(Tensor) Polarized Deuteron at an EIC

Next Gen. Physics @ JLab12/EIC Workshop
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Hampton University
Outline

• Background/Motivation
• Spin-1/Tensor-Polarization Concept
• Physics possibilities with an EIC
Why Deuteron?

- Relatively simple lab for nuclear physics
- Spin-1 system
- Reasonably “easy” to polarize.

Spatial distribution depends on the spin state

J. Carlson, R. Schiavalla
Rev. Mod. Phys. 70 743 (1998)

J.L. Forrest et al.
Spin-1

Spin-1 system in a B-field leads to 3 sublevels via Zeeman interaction.

\[ m = \begin{cases} -1 \\ 0 \\ 1 \end{cases} \]

Vector polarization: \((n^+ - n^-); -1 < P_z < +1\)

Tensor polarization: \((n^+ - n^0) - (n^0 - n^-); -2 < P_{zz} < +1\)  Normalization: \((n^+ + n^- + n^0) = 1\)

Some research has been done with deuteron beams (Thesis: V. Morozov)
Inclusive Scattering with Spin-1

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

\[
\frac{d^2 \sigma}{d\Omega dE^e} = \sigma_{\text{Mott}} \left[ \frac{1}{y} F_2(x, Q^2) + \frac{2}{M} F_1(x, Q^2) \tan^2(\theta/2) \right] + \gamma g_1(x, Q^2) + \delta g_2(x, Q^2) + \zeta b_1(x, Q^2) + \epsilon b_2(x, Q^2) + \zeta b_3(x, Q^2) + \eta b_4(x, Q^2)
\]

Spin-1 => 4 more structure-functions: \(b_1, b_2, b_3, b_4\)
Deuteron essentially combination of nuclear and quark physics.
Measured via DIS, but dependent on deuteron spin-state.
Allows for investigation of nuclear effects at parton level.
$b_1^d$

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

$b_1$ vanishes in the absence of nuclear effects. 

i.e., if

$p_n = d$

Even accounting for D-state admixture, $b_1^d$ expected to be very 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*
Experimental Method

Observable is the Normalized XS Difference: HERMES

\[\sigma_{meas} = \sigma_U [1 - P_B P_Z A_\parallel + \frac{1}{2} P_{ZZ} A_{ZZ}]\]

\[A_{ZZ} = \frac{1}{P_{ZZ}} \frac{2\sigma^1 - 2\sigma^0}{3\sigma_U}\]

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

\[P_{ZZ} = \frac{(n^+ + n^-) - 2n^0}{n^+ + n^- + n^0}, -2 < P_{ZZ} < 1\]
HERMES Measurement: $b_1^d$

$\begin{align*}
    b_1 &= -\frac{3}{2} F_1 A_{ZZ} \\
    A_{ZZ} &= \frac{1}{P_{ZZ}} \frac{2\sigma^1 - 2\sigma^0}{3\sigma^U}
\end{align*}$

Rising of $b_1$ as $x \rightarrow 0$ can be related to the same mechanism responsible for nuclear shadowing.


Can also be described in models involving double-scattering of leptons

HERMES Details in C. Riedl’s thesis.

Proposed measurements at JLab12 (E. Long’s talk).
HERMES Measurement: $b_2^d$

$b_2$ related to $b_1$ via Callan-Gross-type relation.

\[ b_2 = 2x b_1 \frac{1 + R}{1 + \gamma^2} \]

\[ R = (1 + \gamma^2) \frac{F_2}{2x F_1} - 1 \]
HERMES Close-Kumano Sum Rule

F.E.Close, S.Kumano, PRD42 2377(1990)

If sea quark and antiquark tensor polarization vanishes i.e.

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

HERMES measurement:

\[ \int_{0.02}^{0.85} b_1(x)dx = 0.0105 \pm 0.0034 \pm 0.0035 \]  
2σ result, over measured range

\[ \int_{0.02}^{0.85} b_1(x)dx = 0.0035 \pm 0.0010 \pm 0.0018 \]  
1.7σ result, with \( Q^2 > 1 \text{GeV}^2 \)

PRL 95 242001(2005)
Possibilities

- $A_{zz}$, $b_1^d$, ..., not very easy: susceptible to backgrounds ($A_{PV}$) and FSIs.
- With spectator (nucleon) tagging, can access angular modulations, as well as minimizing FSIs.
- With exclusive channels (DVCS); can access information for sum rules, enhance $b_1$.

