Recent Results from the Transversity Experiment (E06-010)

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Evaristo Cisbani(INFN, Rome), Jen-Chieh Peng(UIUC)
Outline

• General introduction of spin structure study
• Introduction of the Transversity experiment
  ✓ Physics motivation
  ✓ Experimental setup
• New results from our experiment
• Future measurements with SoLID at 12-GeV Jlab
• Summary
### Milestones of Spin

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1896</td>
<td>Zeeman effect (milestone 1)</td>
</tr>
<tr>
<td>1922</td>
<td>Stern–Gerlach experiment (milestone 2)</td>
</tr>
<tr>
<td>1925</td>
<td>The spinning electron (milestone 3)</td>
</tr>
<tr>
<td>1928</td>
<td>Dirac equation (milestone 4); Quantum magnetism (milestone 5)</td>
</tr>
<tr>
<td>1932</td>
<td>Isospin (milestone 6)</td>
</tr>
<tr>
<td>1940</td>
<td>Spin–statistics connection (milestone 7)</td>
</tr>
<tr>
<td>1946</td>
<td>Nuclear magnetic resonance (milestone 8)</td>
</tr>
<tr>
<td>1950s</td>
<td>Development of magnetic devices (milestone 9)</td>
</tr>
<tr>
<td>1950–1951</td>
<td>NMR for chemical analysis (milestone 10)</td>
</tr>
<tr>
<td>1951</td>
<td>Einstein–Podolsky–Rosen argument in spin variables (milestone 11)</td>
</tr>
<tr>
<td>1964</td>
<td>Kondo effect (milestone 12)</td>
</tr>
<tr>
<td>1971</td>
<td>Supersymmetry (milestone 13)</td>
</tr>
<tr>
<td>1972</td>
<td>Superfluid helium-3 (milestone 14)</td>
</tr>
<tr>
<td>1973</td>
<td>Magnetic resonance imaging (milestone 15)</td>
</tr>
<tr>
<td>1975–1976</td>
<td>NMR for protein structure determination (milestone 16)</td>
</tr>
<tr>
<td>1978</td>
<td>Dilute magnetic semiconductors (milestone 17)</td>
</tr>
<tr>
<td>1988</td>
<td>Giant magnetoresistance (milestone 18)</td>
</tr>
<tr>
<td>1990</td>
<td>Functional MRI (milestone 19)</td>
</tr>
<tr>
<td>1991</td>
<td>Proposal for spin field-effect transistor (milestone 20)</td>
</tr>
<tr>
<td>1996</td>
<td>Magnetic resonance force microscopy (milestone 21)</td>
</tr>
<tr>
<td>1997</td>
<td>Mesoscopic tunnelling of magnetization (milestone 22)</td>
</tr>
<tr>
<td></td>
<td>Semiconductor spintronics (milestone 23)</td>
</tr>
</tbody>
</table>

**What is spin?**

**What is spin structure of the nucleon?**
Deep-Inelastic Scattering (DIS)

- QED probe is clean
- $\alpha_{EM} \sim 1/137$ with broad Q coverage
- One-photon exchange approximation: ~1% accuracy
- Detection scale is determined by $Q^2$: $1\text{GeV}^2 \sim$ nucleon size
# Structure functions and PDFs

## Experimental observables

<table>
<thead>
<tr>
<th>Unpolarized cross section</th>
<th>Unpolarized structure functions</th>
<th>Polarized structure functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{LL}$</td>
<td>$A_{LT}$</td>
<td>$g_1$</td>
</tr>
<tr>
<td>$A_{LT}$</td>
<td></td>
<td>$g_2$</td>
</tr>
</tbody>
</table>

## PDFs

Unpolarized pdfs

\[
f(x) = q^+(x) + q^-(x)
\]

Polarized pdfs

- Helicity distribution: $\Delta q = q^+(x) - q^-(x)$

\[
g_1(x) = \frac{1}{2} \sum_q e_q^2 \Delta q(x).
\]

No $g_2$ interpretation in QPM

- What about $q^-(x) - q^+(x)$?
- It is defined as $h_1(x)$, named as transversity.
Transversity function $h_1(x)$

