New Experiments with Tensor Polarized Targets

The Proton Mass: At the heart of most visible matter

Trento, Italy
4/4/2017

Karl Slifer
University of New Hampshire
This Talk

Brief Review of Tensor Polarization

JLab Tensor Structure Program

E12-13-011: “The $b_1$ experiment”
E12-15-005: “$A_{zz}$ for $x>1$”
LOI-12-16-006: “Nuclear Gluometry”

Latest Technical Developments

Future
thank you to the organizers for accommodating a talk slightly off-topic!
Spin-1/2 system in B-field leads to 2 sublevels due to Zeeman interaction

\[ m = -\frac{1}{2} \quad \text{and} \quad m = +\frac{1}{2} \]

\[ P_z = \frac{N_+ - N_-}{N_+ + N_-} \]

\(-1 < P_z < +1\)
Spin-1

\[ P_z = \frac{N_+ - N_-}{N_+ + N_-} \]

\[ P_{zz} = \frac{(N_+ - N_0) - (N_0 - N_-)}{N_+ + N_0 + N_-} = \frac{(N_+ + N_-) - 2N_0}{N_+ + N_0 + N_-} \]
Spin-1

\[ P_{zz} = \frac{(N_+ - N_0) - (N_0 - N_-)}{N_+ + N_0 + N_-} = \frac{(N_+ + N_-) - 2N_0}{N_+ + N_0 + N_-} \]

\[-2 < P_{zz} < +1\]
Spin-1

$P_{zz} = -2$

Pure Tensor Polarization
All spins in the $m=0$ level

$P_{zz} = +1$

Pure Vector Polarization
$m=0$ level depopulated

$$P_{zz} = \frac{(N_+ - N_0) - (N_0 - N_-)}{N_+ + N_0 + N_-} = \frac{(N_+ + N_-) - 2N_0}{N_+ + N_0 + N_-}$$

$-2 < P_{zz} < +1$
Inclusive Scattering

Construct the most general Tensor $W$ consistent with Lorentz and gauge invariance

Frankfurt & Strikman (1983)
Hodgbhoy, Jaffe, Manohar (1989)

Unpolarized Scattering

Vector Polarization

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P_\nu}{\nu}$$

$$+ i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma)$$
Tensor Structure Functions

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P_\nu}{\nu}$$

$$+ i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot qp^\sigma)$$

$$- b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu})$$

$$+ \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu})$$

Tensor Polarization

Caution: There is an alternate similar formulation by Edelmann, Piller, Weise

Frankfurt & Strikman (1983)
Hoodbhoy, Jaffe, Manohar (1989)
## Tensor Structure Functions

<table>
<thead>
<tr>
<th></th>
<th>Nucleon</th>
<th>Deuteron</th>
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<tbody>
<tr>
<td>$F_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q^1_{1/2} + q^-_{1/2}]$</td>
<td>$\frac{1}{3} \sum_q e_q^2 [q^1_{1} + q^-<em>{1} + q^0</em>{1}]$</td>
</tr>
<tr>
<td>$g_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q^1_{1/2} - q^-_{1/2}]$</td>
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</tr>
<tr>
<td>$b_1$</td>
<td>$\ldots$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q^0 - q^1]$</td>
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Leading Twist
## Tensor Structure Functions

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$b_2$: related to $b_1$ by a Callan-Gross relation

$b_4$: Also Leading Twist, but kinematically suppressed for a longitudinally polarized target.

