HERMES highlights

HERA Symposium
Hamburg, Germany, 2010

Ami Rostomyan
(on behalf of the HERMES collaboration)
fixed target experiment
- longitudinally/transversely polarized or unpolarized internal gas target (H, D, He, N, ... Xe)

using self-polarizing HERA lepton beam
- cross section asymmetry in synchrotron radiation emission leads to build-up of transverse polarization (Sokolov-Ternov effect)

spin-rotators provide longitudinal polarization at HERMES interaction region
nucleon structure

proton = $uud + \text{sea} + \text{gluons}$

charge, momentum, magnetic moment, spin, vector charge, axial charge, tensor charge

- **momentum:**

$$\int_{0}^{1} x \left( \sum_{i} (q_{i}(x) + \bar{q}_{i}(x)) + g(x) \right) = 1$$

- quarks only carry $\approx 50\%$

- **spin 1/2:**

"You think you understand something? Now add spin..."

- **Jaffe**

- total quark spin contribution only $\approx 30\%$
using the spin in NMR

Nobel Prize, 1943: "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

\[ \mu_p = 2.5 \text{ nuclear magnetons, } \pm 10\% \quad (1933) \]

Proton spins are used to image the structure and function of the human body using the technique of magnetic resonance imaging.

Paul C. Lauterbur

Sir Peter Mansfield

Nobel Prize, 2003: "for their discoveries concerning magnetic resonance imaging"
where does the proton spin come from

Jaffe and Manohar spin sum rule
- longitudinal spin structure
  \[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L^q_z + L^g_z \]
- \( \Delta \Sigma \) and \( \Delta G \) can be measured in semi-inclusive deep inelastic \( ep \) scattering

Ji sum rule
- longitudinal spin structure
  \[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + J^q + J^g \]
  \[ \frac{1}{2} \Delta \Sigma + L^q_z \]
- \( J^q \) and \( J^g \) accessible through exclusive \( ep \) scattering

Bakker, Leader, Trueman sum rule
- transversity sum rule (?)
  \[ S_T = \frac{1}{2} = \frac{1}{2} \delta \Sigma + L^q_{ST} + L^g_{ST} \]
where does the proton spin come from

Jaffe and Manohar spin sum rule

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L^q_z + L^g_z \]

\( \Delta \Sigma \) and \( \Delta G \) can be measured in semi-inclusive deep inelastic \( e p \) scattering.


\( \Delta \Sigma \):

\( \Delta G \):

orbital angular momentum: relations to GPDs and TMDs

tensor charge: transversity sum rule (?)

\( J^q \) and \( J^g \) accessible through exclusive \( e p \) scattering.

Bakker, Leader, Trueman sum rule

\[ S_T = \frac{1}{2} = \frac{1}{2} \delta \Sigma + L^q_{ST} + L^g_{ST} \]

transversity sum rule (?)
quark structure of the nucleon

integrated over transverse momentum

$$\sigma^{ep\rightarrow ehX} \propto \sum_q DF(x) \otimes \sigma^{eq\rightarrow eq} \otimes FF^q\rightarrow h(z)$$

\[ f^q_1 = \quad g^q_1 = \quad h^q_1 = \]
unpolarized quarks and nucleons
longitudinally polarized quarks and nucleons
transversely polarized quarks and nucleons
quark structure of the nucleon

\[ f_1^q = \quad g_1^q = \]

unpolarized quarks and nucleons
longitudinally polarized quarks
vector charge

\[ f_1^q : \text{spin averaged} \]
(well known)

\[ F_1(x) = \frac{1}{2} \sum_q e_q^2 f_1^q(x) \]
\[ F_2(x) = x \sum_q e_q^2 f_1^q(x) \]
quark structure of the nucleon

\[ f_1^q = \quad g_1^q = \]

unpolarized quarks and nucleons
longitudinally polarized quarks and nucleons

\[ f_1^q: \text{spin averaged} \quad (\text{well known}) \]
vector charge

\[ F_1(x) = \frac{1}{2} \sum_q e_q^2 f_1^q(x) \]

\[ F_2(x) = x \sum_q e_q^2 f_1^q(x) \]

\[ g_1^q: \text{helicity difference} \quad (\text{known}) \]
axial charge

\[ g_1(x) = \frac{1}{2} \sum_q e_q^2 g_1^q(x) \]
quark structure of the nucleon

integrated over transverse momentum

\[ \sigma^{ep \rightarrow ehX} \propto \sum_q DF(x) \otimes \sigma^{eq \rightarrow eq} \otimes FF^q \rightarrow h(z) \]

