Tensor Polarized Deuteron Experiments

Elena Long
High Energy Nuclear Physics With Spectator Tagging, ODU
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Today’s Discussion

- Background
  - Definitions, Early Experiments, Target Development
- C12-13-011: Deuteron Structure Function $b_1$
- LOI12-14-002: Tensor Asymmetry $A_{zz}$
- LOI12-14-001: Exotic Gluonic States from $\Delta (b_4)$
- Summary
Background
Tensor Polarization

For tensor polarization, need spin-1 particles

\[ m_j = \pm 1 \]
\[ m_j = 0 \]


Elena Long <ellie@jlab.org>
Tensor Polarization

Vector $P_z = p_+ - p_-$

Tensor $P_{zz} = (p_+ + p_-) - 2p_0$

For $m_j = \pm 1$:

- $(p_+ + p_-) = 1$, $p_0 = 0$, $P_{zz} = +1$
- $(p_+ + p_-) = 2/3$, $p_0 = 1/3$, $P_{zz} = 0$
- $(p_+ + p_-) = 0.5$, $p_0 = 0.5$, $P_{zz} = -1$
- $(p_+ + p_-) = 0$, $p_0 = 1$, $P_{zz} = -2$
Tensor Polarization Experiments

- **Unpolarized Target + Polarimeter**
  - $D_2O$ waterfall\[^1\]
  - Liquid $D_2$\[^2\]
  - Medium-high luminosity, no polarization enhancement

- **Gas Jet/Storage Cell Target\[^3\]**
  - Low luminosity, very high tensor polarization

- **Solid Polarized DNP Target\[^4\]**
  - High luminosity, polarization enhancement, large dilution at high $x$

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\[^3\] AV Evstugneev, *et al*, NIM A 238 12 (1985)
Deuteron Wave Function

- Deuteron is the simplest composite nuclear system
- "Nuclear hydrogen"
- Yet theoretical understanding remains unsatisfactory
- Previous tensor-polarized experiments focused on $T_{20}$
- Can be used with A & B to determine deuteron form factors $G_C$, $G_Q$, and $G_M$
- New experiments will probe deuteron structure in QE and DIS

Elastic Tensor Observables

\[
A = G_C^2 + \frac{2}{3} \eta G_M^2 + \frac{8}{9} \eta^2 G_Q^2
\]

\[
B = \frac{4}{3} \eta (1 + \eta) G_M^2
\]

\[
T_{20} = -\frac{8}{9} \eta^2 G_C^2 + \frac{8}{3} \eta G_C G_Q + \frac{2}{3} \eta G_M^2 \left[ \frac{1}{2} + (1 + \eta) \tan^2 \left( \frac{\theta}{2} \right) \right] + \frac{1}{2} \eta G_C G_Q \left[ \frac{1}{2} + (1 + \eta) \tan^2 \left( \frac{\theta}{2} \right) \right] \]

\[
Q = 7 \text{ fm}^{-1} \rightarrow Q^2 = 1.9 \text{ GeV}^2
\]
Elastic Tensor Observables


\[ W_{\mu\nu} = -\alpha F_1 + \beta F_2 \]
\[ + i \gamma g_1 + i \delta g_2 \]
\[ - \epsilon b_1 + \zeta b_2 + \eta b_3 + \kappa b_4 \]

Scattering on Unpolarized Targets
Scattering on Vector Polarized Targets
Scattering on Tensor-Polarized Targets

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>Deuteron</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_1 )</td>
<td>( \frac{1}{3} \sum_q e_q^2 [q^1_\uparrow + q^{-1}<em>\uparrow + q^0</em>\uparrow] )</td>
</tr>
<tr>
<td>( g_1 )</td>
<td>( \frac{1}{2} \sum_q e_q^2 [q^1_\uparrow - q^{-1}_\uparrow] )</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>( \frac{1}{2} \sum_q e_q^2 [2q^0_\uparrow - (q^1_\downarrow + q^{-1}_\downarrow)] )</td>
</tr>
</tbody>
</table>
DIS Tensor Observables