$b_3$: Higher twist, like $g_2$
Parton Distributions

\[ q_{\uparrow\downarrow}^m \] Probability to scatter from a quark with spin up/down carrying momentum fraction \( x \) while the \textit{Deuteron} is in state \( m \)
Parton distributions

$q_{\uparrow \downarrow}^m$  Probability to scatter from a quark with spin up/down carrying momentum fraction $x$ while the Deuteron is in state $m$

\[
q_1(x) = q_{\uparrow}^1(x) + q_{\downarrow}^1(x)
\]

\[
q_0(x) = q_{\uparrow}^0(x) + q_{\downarrow}^0(x)
\]
Parton distributions

$q^m_{\uparrow\downarrow}$ Probability to scatter from a quark with spin up/down carrying momentum fraction $x$ while the Deuteron is in state $m$

$q^1(x) = q^1_\uparrow(x) + q^1_\downarrow(x)$

$q^0(x) = q^0_\uparrow(x) + q^0_\downarrow(x)$

$q^0$ : Probability to scatter from a quark (any flavor) carrying momentum fraction $x$ while the Deuteron is in state $m=0$

$q^1$ : Probability to scatter from a quark (any flavor) carrying momentum fraction $x$ while the Deuteron is in state $|m| = 1$
$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$

measured in DIS (so probing quarks), but depends solely on the deuteron spin state

Investigate nuclear effects at the level of partons!

$q^0$ : Probability to scatter from a quark (any flavor) carrying momentum fraction $x$ while the Deuteron is in state $m=0$

$q^1$ : Probability to scatter from a quark (any flavor) carrying momentum fraction $x$ while the Deuteron is in state $|m| = 1$
**b_1 Structure Function**

**Hoodbhoy, Jaffe and Manohar (1989)**

\[ b_1 \text{ vanishes in the absence of nuclear effects} \]

i.e. if...

\[ \text{deuteron} = \text{n} + \text{p} \]

Proton Neuron in relative S-state

Even accounting for D-State admixture, \( b_1 \text{ expected to be vanishingly small} \)

Khan & Hoodbhoy, PRC 44, 1219 (1991) : \( b_1 \approx O(10^{-4}) \)
Relativistic convolution model with binding

Umnikov, PLB 391, 177 (1997) : \( b_1 \approx O(10^{-3}) \)
Relativistic convolution with Bethe-Salpeter formalism
Data from HERMES

C. Reidl PRL 95, 242001 (2005)
Data from HERMES

\[ b_1 = -\frac{3}{2} F_1 A_{zz} \]

C. Reidl PRL 95, 242001 (2005)
Tensor polarization of the sea

Fit improves when tensor polarization of the antiquark distributions is included

S Kumano, PRD 82 017501 (2010)
Close-Kumano Sum Rule

\[ \int b_1(x) \, dx = \frac{1}{9} \Theta Q_s \]

\[ \int b_1(x) \, dx = 0 \]

if the sea quark tensor polarization vanishes
Close-Kumano Sum Rule

\[ \int b_1(x) \, dx = \frac{1}{9} \Theta Q_s \]

\[ \int b_1(x) \, dx = 0 \]

if the sea quark tensor polarization vanishes

\[ \int_{0.0002}^{0.85} b_1(x) \, dx = 0.0105 \pm 0.0034 \pm 0.0035 \]

Hermes result

2.2 \( \sigma \) difference from zero
6-quark, Hidden Color

G. Miller  
PRC89 (2014) 045203

“Pionic and Hidden-Color, Six-Quark Contributions to the Deuteron $b_1$ Structure Function”
6-quark, Hidden Color

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PRC89 (2014) 045203

“Pionic and Hidden-Color, Six-Quark Contributions to the Deuteron $b_1$ Structure Function”

\[ |6q\rangle = \sqrt{\frac{1}{9}} |NN\rangle + \sqrt{\frac{4}{45}} |\Delta\Delta\rangle + \sqrt{\frac{4}{5}} |CC\rangle \]

Pionic effects alone would violate the Ck sum rule
no conventional nuclear mechanism can reproduce the Hermes data,

but that the 6-quark probability needed to do so ($P_{6Q} = 0.0015$) is small enough that it does not violate conventional nuclear physics.
Gluon Contribution to Tensor Structure

Efremov and Teryaev (1982, 1999)

\[ \int b_1(x)dx = 0 \]
\[ \int x b_1(x)dx = 0 \]

Gluons (spin 1) contribute to both moments
Quarks satisfy the first moment, but
Gluons may have a non-zero first moment!

\[ b_1 \text{ should have 2 zero crossings} \]

A.V. Efremov, O. V. Teryaev JINR-E2-94-95 (1999)
Gluon Contribution to Tensor Structure

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Gluons (spin 1) contribute to both moments.

