{2}[-|M1(^1S_0)|^2 - |E1(^3P_0)|^2 - \frac{3}{2}|E1(^3P_1)|^2 + \frac{5}{2}|E1(^3P_2)|^2 - \frac{3}{2}|E2(^3D_1)|^2 - \frac{5}{6}|E2(^3D_2)|^2 + \frac{7}{3}|E2(^3D_3)|^2], \quad (4)$$

If all P- wave amplitudes are set to be equal and likewise for the D-waves, then:

$$\sigma_P - \sigma_A = \frac{\pi\lambda^2}{2}[-|M1(^1S_0)|^2] \quad (5)$$

Compare it to Photodisintegration of Unpolarized Deuteron Using Linearly Polarized γ-Rays : Measurement of the Analyzing Power ($\Sigma(\theta)$)

$$\sigma(\theta,\phi) = \frac{\lambda^2}{6}[\frac{1}{4}|S|^2 + \frac{27}{8}|P|^2\sin^2\theta(1+\cos 2\phi)]\ , \tag{6}$$

$$\Sigma(\theta) = \frac{\frac{27}{8}|P|^2\sin^2\theta}{\frac{1}{4}|^1S_0|^2 + \frac{27}{8}|P|^2\sin^2\theta}\ . \tag{7}$$

Therefore, $|^1S_0|^2$ (M1) fractional contribution to the total cross section can be extracted from the $\Sigma(\theta)$ measurement.

By multiplying the fractional M1 contribution to the theoretical total cross section we can obtain absolute σ(M1)

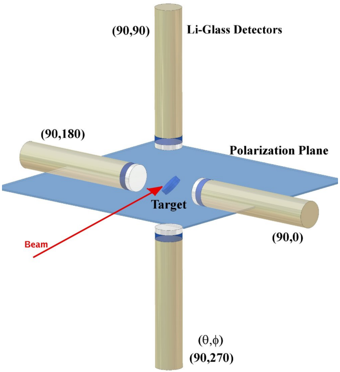
But Recall ...

$$\begin{aligned}
\sigma_P - \sigma_A &= \frac{\pi\lambda^2}{2}[-|M1(^1S_0)|^2] \text{ and,} \\
\sigma(M1) &= \frac{\pi\lambda^2}{6}[|M1(^1S_0)|^2] \\
\longrightarrow \sigma_P - \sigma_A &= -3\sigma(M1) \qquad (8)
\end{aligned}$$

Measurement of $\Sigma(\theta)$ (hence the σ(M1)) in Deuteron Photodisintegration is an indirect determination of the GDH$_D$ Sum Rule Integrand !

$$\Sigma(90^\circ) = \frac{Yield_{Hor} - Yield_{Ver}}{Yield_{Hor} + Yield_{Ver}}$$

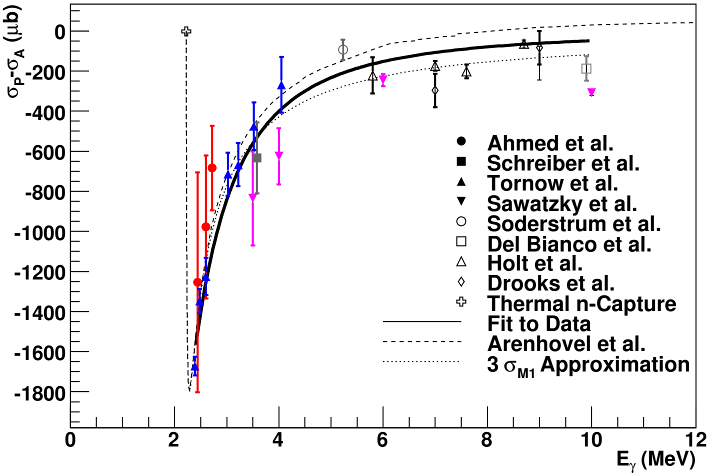
A Photodisintegration Experiment at HIγS



Analysis of Other Experiments to Extract σ(M1)

