Tensor Polarized Deuteron at and EIC

Tensor Polarized Observables Workshop
March 10-12, 2014

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Hampton University
Outline

• Background/Motivation
• Spin-1/Tensor-Polarization Concept
• Starting point (Spin-1) Physics with an EIC
Why Deuteron?

- Spin-1 system
- Simple lab for nuclear physics
- 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 system in a B-field leads to 3 sublevels via Zeeman interaction.

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)
Possibilities

- Small $x$ aspect of tensor pol. (deuteron) could access anti-shadowing and 2 nucleon (coherent) scattering.
- A good starting point would be to extract $b_1^d$ with an EIC.

Issues to Address:

- How well can polarization, beam stability be understood and controlled?
- Need simulation studies.
Inclusive Scattering with Spin-1

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

\[b_1, b_2 \sim \frac{1}{P_{zz}^{\text{eff}}}\]

Spin-1 => 4 more structure-functions: \(b_1, b_2, b_3, b_4\)

Frankfurt & Strikman (1983)
Hoodbhoy, Jaffe, Manohar (1989)
\[ b_1^d \approx \frac{1}{2}(q^0 - q^1) \]

- 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.

\[ b_1 = p + n \]

i.e., if $p, n$ in relative S-state

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

Details in S. Kumano, G. Miller, S. Liuti Talks
Experimental Method

Observable is the Normalized XS Difference

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

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

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

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

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

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

Rising of $b_1$ as $x \to 0$ 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 talk.

Proposed measurement at JLab (K. Slifer’s talk).
$b_1^d$ Predictions

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

- Disentangling possible at lower $x$.
- (HERMES) errors are statistical here.
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$^2$

\[ T_{20} = 2 \left( \frac{\sigma^+ - \sigma^0}{\sigma^+ + \sigma^0} \right) \]

\[ b_1^d(x,Q^2) = -\frac{F_2^d(x,Q^2)}{2x} T_{20}(x,Q^2) \]
The (M)EIC at JLab

- 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
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
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)
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.
- Simulation 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

![Graphs showing polarization changes over time](image)
Summary

- Tensor Polarized deuteron provides Spin-1 quark/nuclear system.
- Spin-1 produces 4 new SSFs.
- HERMES measurement, complementary proposal at Jlab.
- Access to lower $x$, with tensor polarized deuteron, could open new physics capabilities.
- $b_1^d$ would be a good starting point.
- Study underway for polarized deuteron beam for MEIC.

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

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

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

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

From reflection-symmetry

$q^m_\uparrow = q^{-m}_\downarrow$

$b_1$ 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.

$q_0^0 = (q_0^0 + q_0^0) = 2q_0^0$

$q_1^1 = (q_1^1 + q_1^1) = (q_1^1 + q_{1,-1}^1)$

$b_1$ depends on spin-averaged distributions

$\frac{1}{2} \sum_q e_q^2 [q_0^0 - q_1^1]$
Spin-1 Structure Functions

Leading Twist: $F_1, g_1, b_1$

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</tr>
<tr>
<td>$g_1$</td>
<td>$\frac{1}{2} \sum_q e_q^2 \left[ q_{\uparrow}^{1/2} - q_{\downarrow}^{-1/2} \right]$</td>
<td>$\frac{1}{2} \sum_q e_q^2 \left[ q_0^0 - q_1^1 \right]$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>...</td>
<td>$\frac{1}{2} \sum_q e_q^2 \left[ q_0^0 - q_1^1 \right]$</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 $g_2$. 
HERMES Measurement: \(A_{zz}^d\)

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

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

Tensor spin asymmetry

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

\(0.01 < x < 0.45\)

\(0.5 < Q^2 < 5\text{GeV}^2\)
HERMES Measurement: $b_2^d$

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

\[
b_2 = 2xb_1 \left( \frac{1+R}{1+\gamma^2} \right)
\]

\[
R = (1+\gamma^2) \frac{F_2}{2xF_1} - 1
\]
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:

\[ \int_{0.02}^{0.85} b_1(x) \, dx = 0.0105 \pm 0.0034 \pm 0.0035 \]  \hspace{1cm} \text{2\(\sigma\) result, over measured range}

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

PRL 95 242001 (2005)
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.
# MEIC accelerator parameters

<table>
<thead>
<tr>
<th></th>
<th>50 x 5 GeV²</th>
<th>100 x 5 GeV²</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Proton</td>
<td>Electron</td>
</tr>
<tr>
<td></td>
<td>Proton</td>
<td>Electron</td>
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<tr>
<td>Beam energy</td>
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<tr>
<td>Collision frequency</td>
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<tr>
<td>Particles per bunch</td>
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<tr>
<td>Beam Current</td>
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<tr>
<td>Polarization</td>
<td>%</td>
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<tr>
<td>Energy spread</td>
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<td>~3</td>
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<tr>
<td>RMS bunch length</td>
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<tr>
<td>Horizontal emittance,</td>
<td>µm rad</td>
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<tr>
<td>Vertical emittance,</td>
<td>µm rad</td>
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<td>normalized</td>
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<tr>
<td>Horizontal and vertical $\beta^*$</td>
<td>cm</td>
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<tr>
<td>Vertical beam-beam tune shift</td>
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<tr>
<td>Laslett tune shift</td>
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<tr>
<td>Distance from IP to 1st quad</td>
<td>m</td>
<td>7 (downstream)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5 (upstream)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 (downstream)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5 (upstream)</td>
</tr>
<tr>
<td>Luminosity per IP*</td>
<td>cm²s⁻¹</td>
<td>$2.6 \times 10^{33}$</td>
</tr>
</tbody>
</table>

*Includes space-charge effects and assumes conventional electron cooling

Red indicates parameters specific to the full-acceptance detector