Issues to Address:

- How well can polarization and beam stability be understood and controlled (Systematics)?
- Need to do simulation studies.
$b_1^d$ Predictions

- Both models predict $b_1$ (rapidly) increasing as $x \to 0$: Double-scattering
- Errors for (HERMES) data shown are statistical only.
Predictions for $b_2^d$, $A_{2(zz)}^d$

- Disentangling possible at lower $x$.
- (HERMES) errors are statistical here; $Q^2 = 10$GeV$^2$.

$$A_2(x, Q^2) = \frac{b_2(x, Q^2)}{F_2(x, Q^2)}$$
Tens. Pol. Scattering at low $x$

L. Frankfurt, V. Guzey, M. Strikman

Solid curve: $Q^2 = 2$ GeV$^2$
Dashed: $5$ GeV$^2$
Dotted: $10$ GeV$^2$

\[
T_{20} = \frac{2\sigma^+ - 2\sigma^0}{2\sigma^+ - \sigma^0}
\]

\[
b_1^d(x, Q^2) = -\frac{F_2^d(x, Q^2)}{2x} T_{20}(x, Q^2)
\]
Exclusive

$H_5 \Rightarrow b_1$

Taneja,Kathuria,Liuti,Goldstein, PRD86 (2012)

\[
H_5(x, \xi, t) = \frac{1}{2} \left( 2f_{00}^{11} - f_{++}^{11} - f_{--}^{11} \right)
\]

\[
= \int_x^t \, dz \, f_{D}^{l=2} (z) \, H \left( \frac{x}{z}, \frac{\xi}{z}, t \right)
+ c_E \frac{\sqrt{t_0 - t}}{2M} \, E \left( \frac{x}{z}, \frac{\xi}{z}, t \right)
\]

GPD E makes $b_1$ increase!

$b_1$ in forward limit

$b_1^d = H_5(x, 0, 0)$

(S. Liuti’s talk).

16
Cross Section Calculation w/ Tagging

**Carried out by W. Cosyn, M. Sargsian, and C. Weiss (very much in progress)**

- Cross-section for pol. Deuteron, w/ tagged nucleon -> 16 SFs sensitive to tensor pol.
- These all go like the deuteron S-D-wave interference and D-wave density so will be small.
- All have their own modulation with azimuthal angles like \( \sin n \Phi_h \Phi_{offset} \) -with 2 different offset angles.
- There is a \( 4 \Phi_h \) modulation that does not appear in the unpolarized or vector-polarized part of the cross section.
- Integrated over all tagged nucleons (inclusive) 4 of the structure functions survive, which can be related to SSFs \( b_{1-4} \).
The (M)EIC at JLab (nka JLEIC)

- Both the MEIC and CEBAF have a ~1.4 km circumference
- 12 GeV CEBAF is a full-energy lepton injector
  - Parallel running with fixed target possible
- Both the MEIC and CEBAF have a ~1.4 km circumference
- MEIC can store 20-100 GeV protons, or heavy ions up to 40 GeV/A.
- The stage II EIC will increase the energy to 250 GeV for protons and 20 GeV for electrons.
- Two detectors
  - IP2 could host ePHENIX

See P. Nadel-Turonski’s Talk
MEIC – design goals

Spin control for all light ions

- Figure-8 layout
- Vector- and tensor polarized deuterium

Full-acceptance detector

- Ring designed around detector requirements
- Detection of all fragments – nuclear and partonic

Stable concept – detailed design report released August 2012

(\textit{arXiv:1209.0757})
Polarized Deuterons in Figure-8

- Maintaining pol. deuteron difficult with present tech., due to small magnetic moment.
- Figure-8 design allows one to control the stable spin orientation with a small spin rotation around a certain axis using magnetic inserts.
- Deuteron pol. is then stable and points along the rotation axis at the insert’s location.
- Simulations in progress for MEIC (figure-8) concept.

(arXiv:1209.0757)
Deuteron Beam Polarization Studies

- Studied deuteron spin manipulation with a 270 MeV vertically polarized beam stored in IUCF storage ring. Similar study done at COSY.
- Beam Fast RF cycled through 4 vertical polarization states (to reduce systematic errors).
- Spin-1 linear combination: Flip by bunches or extract at experiment.

\[(P_V, P_T) = (1, 1), (-1, 1), (0, 1), (0, -2)\]

Thesis: V. Morozov
Summary

• (Tensor) Polarized deuteron provides Spin-1 quark/nuclear system.
• Spin-1 introduces new observables of interests.
• HERMES measurement, complementary proposals at Jlab12.
• Access to lower $x$, with tensor polarized deuteron, could open new physics capabilities.
• Study underway for polarized deuteron beam for MEIC – (others interested welcome to join!).

