Deuteron spin structure in inclusive and tagged spectator processes in the virtual nucleon approximation

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DIS XXV
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Inclusive DIS from polarized deuteron


Tagged spectator DIS from polarized deuteron


Polarized spin 1 particle

- Spin state described by a 3*3 density matrix in a basis of spin 1 states polarized along the collinear virtual photon-target axis

\[ W_D^{\mu\nu} = \text{Tr}[\rho_{\lambda\lambda'} W^{\mu\nu}(\lambda'\lambda)] \]

- Characterized by 3 vector and 5 tensor parameters

\[ S^\mu = \langle \hat{W}^\mu \rangle, \quad T^{\mu\nu} = \frac{1}{2} \sqrt{\frac{2}{3}} \langle \hat{W}^\mu \hat{W}^\nu + \hat{W}^\nu \hat{W}^\mu + \frac{4}{3} \left( g^{\mu\nu} - \frac{\hat{P}^\mu \hat{P}^\nu}{M^2} \right) \rangle \]

- Split in longitudinal and transverse components

\[
\rho_{\lambda\lambda'} = \frac{1}{3} \begin{bmatrix}
1 - \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} & \frac{3}{2\sqrt{2}} S_\perp e^{i(\phi_h - \phi_S)} + \sqrt{3} T_{L\perp} e^{i(\phi_h - \phi_{T_L})} & \frac{3}{2} T_{\perp\perp} e^{i(2\phi_h - 2\phi_{T\perp})} \\
\frac{3}{2\sqrt{2}} S_\perp e^{-i(\phi_h - \phi_S)} & 1 - \sqrt{6} T_{LL} & \frac{3}{2\sqrt{2}} S_\perp e^{i(\phi_h - \phi_S)} - \sqrt{3} T_{L\perp} e^{i(\phi_h - \phi_{T_L})} \\
\sqrt{\frac{3}{2}} T_{\perp\perp} e^{-i(2\phi_h - 2\phi_{T\perp})} & \frac{3}{2\sqrt{2}} S_\perp e^{-i(\phi_h - \phi_S)} - \sqrt{3} T_{L\perp} e^{-i(\phi_h - \phi_{T_L})} & 1 + \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL}
\end{bmatrix}
\]
\[ \frac{d\sigma}{dx\,dQ^2} = \frac{\pi y^2 \alpha^2}{Q^4(1 - \epsilon)} \left[ F_{UU,T} + \epsilon F_{UU,L} + T_{LL} \left( F_{UT_{LL,T}} + \epsilon F_{UT_{LL,L}} \right) ight. \\
+ \left. T_{L\perp} \cos \phi_{TL} \sqrt{2\epsilon(1 + \epsilon)} F_{UT_{LT}}^{\cos \phi_{TL}} + T_{\perp\perp} \cos(2\phi_{TL}) \epsilon F_{UT_{TT}}^{\cos(2\phi_{TL})} \right], \]

- 4 tensor polarized structures can be related to the \( b_{1-4} \) introduced by Hoodbhoy, Jaffe, Manohar [Nucl. Phys. B 312]

\[ F_{UT_{LL,T}} = -\frac{1}{x} \sqrt{\frac{2}{3}} \left[ 2(1 + \gamma^2)xb_1 - \gamma^2 \left( \frac{1}{6}b_2 - \frac{1}{2}b_3 \right) \right] \]

- Alternative set of \( b_{1-3, \Delta} \) by Edelmann Piller Weise [Z. Phys. A 357]. Two sets are **equal only in the scaling limit**!

- In the parton model: distribution of unpol. quarks in pol. hadron

\[ b_1 = \frac{1}{2} \sum_q e_q^2 (q^0 - q^1) \]

- Obeys Callan-Gross like relation in the scaling limit \( 2xb_1(x) = b_2(x) \)

- Obeys Kumano-Close sum rule \( \int dx b_1(x) = 0 \) [PRD42, 2377]
\[ b_1 \] for the deuteron

- \( np \)-component: \( b_1 \) is only non-zero due to the \( D \)-wave admixture in the deuteron, small.