- HERMES $b_1$ -- First tensor structure function measurement

27.6 GeV Positron Beam
Internal Gas Tensor-Polarized Target

DIS Tensor Observables

- HERMES $b_1$ -- First tensor structure function measurement

C12-13-011: The Deuteron Tensor Structure Function $b_1$

Spokespeople:
Tensor Structure Function, $b_1$

$b_1 \rightarrow$ Leading twist

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

$b_1$ is the measure of quark distributions when the nucleus is in a particular spin state

**Looks at nuclear effects at the resolution of quarks!**

If there are no nuclear effects, then $b_1$ vanishes.

Even with D-state admixture, it’s expected to be vanishingly small

Deuteron $= n + p \rightarrow b_1 = 0$

Khan & Hoodbhoy, PRC 44 1219 (1991)
Tensor Structure Function, $b_1$

All conventional models predict small or vanishing values of $b_1$ in contrast with the HERMES data.

Any measurement of a $b_1 < 0$ indicates exotic physics.

K Slifer et al, JLab E12-13-011
Close-Kumano Sum Rule

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

- Related to the electric quadrupole structure
- Vanishes in any model with an unpolarized sea

\[ b_1 = \frac{1}{36} \delta_T w[5(u_v + d_v)] + 4\alpha_{\bar{q}}[2\bar{u} + 2\bar{d} + s + \bar{s}] \]

- Looked at difference between \( \alpha_{\bar{q}} = 0 \) and floating \( \alpha_{\bar{q}} \)
- \( \alpha_{\bar{q}} \sim \) Tensor polarization of sea
- \( \alpha_{\bar{q}} = 3.20 \pm 0.212 \) improved \( \chi^2 \), indicating significant tensor polarization in antiquark distributions

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

\[ \frac{\chi}{dof} = 2.83 \]

\[ \frac{\chi}{dof} = 1.57 \]

---

S Kumano, PRD 82 017501 (2010)
6-Quark, Hidden Color

- Deuteron wave function can be expressed as
  \[ |6q\rangle = \sqrt{\frac{1}{9}} |NN\rangle + \sqrt{\frac{4}{45}} |\Delta\Delta\rangle + \sqrt{\frac{4}{5}} |CC\rangle \]

- Early hidden color calculations gave small results, but author noted "as experimental techniques have improved dramatically, the meaning of small has changed."

- Even though experimental upper limit of \( P_{6q} < 1.5\% \), a much smaller value (0.15\%) can have a significant effect on \( b_1 \)

G Miller, PRC 89 045203 (2014)
6-Quark, Hidden Color

- Pionic effects alone would violate Close-Kumano Sum Rule

\[ \int b_1(x) dx = 0 \]
6-Quark, Hidden Color

- 6-quark, hidden color states predict large negative $b_1$ at large $x$
- Using central values $R=1.2$ fm, $m=338$ MeV

G Miller, PRC 89 045203 (2014)
6-Quark, Hidden Color

- First theory to reproduce anomalous HERMES result
- $b_1^\pi + b_1^{6q}$ predictions made for upcoming JLab $b_1$ measurement

G Miller, PRC 89 045203 (2014)
Deuteron angular momentum dominated by the GPD $H$

\[ J_q = \frac{1}{2} \int dxx H_2^q(x,0,0) \]

DVCS ($A_{UT}$) on tensor-polarized deuterons would be an ideal observable to test this sum rule.

Sum rule can calculate normal nuclear effects with high precision, giving $H_2 \approx H + E$.

Any measured deviation might shed light on elusive gluon angular momentum components.