*Many thanks to W. Cosyn, V. Morozov, S. Liuti, P. Nadel-Turonski C. Weiss
Support Slides
Spin-1 Structure Functions

**Leading Twist:** $F_1, g_1, b_1$

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

$q^0 = (q_{\uparrow}^{0} + q_{\downarrow}^{0}) = 2q_{\uparrow}^{0}$

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

$F_1$: quark distributions averaged over spin states

$g_1$: difference of distributions of quarks aligned/anti-aligned with nucleon

$b_1$: difference of helicity-0/helicity non-zero states of the **deuteron**
Spin-1 Structure Functions

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>$b_1$</td>
<td>$\frac{1}{2} \sum q e_q^2 [2q_0^0 - (q_1^1 + q_{-1}^1)]$</td>
</tr>
</tbody>
</table>

$1$ \text{ depends on spin-averaged distributions}

From reflection-symmetry

$q_m^\uparrow = q_m^\downarrow$

$1$ \text{ d.n.e for spin-1/2 and vanishes in absence of nuclear effects.}

In relative S-state $b_1$ describes difference between helicity-0 and averaged nonzero.

$q^0 = (q_\uparrow^0 + q_\downarrow^0) = 2q_\uparrow^0$

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

$1$ \text{ depends on spin-averaged distributions}

Hoodbhoy, Jaffe, Manohar (1989)
Spin-1 Structure Functions

**Leading Twist: $F_1, g_1, b_1$**

<table>
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<tr>
<td>$F_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q_\uparrow^{1/2} + q_\downarrow^{-1/2}]$</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>
</tr>
<tr>
<td>$b_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 [q^0 - q^1]$</td>
</tr>
</tbody>
</table>

$b_2$: related to $b_1$ by relation similar to Callan-Gross.

$b_4$: kinematically suppressed at longitudinal polarization. Also, leading twist.

$b_3$: higher twist, similar to $g_2$.  

26
**HERMES result was about 2\( \sigma \) from 0.

- 27.6 GeV longitudinally polarized positron beam
- Internal tensor polarized \( d_2 \) gas target; \( P_{zz} \sim 0.8 \) (negligible \( P_z \)), dilution \( \sim 0.9 \).
- 1 month of data taking.

Tensor spin asymmetry

\[
A_{zz} = \frac{1}{P_{zz}} \frac{2\sigma^1 - 2\sigma^0}{3\sigma U}
\]

\(0.01 < x < 0.45\)
\(0.5 < Q^2 < 5 \text{GeV}^2\)
Proposal To Determine $b_1^d$ at JLab

- Measurement at Jlab 12GeV could be complementary to HERMES.
- Advantage would be higher luminosity: $\sim 10^{35}\text{cm}^{-2}\text{s}^{-1}$ compared to $\sim 10^{31}\text{cm}^{-2}\text{s}^{-1}$.
- Some research has been done tensor polarizing solid deuteron (ND$_3$) target via NMR*: $P_{zz} \sim 0.2$, dilution$\sim 0.24,0.36$.
- Submitted at PAC 40; Conditionally approved.
OAM Sum Rule

- OAM obtained from $A_{UT}$ (vector pol.)
- Small, hatched area, for ratio, experimental (1109.6197[hep-ph])
- $b_1^d$ adds complementary information.
- Further development in progress.

$$b_1^d = H_5(x, 0, 0)$$

(S. Liuti’s talk).
# MEIC accelerator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>50 x 5 GeV²</th>
<th>100 x 5 GeV²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proton</td>
<td>Electron</td>
</tr>
<tr>
<td>Beam energy</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>748.5</td>
<td>748.5</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>10¹⁰</td>
<td>0.21</td>
</tr>
<tr>
<td>Beam Current</td>
<td>0.25</td>
<td>2.2</td>
</tr>
<tr>
<td>Energy spread</td>
<td>10⁻⁴</td>
<td>~3</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>Horizontal emittance, normalized</td>
<td>0.3</td>
<td>54</td>
</tr>
<tr>
<td>Vertical emittance, normalized</td>
<td>0.06</td>
<td>5.4</td>
</tr>
<tr>
<td>Horizontal and vertical β*</td>
<td>10 and 2</td>
<td>10 and 2</td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td>0.015</td>
<td>0.014</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td>0.053</td>
<td>&lt;0.0005</td>
</tr>
<tr>
<td>Distance from IP to 1st quad</td>
<td>7 (downstream)</td>
<td>3 (upstream)</td>
</tr>
<tr>
<td>Luminosity per IP*</td>
<td>2.4 x 10³³</td>
<td>8.3 x 10³³</td>
</tr>
</tbody>
</table>

*Includes space-charge effects and assumes conventional electron cooling.

Red indicates parameters specific to the full-acceptance detector.
EIC Staging

Already the first stage of an EIC gives access to sea quarks and gluons.

Need polarization and good acceptance to detect spectators & fragments.

An EIC aims to study the sea quark and gluon-dominated matter.
MEIC – full-acceptance detector

Design goals:

1. Detection/identification of complete final state
2. Spectator $p_T$ resolution $\ll$ Fermi momentum
3. Low-$Q^2$ electron tagger for photoproduction

(from GEANT4, top view)