Quarks satisfy the first moment, but Gluons may have a non-zero first moment!

2\textsuperscript{nd} moment more likely to be satisfied experimentally since the collective glue is suppressed compared to the sea.

Study of \( b_1 \) allows to discriminate between deuteron components with different spins (quarks vs gluons)

\[ b_1 \text{ should have 2 zero crossings} \]

\[ \text{Рис.1} \]

A.V. Efremov, O. V. Teryaev JINR-E2-94-95 (1999)
E12-13-011: “The $b_1$ experiment”
30 Days in Jlab Hall C
A- Physics Rating
Conditional Approval (Target Performance)
Contact: K. Slifer

E12-15-005: “$A_{zz}$ for $x > 1$”
44 Days in Jlab Hall C
A- Physics Rating
Conditional Approval (Target Performance)
Contact: E. Long
The Deuteron Polarized Tensor Structure Function $b_1$

JLAB E12-14-011

A- rating by PAC40

(C1: conditional on target performance)

Spokespersons
Slifer, Solvignon, Long, Chen, Rondon, Kalantarians
Experimental Method

\[
A_{zz} = \frac{2}{f P_{zz}} \frac{\sigma_{\uparrow} - \sigma_0}{\sigma_0} \\
= \frac{2}{f P_{zz}} \left( \frac{N_{\uparrow}}{N_0} - 1 \right)
\]

Observable is the Normalized XS Difference

B-Field, density, temp, etc. held same in both states

\[b_1 = -\frac{3}{2} F^d_{1} A_{zz}\]

\[\sigma_{\uparrow} : \text{Tensor Polarized cross-section}\]
\[\sigma_0 : \text{Unpolarized cross-section}\]
\[P_{zz} : \text{Tensor Polarization}\]

\[f \approx \frac{6}{20}\]
Unpolarized Beam
UVa/JLab Polarized Target

Magnetic Field Held Along Beam Line at all times $L = 10^{35}$
Projected Results for $P_{zz} = 35\%$

30 Days in Jlab Hall C
Projected Results for $P_{zz} = 35\%$

30 Days in Jlab Hall C

verification of zero crossing essential for satisfaction of CK Sum
Projected Sargsian Light Cone

Ellie Long, Slifer, Solvignon, Day, Higinbothan, Keller

Very Large Tensor Asymmetries predicted
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Sensitive to the S/D-wave ratio in the deuteron wave function

$4\sigma$ discrim between hard/soft wave functions

$6\sigma$ discrim between relativistic models
Very Large Tensor Asymmetries predicted

Sensitive to the S/D-wave ratio in the deuteron wave function

$4\sigma$ discrim between hard/soft wave functions
$6\sigma$ discrim between relativistic models

"further explores the nature of short-range pn correlations, the discovery of which was one of the most important results of the 6 GeV nuclear program."

PAC44 Theory Report
**A_{zz} experiment**

We simultaneously measure nuclear elastic

\[ \rightarrow T_{20} \text{ over huge } Q^2 \text{ range} \]

\[ \rightarrow \text{measure } T_{20} \text{ at largest } Q^2 \text{ yet} \]

\[ \rightarrow \text{will use to cross-check } P_{zz} \]
Tensor Spin Observables

Quasi-Elastic

\[ A_{zz} = \frac{2}{f P_{zz}} \frac{\sigma_\uparrow - \sigma_0}{\sigma_0} \]
Tensor Spin Observables

\[ b_1 = -\frac{3}{2} F_1^d A_{zz} \]

\[ A_{zz} = \frac{2 f P_{zz} \sigma_\uparrow - \sigma_0}{f P_{zz} \sigma_0} \]