- Difference between $\Delta q$ and $h_1(x)$
  - Non-relativistic
  - Relativistic: Lorentz boost and rotation don’t commute
    - Imply the relativistic nature of the nucleon spin structure
    - Exist of orbital angular momentum of quarks

- Hard to access in Inclusive DIS process
  - OPE: $g_2 \sim (m_q/M)h_1(x) + …$

- Interesting features:
  - Valence-like behavior
  - Soffer’s inequality: $|h_1(x)| < \frac{1}{2}(f(x) + \Delta q(x))$
  - Chiral-odd nature etc.
From DIS to Semi-inclusive DIS (SIDIS)

- Scattered electron and a final state hadron are detected simultaneously
- Chiral odd transversity function coupled with chiral odd Collins fragmentation function
- Involves the transverse momentum ($k_T$) dependent pdfs (TMDs): from 1D to 3D

Are you ready for 3D?
Unified View of Nucleon Structure

\[ W_p^u(x, k_T r) \] Wigner distributions  \( (X. Ji) \)

\[ f_1^u(x, k_T), \ldots h_1^u(x, k_T) \]

\[ d^2k_T dr_z \]

\[ d^3r \]

TMD PDFs

GPDs/IPDs

3D imaging

dx & Fourier Transformation

PDFs

1D

Form Factors

\[ G_E(Q^2), G_M(Q^2) \]
## Leading-Twist TMD PDFs (TMDs)

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpolarized (U)</td>
<td>Longitudinally Polarized (L)</td>
</tr>
<tr>
<td>$f_1$</td>
<td>$g_1$</td>
</tr>
<tr>
<td>$f_{1T}\perp$ = Sivers</td>
<td>$g_{1T}$ = Worm Gear</td>
</tr>
<tr>
<td>$h_1$ = Transversity</td>
<td>$h_{1T}\perp$ = Pretzelosity</td>
</tr>
</tbody>
</table>

Survive the $k_T$ integration, yield 1D pdf.
# Leading-Twist TMD PDFs (TMDs)

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<th>Unpolarized (U)</th>
<th>Longitudinally Polarized (L)</th>
<th>Transversely Polarized (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1 = \bigcirc$</td>
<td></td>
<td>$g_1 = \bigcirc \rightarrow - \bigcirc$</td>
<td>$h_{1\perp} = \bigcirc - \bigcirc$ Boer-Mulders</td>
</tr>
<tr>
<td>L</td>
<td>$f_{1T} = \bigcirc \rightarrow - \bigcirc$ Sivers</td>
<td>$g_{1T} = \bigcirc - \bigcirc$ Worm Gear</td>
<td>$h_{1L\perp} = \bigcirc - \bigcirc$ Worm Gear</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T} = \bigcirc \rightarrow - \bigcirc$ Sivers</td>
<td>$g_{1T} = \bigcirc - \bigcirc$ Worm Gear</td>
<td>$h_{1T\perp} = \bigcirc - \bigcirc$ Pretzelosity</td>
<td></td>
</tr>
</tbody>
</table>

- **Quark Spin**
- **Nucleon Spin**

: Probed with transversely polarized target

HERMES, COMPASS, JLab E06-010
TMDs in SIDIS Cross Section

\[
\frac{d\sigma}{dx dy d\phi_s dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)}.
\]

\begin{align*}
F_{UU\perp} &+ \ldots \\
\varepsilon \cos(2\phi_h) \cdot F_{UU}^{\cos(2\phi_h)} &+ \ldots \\
S_T [\varepsilon \sin(2\phi_h) \cdot F_{UU}^{\sin(2\phi_h)}] &+ \ldots \\
S_T [\varepsilon \sin(\phi_h + \phi_S) \cdot F_{UT}^{\sin(\phi_h + \phi_S)}] &+ \sin(\phi_h - \phi_S) \cdot (F_{UL}^{\sin(\phi_h - \phi_S)} + \ldots) \\
\varepsilon \sin(3\phi_h - \phi_S) \cdot F_{UT}^{\sin(3\phi_h - \phi_S)} &+ \ldots \\
S_L \lambda_e [\sqrt{1-\varepsilon^2} \cdot F_{LL} + \ldots] &+ \ldots \\
S_T \lambda_e [\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) \cdot F_{LT}^{\cos(\phi_h - \phi_S)} + \ldots] &+ \ldots
\end{align*}