Measurement of $b_1 = H_5(x,0,0)$ will provide necessary information for assumptions in the above sum rule and relates to gravitomagnetic form factors.

\[ \int dxxH_5(x,\xi,t) = -\frac{t}{8M_D^2} G_6(t) + \frac{1}{2} G_7(t) \]

Tensor Structure Function, $b_1$

Measured by ratio method

\[ \frac{N_{Pol}}{N_u} - 1 = f \frac{1}{2} A_{zz} P_{zz} \]

\[ A_{zz} = \frac{2}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right) \]

\[ b_1 = -\frac{3F_1}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right) = -\frac{3}{2} F_1 A_{zz} \]

<table>
<thead>
<tr>
<th>Detector</th>
<th>$x$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>$E_{e'}$ (GeV)</th>
<th>$\theta_{e'}$ (deg.)</th>
<th>$\theta_q$ (deg.)</th>
<th>Rates (kHz)</th>
<th>Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHMS</td>
<td>0.15</td>
<td>1.21</td>
<td>2.78</td>
<td>6.70</td>
<td>7.35</td>
<td>11.13</td>
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<tr>
<td>SHMS</td>
<td>0.30</td>
<td>2.00</td>
<td>2.36</td>
<td>7.45</td>
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<td>17.66</td>
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<td>SHMS</td>
<td>0.45</td>
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<td>2.00</td>
<td>7.96</td>
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<td>23.31</td>
<td>0.38</td>
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<td>HMS</td>
<td>0.55</td>
<td>3.81</td>
<td>2.00</td>
<td>7.31</td>
<td>12.50</td>
<td>22.26</td>
<td>0.11</td>
<td>30</td>
</tr>
</tbody>
</table>
Tensor Structure Function, $b_1$

- Jefferson Lab’s Hall C
- Unpolarized beam, tensor polarized target (longitudinal alignment)

03/11/2015 Spectator Tagging Workshop Elena Long <ellie@jlab.org>
Tensor Structure Function, $b_1$

- Dynamic Nuclear Polarization of ND$_3$
- PAC Condition: $P_{zz} \sim 30\%$
- 5 Tesla at 1 K
- 3cm Target Length
- $p_f \sim 0.65$
- $f_{dil} \sim 0.27$

![Graph showing tensor polarization as a function of vector polarization]

"Brute Force" Tensor Polarization

Vector Polarization (%) vs. Tensor Polarization (%)

$A = 2 \cdot (4 - 3P^2)^{1/2}$
Tensor Structure Function, $b_1$

- Dynamic Nuclear Polarization of ND$_3$
- PAC Condition: $P_{ZZ} \sim 30\%$
- 5 Tesla at 1 K
- 3cm Target Length
- $p_f \sim 0.65$
- $f_{dil} \sim 0.27$

![Diagram showing tensor enhancement and hole burning](image)

D Keller, HiX Workshop (2014)

UVA Tensor Enhancement on Butanol (2014)
Tensor Structure Function, $b_1$

- UNH Target Lab is ramping up, magnet tested, first helium fridge (and TE?) test expected in May
Tensor Structure Function, $b_1$

Measuring $b_1$ will give insight into:

- Close-Kumano sum rule\[^1\]
- 6-quark hidden color\[^2\]
- OAM and spin crisis\[^3\]
- Pionic effects\[^2,4\]
- Polarized sea quarks\[^4\]

**Approved** JLab Experiment C12-13-011

\[^2\] G Miller, Phys. Rev. **C89**, 045203 (2014)
LOI12-14-002: Tensor Asymmetry $A_{zz}$ in the $x > 1$ Region

Spokespeople:
Quasi-Elastic $A_{zz}$

- Repeat same experiment, only look at $A_{zz}$ in the quasi-elastic region
- DIS $\rightarrow b_1 \propto F_1 A_{zz}$; QE $\rightarrow A_{zz}$; Elastic $\rightarrow T_{20} \propto A_{zz}$
- Can give insight to short range deuteron structure

$$A_{zz} = \frac{2}{f \cdot P_{zz}} \left( \frac{N_{Pol}}{N_u} - 1 \right)$$

$$A_{zz} \propto \frac{1}{2} \frac{w^2 - uw\sqrt{2}}{u^2 + w^2}$$

Quasi-Elastic $A_{zz}$ Experimental Set-Up

- Hall C
- Identical equipment as $b_1$ (E12-13-011)
- ( Mostly?? )

