Tensor Polarized DIS Experiments

Polarized Light Ion Physics with EIC

Gent, Belgium
2018-02-08

Karl Slifer
University of New Hampshire
This Talk

Brief Review of Tensor Polarization

Solid Tensor PolTarg Experiments

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

Latest Target Developments

- $P_{zz} \approx 40\%$ @ UVa
- New Lab at UNH coming online

Future
Spin-$\frac{1}{2}$ system in B-field leads to 2 sublevels due to Zeeman interaction

$$m = -\frac{1}{2}$$

$$m = +\frac{1}{2}$$

$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$

$$-1 < P_z < +1$$
Spin-1

$$P_z = \frac{N_+ - N_-}{N_+ + N_-}$$

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

$$-1 < P_z < +1$$

$$-2 < P_{zz} < +1$$
\[ P_{zz} = +1 \]
Pure Vector Polarization
m=0 level depopulated

\[ P_{zz} = -2 \]
Pure Tensor Polarization
All spins in the m=0 level
Splitting

red : 0 \leftrightarrow -1
blue : 0 \leftrightarrow +1

Energy Levels shifted asymmetrically
due to quadrupole interaction
Splitting

Energy Levels shifted asymmetrically due to quadrupole interaction

red : 0 \leftrightarrow -1
blue : 0 \leftrightarrow +1
At Equilibrium

\[ P_z = \frac{4 + \tanh \frac{\mu B}{2kT}}{3 + \tanh^2 \frac{\mu B}{2kT}} \]

\[ P_{zz} = \frac{4 + \tanh^2 \frac{\mu B}{2kT}}{3 + \tanh^2 \frac{\mu B}{2kT}} \]
At Equilibrium

\[ P_z = \frac{4 + \tanh \frac{\mu B}{2kT}}{3 + \tanh^2 \frac{\mu B}{2kT}} \]

\[ P_{zz} = \frac{4 + \tanh^2 \frac{\mu B}{2kT}}{3 + \tanh^2 \frac{\mu B}{2kT}} \]

\[ P_{zz} = 2 - \sqrt{4 - 3P_z^2} \]

(Only when in Thermal Equilibrium with the Solid Lattice)

\[ A = 2 - (4 - 3P^2)^{1/2} \]
Inclusive Scattering

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

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

$$W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P_\nu}{\nu} + i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma)$$

Unpolarized Scattering

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

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

\[ W_{\mu\nu} = -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P_\nu}{\nu} + i \frac{g_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i \frac{g_2}{\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma) - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) \]

Caution: There is an alternate similar formulation by Edelmann, Piller, Weise
### Tensor Structure Functions

<table>
<thead>
<tr>
<th></th>
<th>Nucleon</th>
<th>Deuteron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q_\uparrow^{1/2} + q_{\downarrow}^{-1/2}]$</td>
<td>$\frac{1}{3} \sum_q e_q^2 [q_\uparrow^1 + q_{\downarrow}^{-1} + q_0^0]$</td>
</tr>
<tr>
<td>$g_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q_\uparrow^{1/2} - q_{\downarrow}^{-1/2}]$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q_\uparrow^1 - q_{\downarrow}]$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$\ldots$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q_0^0 - q_1^1]$</td>
</tr>
</tbody>
</table>

**Leading Twist**
### Tensor Structure Functions

<table>
<thead>
<tr>
<th></th>
<th>Nucleon</th>
<th>Deuteron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>$\frac{1}{2} \sum q e^2_q [q_{\uparrow}^{1/2} + q_{\downarrow}^{-1/2}]$</td>
<td>$\frac{1}{3} \sum q e^2_q [q_{\uparrow}^{1} + q_{\downarrow}^{-1} + q_{\perp}^{0}]$</td>
</tr>
<tr>
<td>$g_1$</td>
<td>$\frac{1}{2} \sum q e^2_q [q_{\uparrow}^{1/2} - q_{\downarrow}^{-1/2}]$</td>
<td>$\frac{1}{2} \sum q e^2_q [q_{\uparrow}^{1} - q_{\downarrow}]$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>...</td>
<td>$\frac{1}{2} \sum q e^2_q [q^{0} - q_{\perp}]$</td>
</tr>
</tbody>
</table>