\( S_L, S_T: \) Target Polarization; \( \lambda_e: \) Beam Polarization

SSA/DSA in SIDIS process
Separation of Collins, Sivers and pretzelosity effects through azimuthal angular dependence

\[
A_{UT}(\phi_h^l, \phi_S^l) = \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}
\]

\[
= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)
+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)
\]

**UT**: Unpolarized beam + Transversely polarized target

\[
A_{UT}^{Collins} \propto \left\langle \sin(\phi_h + \phi_S) \right\rangle_{UT} \propto h_1 \otimes H_{1T}^\perp
\]

\[
A_{UT}^{Sivers} \propto \left\langle \sin(\phi_h - \phi_S) \right\rangle_{UT} \propto f_{1T}^\perp \otimes D_1
\]

\[
A_{UT}^{Pretzelosity} \propto \left\langle \sin(3\phi_h - \phi_S) \right\rangle_{UT} \propto h_{1T}^\perp \otimes H_{1T}^\perp
\]

→ TMD: Transversity

→ TMD: Sivers

→ TMD: Pretzelosity
Introduction of E06-010 experiment

- Beam energy: 5.89 GeV (30Hz)
- $^3$He target: (World record!!!)
  - Transversely and vertically polarized
  - In beam polarization: ~60%
  - Spin flips: 20 minutes
- BigBite:
  - 3 Drift chambers, pre-shower, scin., shower
  - Momentum: 0.6 --- 2.5 GeV
- LHRS:
  - VDC, S1, S2m(CTOF),
    - A1, CO$_2$ gas Cer., RICH, pion rejector
  - Momentum: 2.35 GeV
  - PID: pion, kaon, proton separation

- Trigger:  Singles triggers on HRS/BigBite
  Coincidence trigger
- Polarized target and Beam

- SIDIS or Inclusive
- SSA or DSA
Experiment Setup

Rest of Left-HRS ~25 m

Only Small Part of Left-HRS and He-3 Target is Shown
# High resolution spectrometer (HRS)

<table>
<thead>
<tr>
<th>(2.35GeV)</th>
<th>Electron</th>
<th>Pion</th>
<th>Kaon</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerogel 1 (n=1.015)</td>
<td>✓</td>
<td>✓</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>CO2 Gas Cherenkov</td>
<td>✓</td>
<td>❌</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>RICH</td>
<td>Large ring</td>
<td>Large ring</td>
<td>Middle ring</td>
<td>Small ring</td>
</tr>
<tr>
<td>Lead Glass</td>
<td>Large signal</td>
<td>Small signal</td>
<td>Very small</td>
<td>Very small</td>
</tr>
</tbody>
</table>

- **Detector Hut**
- **Detector Package**
- **Polarized He Target**
- **Luminosity Monitor**
- **BigBite**
- **Beam Polarimetry (Møller + Compton)**

**2.35GeV particles**
Bigbite spectrometer

- Detects electrons
- Single dipole magnet
- A “big bite” of acceptance
  - $\Delta \Omega = 64 \text{ msr}$
  - $P : 0.6 \sim 2.2 \text{ GeV/c}$
- 3 wire chambers: 18 planes for precise tracking
- Bipolar momentum reconstruction
- Pre-shower and shower for electron PID
- Scintillator for coincidence with left HRS
Electron(BB) PID for SIDIS

Preshower Energy VS E/P

Electron identification on Bigbite side

Electron selection is improved by additional momentum dependent E/P cut
Hadron PID for SIDIS

Hadron PID for SIDIS

K+/$\pi^+$ ratio: ~5%   K-/π- ratio: ~1%

Pion yield can be suppressed by Aerogel detector (A1) when selecting kaon
Published/submitted results

- **SIDIS** results
- Inclusive hadron **SSA/DSA**
Sizable Collins $\pi^+$ asymmetries at $x=0.34$?
- Hints of violation of Soffer’s inequality?
- Data are limited by stat. Needs more precise data!