- Interplay of nuclear and quark degrees of freedom.

- Measured @ Hermes [PRL95, 242001], not small + sign change. No agreement with conventional deuteron models.

- Upcoming measurements at JLab12 for \( x < 1 \) (DIS) and \( x > 1 \) (QE) [arXiv:1311.4835]

- Also possible @ Fermilab in DY [Kumano, Song, PRD94, 054022], EIC with polarized deuteron beam and ILC with a fixed target experiment
Conventional calculations for deuteron $b_1$

- Important to provide an accurate calculation of deuteron $b_1$ in a conventional nuclear model to constrain possible exotic mechanisms.

- Consider $np$ component, convolution approach [unpol. nucleon structure $\otimes$ pol. deuteron momentum distribution].

- Only one (?) published Khan, Hoodbhoy [PRC44, 1219].

![Chart](image)

**FIG. 2.** $b_1^p(x)$ (solid curve), the $s$-$d$ contribution to $b_1^p(x)$ (dashed curve), and the $d$-$d$ contribution to $b_1^p(x)$ (dot-dashed curve).

- Updated check in two similar models: one standard convolution model with instant form deuteron wave function, one in the virtual nucleon approximation with light-front deuteron wf [arXiv:1702.05337].
Model 1: standard convolution picture

- $W_{\mu\nu}^A(P_A, q) = \int d^4 p \, S(p) \, W_{\mu\nu}^N(p, q)$

- Relation between $b_1$ and helicity amplitudes in **scaling limit**

  $b_1 = A_{+0,+0} - \frac{A_{++,++} + A_{+-,+-}}{2}$

\[
\begin{align*}
  b_1(x, Q^2) &= \int \frac{dy}{y} \, \delta_T f(y) \, F_1^N(x/y, Q^2) \\
  \delta_T f(y) &= \int d^3 p \, y \left[ -\frac{3}{4\sqrt{2\pi}} \phi_0(p)\phi_2(p) + \frac{3}{16\pi} |\phi_2(p)|^2 \right] \times (3 \cos^2 \theta - 1) \, \delta \left( y - \frac{p \cdot q}{M_{N\nu}} \right)
\end{align*}
\]

- Deuteron wave function obeys baryon number conservation
- Nucleon structure functions include HT contributions, nuclear part does not
Model 2: virtual nucleon approximation

- Non-interacting “spectator” on-shell, photon interacts with off-shell nucleon

\[ b_1 = -\frac{1}{1+\gamma^2} \sqrt{\frac{3}{8}} \left[ F_{UT_{LL},T} + F_{UT_{TT}}^\text{cos}(2\phi_{T\perp}) \right]. \]

- Structure functions computed in the IA, no scaling limit applied, HT nuclear effects included.

- Deuteron light-front wave function, obeys baryon and momentum sum rules.

\[
W_{\mu\nu}^{\lambda',\lambda}(P, q) = 4(2\pi)^3 \int \frac{\alpha_i d^3 k}{2E_k(2\pi)^3} \frac{\alpha_N}{\alpha_i} W_{\mu\nu}^N(p_i, q) \rho_D(\lambda', \lambda)
\]

\[
b_1(x, Q^2) = \frac{3}{4(1 + \gamma^2)} \int \frac{k^2}{\alpha_i} dk d(\cos \theta_k) \left[ F_1^N(x_i, Q^2) \left( 6 \cos^2 \theta_k - 2 \right) \right. \\
\left. - \frac{T^2}{2 p_i \cdot q} F_2^N(x_i, Q^2) \left( 5 \cos^2 \theta_k - 1 \right) \right] \left[ \frac{U(k) W(k)}{\sqrt{2}} + \frac{W(k)^2}{4} \right]
\]
Comparison between two models

MSTW08 nucleon pdfs, CDBonn deuteron wf, SLAC $R = F_L/F_T$

- Differences with Khan, Hoodbhoy calculation
  - different sign $SD$ term
  - non-zero distribution at $x > 1$

- Significant nuclear higher-twist effects at low $Q^2$
- $DD$-term is not small (given $\sim 5\% D$-wave admixture)
Comparison with Hermes data

\[ Q^2 = 2.5 \text{ GeV}^2 \]

- Clear mismatch between data and calculations in size
- Future JLab12 data should shed more light
- Possible contribution from exotic mechanism → Miller [PRC89, 045203]
  - hidden color + pions
- Higher twist effects?