### Kinematics

$I = 90$ nA  
$\mathcal{L}_D = 1.3 \times 10^{35}$ cm$^{-1}$s$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>$E_0$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$E'$ (GeV)</th>
<th>$\theta_{e'}$ (°)</th>
<th>Rates (kHz)</th>
<th>PAC Time (Days)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>8.8</td>
<td>1.5</td>
<td>8.36</td>
<td>8.2</td>
<td>0.43</td>
<td>25</td>
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<tr>
<td>B</td>
<td>6.6</td>
<td>0.7</td>
<td>6.50</td>
<td>8.2</td>
<td>3.19</td>
<td>3.75</td>
</tr>
<tr>
<td>C</td>
<td>2.2</td>
<td>0.3</td>
<td>2.11</td>
<td>14.4</td>
<td>3.73</td>
<td>1.25</td>
</tr>
</tbody>
</table>

E. Long, et al, JLab LOI12-14-002
Quasi-Elastic $A_{zz}$

E. Long, et al, JLab LOI12-14-002
Quasi-Elastic $A_{zz}$

- Very large asymmetry
- Identical equipment as $b_1$ (?? + tagging??), less dependent on systematics
- Direct access to the tensor component of the deuteron, which is necessary to understand SRC
- Potential for parasitic $T_{20}$ measurement
  - Can also be used to calibrate target polarization at low $Q^2$

E. Long, et al, JLab LOI12-14-002
Quasi-Elastic $A_{zz}$

First measurement of quasi-elastic $A_{zz}$ will give insight into:

- SRCs & pn dominance\(^3\)
- Differentiate light cone and VN models\(^{1,2}\)
- Better understanding of deuteron $wf$\(^4\)
- Final state interaction models\(^5\)

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\(^1\) E. Long, et al, JLab LOI12-14-002
\(^4\) L Frankfurt, M Strikman, Phys. Rept. 160, 235
\(^5\) W Cosyn, M Sargsian, arXiv:1407.1653
Quasi-Elastic $A_{zz}$

Encouraged for full submission by PAC42

“The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range $pn$ correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program.”

-JLab PAC42 Theory Advisory Committee
LOI12-14-001: Search for Exotic Gluonic States in the Nucleus

Authors:

Tensor Structure Function, $b_4$ (or $\Delta$)

- Hadronic double helicity flip structure function, $\Delta(x, Q^2) = b_4$

- Unpolarized electron beam on transversely-aligned tensor polarized target

- Insensitive to bound nucleons or pions

- Any non-zero value indicates exotic gluonic components

- Encouraged for full submission by PAC42


J. Maxwell, et al, JLab LOI-14-001
Summary

- Previous tensor-polarized measurements focused on low $Q^2$ elastic $T_{20}$
- Expanding tensor measurements into quasi-elastic ($A_{zz}$) and DIS ($b_1, b_4$) will provide important information in a variety of topics
  - Deuteron wave function ("Nuclear Hydrogen")
  - Close-Kumano Sum Rule
  - Orbital Angular Momentum & Spin Crisis
  - 6-Quark, Hidden Color
  - Pionic Effects
  - Polarized Sea Quarks
  - Short Range Correlations and p-n Dominance
  - Differentiate Light Cone and Virtual Nucleon Models
  - Final State Interactions
  - Gluonic Effects
- ...and we’re just getting started!
Thank you
Backup Slides
Quasi-Elastic $A_{zz}$

Encouraged for full submission by PAC42

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E. Long, et al, JLab LOI12-14-002
## Elastic Tensor Observables

