Small Angle GDH &
polarized $^3$He target

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Outline

• Physics:
  • Electron scattering
  • GDH theory: *sum rules*.

• Experiment E97110 at Jefferson Lab:
  • Setup
  • Analysis status: asymmetries, elastic carbon cross sections
  • Future plan

• Polarized $^3$He target:
  • Spin exchange optical pumping
  • Polarimetries: NMR, EPR and Pulse-NMR
Small angle GDH (Gerasimov-Drell-Hearn)

• **Theory:**

• Electron scattering

• Sum rules:
  - GDH for real photon.
  - GDH for virtual photon.
Proton
Spin
1/2

Spin crisis

Distance [m]

10^{-10}

10^{-14}

10^{-15}

Nucleus

nuclear binding force

strong force

Proton spin 1/2
Advantages of electron scattering?
• QED is well-known and perturbative calculable.
• Clean probe.
Kinematic variables

- 4-momentum: $q^2 = -Q^2$.
- Virtual photon energy: $\nu = E - E'$

**Final state invariant mass**

$$W^2 = M^2 + 2M\nu - Q^2$$

In Bjorken limit $Q^2, \nu \to \infty$

$$x = \frac{Q^2}{2M\nu}$$

in deep inelastic region
Electron scattering
Cross section

Cross section = (point-like) x (spin-independent + spin-dependent)

- $F_1, F_2$: unpolarized structure function.
- $F_1 = \frac{1}{2} \sum_i e_i^2 q_i(x)$ Quark’s momentum distribution.
- $g_1, g_2$: polarized structure function.
- $g_1 = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x)$ Quark’s polarization distribution.

Electron scattering cross section with exchange of virtual photon:

Cross section = $f(\sigma_T, \sigma_L, \sigma_{TT}, \sigma_{LT})$

$$\sigma_T = \frac{\sigma_{3/2} + \sigma_{1/2}}{2}$$

$$\sigma_{TT} = \frac{\sigma_{3/2} - \sigma_{1/2}}{2}$$
Sum rule

\[ \sum \text{Internal properties:} \]
Form factors, Structure functions

\[ \text{Global properties:} \]
Mass, anomalous magnetic moment, Coupling constant (Compton scattering amplitude)
Gerasimov-Drell-Hearn (GDH) sum rule \((Q^2=0, \text{real photon})\)

\[
I_{GDH} = \int_{\nu_{thr}}^{\infty} \left( \sigma^{1/2} - \sigma^{3/2} \right) \frac{d\nu}{\nu} = -\frac{2\alpha\pi^2\kappa^2}{M^2}
\]

\(\sigma^{1/2}, \sigma^{3/2}\): photon absorption cross section, with photon helicity is anti-parallel or parallel to target spin.

\(\kappa\): anomalous magnetic moment

\(M\): target’s mass
Generalized GDH sum rule (virtual photon, $Q^2 > 0$)

- From real to virtual photon: change photon production cross section with electro-production cross section

$$\sigma^{1/2}(\nu), \sigma^{3/2}(\nu) \rightarrow \sigma^{1/2}(\nu, Q^2), \sigma^{3/2}(\nu, Q^2)$$

Or rewrite it in term of Compton scattering amplitudes (By Ji and Osborne): $S_1(Q^2), S_2(Q^2)$ which are calculable at all $Q^2$.

$$\frac{16\alpha\pi^2}{Q^2} \int_0^1 g_1 dx = 2\alpha\pi^2 S_1$$

Hadronic d.o.f

Generalized GDH

GDH at $Q^2 = 0$
Bjorken sum rule

\[ \int_0^1 (g_1^p(x) - g_1^n(x)) \, dx = \frac{1}{6} g_a \]

- Experimentally measured difference in spin structure functions
- Theory
- Well-measured axial charge from neutron decay

GDH at \( Q^2 = 0 \)

\( Q^2 \rightarrow \infty \)
**Bjorken sum rule**

\[ \int_0^1 (g_1^p(x) - g_1^n(x)) \, dx = \frac{1}{6} g_a \]