\( h^q_1 \): transversity
  (unmeasured for long time)

**tensor charge**
- chiral-odd \( h^q_1 \) involves quark helicity flip
- need to couple to chiral-odd FF: Collins FF

\( f^q_1 \): spin averaged
- well known

\( F_1 \):
- vector charge

\( F_2 \):
- axial charge

\( g^q_1 \):
- helicity difference
- known

\( g_1 \):
- tensor charge

unpolarized quarks and nucleons
longitudinally polarized quarks and nucleons
transversely polarized quarks and nucleons
quark structure of the nucleon

integrated over transverse momentum

\[ \sigma^{ep \rightarrow e h X} \propto \sum_q h^q_1(x) \otimes \sigma^{eq \rightarrow eq} \otimes H^h_1,q \rightarrow (z) \]

\[ h^q_1 = \begin{array}{c} \text{transversely polarized} \\
\text{quarks and nucleons} \end{array} \]

\[ f^q_1: \text{spin averaged} \quad \text{(well known)} \]

\[ F_1, F_2: \text{vector charge} \]

\[ g^q_1(x): \text{tensor charge} \]

\[ h^q_1: \text{transversity} \quad \text{(unmeasured for long time)} \]

\[ \text{chiral-odd } h^q_1 \text{ involves quark helicity flip} \]

\[ \text{need to couple to chiral-odd FF: Collins FF} \]

\[ \text{unpolarized quarks and nucleons} \]

\[ \text{longitudinally polarized quarks and nucleons} \]

\[ \text{transversely polarized quarks and nucleons} \]
quark structure of the nucleon

transverse-momentum-dependent (TMD) DF

\[ \sigma^{ep \rightarrow e h X} \propto \sum_q DF(x, p_T) \otimes \sigma^{eq \rightarrow eq} \otimes FF^q \rightarrow h(z, k_T) \]

\[ D = \]

\[ H_1^\perp = \]

\[
\begin{array}{c|c|c}
\text{quark} & \text{U} & \text{L} & \text{T} \\
\hline
\text{U} & f_1 & & h_1^\perp \\
\text{L} & & g_1 & h_{1L}^\perp \\
\text{T} & f_{1T}^\perp & & h_1 \\
& g_{1T}^\perp & & h_{1T}^\perp \\
\end{array}
\]
1-hadron production x-section \((ep \rightarrow ehX)\)

\[
d\sigma = d\sigma_{UU}^0 + \cos(2\phi)d\sigma_{UU}^1 + \frac{1}{Q}\cos(\phi)d\sigma_{UU}^2 + Pl\frac{1}{Q}\sin(\phi)d\sigma_{LU}^3 + \\
+ S_L \left[ \sin(2\phi)d\sigma_{UL}^4 + \frac{1}{Q}\sin(\phi)d\sigma_{UL}^5 + Pl\left( d\sigma_{LL}^6 + \frac{1}{Q}\sin(\phi)d\sigma_{LL}^7 \right) \right] + \\
+ S_T \left[ \sin(\phi - \phi_s)d\sigma_{UT}^8 + \sin(\phi + \phi_s)d\sigma_{UT}^9 + \sin(3\phi - \phi_s)d\sigma_{UT}^{10} + \right. \\
\left. \frac{1}{Q}\sin(2\phi - \phi_s)d\sigma_{UT}^{11} + \frac{1}{Q}\sin(\phi_s)d\sigma_{UT}^{12} + Pl\left( \cos(\phi - \phi_s)d\sigma_{LT}^{13} + \frac{1}{Q}\cos(\phi_s)d\sigma_{LT}^{14} + \frac{1}{Q}\cos(2\phi - \phi_s)d\sigma_{LT}^{15} \right) \right]
\]
"Collins-effect" accounts for the correlation between the transverse polarization of the fragmenting quark and the transverse momentum of the produced unpolarized hadron sensitive to quark transverse spin generates left-right (azimuthal) asymmetries in the direction of the outgoing parton.
Collins amplitudes

\[ 2 \langle \sin(\phi_S) \rangle^{\pi^+}_{\text{UT}} \]

\[ 2 \langle \sin(\phi_S) \rangle^{\pi^0}_{\text{UT}} \]

\[ 2 \langle \sin(\phi_S) \rangle^{\pi^-}_{\text{UT}} \]

\[ 2 \langle \sin(\phi_S) \rangle^{K^+}_{\text{UT}} \]

\[ 2 \langle \sin(\phi_S) \rangle^{K^-}_{\text{UT}} \]

\[ h_1^q(x) \otimes H_{1\perp}^q, q(z) \]

final results!!!