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>$Q$ (GeV)</th>
<th>Observables</th>
<th>Number of points</th>
<th>Year and reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bates</td>
<td>Polarimeter</td>
<td>0.34, 0.40</td>
<td>$t_{20}$</td>
<td>2</td>
<td>1984 [56]</td>
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<tr>
<td>Novosibirsk VEPP-2</td>
<td>Atomic beam</td>
<td>0.17, 0.23</td>
<td>$T_{20}$</td>
<td>2</td>
<td>1985 [57, 58]</td>
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<tr>
<td>Novosibirsk VEPP-3</td>
<td>Storage cell</td>
<td>0.49, 0.58</td>
<td>$T_{20}$</td>
<td>2</td>
<td>1990 [59]</td>
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<td>Bonn</td>
<td>Polarized target</td>
<td>0.71</td>
<td>$T_{20}$</td>
<td>1</td>
<td>1991 [60]</td>
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<tr>
<td>Bates</td>
<td>Polarimeter</td>
<td>0.75–0.91</td>
<td>$t_{20}, t_{21}, t_{22}$</td>
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<td>1991 [61, 62]</td>
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<tr>
<td>Novosibirsk VEPP-3</td>
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<td>0.71</td>
<td>$T_{20}$</td>
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<td>1994 [63]</td>
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<td>NIKHEF</td>
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<td>$T_{20}, T_{22}$</td>
<td>1</td>
<td>1996 [64]</td>
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<td>NIKHEF</td>
<td>Storage cell</td>
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<td>$T_{20}$</td>
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<td>1999 [65]</td>
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<td>JLab Hall C 94-018</td>
<td>Polarimeter</td>
<td>0.81–1.31</td>
<td>$t_{20}, t_{21}, t_{22}$</td>
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<td>Novosibirsk VEPP-3</td>
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<td>VEPP-3</td>
<td>Internal gas</td>
<td>1.65–4.26</td>
<td>$T_{20}, T_{21}$</td>
<td>6</td>
<td>2003</td>
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<tr>
<td>Bates</td>
<td>Internal gas</td>
<td>0.42–0.89</td>
<td>$T_{20}, T_{21}$</td>
<td>9</td>
<td>2011</td>
</tr>
</tbody>
</table>

Frankfurt and Strikman Light Cone Calculations

\[ A_{zz} = \left( 3 \frac{k^2}{k^2} \right) \frac{1}{2} \frac{u^2(k) - u(k)w(k)\sqrt{2}}{u^2(k) + w^2(k)} \]

- \( u(k) \) is the momentum-dependent S state
- \( w(k) \) is the momentum-dependent D state
- Recent study indicates dependence on choice of NN potential

Connection to Short Range Correlations

Short range correlations caused by tensor force – why not probe it through tensor polarization?


Connection to Short Range Correlations

Short range correlations caused by tensor force – why not probe it through tensor polarization?

Tensor Polarization Measurement

Vector optimize with microwaves
Fit peaks with convolution
Tensor optimize with RF
Measure change in peaks using Riemann Sum segments

\[ P_{zz}^{HB} \approx \frac{A^{NMR}}{A^I} \left( P_{zz}^I + r_0(P^I - P_{zz}^I) \right) \]

- Ratio of instantaneous to initial NMR signal area
- Percentage of initial peak shifted any time (from reduced side)
- Available tensor enhancement
Brute Force Tensor Polarization

When vector polarizing deuterium, some amount of tensor polarization occurs.