- Experimental measured Difference in spin structure functions
- Well-known Axial coupling constant from neutron decay

**For finite \( Q^2 \), Bjorken sum rule is:**

\[ \int_0^1 (g_1^p(x, Q^2) - g_1^n(x, Q^2)) \, dx = \frac{1}{6} g_a \left(1 + \frac{\alpha_s (\ln(Q^2))}{\pi} + \ldots \right) + \ldots \]

- Hadronic d.o.f
- Generalized GDH
- Partonic d.o.f

GDH at \( Q^2 = 0 \)
Low $Q^2$

- Chiral perturbation theory: effective theory at low energy
- Virtual forward Compton spin-dependent scattering amplitudes $S_{1,2}(Q^2)$

High $Q^2$

- Use Operator Product Expansion: (perturbative)\*(non-perturbative).
- $g_a \sim g_a^* (1+\text{QCD radiative corrections})$

\[
\Gamma_p(Q^2) - \Gamma_n(Q^2) = \int_0^{x_0} (g_1^p - g_1^n)dx \\
\int_0^1 (g_1^p - g_1^n)dx = \frac{g_a}{6}(pQCD) \\
\Gamma_N(Q^2) \equiv \int_0^{x_0} g_1^N(x, Q^2)dx
\]

$\chi$PT effective theory

$pQCD$

Generalized GDH

$Q^2$ (GeV$^2$)
Current data for GDH at low $Q^2$ region

Experiment:
- E94010 (1998) Hall A.
- E97110 (2003) Hall A.

Show a smooth transition from partonic to hadronic, we expect a sharp change in slope at $Q^2<0.1$ GeV$^2$ → important to do experiment at lower $Q^2$
Gerasimov-Drell-Hearn (GDH) sum rule ($Q^2 = 0$, real photon)

\[ I_{GDH} = \int_{\nu_{thr}}^{\infty} \left( \sigma^{1/2} - \sigma^{3/2} \right) \frac{d\nu}{\nu} = \frac{-2\alpha\pi^2\kappa^2}{M^2} \]

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GDH at $Q^2 = 0$
Current data for GDH at low $Q^2$ region

Experiment:
- E94010 (1998) Hall A.
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Show a smooth transition from partonic to hadronic, we expect a sharp change in slope at $Q^2<0.1 \text{ GeV}^2$ → important to do experiment at lower $Q^2$
**Experiment E97110**

- Precise measurement of generalized GDH integral at $0.02 < Q^2 < 0.3 \text{ GeV}^2$.

- Inclusive experiment: $^3\text{He}(e, e')X$

- Measured polarized cross section differences.

- Continuous beam with $P_e \sim 85\%$. Seven different beam energies from 1.1 GeV to 4.4 GeV and two angles ($6^\circ$ and $9^\circ$).

- Polarized $^3\text{He}$: $P_t \sim 40\%$.

Experiment setup

Hall A Floor Plan

- 1st period: mis-wired septum
- 2nd period: good septum

0.02 < Q^2 < 0.3 GeV^2
6 GeV target cell

Pumping chamber

Laser

e beam

Target chamber
Kinematic plot for experiment

- First Period
- Second Period
- 2 Body Breakup
- Constant $Q^2$
Analysis working people

- Supervisors: Jian-ping Chen, Alexandre Deur.
- Ph. D thesis: Vincent Sulkosky, Jaideep Singh, Jing Yuan (2nd period).
- Others: Nilanga Liyanage, Timothy Holmstrom, Hai-jiang Lu.
- Present students: Chao Peng (work on 2nd period), Nguyen Ton (work on 1st period)
Data