MSTW08

SLAC (Bodek, Ricci)
How was $b_1$ extracted?

- **Experimental measured asymmetry** [$\theta_q$ is angle between momentum transfer and polarization axis]

$$A_{zz} = \frac{2\sigma^+ - 2\sigma^0}{2\sigma^+ + \sigma^0} = \frac{\sqrt{2}}{4\sqrt{3}(F_{UU,T} + \epsilon F_{UU,L})} \left\{ [1 + 3 \cos 2\theta_q] (F_{UT_{LL},T} + \epsilon F_{UT_{LL},L}) + 
\right.$$\

$$\left. 3 \sin 2\theta_q \sqrt{2\epsilon (1 + \epsilon)} F_{UT_{LL}}^{\cos \phi_T} + 3[1 - \cos 2\theta_q] \epsilon F_{UT_{TT}}^{\cos 2\phi_T} \right\},$$

- **Only** when $\theta_q = 0$ and scaling relations applied, higher twist $b_{3,4}$ neglected, we have

$$A_{zz} \rightarrow \sqrt{\frac{2}{3}} \frac{F_{UT_{LL},T}}{F_{UU,T}} \rightarrow -\frac{2}{3} \frac{b_1}{F_1}$$

- $Q^2$-range of Hermes experiment quite low values: 0.5–5 GeV$^2$
Calculation of $b_{1,4}$ in VNA model

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$b_1 (10^{-4})$</th>
<th>$b_2 (10^{-5})$</th>
<th>$b_3 (10^{-3})$</th>
<th>$b_4 (10^{-3})$</th>
<th>$b_2/(2xb_1)$</th>
<th>$\gamma = 2Mx/Q$</th>
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<tr>
<td>0.012</td>
<td>0.51</td>
<td>2.81</td>
<td>0.264</td>
<td>-1.34</td>
<td>5.06</td>
<td>0.783</td>
<td>0.0315</td>
</tr>
<tr>
<td>0.032</td>
<td>1.06</td>
<td>6.92</td>
<td>1.97</td>
<td>-1.87</td>
<td>7.51</td>
<td>0.890</td>
<td>0.0583</td>
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<td>1.65</td>
<td>3.50</td>
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<td>0.120</td>
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<tr>
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<td>-21.7</td>
<td>-1.11</td>
<td>-0.58</td>
<td>0.777</td>
<td>0.392</td>
</tr>
</tbody>
</table>

- VNA calculation only including $pn$ IA contribution
- Higher twist $b_3, b_4$ not small compared to $b_1, b_2$
- Callan–Gross relation not satisfied
- “Improved” extraction feasible?
- Direct comparison of VNA calculations of $A_{zz}$ at largest $x$ value is still two orders of magnitude too small!
Final-state interactions in $A_{zz}$

- Only resonance contributions considered in the FSI, eikonal rescattering of produced $X$ with spectator nucleon
- JLab 12 GeV kinematics considered
- Only spin independent FSI included
- Non-negligible contribution from FSI even at low $x$, but not enough to match Hermes data
- Convolution (D-wave dominance $\rightarrow$ high spectator momenta) can pick up resonance contributions through the convolution
- Size of FSI effects decreases at higher $Q^2$ (phase-space effect)

WC, W. Melnitchouk, MS, PRC89 ('14)
Tagged spectator DIS process with deuteron

- DIS off a nuclear target with a slow (relative to nucleus c.m.) nucleon detected in the final state
- Control nuclear configuration
- Advantages for the deuteron
  - simple $NN$ system, non-nucleonic ($\Delta\Delta$) dof suppressed
  - active nucleon identified
  - recoil momentum selects nuclear configuration (medium modifications)
  - limited possibilities for nuclear FSI, calculable