$b_2$: 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 Deuteron is in state \( m \)
Probability to scatter from a quark with spin up/down carrying momentum fraction $x$ while the Deuteron is in state $m$

\[
q_m^{m} = q_{\uparrow}(x) + q_{\downarrow}(x)
\]

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

\[
q_{0}(x) = q_{\uparrow}(x) + q_{\downarrow}(x)
\]
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 $m$

$q_{\uparrow}(x) = q_{\uparrow}^{1}(x) + q_{\downarrow}^{1}(x)$

$q_{\downarrow}(x) = q_{\uparrow}^{0}(x) + q_{\downarrow}^{0}(x)$

$q^{0}$: 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!

\[ q^0 : \text{Probability to scatter from a quark (any flavor) carrying momentum fraction } x \text{ while the } \text{Deuteron} \text{ is in state } m=0 \]

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

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

*b_1 vanishes in the absence of nuclear effects*

i.e. if...

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

Proton Neutron in relative S-state

Even accounting for D-State admixture *b_1 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
Data from HERMES

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

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

S Kumano,
PRD 82 017501 (2010)

Fit improves when tensor polarization of the antiquark distributions is included.
if the sea quark tensor polarization vanishes
**Close-Kumano Sum Rule**

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

\[ \int b_1(x)dx = 0 \quad \text{if the sea quark tensor polarization vanishes} \]

**Hermes result**

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

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

G. Miller  
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.
b_1 in standard convolution description

W. Cosyn, Y. Dong, S. Kumano, M. Sargsian
PRD95 (2017) 074036

[need a] "new mechanism to explain large differences between current data and our theoretical results"

"room for more advanced or exotic mechanisms playing an important role"
Gluon Contribution to Tensor Structure

Efremov and Teryaev (1982, 1999)

Gluons (spin 1) contribute to both moments

Quarks satisfy the first moment, but

Gluons may have a non-zero first moment!

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

A.V. Efremov, O. V. Teryaev JINR-E2-94-95 (1999)
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!

2nd 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)

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
PAC Conditions

Scientific Rating: A-
Recommendation: Conditional Approval (C1)

- E12-13-011 (*The Deuteron Tensor Structure Function b1*)
- E12-15-005 (*Tensor Asymmetry in Quasielastic Region*)

**Issues:**
In order to obtain conclusive data with sufficient precision it is crucial to achieve a tensor polarization significantly higher than the value of 20% assumed in the proposal. While methods such as RF- “hole burning” are known to increase the tensor polarization above the thermal equilibrium value, these techniques including the polarization measurement have to be developed further to allow for a reliable operation under experimental conditions.

**Conditions:**
The experiment is conditionally approved with the condition that a **tensor polarization of at least 30%** be achieved and reliably demonstrated under experimental conditions.
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
Unpolarized Beam
UVa/JLab Polarized Target

Magnetic Field Held Along \( \mathbf{q} \) vector

\[ L = 10^{35} \]
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

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

\( \sigma_\uparrow \): Tensor Polarized cross-section

\( \sigma_0 \): Unpolarized cross-section

\( P_{zz} \): Tensor Polarization

\( f \approx \frac{6}{20} \) 

dilution factor
Impact on the observable

\[ \delta A_{zz} = \pm \frac{2}{f P_{zz} \sqrt{N_{cycles}}} \delta \xi \]

Dedicated team to systematics/false asyms
similar manpower requirement to g2p exp.
where we had several teams completely separate from the polarized target effort.