non-zero Collins effect observed!
both Collins FF and transversity sizeable
Collins amplitudes for pions

$$h_1^q(x) \otimes H_{1,q}^\perp(z)$$

- positive amplitude for $\pi^+$
- compatible with zero amplitude for $\pi^0$
- negative amplitude for $\pi^-$
- large $\pi^-$ asymmetry

role of disfavored Collins FF:

$$H_{1,\text{disfav}}^\perp \approx -H_{1,\text{fav}}^\perp$$

$$u \Rightarrow \pi^+; \quad d \Rightarrow \pi^- (\text{fav})$$

$$u \Rightarrow \pi^-; \quad d \Rightarrow \pi^+ (\text{disfav})$$

positive for $\pi^+$ and negative for $\pi^-$

$$h_1^u > 0$$

$$h_1^d < 0$$
Collins amplitudes for kaons

- $K^+$ amplitudes are similar to $\pi^+$ as expected from $u$-quark dominance
- $K^+$ are larger than $\pi^+$

- $K^-$ consistent with zero
- $K^- (\bar{u}s)$ is all-sea object

Differences between amplitudes of $\pi$ and $K$:
- Role of sea quarks in conjunction with possibly large FF
- Various contributions from decay of semi-inclusively produced vector-mesons
- The $k_T$ dependences of the fragmentation functions
\[
d\sigma = d\sigma_{UU}^0 + \cos(2\phi)d\sigma_{UU}^1 + \frac{1}{Q}\cos(\phi)d\sigma_{UU}^2 + P_l\frac{1}{Q}\sin(\phi)d\sigma_{LU}^3 \\
+ S_L\left[\sin(2\phi)d\sigma_{UL}^4 + \frac{1}{Q}\sin(\phi)d\sigma_{UL}^5 + P_l\left(d\sigma_{LL}^6 + \frac{1}{Q}\sin(\phi)d\sigma_{LL}^7\right)\right] \\
+ S_T\left[\sin(\phi - \phi_s)d\sigma_{UT}^8 + \sin(\phi + \phi_s)d\sigma_{UT}^9 + \sin(3\phi - \phi_s)d\sigma_{UT}^{10}\right] \\
\]

Sivers distribution function \( f_{1T}^{q}(x, p_{T}^{2}) \) gives the correlation between parton transverse momentum and transverse spin of the nucleon

- non-zero Sivers function implies non-zero orbital angular momentum
- generates left-right (azimuthal) asymmetries
Sivers amplitudes for pions

\[ 2 \langle \sin(\phi - \phi_s) \rangle_{UT} = - \frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes w D_1^q(z, k_T^2)}{\sum_q e_q^2 f_1^q(x, p_T^2) \otimes D_1^q(z, k_T^2)} \]

\[ \pi^+ \]
- significantly positive
- clear rise with \( z \)
- rise at low \( P_{h\perp} \), plateau at high \( P_{h\perp} \)
- dominated by \( u \)-quark scattering:

\[ \sim - \frac{f_{1T}^{u\perp}(x, p_T^2) \otimes w D_1^{u\rightarrow \pi^+}(z, k_T^2)}{f_1^u(x, p_T^2) \otimes D_1^{u\rightarrow \pi^+}(z, k_T^2)} \]

\( u \)-quark Sivers \( DF < 0 \)
- non-zero orbital angular momentum

\[ \pi^0 \]
- slightly positive

\[ \pi^- \]
- consistent with zero
- \( u \)- and \( d \)-quark cancellation
- \( d \)-quark Sivers \( DF > 0 \)