Experiment	Measurement
$\vec{\gamma}$d$\rightarrow$ np[5]	Analyzing Power
$\vec{\gamma}$d$\rightarrow$ np[6]	Analyzing Power
$\vec{\gamma}$d$\rightarrow$ np[7]	Analyzing Power
$\vec{\gamma}$d$\rightarrow$ np[8]	Analyzing Power & Angular Cross Section
γd$\rightarrow$ $\vec{n}$p[9]	Neutron Polarization
$\vec{n}$p$\rightarrow$dγ[10]	Radiative Capture

[5] Schreiber *et al.*, Phys. Rev. C61, 061604R (2000)
[6] Tornow *et al.*, Phys. Lett. B574, 8-13 (2003)
[7] Del Bianco *et al.*, Phys. Rev. Lett. 47, 1118 (1981)
[8] Sawatzky *et al.*
[9] Holt *et al.* Phys. Rev. Lett, 50, 577 (1983)
[10] Soderstrum *et al.* Phys. Rev. C35, 1246 (1987)



σ_P-σ_A (μb)
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
0
2
4
6
8
10
12
E_γ (MeV)
Ahmed et al.
Schreiber et al.
Tornow et al.
Sawatzky et al.
Soderstrum et al.
Del Bianco et al.
Holt et al.
Drooks et al.
Thermal n-Capture
Fit to Data
Arenhovel et al.
3 σ_{M1} Approximation

The GDH$_D$ Integral

Fit to Data	Theory	$-3\sigma_{M1}$ approximation
-587^{+168}_{-134}	-518	-632

Table: An indirect measurement of the GDH sum rule integrand for the deuteron.All value are obtained by integrating the GDH integrand from E_γ = 2.39 MeV to 10 MeV.

It is now even more important to directly measure the part between 10 MeV up to pion threshold to look for the large positive contribution as predicted by the theory. This measurement will start in early 2008.

Compton Scattering at HI$\vec{\gamma}$S

Remember $\cdots$ When expanding Compton scattering amplitude in the energy of the photon,

$O(\omega^0) \rightarrow$ charge, mass

$O(\omega^1) \rightarrow$ anomalous magnetic moment

$O(\omega^2) \rightarrow$ nucleon response to E & M dipole field

$O(\omega^3) \rightarrow$ internal spin structure

$$
\begin{aligned}
H_{eff}^{(2)} &= -4\pi[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2] \\
H_{eff}^{(3)} &= -4\pi[\frac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}})\frac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) \\
&- \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j]
\end{aligned}
$$

ChPT[11] $\longrightarrow \mathcal{O}(p^3)$

$$\begin{aligned}\alpha^p_{E1} &= 10\beta^p_{M1} \\ &= \frac{5\alpha g_A^2}{96\pi f_\pi^2 m_\pi} \\ &= 12.2 \times 10^{-4}\mathrm{fm}^3\end{aligned}$$

Experimental $\longrightarrow$

α^p_{E1} = 12.1 $\pm 0.3(\mathrm{stat}) \mp 0.4(\mathrm{syst}) \pm 0.3(\mathrm{mod}) \times 10^{-4}\mathrm{fm}^3$
Good agreement between ChPT calculation and experimental data for α^p_{E1}
β^p_{M1} = 1.6 $\pm 0.4(\mathrm{stat}) \mp 0.4(\mathrm{syst}) \pm 0.4(\mathrm{mod}) \times 10^{-4}\mathrm{fm}^3$

[11] BKM, Phys, Rev, Lett. **67**, 1515 (1991)

There are 6 independent structure functions ($A_i(\nu$,t)) in T-Matrix of real Compton scattering. These can be expressed as combinations of γs :

$$
\begin{aligned}
\gamma_0 &= \gamma_1 + \gamma_5 \\
\gamma_\pi &= \gamma_1 - \gamma_5 \\
\gamma_5 &= -\gamma_2 - 2\gamma_4
\end{aligned}
$$

where;

$$
\begin{aligned}
\gamma_{M1M1} &\equiv \gamma_4 \\
\gamma_{E1M2} &\equiv \gamma_3 \\
\gamma_{E1E1} &= -\gamma_1 - \gamma_3 \\
\gamma_{M1E2} &= \gamma_2 + \gamma_4
\end{aligned}
$$

