Experimental study of the $^3$He and neutron spin structure at low $Q^2$ using a polarized $^3$He target

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Outline

• Theory:
  • Electron scattering
  • Sum rules:
    • GDH sum rule for real photons
    • Generalized GDH sum rule for virtual photons

• Jefferson Lab Experiment E97-110:
  • Setup
  • Analysis status
  • Future plans
Probing a nucleon via electron scattering

\[ k'^\mu (E', \vec{k}') \]

\[ k^\mu (E, \vec{k}) \]

\[ q^\mu (\nu, \vec{q}) \]

detect
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”
Cross section

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

- $F_1, F_2$: unpolarized structure functions.
- $F_1 = \frac{1}{2} \sum_i e_i^2 q_i(x)$ Quark's momentum distributions (in parton model interpretation).
- $g_1, g_2$: polarized structure functions.
- $g_1 = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x)$ Quark's polarization distributions (parton model).

Cross section parameterize in term of virtual photon quantities:

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

\[ \sigma_T = \frac{\sigma_{3/2} + \sigma_{1/2}}{2} \]
\[ \sigma_{TT} = \frac{\sigma_{3/2} - \sigma_{1/2}}{2} \]

$F_1, F_2$
$g_1, g_2$
Sum rule

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

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

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

$\sigma^{1/2}, \sigma^{3/2}$: photon absorption cross sections, with photon helicity 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 amplitude (by Ji and Osborne): $S_1(Q^2), S_2(Q^2)$ which are calculable in principle at all $Q^2$.

\[ \frac{16\alpha\pi^2}{Q^2} \int_0^1 g_1 dx = 2\alpha\pi^2 S_1 \]
Current data for GDH in low $Q^2$ region

Experiments:
• E94010 Hall A.
• E97110 Hall A.
• EG1a,b, EG4 Hall B.

Show a smooth transition from partonic to hadronic regions.

We expect a sharp change in slope at $Q^2<0.1 \text{ GeV}^2$ → need to pass the turn over to check GDH for real photon
Hall A 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 $P_e \sim 85\%$. Two angles ($6^\circ$ and $9^\circ$).

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

Students: J. Singh, V. Sulkosky, J. Yuan, C. Peng, N. Ton
Experiment setup

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

0.02<Q^2<0.3 GeV^2
Kinematic plot for experiment
Preliminary result from 2\textsuperscript{nd} period

- Projected result from 1\textsuperscript{st} period
Analysis flow chart for 1st period

Data

Detector eff, deadtime acceptance/optic, target density

$\sigma_{raw}$ → $\sigma_0$

Radiative corrections

$\Delta \sigma$ → $g_1$, $g_2$

$N^+; N^-$ → $A_{raw}$

Charge livetime

$A^{\perp}, A^{\parallel}$

PID acceptance cuts

PID done by H. Lu

Green: done
Blue: in progress
Black: to be done
Septum+ HRS (High Resolution Spectrometer) optics

\[
\begin{pmatrix}
\chi \\
\gamma \\
\varphi \\
\theta \\
\end{pmatrix}
= 
\begin{pmatrix}
\delta \\
\gamma_{\text{target}} \\
\varphi_{\text{target}} \\
\theta_{\text{target}} \\
\end{pmatrix}
\]

Forward

Only 1st order

Target plane variables

Focal plane variables

HRS optics

VDC

Focal plane

Target

Septum magnet

Q1

Q2

Dipole
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.

• **For 1\textsuperscript{st} period,** transport for septum is complicated and we don’t have enough data to do in the standard way. We choose to work only with focal plane quantities (which come from detectors). First time we apply this method in Hall A.

**Standard procedure**
Optics study

- **Mis-wired:**
  - Use forward matrix to transport particle from target to focal plane (simulation).
  - Apply cuts at focal plane on both data and simulation. The cuts are defined by a look-up table which is created from simulation.

![Diagram showing target to focal plane transport and focal plane cuts](image)
4D+ cut with multifoil

Multi foil, 0 dp without cut

Multi foil, -3 dp without cut

Multi foil, 0 dp with cut

Multi foil, -3 dp with cut
Future plans

- Get elastic carbon cross section for all beam energies to check optic/acceptance.

- Study elastic cross sections with extended targets: $^3\text{He (N}_2\text{)}$.

- Inelastic cross sections and asymmetries.
Analysis working people

- 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)
Bjorken sum rule

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

Experimentally measured
Difference in spin structure functions

Theory

Well-measured Axial charge from neutron decay

GDH at \( Q^2 = 0 \)
Bjorken sum rule

For finite $Q^2$, Bjorken sum rule is:

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

Well-known Axial coupling constant from neutron decay

Experimental measured Difference in spin structure functions

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

GDH at $Q^2=0$
Experimental data from $1^{st}$ period