Negative Sivers $\pi^+$ Asymmetry
- Consistent with HERMES/COMPASS
- Independent demonstration of negative $d$ quark Sivers function.
Pion SIDIS DSA
---Worm-Gear $g_{1T}$

- Access
  \[
  g_{1T} = \begin{array}{c}
  \text{dominated by real part of} \\
  \text{interference between} \\
  L=0 (S) \text{ and } L=1 (P) \text{ states}
  \end{array}
  \]
  \[
  \begin{aligned}
  \text{Imaginary part} & \rightarrow \text{Sivers effect} \\
  \text{Measured by COMPASS and HERMES on } p \text{ and } D \text{ targets}
  \end{aligned}
  \]

- E06-010 - First data on effectively neutron target
- Consistent with models in signs
- Suggest larger asymmetry, possible interpretations:
  - Larger quark spin-orbital interference
  - Different $P_T$ dependence
  - Larger subleading-twist effects
Pretzelosity

Rest frame:

\[
- \quad = \quad 0
\]

Boost to Infinite momentum frame (relativistic quark models):

\[
- \quad = \quad \text{Pretz.}
\]
Pion SIDIS SSA ---Pretzelosity

Y. Zhang et al. (Hall A Collaboration)

- Within statistic uncertainties Pretzelosity is consistent with zero
- Pretz. Suppressed by $k_T^2/M^2$
- The neutron results are compared to two models
  - Quark-diquark model
  - Light-cone consttitute-quantum model
Contamination of pion in kaon sample is well controlled:

- $\pi^+$ in $k^+$: <2%
- $\pi^-$ in $k^-$: <5%
Kaon SIDIS SSA
--- why kaon is interesting

• Collins effect
  ✓ Hermes: $\pi^- > \pi^+$ and kaon $>$ pion
  ✓ Unfavored Collins fragmentation function plays a more important role???
  ✓ Importance of favored or unfavored Collins fragmentation function

• Sivers effect
  ✓ Difference between $\pi^+$ and $K^+$: $d$-bar $\leftrightarrow$ $s$-bar
    • Sea quark effect
    • Fragmentation effect

• Important inputs to the global kaon data from our He-3 target

• Current theoretical understanding or phenomenological fits could be tested or improved
Kaon Collins and Sivers asymmetries on He-3 target

Y. X. Zhao, Y. Wang et al. (Hall A Collaboration)

Phys. Rev. C 90, 055201

To interpret kaon data:
1. Validation of TMD factorization
2. Higher twist effects
3. Current/target fragmentation
4. Fragmentation function
Inclusive hadron **SSA/DSA**

\[
A_{UT}(x_F, p_T) = \frac{1}{P} \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = A_N \sin \phi_S
\]

\[
A_{LT} = \frac{1}{|P_B P_{target}|} \frac{d\sigma^{\uparrow\rightarrow} - d\sigma^{\downarrow\rightarrow}}{d\sigma^{\uparrow\rightarrow} + d\sigma^{\downarrow\rightarrow}} = A_{LT}^{\cos(\phi_s)} \cos(\phi_s)
\]
Inclusive hadron SSA

- Indication of our false asymmetry: <0.1%

\[ A_{UT}(x_F, p_T) = \frac{1}{P} \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \sin \phi_S = A_N \sin \phi_S \]

- \( \phi_S = 90^\circ \)
- Clear non-zero asymmetries are observed for \( \pi^+ \) and \( \pi^- \) and \( K^+ \)
- \( \pi^+ \) and \( \pi^- \) asymmetries have opposite sign

\[ e + ^3\text{He}^\uparrow \rightarrow h + X \]

\[ <p_T> = 0.64 \text{ GeV/c} \]
Inclusive hadron SSA

K. Allada, Y. X. Zhao et al.
(Hall A Collaboration)
Phys. Rev. C 89, 042201(R)
Inclusive hadron DSA

Y.X. Zhao et al. (Hall A Collaboration)
arXiv:1502.01394
Submitted to PRC

Collinear twist-3:
Worm-Gear type function
Andrei & Carl Carlson:
PRD 61, 034014 (2000)
Short Summary