The Spin Polarizabilities

γ	P[12]	N	P[13]	N	Exp_p	Exp_n
γ_0	-3.9	-0.9			$-1.0 \pm 0.08 \pm 0.10$	$\sim$ -0.38
γ_π	-36.6	51			-37.7 ± 1.8	59 ± 4
γ_1	1.1	4.7	1.2	3.8		
γ_2	-1.5	-0.1	1.5	1.9		
γ_3	0.2	0.3	0.7	0.5		
γ_4	3.3	2.3	0.4	0.4		

Table: Predictions for γ s by Judith McGovern and Gellas, Hemmert, Meißner. Experimental Data is from Mainz, J. Ahrens, PRL, 87, (2001). Units of γ are 10^{-4} fm^4

[12] J. McGovern, CD2006
[13] GHM, PRL, 85, 14 (2000)

Experimental Program at the Upgraded HI$\vec{\gamma}$S Facility

Following quantities are planned to be measured :

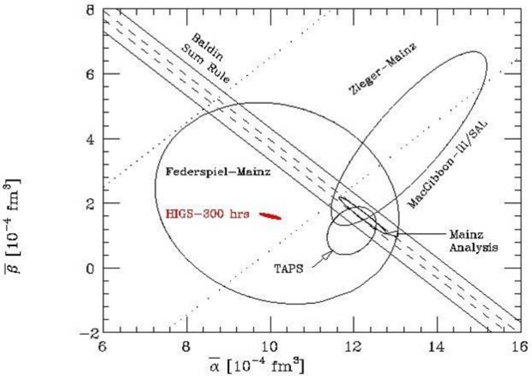
- α_E^p, and β_M^p;
- α_E^n, and β_M^n;
- γ^p, and γ^n;

α_E^p, and β_M^p (100 - 120 MeV, Early 2009)

Method : 100 % Linearly Polarized Beam on Unpolarized Proton Target

$$\left[\frac{d\sigma_\perp}{d\Omega} - \frac{d\sigma_\perp^{pt}}{d\Omega}\right]^{\frac{1}{2}} - \cos\theta \left[\frac{d\sigma_\parallel}{d\Omega} - \frac{d\sigma_\parallel^{pt}}{d\Omega}\right]^{\frac{1}{2}} = +\bar{\alpha}\sin^2\theta \left(\frac{E_\gamma}{hc}\right)^2,$$

$$\cos\theta \left[\frac{d\sigma_\perp}{d\Omega} - \frac{d\sigma_\perp^{pt}}{d\Omega}\right]^{\frac{1}{2}} - \left[\frac{d\sigma_\parallel}{d\Omega} - \frac{d\sigma_\parallel^{pt}}{d\Omega}\right]^{\frac{1}{2}} = -\bar{\beta}\sin^2\theta \left(\frac{E_\gamma}{hc}\right)^2,$$

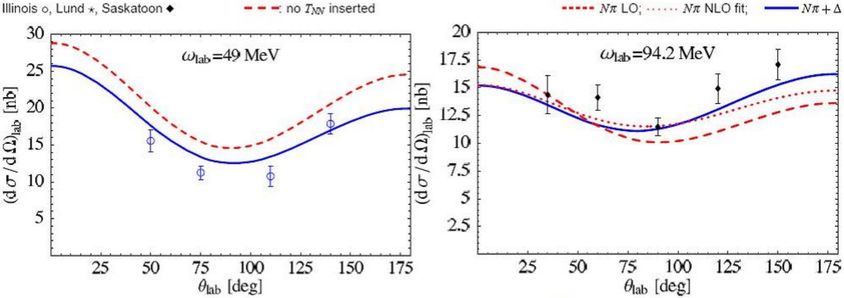


300 hours with 10^7 γ/s, 80 mg/cm^2 target will yield[14] $\sim$ 5 % errors on both α^p and β^p

[14] Calculations by B. Norum

α_E^n, and β_M^n (50 -80 MeV, Early 2008)