DIS

Quasi-Elastic

\( x \approx 0.3 \)

\( x = 1 \)

\( x = 2 \)
Tensor Spin Observables

\[ b_1 = -\frac{3}{2} F_1^d A_{zz} \]

\[ A_{zz} = \frac{2}{f P_{zz}} \frac{\sigma_+ - \sigma_0}{\sigma_0} \]

\[ T_{20} \approx \frac{A_{zz}}{d_{20} \sqrt{2}} \]

\( x \approx 0.3 \quad x = 1 \quad x = 2 \)

DIS

Quasi-Elastic

Nuclear Elastic
James Maxwell (contact)

"Nuclear Gluonometry"

Look for novel gluonic components in nuclei that are not present in nucleons

Non-zero value would be a clear signature of exotic gluon states in the nucleus

$\Delta(x,Q^2)$ double helicity flip structure function
"Nuclear Gluonometry"

Look for novel gluonic components in nuclei that are not present in nucleons.

Non-zero value would be a clear signature of exotic gluon states in the nucleus.

Deep inelastic scattering experiment:
- Unpolarized electrons
- Polarized \(^{14}\text{NH}_3\) Target
- Target spin aligned transverse to beam

\(\Delta(x,Q^2)\) double helicity flip structure function

Encouraged for full submission by PAC44.
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Encouraged for full submission by PAC44
Technical Developments
Tensor Polarized Target

D-butanol

**Significant progress at UVa**

Enhancing $P_{zz}$ via semi-selective saturation

understanding the NMR lineshape


Promising, but need to confirm in ND$_3$

$T_{20}$ measurement at Higgs to verify NMR analysis
Tensor Polarization progress

\[ p_{zz} \approx 12\% \]

\[ b_1 \text{ approved C1} \]
Tensor Polarization progress

$P_{zz} \approx 12\%$

$b_1$ approved C1

$P_{zz} \approx 20\%$

(Butanol)

$A_{zz}$ approved C2
Tensor Polarization progress

\[ P_{zz} \approx 12\% \] approved C1

\[ P_{zz} \approx 20\% \] (Butanol) approved C2

\[ P_{zz} > 30\% \] (Butanol) approved C1
Tensor Polarization progress

- $P_{zz} \approx 12\%$ b$_{1}$ approved C1
- $P_{zz} \approx 20\%$ (Butanol) A$_{zz}$ approved C2
- $P_{zz} > 30\%$ (Butanol) Future
- $P_{zz} > 30\%$ (Butanol+ND3,LID) Remove Conditional
Very complicated / difficult system!

hats off to Uva for making this look easy for 30 years!
Reached 1K/7T
Have Working NMR system
Developing high vacuum expertise
Just Began Construction of new fridge
Still need to finish the microwave subsystem
UNH Polarized Target Lab

New Faculty hire (Elena Long)
University made a significant investment in infrastructure
We should be fully operational by end of year

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Tensor Program

E12-13-001: Tensor Polarized Structure function $b_1$ of the Deuteron
E12-14-002: Tensor Asymmetry $A_{zz}$ for $x>1$
LOI12-14-001: Tensor Structure Function $\Delta$

Significant progress

High tensor polarizations demonstrated at Uva

Next step is to remove the Conditional status

UNH target lab goal to be fully operational by end of year.

Seeking Theory input to:

Make sure there is a clear interpretation of the observables we can measure

Brainstorm ideas for new physics to investigate with this target.
Splitting

\[ m = -1 \]
\[ \nu_D - 3\nu_Q \]
\[ \nu_D + 3\nu_Q \]
\[ m = 0 \]
\[ \nu_D - 6\nu_Q \]
\[ \nu_D + 6\nu_Q \]
\[ m = +1 \]
\[ \theta = \pi/2 \]
\[ \theta = 0 \]