- M. Burkardt (2002)
Sivers amplitudes for kaons

$K^+:
- $\chi$ significantly positive
- $\chi$ clear rise with $z$
- $\chi$ rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- $\pi^+/K^+$ production dominated by scattering off $u$-quarks:

$$\propto - \frac{f^u_T(x, p_T^2) \otimes w D^u_{1\rightarrow \pi^+/K^+}(z, k_T^2)}{f^u_T(x, p_T^2) \otimes D^u_{1\rightarrow \pi^+/K^+}(z, k_T^2)}$$

- $\pi^+ \equiv | ud \rangle$, $K^+ \equiv | us \rangle \Rightarrow$ non trivial role of sea quarks

$K^-$
- $\chi$ slightly positive
"Pretzelosity"

\[ d\sigma = d\sigma_{UU}^0 + \cos(2\phi) d\sigma_{UU}^1 + \frac{1}{Q} \cos(\phi) d\sigma_{UU}^2 + P_t \frac{1}{Q} \sin(\phi) d\sigma_{LU}^3 + S_L \left[ \sin(2\phi) d\sigma_{UL}^4 + \frac{1}{Q} \sin(\phi) d\sigma_{UL}^5 + P_t \left( d\sigma_{LL}^6 + \frac{1}{Q} \sin(\phi) d\sigma_{LL}^7 \right) \right] + S_T \left[ \sin(\phi - \phi_s) d\sigma_{UT}^8 + \sin(\phi + \phi_s) d\sigma_{UT}^9 + \sin(3\phi - \phi_s) d\sigma_{UT}^{10} \right] + \]

"pretzelosity" DF \( h_{1T}^q(x) \) gives a measure of the deviation of the "nucleon shape" from a sphere

\[ \Rightarrow \]

correlation between parton transverse momentum and parton transverse polarization in a transversely polarized nucleon

it is expected to be suppressed w.r.t. \( f_1^q, g_1^q, h_1^q \)
\[ \sin(3\phi - \phi_s) \] Fourier component

\[ h_{1T}^q(x) \otimes H_{1T}^q(z) \]

suppressed by two powers of \( P_{h_{\perp}} \)
comparing to Collins and Sivers amplitudes
compatible with zero within uncertainties
\( h_{1T}^q(x) \) might be non-zero at higher \( P_{h_{\perp}} \)

\[ 2 \langle \sin(3\phi - \phi_s) \rangle \Rightarrow \]

\[ \begin{array}{c}
\pi^+ \\
\pi^0 \\
\pi^-
\end{array} \]

\( 10^{-1} \) \( x \) \( 0.4 \) \( 0.6 \) \( z \) \( 0.5 \) \( 1 \)

\( P_{h_{\perp}} \) [GeV]
extraction of transversity and Sivers function

\[ A_{UT}^{\sin(\phi_+\phi_\pm)} \propto h_1(x) \otimes H_1^{\perp_q}(z) \]

\[ A_{UT}^{\sin(\phi-\phi_\pm)} \propto f_{1,T}^\perp(x) \otimes D_1^q(z) \]

Known

- Anselmino et al. Phys. Rev. D 75 (2007) -

**TSA in inclusive hadron production in $p^+p$**

Measurements of $A_N = \frac{N_R - N_L}{N_R + N_L}$ in $p^+p \rightarrow \pi X$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Energy (GeV)</th>
</tr>
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<tbody>
<tr>
<td>ANL (1976)</td>
<td>4.9</td>
</tr>
<tr>
<td>BNL (2002)</td>
<td>6.6</td>
</tr>
<tr>
<td>FNAL (1991)</td>
<td>19.4</td>
</tr>
<tr>
<td>RHIC (2008)</td>
<td>62.4</td>
</tr>
</tbody>
</table>

Interpretations:
- TMDs (Sivers effect)
- Twist-3 $qg$ correlators

Suggest:
- Increase of $A_N$ with increase of $x_F$
- Decrease of $A_N$ with increase of $p_T$ at fixed $x_F$
- $A_N \rightarrow 0$ at high $p_T$
**TSA in inclusive hadron production in $p^\uparrow p$**

**Interpretations:**
- TMDs (Sivers effect)
- Twist-3 $qg$ correlators

**Suggest:**
- Increase of $A_N$ with increase of $x_F$
- Decrease of $A_N$ with increase of $p_T$ at fixed $x_F$
- $A_N \to 0$ at high $p_T$