Method: Un-Polarized Beam on Unpolarized Deuteron Target

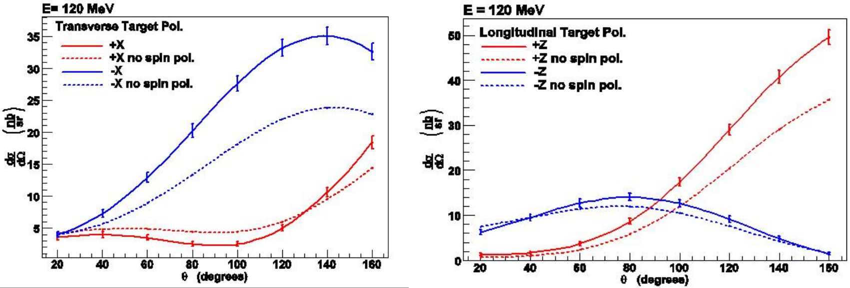


Fit to *all* deuteron data: $\bar{\alpha}^s = 11.3 \pm 0.7_{stat} \pm 0.6_{\Sigma} \pm 1_{theory}$ $\bar{\beta}^s = 3.2 \mp 0.7_{stat} \pm 0.6_{\Sigma} \pm 1_{theory}$

Proton Pasquini/...2003: $\bar{\alpha}^p = 11.0 \pm 1.4_{stat} \pm 0.4_{\Sigma} \pm 1_{theory}$ $\bar{\beta}^p = 2.8 \mp 1.4_{stat} \pm 0.4_{\Sigma} \pm 1_{theory}$

γ^p (120 MeV, 2009)

Method: Circular Polarized Beam on Transversed and Longitudinal Polarized Proton Target



A 200 hour run (100 hrs at both target polarizations) at 120 MeV and 10^7 γ/s , and using the present values of γ_0 and γ_π, will give[15] γ_{E1E1} and γ_{M1M1} to 5 % level and γ_{E1M2} and γ_{M1E2} to $\sim$ 30 %.

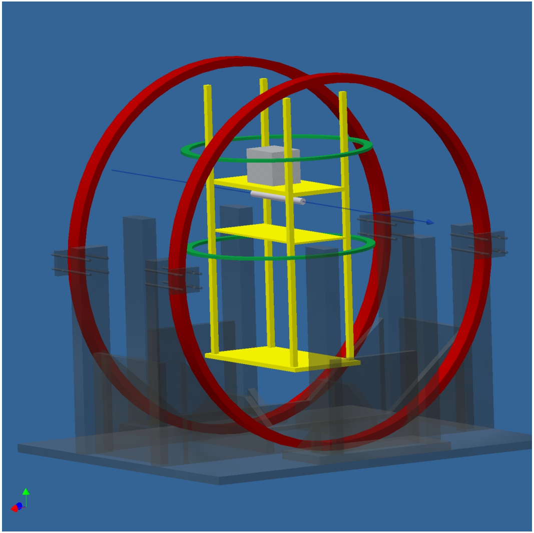
[15] PI: Rory Miskimen

γ^n (120 MeV, 2009)

Method: Circular Polarized Beam on Transversed Polarized ^{3}He Target [16]

- New theoretical calculations by Choudhury, Nogga, and Phillips on $^3\vec{He}(\vec{\gamma}, \gamma')$
- Extraction of spin polarizabilities
- Haiyan Gao has bulit a high pressure spin-polarized ^{3}He target. Target thickness is $\sim 10^{22}$ atoms/cm^2 with a length of 40 cm.
- With 2×10^7 γ/sec and the polarized target, a 350 hour run will provide neutron spin polarizabilities with errors of $\sim \pm 0.5 \times 10^{-4}$ fm^4.

[16] PI: H. Gao



Maximizing sensitivity $\rightarrow$ e.g., at 90° the longitudinal cross section difference is sensitive to γ_1, whereas, the transverse polarization cross section is sensitive to γ_4. Assuming the value of γ_0 fixed by Mainz at 13 %, the HIγS projected measurements are :

•Proton HIγS projected uncertainties		•Neutron HIγS projected uncertainties	
•$\gamma^p{}_1$=1.1	±0.25	•$\gamma^n{}_1$=3.7	±0.40
•$\gamma^p{}_2$=-1.5	±0.36	•$\gamma^n{}_2$=-0.1	±0.50
•$\gamma^p{}_3$=0.2	±0.24	•$\gamma^n{}_3$=0.4	±0.50
•$\gamma^p{}_4$=3.3	±0.11	•$\gamma^n{}_4$=2.3	±0.35

The HINDA Array: 8 NaI Core Detectors with Segmented Shields