$\sigma_{raw}$

$\sigma_0$

Radiative corrections

$\Delta \sigma$

$g_1, g_2$

$N^+; N^-$

$A_{raw}$

$A^\parallel, A^\perp$

Detector eff, deadtime, acceptance/optic, target density

PID acceptance cuts

Charge livetime

PID done by H. Lu

$N_2, \text{glass, unpolarized bkgd dilution}$

$P_b, P_t$

$N_2, \text{glass, unpolarized bkgd dilution}$
Scaler asymmetry

• Charge asymmetry: \[ A_Q = \frac{Q^+ - Q^-}{Q^+ + Q^-} \]

• Livetime asymmetry: \[ A_{LT} = \frac{N_{acc}^+ - N_{acc}^-}{N_{acc}^+ + N_{acc}^-} \]

• Raw/scaler asymmetry: \[ A_{raw} = \frac{N^+ - N^-}{N^- + N^-} \]

Where \( Q^+ \), \( Q^- \) are accumulated beam charge for helicity plus and helicity minus. \( N^+, N^- \) are number of total trigger for each helicity. \( N_{acc}^+, N_{acc}^- \) are number of accepted trigger for each helicity.
Charge asymmetry for 1\textsuperscript{st} period

Charge Asymmetry for 1.1GeV beam, x3

Charge Asymmetry for 2.2GeV beam, x3

Charge Asymmetry for 1.5GeV beam, x3

Charge asymmetry for 3.3GeV, x3
Livetime and raw asymmetry

$A_{LT}$, $A_{raw}$ for 1.1GeV

$A_{LT}$, $A_{raw}$ for 2.2GeV

$A_{LT}$, $A_{raw}$ for 1.5GeV

$A_{LT}$, $A_{raw}$ for 3.3GeV

Livetime asymmetry (∥ case)

Livetime asymmetry (⊥ case)

Raw asymmetry (∥ case)

Raw asymmetry (⊥ case)
Septum+ HRS (high resolution spectrometer) optics

Focal plane variables:
- $x$
- $y$
- $\phi$
- $\theta$

Forward:
- Only 1st order

Target plane variables:
- $\delta$
- $\gamma_{\text{target}}$
- $\phi_{\text{target}}$
- $\theta_{\text{target}}$

Septum magnet

HRS optics

Target

VDC

Focal plane
Optics study

- Normal analysis procedure (2\textsuperscript{nd} period), we have both forward and reverse matrices. Optimize transport matrix to get best match between target reconstructed variables and target quantities from survey.

- Our case (1\textsuperscript{st} period), only have focal plane quantities (which come from detector). There is no standard way to deal with this.
Optics study

- Use forward matrix to transport from target to focal plane (simulation).
- Use target variables (phi and theta) to get geometry solid angle and then get experimental cross section.

How good is our optics? How to test it?

Single carbon foil + elastic
Procedure to get cross section for focal plane method

From analysis cut

At target

Count events inside

Transport

Count events after focal plane cut, -> get cross section
Elastic carbon cross section result with focal plane method for 2nd period (with good septum)

<table>
<thead>
<tr>
<th>Center foil</th>
<th>( \delta p=0% )</th>
<th>( \delta p=-2% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{sim}} ) (ub)</td>
<td>250</td>
<td>262</td>
</tr>
<tr>
<td>( \sigma_{\text{data}} ) (ub)</td>
<td>270</td>
<td>246</td>
</tr>
<tr>
<td>% data &amp; sim</td>
<td>7%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Conclusion: Focal plane method works well
Apply focal plane method to 1\textsuperscript{st} period
Elastic carbon cross section result for 1\textsuperscript{st} period (with defective septum)

<table>
<thead>
<tr>
<th>Center foil</th>
<th>$\delta p = 0\ %$</th>
<th>$\delta p = -2\ %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{sim}$ (ub)</td>
<td>4466</td>
<td>4540</td>
</tr>
<tr>
<td>$\sigma_{data}$ (ub)</td>
<td>4337</td>
<td>4853</td>
</tr>
<tr>
<td>% difference</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

Focal plane method works well for 1\textsuperscript{st} period (with defective septum) with single foil at center position.
Future plan

• Finish single carbon foil for other beam energies, and foil positions.

