The Spin Structure of the proton at low $Q^2$ from CLAS EG4

A. Deur

Jefferson Lab

03/08/2019

On behalf of the EG4-proton analysis team: X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, H. Kang
The EG4 experiment Group

Main goal: measurement of the generalized Gerasimov-Dreall-Hearn (GDH) sum for the proton and deuteron at low $Q^2$.

E03-006 (NH$_3$):
Spokespeople: M. Ripani, M. Battaglieri, A.D., R. de Vita
Students: H. Kang (Seoul U.), K. Kovacs* (UVa)

E06-017 (ND$_3$)
Spokespeople: A.D., G. Dodge, M. Ripani, K. Slifer
Students: K. Adhikari* (ODU)


Main goal: inclusive analyses. Also, exclusive analysis

X. Zheng et al. (CLAS Collaboration), PRC 94, 045206 (2016)

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K.P. Adhikari et al. (CLAS Collaboration),
"Measurement of the $Q^2$ dependence of the Deuteron Spin Structure Function $g_1$ and its Moments at Low $Q^2$ with CLAS” PRL 120, 062501 (2018)


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The GDH and Generalized GDH Sum Rules

Sum rule: relation between an integral of a dynamical quantity (cross section, structure function,...) and a global property of the target (mass, spin,...). Can be used to:

- Test theory (e.g. QCD) and hypotheses with which they are derived. Ex: GDH, Ellis-Jaffe, Bjorken sum rules.
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**GDH sum rule:** derived for real photons ($Q^2=0$):

\[
\int_{\nu_{\text{thr}}}^{\infty} \frac{\sigma_A(\nu) - \sigma_P(\nu)}{\nu} \, d\nu = \frac{-4\pi^2 S\alpha\kappa^2}{M^2}
\]

- QED coupling constant
- Target anomalous magnetic moment
- Target mass
- Target spin
- Photon spin parallel to $S$
- Photoprod. cross section with photon spin anti-parallel to $S$
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- target anomalous magnetic moment
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Generalized GDH sum rule: valid for any $Q^2$. Recover the original GDH sum rule as $Q^2 \to 0$

$$
\Gamma_1(Q^2) = \int_0^{\nu_{\text{thr}}} g_1(x,Q^2) \, dx = \frac{Q^2}{2M^2} \, I_1(0,Q^2)
$$

g_1(\nu,Q^2): \text{first spin structure function (mostly a longitudinal target pol. observable)}

$\Gamma_1(0,Q^2)$: first covariant polarized VVCS amplitude

⇒ Study QCD at any scale

Hadronic degrees of freedoms
Partonic degrees of freedoms

Chiral perturbation theory (χpt)
OPE, pQCD

Lattice QCD, SDE, AdS/QCD

A. Deur, CLAS col. meeting. 03/08/2019
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EG4
Spin polarizabilities sum rules

Sum rule: relation between an integral of a dynamical quantity (cross section, structure function,...) and a global property of the target (mass, spin,...).

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• Test theory (e.g. QCD) and hypotheses with which they are derived. Ex: GDH, Ellis-Jaffe, Bjorken sum rules.
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Spin polarizability sum rules involve higher moments:

Generalized forward spin polarizability:
\[ \gamma_0 = \frac{4e^2M^2}{\pi Q^6} \int x^2\left(g_1 - \frac{4M^2}{Q^2}\right) x^2g_2 dx \]
\[ g_2(\nu, Q^2): \text{second spin structure function (mostly a perp. target pol. observable)} \]

Longitudinal-Transverse polarizability:
\[ \delta_{LT} = \frac{4e^2M^2}{\pi Q^6} \int x^2(g_1 + g_2) dx \]
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\]

\( g_2(v,Q^2) \) suppressed in \( \gamma_0 \)
Precise mapping of spin structure function moments in intermediate $Q^2$ region for p, n and d.

PQCD, models and data agree.
Not so clear for $\chi_{pT}$.
Previous data: high to intermediate $Q^2$

State of $\chi pT$ affairs before EG4 run (2006):

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Volker D. Burkert  
PRD 63, 097904 (2001)  
[nucl-th/0004001]

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- Mixed success of $\chi pT$;
- Surprising discrepancies ($\delta_{LT}$ crisis);
- Validity range smaller than hoped for: $Q^2 < \sim 0.1$ GeV$^2 \Rightarrow$ Ambiguous $\chi pT$ tests.

$\Rightarrow$ Need new data on $p$ and $n$ ($d$, $^3$He) at very low $Q^2$ (i.e. for integrals over $v$: low angles).