- Wealth of possibilities to study (nuclear) QCD dynamics
- Will be possible in a wide kinematic range @ EIC (polarized for JLEIC)
- suited for colliders: no target material, forward detection, transverse pol. → R. Ent’s talk on Wed
- fixed target CLAS BONuS limited to recoil momenta $\sim 70$ MeV
Pole extrapolation for on-shell nucleon structure

- Allows to extract free neutron structure in a **model independent** way
  - Recoil momentum $p_R$ controls off-shellness of neutron $t - m_N^2$
  - Free neutron at pole $t - m_N^2 \to 0$: "on-shell extrapolation"
  - Small deuteron binding energy results in small extrapolation length
  - Eliminates nuclear binding and FSI effects
    [Sargsian, Strikman PLB ’05]

- D-wave suppressed at on-shell point $\to$ neutron $\sim 100\%$ polarized

- Precise measurements of neutron structure at an EIC
Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ($qW = Wq = 0$)
- Cross section has 41 structure functions,

$$\frac{d\sigma}{dx dQ^2 d\phi} = \frac{y^2 \alpha^2}{Q^4(1-\epsilon)} (F_U + F_S + F_T) d\Gamma_{ph},$$

$U + S$ part identical to spin 1/2 case [Bacchetta et al. JHEP ('07)]

\[
F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h\sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h}
\]

\[
F_S = S_L \left[ \sqrt{2\epsilon(1+\epsilon)} \sin \phi_h F_{USL}^{\sin \phi_h} + \epsilon \sin 2\phi_h F_{USL}^{\sin 2\phi_h} \right]
\]

\[
+ S_L h \left[ \sqrt{1-\epsilon^2} F_{LSL} + \sqrt{2\epsilon(1-\epsilon)} \cos \phi_h F_{LSL}^{\cos \phi_h} \right]
\]

\[
+ S_L \left[ \sin(\phi_h - \phi_S) \left( F_{UST,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UST,L}^{\sin(\phi_h-\phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{UST}^{\sin(\phi_h+\phi_S)} 
\right]
\]

\[
+ \epsilon \sin(3\phi_h - \phi_S) F_{UST}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left( \sin \phi_S F_{UST}^{\sin \phi_S} + \sin(2\phi_h - \phi_S) F_{UST}^{\sin(2\phi_h-\phi_S)} \right)
\]

\[
+ S_L h \left[ \sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LSL}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \left( \cos \phi_S F_{LSL}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LSL}^{\cos(2\phi_h-\phi_S)} \right) \right]
\]
Spin 1 SIDIS: General structure of cross section

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- Cross section has 41 structure functions,

\[
\frac{d\sigma}{dx dQ^2 d\phi'} = \frac{y^2 \alpha^2}{Q^4(1-\epsilon)} (F_U + F_S + F_T) d\Gamma_{P_h},
\]

- 23 SF unique to the spin 1 case (tensor pol.), 4 survive in inclusive \((b_{1-4})\) [Hoodbhoy, Jaffe, Manohar PLB’88]

\[
F_T = T_{LL} \left[ F_{UT_{LL},T} + \epsilon F_{UT_{LL},L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UT_{LL}}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \right]
\]

\[
+ T_{LL} h \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LT_{LL}}^{\sin \phi_h}
\]

\[
+ T_{L\perp} [\cdots] + T_{L\perp} h [\cdots]
\]

\[
+ T_{\perp\perp} \left[ \cos(2\phi_h - 2\phi_{T\perp}) \left( F_{UT_{TT},T}^{\cos(2\phi_h-2\phi_{T\perp})} + \epsilon F_{UT_{TT},L}^{\cos(2\phi_h-2\phi_{T\perp})} \right) + \epsilon \cos 2\phi_{T\perp} F_{UT_{TT}}^{\cos 2\phi_{T\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos 4\phi_h-2\phi_{T\perp}} \right.
\]

\[
+ \sqrt{2\epsilon(1+\epsilon)} \left( \cos(\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(\phi_h-2\phi_{T\perp})} + \cos(3\phi_h - 2\phi_{T\perp}) F_{UT_{TT}}^{\cos(3\phi_h-2\phi_{T\perp})} \right) \right]
\]

\[
+ T_{\perp\perp} h [\cdots]
\]
Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

$$\mathcal{W}^\mu_\nu_D(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} \mathcal{W}^\mu_\nu_N,i\rho_D^i(\lambda', \lambda),$$