• Move to extended target: N$_2$, $^3$He.

• Inelastic cross sections and asymmetries.
Polarized $^3$He target for 6 GeV experiments
Polarized $^3$He Target

✓ $^3$He as an effective polarized neutron target.

(operation) Neutron decay time $\sim 15$ mins (no free neutron target).

Questions:

- Deuteron (1p+1n -> uncertainty comes from extracting n and there is $>50\%$ contribution from p).

$^3$He wavefunction = 

\[
^3\text{He} \sim (S\text{-wave 90\%}) + (S'\text{-wave 1.5\%}) + (D\text{-wave 8\%})
\]
How to polarized $^3$He

- We can polarized $^3$He directly by metastability exchange optical pumping. Usually for low density gas.

- For our case, high density (use for electron scattering), we use spin exchange optical pumping. An indirect method: use electron from alkali atom.

![Diagram showing Optical pumping and Spin-exchange alkali-$^3$He]
Optical pumping

- Apply magnetic field, energy split between $5S_{1/2}$ & $5P_{1/2}$.
- Use circularly polarized laser with 795nm.
Optical pumping

- Apply magnetic field, energy split between $5S_{1/2}$ & $5P_{1/2}$.
- Use circularly polarized laser with 795nm.
- $5S_{1/2}$ absorbs $\sigma^+$ -> excited state.
- Decay back to $m_s = +1/2$ or $m_s = -1/2$ equally.
- Finally, electrons end up in $m_s = 1/2$ state.
Spin-exchange

- Alkali-$^3$He interact through: hyperfine interaction.

$^3$He is polarized
6 GeV target cell

- Laser
- e beam
- Target chamber
- Pumping chamber
- Glass cell
Polarimetry (polarization measurement)

- **NMR**: nuclear magnetic resonance (relative/absolute).
- **EPR**: electron paramagnetic resonance (absolute).
General principle

Change to transverse plane (NMR).

Keep along Z-axis but flip (EPR)
NMR (nuclear magnetic resonance)

At the right frequency, resonance will happen.

Natural frequency of spin is the Larmor frequency: \( \omega = \gamma \cdot B_0 \)

Where \( \gamma \) is the gyromagnetic magnetic ratio of \(^3\text{He}\)
**NMR cont.**

- AFP (adiabatic fast passage): slow & fast.
- Measure the transverse component of magnetization which induces signal in pair of pick-up coils.
- Relative measurement, need to calibrate with EPR or with known thermal equilibrium polarization of water.

![Diagram illustrating RF field and sweep of B₀ field](image)

Sweep the B₀ field
**EPR (electron paramagnetic resonance)**

- **Principle:** Use Alkali EPR resonance frequency and the shift in frequency due to small contribution from $^3\text{He}$ field.

- From frequency difference, $^3\text{He}$ polarization is extracted.
6 GeV improvements from target

- Spectrally-narrowed diode laser (FWHM = 0.2 nm), improves absorption efficiency.
- Hybrid mixture (K-Rb) increases spin-exchange efficiency.

Polarization 42% -> 60% (in-beam)
70% without beam
Overview of $^3$He target upgrade plan

- Target will take 30 uA beam current with convection cell.
- 3% systematic uncertainty for polarimetry.
- Using convection cell: decrease polarization gradient.
- Pulse NMR calibrated with EPR/NMR.
Pulse NMR

- **PNMR**: metal windows target chamber, can’t send RF field through metal. (end of target chamber).