Purpose of EG4.
**EG4 setup**

- $Q^2>0$: electron beam (polarized). Energies: 3.0, 2.3, 2.0, 1.3 & 1.0 GeV
- $g_1^{p,n}$: ~longitudinally polarized target

DNP NH$_3$ and ND$_3$ target:

![Diagram of EG4 setup showing calormeters, Cerenkov counters, drift chambers, torus field, and polarized target.](image)
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**DNP NH$_3$ and ND$_3$ target:**

- $g_1$ from pol. cross-section differences (not asymmetries, as in EG1, EG1dvcs)
- Advantage: dilution from unpol. target material cancels out
- Small angles: outbending torus field, new Möller shield; target at -1m
- Cross-sections $\Rightarrow$ controlled (i.e high) efficiency at small angles. New Cerenkov detector (INFN). Installed in sector 6. Covered down to 6°.
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DNP NH$_3$ and ND$_3$ target:

Two different target lengths to verify external radiative corrections (big elastic tails at low $Q$+high $\nu$).

So far, only long target data have been analyzed.

(Deuteron data: only on long target.)
EG4 kinematic coverage

Proton

Deuteron

$Q^2 (\text{GeV/c})^2$

$W (\text{GeV})$

$E = 1.05$

$E = 1.34$

$1.99$ GeV

$2.26$ GeV

$2.99$ GeV

$W (\text{GeV})$

$Q^2 (\text{GeV/c})^2$

$1.99$ GeV

$E = 1.34$
g_{1p} from EG4 polarized cross-section difference

X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, A. D., …

EG4 data

“Model” (Fit to EG1b (+ other published data)+extrap. Used as intermediary step to extract g_{1p}.)

Example of “Model” variation: assess uncertainties on extraction method, radiative corrections, …
g$_{1p}$ from EG4 polarized cross-section difference

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$\langle Q^2 \rangle = 0.12$ GeV$^2$

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$\langle Q^2 \rangle = 0.12 \text{ GeV}^2$

Example of “Model” variation: assess uncertainties on extraction method, radiative corrections, …

$g_{1p}$ not model-dependent
\[ \Gamma_{1p} = \int g_{1p}(x,Q^2)dx \]

X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, A. D.,...

- Lowest \( Q^2 \) decreased by factor of \( \sim 4 \)
- Much improved precision
- Small unmeasured low-\( x \) contribution

⇒ Clean test of \( \chi pt \)
\[ \Gamma_{1p} = \int g_{1p}(x, Q^2) \, dx \]

X. Zheng, J. Zhang, S. Kuhn, M. Ripani, M. Osipenko, A. D.,…

- Tension between EG4 and EG1 above \( Q^2 \sim 0.1 \text{ GeV}^2 \).
- EG4 data and \( \chi \text{PT} \) results agree up to \( Q^2 \sim 0.04 \text{ GeV}^2 \).
- Phenomenological models (Pasechnik et al, Burkert-Ioffe) agree well.
Another generalization of GDH sum: \( I_{TT} = \int_{\nu_{th}}^{\infty} \frac{K_f}{v} \frac{\sigma_A(v,Q^2) - \sigma_P(v',Q^2)}{v} dv \)

No suppressing \( Q^2 \) factor.
Contains \( g_2 \) (not measured by EG4)

Original GDH sum rule: \(-0.526 \text{ GeV}^{-2}\)

- \( \chi PT \) results of Lensky et al. agree with data up to \( Q^2 \sim 0.035 \text{ GeV}^2 \).
- Bernard et al. \( \chi PT \) calculation agrees with data up to \( Q^2 \sim 0.02 \text{ GeV}^2 \).
- Data compatible with GDH sum rule.
• Tension with EG1b, but EG4 and Hall A preliminary data agree.
• χPT results of Lensky et al. disagree with data.
• Bernard et al. χPT calculation agrees for lowest $Q^2$ points only.
What left to do for EG4:

• Finalize systematic analysis (soon);
• Include short target data into analysis (soon);
• Finalize analysis note, and write paper.
Conclusion

General agreement with \( \chiPT \), but its \( Q^2 \)-range of validity is limited (up to \( Q^2 \sim 0.04 \text{ GeV}^2 \))
General agreement with $\chi$PT, but its $Q^2$-range of validity is limited (up to $Q^2 \sim 0.04$ GeV$^2$).

For the EG4 results from deuteron: Lensky et al. agrees (typically up to $Q^2 \sim 0.1$ GeV$^2$)

A satisfactory theoretical description of spin observables at low $Q^2$ remains challenging.
Previous data: high to intermediate $Q^2$

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Purpose of EG4.
### Up to date state of $\chi pT$ affairs (2019)

Agreement between data and $\chi pT$ up to $Q^2 = 0.1$ GeV$^2$:

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$\Gamma_1^p$</th>
<th>$\Gamma_1^n$</th>
<th>$\Gamma_1^{p-n}$</th>
<th>$\Gamma_1^{p+n}$</th>
<th>$\gamma_0^p$</th>
<th>$\gamma_0^n$</th>
<th>$\gamma_0^{p-n}$</th>
<th>$\gamma_0^{p+n}$</th>
<th>$\delta_{LT}$</th>
<th>$d_2^n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ji et al. 1999</td>
<td>X</td>
<td>X</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bernard et al. 2002</td>
<td>X</td>
<td>X</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Kao et al. 2002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Bernard et al. 2012</td>
<td>X</td>
<td>X</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>Lensky et al. 2014</td>
<td>X</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>A</td>
</tr>
</tbody>
</table>

- **A**: agree with data
- **X**: disagree with data
- **-**: no calculation available

Table would have more **A** if we lower the $Q^2$ range for comparison.