Higher vector polarization $\rightarrow$ Higher tensor polarization

$$A = 2 \cdot (4 - 3P^2)^{1/2}$$
Systematics Estimate for $A_{zz}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic</th>
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<tbody>
<tr>
<td>$P_{zz}$ Polarimetry</td>
<td>12%</td>
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<tr>
<td>Dilution Factor</td>
<td>6.0%</td>
</tr>
<tr>
<td>Packing Fraction</td>
<td>3.0%</td>
</tr>
<tr>
<td>Trigger/Tracking Efficiency</td>
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</tr>
<tr>
<td>Acceptance</td>
<td>0.5%</td>
</tr>
<tr>
<td>Charge Determination</td>
<td>1.0%</td>
</tr>
<tr>
<td>Detector Resolution and Efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total</td>
<td>14%</td>
</tr>
</tbody>
</table>
Interest from Theorists

M. Strikman and M. Sargsian have already been involved in providing $A_{zz}$ calculations.

“This is an important measurement. Accessing the large x region will provide insights on the partonic structure of the D-wave dominated deuteron tensor structure function, $b_1$. This process should be calculated more thoroughly.” – S. Liuti

“This measurement was a highlighted need early at Jlab. A new measurement at higher $Q^2$ would be very interesting. In principle such could test my model. I could calculate the influence of my 6-quark configurations on elastic scattering.” – G. Miller

“I hope to do some calculations soon and could easily do them for the kinematics in your proposal.” – W. Cosyn

W. Van Orden has agreed to look into tensor polarization observables at low $Q^2$ using a variety of NN potentials.
Rates for D(e,e’)X

\[ R_{\text{Pol}} = A \left[ \mathcal{L}_{\text{He}} \sigma_{\text{He}}^u + \mathcal{L}_{\text{N}} \sigma_{\text{N}}^u + \mathcal{L}_{\text{D}} \sigma_{\text{D}}^u \left( 1 + \frac{1}{2} P_{zz} A_{zz} \right) \right] \]

\[ R_{\text{Unpol}} = A \left[ \mathcal{L}_{\text{He}} \sigma_{\text{He}}^u + \mathcal{L}_{\text{N}} \sigma_{\text{N}}^u + \mathcal{L}_{\text{D}} \sigma_{\text{D}}^u \right] \]

\[ N = R t \]

\[ A_{zz} = \frac{2}{f_{dit} P_{zz}} \left( \frac{N_{\text{Pol}}}{N_{\text{Unpol}}} - 1 \right) \]

\[ \delta A_{zz} = \frac{2}{f_{dit} P_{zz}} \sqrt{\left( \frac{1}{N_{\text{Unpol}}} \sqrt{N_{\text{Pol}}} \right)^2 + \left( \frac{N_{\text{Pol}}}{N_{\text{Unpol}}^2} \sqrt{N_{\text{Unpol}}} \right)^2} \]

- Used combination of P. Bosted and M. Sargsian code to calculate unpolarized cross sections

Assumptions:
\[ p_{zz} = 30\% \]
\[ p_f = 65\% \]
\[ z_{\text{tgt}} = 3 \text{ cm} \]

P.E. Bosted, V. Mamyen, arXiv:1203.2262
M. Sargsian, Private Communication

Dilution Factor

“...the background from interaction with nuclei increases as $\alpha(x)$ increases. For example, for a $D^{12}C$ target the ratio of the cross sections $\sigma_A$ for $A=^{12}C$ and $A=D$ is of the order of 40 for $x\sim 1.3$ and increases with $x$.”


$$f_{dil} = \frac{L_D \sigma_D}{L_N \sigma_N + L_{He} \sigma_{He} + L_D \sigma_D + \sum L_A \sigma_A}$$

With the 12 GeV upgrade and the new SHMS, this measurement becomes possible even with the low dilution factor at high $x$.
Target Development in Progress

- UVa Target Lab has successfully polarized deuterated butanol in April
- UNH Target Lab is ramping up, first cool-down in January, successfully reached 7T

**7T Field Map, z vs r**

Courtesy of D. Keller
Experimental Details

- D(e,e')X with 90nA beam current
- Same equipment as C1-approved $b_1$ (E12-13-011) experiment

<table>
<thead>
<tr>
<th></th>
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