- **Principle:**
  - Send a pulse at Larmor frequency (81kHz).
  - \(^3\)He spin precesses and tips away from main field.
  - Detect free-induction-decay signal (FID). Measure the transverse component of magnetic moment.

\[
S \sim M_z \sin(\theta_{tip}) e^{-t/T_2} \sin(\omega t)
\]
PNMR setup

Send RF signal

Receive signal

Gate gen

Fun gen 81 kHz

Oscilloscope

Amp

Mixer

Pre amp

Fun gen Ref freq

Coil
R=0.9Ω
L=87μH

50Ω

C=45nF
Hot spin down measurement (2hours). No convection.
Pulse NMR measure at target chamber.
Pulse NMR works for spin up, hot spin down with and without convection.
People at working on $^3$He target (at JLab)

- **Supervisor:** Jian-ping Chen

- **Student:**
  - Kai Jin
  - Jie Liu
  - Nguyen Ton
Next steps

• Get uncertainty at low polarization region and high polarization region.

• Get uncertainty of calibration constant from pNMR vs NMR measurement.

• Aim to reach $1\%$.

• Then move to do measurement at transfer tube instead of target chamber.

• Characterize new cell, optimize conditions to get high polarization.
Conclusion

- Small angle GDH (1st period):
  - Done scaler.
  - Optics is on going.
  - Plans: Finish optics, elastic $^3$He, inelastic $N_2$, $^3$He.

- Polarized target:
  - Finish pulse NMR test and get uncertainty.
  - Characterize new cell, optimize conditions to get high polarization.
Thanks to:

• People at Jlab: Jian-ping Chen, Alexandre Deur.
• People at Uva: Xiaochao Zheng, Vincent Sulkosky, Jie Liu
Probing a nucleon

Nucleon
Constituent quark
Valence quark
Quark, antiquark, gluon
1D plot for target and focal plane quantities for 2\textsuperscript{nd} period

\begin{align*}
\theta_{fp} (\text{rad}) & \quad y_{fp} (\text{m}) \\
\text{y}_{tg} (\text{m}) & \quad W (\text{GeV})
\end{align*}
Reason:

• Falling edge of acceptance.
• Focal plane method works well in this area too. But due to cut was not the same between 2 methods, it created the difference between 2 methods.
Kinematic variables

- 4-momentum: $q^2 = -Q^2 \rightarrow \text{how hard}$
- Virtual photon energy: $\nu = E - E'$
- In Bjorken limit $Q^2, \nu \rightarrow \infty$: $x = \frac{Q^2}{2 M \nu}$ finite

Final state invariant mass

$$W^2 = M_T^2 + 2 M_T \nu - Q^2$$
Relation between electro-production cross section and structure functions

\[
\frac{d^2\sigma}{d\Omega dE'} = \Gamma [\sigma_T + \epsilon \sigma_L - hP_x \sqrt{2\epsilon (1 - \epsilon)} \sigma_{LT} - hP_z \sqrt{1 - \epsilon^2} \sigma_{TT}]
\]

\[
\sigma_T = \frac{4\pi^2 \alpha}{MK} F_1
\]

\[
\sigma_L = \frac{4\pi^2 \alpha}{K} \left[ \frac{F_2}{\nu} (1 + \gamma^2) - \frac{F_1}{M} \right]
\]

\[
\sigma_{LT} = \frac{4\pi^2 \alpha}{MK} \gamma (g_1 + g_2)
\]

\[
\sigma_{TT} = \frac{4\pi^2 \alpha}{MK} (g_1 - \gamma^2 g_2)
\]
### AFP loss and lifetime for protovec-1

<table>
<thead>
<tr>
<th>AFP loss</th>
<th>Pumping chamber(%)</th>
<th>Target chamber(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool without convection</td>
<td>1.18</td>
<td>0.21</td>
</tr>
<tr>
<td>Hot without convection</td>
<td>0.95</td>
<td>0.37</td>
</tr>
<tr>
<td>Hot with convection</td>
<td>1.43</td>
<td>1.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Pumping chamber(hr)</th>
<th>Target chamber(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool without convection</td>
<td>26.57</td>
<td>23.11</td>
</tr>
<tr>
<td>Hot without convection</td>
<td>13.49</td>
<td>15.97</td>
</tr>
<tr>
<td>Hot with convection</td>
<td>14.56</td>
<td>14.54</td>
</tr>
</tbody>
</table>