• Transversity experiment (E06-010) is the first SIDIS experiment on a polarized 3He target

• Very productive experiment
  – Pion SIDIS
    • Collins, Sivers, Pretzelosity, Worm-Gear
  – Kaon SIDIS
    • Collins, Sivers
  – Inclusive hadron
    • SSA
    • DSA

• Ongoing efforts
  – SIDIS cross-section
  – DSA in DIS process to access g2-3He
  – More … …
E06010(6-GeV Transversity) collaboration

Institutions (38)


Collaboration members (115)


Co-spokesperson, Graduate student, Leading Postdoc
The SoLID Spectrometer proposed for Hall A

From exploration to precision study

- Key device to achieve high-precision mapping and minimizing systematics
- High Luminosity target and upgraded beam energy -> 12 GeV
- Large acceptance: enable 4D-mapping of asymmetries, minimize systematics (x, z, pt, Q2)
- Benchmark test of Lattice QCD, probe QCD Dynamics and quark orbital motion

Solenoidal Large Intensity Device (SoLID)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Duration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E12-10-006</td>
<td>90 days</td>
<td>Single Spin Asymmetry on Transverse $^3$He</td>
</tr>
<tr>
<td>E12-11-007</td>
<td>30 days</td>
<td>Single and Double Spin Asymmetry on $^3$He</td>
</tr>
<tr>
<td>E12-11-108</td>
<td>120 days</td>
<td>Single and Double Spin Asymmetries on Transverse Proton</td>
</tr>
</tbody>
</table>
Phase space coverage

- Natural extension of E06-010
- Much wider phase space
- Both transverse and longitudinal polarized target
Collins asymmetry

P_T vs. x for one (Q^2, z) bin
Total > 1400 data points
Tensor Charge

- Fundamental quantity
- Beyond Standard model searches: parameters dep. on precision of tensor charge

\[ \delta q = \int_0^1 dx \left( h^q_1(x) - \bar{h}^q_1(x) \right) \]

Extractions from experiments:
1 - 12 GeV SoLID (projection)
2,3 - Anselmino et al, Phys.Rev. D87 (2016)
5 - Bacchetta, Courtoy, Radici, JHEP 130

Lattice QCD:
6 - Alexandrou et al, PoS(LATTICE 2014)

DSE:
8 - Pitschmann et al, (2014)
9 - Hecht, Roberts and Schmidt, Phys. Rev.

Models:
10 - Cloet, Bentz and Thomas, Phys. Lett
Sivers Function

- Significant Improvement in the valence quark (high-x) region
- illustrated in a model fit (from A. Prokudin)
SoLID Timeline and Status

- 2010-2012 Five SoLID experiments approved by PAC (4 A, 1 A- rating)
  3 SIDIS with polarized $^3$He/p target, 1 PVDIS, 1 threshold J/$\psi$
- 2013: CLEO-II magnet formally requested and agreed
- 2014: Site visit, plan transportation to JLab (2016)

2010-2014: Progress
- Spectrometer magnet, modifications
- Detailed simulations
- Detector pre-R&D
- DAQ

2014: pre-CDR submitted for JLab Director’s Review

2015: Jlab’s Director’s review

Active collaboration,
200+ physicists from 50+ international institutions
significant international contributions (China)
SoLID Detector Development

Simulations now with realistic backgrounds

Light Gas Cerenkov (Temple)

Heavy Gas Cerenkov (Duke)

ECal Module (UVA, W&M, Shandong)

ECal Mounting Design (ANL)
GEM Progress

- First full size prototype assembled at UVA, tested in beam (Fermi Lab)
- 30x30 cm prototype constructed, readout tested (CIAE/USTC/Tsinghua/Lanzhou)
- GEM foil production facility under development at CIAE (China)

MRPC – High Resolution TOF

A MRPC prototype for SOLID-TOF in JLab
World’s largest 2D readout GEM chamber  1.2m x 0.6m
Summary

• Transversity experiment is introduced

• New results are presented

• SoLID will allow us to map the TMDs in multi-dimensions and with high precision
Backup
Kaon SIDIS
DSA---fragmentation process
DSA---direct photoproduction
DSA---resolved photon process