Charge Determination
< \(2 \times 10^{-4}\), mitigated by thermal isolation of BCMs and addition of 1 kW Faraday cup

Luminosity
< \(1 \times 10^{-4}\), monitored by Hall C lumi

Target dilution and length step like changes observable in polarimetry
< \(1 \times 10^{-4}\)

Beam Position Drift effect on Acceptance
< \(1 \times 10^{-4}\) (we can control the beam to 0.1 mm, raster over 2cm diameter)

Effect of using polarized beam
< \(2.2 \times 10^{-5}\), using parity feedback

Want to improve the statistics? Increase \(P_{zz}\)
Want to improve the systematics? Increase \(P_{zz}\)
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
A_{zz} in the x>1 Region

Very Large Tensor Asymmetries predicted
Very Large Tensor Asymmetries predicted

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

\[ 4\sigma \text{ discrim between hard/soft wave functions} \]
\[ 6\sigma \text{ discrim between relativistic models} \]
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
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

\[ A_{zz} = \frac{2}{f P_{zz}} \frac{\sigma_\uparrow - \sigma_0}{\sigma_0} \]
$b_1 = -\frac{3}{2} F_1^d A_{zz}$

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

$\approx 0.3$  \hspace{1cm} $x=1$  \hspace{1cm} $x=2$
$b_1 = -\frac{3}{2} F_1^d A_{zz}$

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

$T_{20} \approx \frac{A_{zz}}{d_{20} \sqrt{2}}$
"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 $^{14}$NH$_3$ Target
- Target spin aligned transverse to beam

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

Encouraged for full submission by PAC44
There should be a session on EIC!

→ Any volunteers? 😊
Technical Developments
Tensor Polarized Target

**Significant progress**

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

& understanding the NMR lineshape


$T_{20}$ measurement at Higgs to verify NMR analysis
Selective Semi-saturation
(or just hole burning)

\[ R = \frac{\omega - \omega_d}{3\omega_q} \]

MC overlap with d-but. NMR experimental points (Pn=51→45, Qn:20→31%)

MC with fit and d-but. NMR experimental points (Pn=48→46, Qn:18→6%)

Achieved so far

- Before recent research (1984): ~20%
- Recent studies SSS (2014-2015): ~30%
- AFP with SSS (2016): ~34%
- Rotation SSS so far: ~38% (neg Q possible)

Still more to come, we can probably do much better than this by improving B/T should expect Q>>40%
Rotating Target cell

Dustin Keller
Hall A/C Collab
Rotating Target cell

Dustin Keller
Hall A/C Collab

Motor Driven Circular Motion
UNH Polarized Target Lab

2 faculty
-K. Slifer & Ellie Long

1 post-doc to hire

2 grad students:
--David R : significant time
--Nathalie S. : partial time

lots of undergrads

Projects

- Polarized Target Material Production & Labview controls for E1039
- Tensor Polarization R&D
+2 part-time technicians at UNH
Very complicated / difficult system!
UNH Polarized Target Lab

Reached 1K/7T
Have Working NMR system
Developed high vacuum expertise
Just Completed Construction of new fridge
Still assembling the microwave subsystem

New Faculty hire (Elena Long)
University made a significant investment in infrastructure
**Status**

- Gas line completed in Dec 2017
- Glycerin contamination from a vacuum gauge delayed 2 weeks. Now 10^{-7} Torr.
- Safety requested we run all lines thru the hood service ports or otherwise keep inside hood.
- First test (CO₂) in December was successful.
- First milestone met: grade 5.5 NH₃ production in January.
- Goal: 200 grams for E1039
**Status**
-Gas line completed in Dec 2017
-glycerin contamination from a vacuum gauge delayed 2 weeks. Now 10^{-7} Torr.
-Safety requested we run all lines thru the hood service ports or otherwise keep inside hood.
-First test (CO₂) in December was successful.
-First milestone met: grade 5.5 NH₃ production in January.
-Goal: 200 grams for E1039
**Status**

- Gas line completed in Dec 2017
- Glycerin contamination from a vacuum gauge delayed 2 weeks. Now $10^{-7}$ Torr.
- Safety requested we run all lines thru the hood service ports or otherwise keep inside hood.
- First test (CO₂) in December was successful.
- First milestone met: grade 5.5 NH₃ production in January.
- Goal: 200 grams for E1039
Status
-Gas line completed in Dec 2017
-glycerin contamination from a vacuum gauge delayed 2 weeks. Now 10^{-7} Torr.
-Safety requested we run all lines thru the hood service ports or otherwise keep inside hood.
-First test (CO_{2}) in December was successful.
-First milestone met: grade 5.5 NH_{3} production in January.
-Goal: 200 grams for E1039
UNH He Evaporation Refrigerator