Δ suppressed

~no low-x

Δ suppressed

Δ suppressed

Δ suppressed “$\delta_{LT}$ crisis”

A. Deur, CLAS col. meeting. 03/08/2019
Summary and perspectives

• EG4: Low $Q^2$ measurement using polarized $e^-$ on polarized $p$ and $d$, over a large $x$-range in order to study spin sum rules.
• New detector necessary to reach these kinematics.
• Main goal: unambiguous test of $\chi$PT.
• Doubly polarized inclusive cross-section analysis.
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• EG4: part of JLab program to measure benchmark spin observables for $\chi$PT $\Rightarrow$ More low $Q^2$ data to come:
  - $g_1$, $g_2$, $\Gamma_1$, $\Gamma_2$, $I_{TT}$, $\gamma_0$ and $\delta_{LT}$ for the neutron and $^3\text{He}$ (Hall A E97110). Coming soon.
  - $g_2$, $g_1$, $\Gamma_2$, $\Gamma_1$, $I_{TT}$, $\delta_{LT}$ and $\gamma_0$ for the proton (Hall A E08027). Coming soon.

X. Zheng et al. (CLAS Collaboration), PRC 94, 045206 (2016)

K.P. Adhikari et al. (CLAS Collaboration). PRL 120, 062501 (2018)
Extra slides
Differences between EG1b and EG4

• **Radiative corrections.**
  Large radiative tails for EG4 kinematics ⇒ revisited standard RCSLACPOL code and improved its handling of elastic tails (external elastic radiative tail seems to have been missing).

• **Different detector** for main trigger and electron ID (new **INFN Cherenkov counter** for EG4).
  Much higher efficiency for outbending electrons, but still some systematic uncertainty for point-to-point electron detection efficiency and acceptance.

• **Absolute cross-sections differences** used to extract \( g_{1p} \), not **relative asymmetries**.
  Absolute normalization needed. But no target dilution (usually, a large correction). No \( F_{1p} \) input needed.

• **Different kinematics** (beam energy, angles) to obtain \( x \) and \( Q^2 \) common to EG4 and EG1b.
  Implies in particular different \( g_{2p} \) inputs.

Some of these differences may be the origin of the tension between the EG4 and EG1b results.

The issue is still being investigated.

Agreement with Hall A preliminary result is reassuring (but non-binding).
The GDH and Generalized GDH Sum Rules

Sum rule: relation between an integral of a dynamical quantity (cross section, structure function,...) and a global property of the target (mass, spin,...).

Can be used to:
- Test theory (e.g. QCD) and hypotheses with which they are derived. Ex: GDH, Ellis-Jaffe, Bjorken sum rules.
- Measure the global property (e.g. spin polarizability sum rules)

**GDH sum rule**: derived for real photons ($Q^2 = 0$):

\[
\int_{\nu_{\text{thr}}}^{\infty} \frac{\sigma_{A}(\nu)-\sigma_{P}(\nu)}{\nu} d\nu = \frac{-4\pi^2 S \alpha \kappa^2}{M^2} \targetanomalousmagneticmoment
\]

- $\nu_{\text{thr}}$: threshold photon energy
- $M$: target mass
- $\sigma_{A}$, $\sigma_{P}$: photoproduction cross section with photon spin parallel to $S$ and anti-parallel to $S$

**Generalized GDH sum rule**: valid for any $Q^2$. Recover the original GDH sum rule as $Q^2 \rightarrow 0$

\[
\int_{\nu_{\text{thr}}}^{\infty} g_1(\nu,Q^2) d\nu = \frac{-4\pi^2 S \alpha \kappa^2}{M^2}
\]

**$\chi$pt**: low energy effective theory of QCD obtained using a Lagrangian consistent with QCD’s chiral symmetry (neglecting quark masses). Captures the main essence of QCD at low $Q^2$, without the complicated details. Systematic perturbative expansion valid for e.g. $Q << m_\pi$. 

- $g_1(\nu,Q^2)$: first spin structure function (mostly a longitudinal target polarization observable)
- $I_1(\nu,Q^2)$: first covariant polarized VVCS amplitude

**OPE, pQCD**: perturbative QCD

**Lattice QCD, SDE, AdS/QCD**: non-perturbative QCD

**Chiral perturbation theory ($\chi$pt)**

*Note*: The diagram and equation represent a simplified visualization of the GDH and Generalized GDH sum rules. The equations and text provide a more detailed and accurate representation of the theoretical framework.