All SF can be written as

$$F^k_{ij} = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{or } g_{1,2}(\tilde{x}, Q^2)\} \times \{\text{bilinear forms in deuteron radial wave function } U(k), W(k)\}$$

In the IA the following structure functions are zero → sensitive to FSI

- beam single-spin asymmetry $[F_{LU}^{\sin \phi_h}]$
- target vector polarized single-spin asymmetry [8 SFs]
- target tensor polarized double-spin asymmetry [7 SFs]
Unpolarized structure function

\[(F_T + \epsilon F_L) \times (m_N^2 - t)^2 / \text{residue}^2\]

CM energy \(s_{eN} = 1000 \text{ GeV}^2\)
\(x = 0.05, Q^2 = 20 \text{ GeV}^2, \alpha_R = 1.\)

- Extrapolation for \((m_N^2 - t) \rightarrow 0\) corresponds to on-shell neutron \(F_{2N}(x, Q^2)\)
- Clear effect of deuteron D-wave, largest in the region dominated by the tensor part of the \(NN\)-interaction
- D-wave drops out at the on-shell point
Tagging: free neutron structure

Precise measurements of $F_{2n}$

- $F_{2n}$ extracted with percent-level accuracy at $x < 0.1$
- Uncertainty mainly systematic (JLab LDRD project: detailed estimates)
- In combination with proton data non-singlet $F_{2p} - F_{2n}$, sea quark flavor asymmetry $\bar{d} - \bar{u}$
Polarized structure function

- **Spin asymmetry**

\[ A_\parallel = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + \sigma(---)}{\sigma(++) + \sigma(-+) + \sigma(+-) + \sigma(---)} \phi_{h_{\text{avg}}} \]

\[ = \frac{F_{LSL}}{F_T + \epsilon F_L} \propto \frac{g_{1n}}{F_{1n}} \]

- Again clear contribution from D-wave at finite recoil momenta

- Relativistic spin nuclear effects through Melosh rotations in deuteron light-front wf, grow with recoil momenta

- Both effects drop out near the on-shell extrapolation point
Tagging: polarized neutron structure

On-shell extrapolation of double spin asymm.

\[ A_{||} = \frac{\sigma(++) - \sigma(\sim\sim) - \sigma(+-) + \sigma(--)}{\sigma(++) + \sigma(\sim\sim) + \sigma(+-) + \sigma(--)} [\phi_{havg}] = \frac{F_{LS}}{F_T + \epsilon F_L} = D \frac{g_{1n}}{F_{1n}} + \cdots \]

Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)

Statistics requirements

- Physical asymmetries
  \[ \sim 0.05 - 0.1 \]
- Effective polarization
  \[ P_e P_D \sim 0.5 \]
- Luminosity required
  \[ \sim 10^{34} \text{cm}^{-2} \text{s}^{-1} \]

Conclusions

- Calculation of $b_1$ in standard convolution models
  - differences with older calculation
  - contributions from nuclear higher twist effects, account for in experimental extraction from the measured asymmetry
  - exotic mechanism contributing?
  - upcoming measurements at JLab12, possibilities at future facilities

- Tagged spectator DIS at an EIC with polarized deuteron
  - new possibilities to probe spin (41 structure functions)
  - pole extrapolation allows to extract neutron structure at the on-shell point, without nuclear effects
  - LDRD project at JLab, open to collaboration!
  - Lots of extensions possible (FSI, exclusive channels, other nuclei, EMC effect,...)