All Machining Complete
✓ Heat Exchanger
✓ Separator Pot
✓ Radiation Baffles
✓ Needle valves
✓ Vacuum Shells

December
1) Pre-Assembly at UNH (pictured) - complete
2) Leak testing new vacuum shells at UNH complete. 10^{-7} Torre
3) Final brazing/welding of needlevalves fittings @ Jlab completed in January

Successful LN2 Cooldown in January
Goals: test indium seals, vacuum all good

UNH Machinist
Phil DeMaine
(assemb “upside down”)
**UNH He Evaporation Refrigerator**

---

**December**

1) Pre-Assembly at UNH (pictured)
- complete

2) Leak testing new vacuum shells at UNH
   1-2 weeks : complete. 10-7 Torre

3) Final brazing/welding of swagelok fittings @ Jlab in January : complete

**LHe Cooldown in Feb**

Goals: 1 K in new fridge
Cross calibrate new NMR with QMeter

---

**All Machining Complete**

- Heat Exchanger
- Separator Pot
- Radiation Baffles
- Needle valves
- Vacuum Shells

---

**Complete Fridge**
Ellie Long

Cross tested an SDR network analyzer against impedance analyzer for 30 MHz oscillator

Results look promising

- Can easily find resonance with 10 MHz (!) sweep
- Will cross check against Qmeter next cooldown.

Also cross testing
- LNAL VME system
- New Pulse NMR
- EPR
Further Improvements to $P_{zz}$

Larger Magnetic Field

Lower Temperature with Optimized Cooling

Directly pumping individual ESR lines simultaneously

Manipulation of polarization with AFP

Different Materials
Tensor Polarization progress

- $P_{zz} \approx 12\%$ (Butanol) $A_{zz}$ approved C1
- $P_{zz} \approx 20\%$ (Butanol) $A_{zz}$ approved C2
- $P_{zz} > 30\%$ (Butanol)
- $P_{zz} \rightarrow 40\%$ (Butanol+ND3,LID) Remove Conditional

$t$

- 2010
- 2013
- 2015
- 2016
- 2018
1) LabView Controls and material production for E1039

2) Fridge parts all Machined. Assembly/leak testing complete. Cooldown in Feb.

3) Ammonia Line: Dry run with CO$_2$ in Dec. 1st Ammonia production in January.

4) NMR : New method using SDR kit. We will cross calibrate against Q-Meter/VME in Feb.

5) microwave subsystem delivery expected in Feb/March. Probably take us a few mos to commission
Summary

Tensor Program

E12-13-001: $b_1$ of the Deuteron (systematics suppressed by $1/P_{zz}$)

E12-14-002: $A_{zz}$ for $x>1$ (HUGE asymmetries expected)

LOI12-14-001: Tensor Structure Function $\Delta$

Other ideas: SIDIS, DVCS, Tensor polarized Drell Yan, ...

Significant progress

High tensor polarizations demonstrated with SSS and rotation: $P_{zz} \rightarrow 40$
Dramatic improvement in statistic and systematic uncertainties.

No reason this represents a limit. Much higher polarizations may be possible.

UNH target lab soon fully functional.

Future

Tensor Workshop
Tensor spin observables with EIC
ND3 vs D-Butanol

- Needs warm (87 K) and cold (1-4 K) to get maximum polarization
- There is a need for the cold produced centers which are not known or understood
- It doesn't stay optimized after cold irradiation
- Never been produced outside of experiments so not clear what temperature, dose or beam energy is needed, or how best to anneal for optimization
- So far only one data point :
  \[(1 \times 10^{15} \text{ e}^{-}/\text{cm}^{2}, 14\text{MeV}, 4\text{K}) \sim 18\%\]

d-but is use under the assumption that the lineshape behaves the same as ND3 and the max polarization from irradiation is about the same