---

**Plot:**

$p + p \to \pi^0 + X$ at $\sqrt{s} = 200$ GeV

$<x_F> = 0.28$

- FPD data
- Sivers (E704 fit)
- Twist-3

$<x_F> = 0.32$

$<x_F> = 0.37$

$<x_F> = 0.43$

$<x_F> = 0.5$

$<x_F> = 0.6$

$p_T$, GeV/c

Better test of models needed!
TSA in inclusive hadron production $e^p \uparrow$

- up to date: all data coming from pp-scattering can be also measured in $e^p \rightarrow \pi X$

$A_N = \frac{N_R - N_L}{N_R + N_L} = \frac{2}{\pi} A_{UT} \sin \phi$

"The measurement of these predicted asymmetries allows a test of the validity of the TMD factorization, largely accepted for SIDIS processes with two scales (small $P_T$ and large $Q^2$), but still much debated for processes with only one large scale ($P_T$), like the one we are considering here. A test of TMD factorization in such processes is of great importance for a consistent understanding of the large SSAs measured in the single inclusive production of large $P_T$ hadrons in proton-proton collisions."

-Anselmino et al. (2009)-
$A_{UT}^\sin \phi \% \ p_T \ & \ x_F$

$\pi^+$ and $K^+$ asymmetries decrease at high $P_T$

- sign change for $\pi^-$
- $A_N$ in $p^\uparrow p$ is larger than in $e p^\uparrow$
- $u$-quark dominance in $e p^\uparrow$ may explain the smaller size of $\pi^-$ asymmetry
- positive $K^-$ for $x_F \approx 0$
GPDs are 'hybrid' objects

**Form factors**

\[ ep \rightarrow e' p' \]

**GPDs**

\[ ep \rightarrow e' X p' \]

**Parton density**

\[ ep \rightarrow e' X \]

- Parton's transverse localization \( b_\perp \) for a given longitudinal momentum fraction \( x \)
- Parton's transverse localization \( b_\perp \) for a given longitudinal momentum fraction \( x \)
- Parton's longitudinal momentum distribution \( q(x) \) at resolution scale \( 1/Q^2 \)
GPDs are 'hybrid' objects

**Form factors**

\[ ep \rightarrow e' p' \]

\[
\int_{-1}^{1} dx H^q(x, \xi, t, \mu^2) = F_1^q(t)
\]

\[
\int_{-1}^{1} dx E^q(x, \xi, t, \mu^2) = F_2^q(t)
\]

\[
\int_{-1}^{1} dx \tilde{H}^q(x, \xi, t, \mu^2) = G_A^q(t)
\]

\[
\int_{-1}^{1} dx \tilde{E}^q(x, \xi, t, \mu^2) = G_P^q(t)
\]

**Parton density**

\[ ep \rightarrow e' X p' \]

\[ ep \rightarrow e' X \]

- Parton density's transverse localization \( b_\perp \) for a given longitudinal momentum fraction \( x \)

- Parton's longitudinal momentum distribution \( q(x) \) at resolution scale \( 1/Q^2 \)
Exclusive reactions, GPDs

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_z \]

Second \( x \)-moment of GPDs

\[ J^q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \, [H^q(x, \xi, t) + E^q(x, \xi, t)] \]
\[ J^g = \frac{1}{2} \lim_{t \to 0} \int_{0}^{1} dx \, [H^g(x, \xi, t) + E^g(x, \xi, t)] \]

\( x, \xi \) longitudinal momentum fractions
\( t \) squared four-momentum transfer

- an experimental evaluation is complicated
- get convolutions of GPDs \( (F : H, E, \tilde{H}, \tilde{E}) \) and hard scattering functions

\[ \mathcal{F}(\xi, t) = \sum_{q} \int_{-1}^{1} dx \, C_q(\xi, x) \, F^q(x, \xi, t) \]

the only presently known way
Deeply virtual compton scattering (DVCS)

\[ \sigma_{ep} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH}T_{DVCS}^* + T_{BH}^*T_{DVCS} \]

Same initial and final states in DVCS and Bethe-Heitler \( \Rightarrow \) Interference!

Bethe-Heitler contribution:
- calculated in QED

DVCS contribution:
- HERMES: \(|T_{DVCS}|^2 < |T_{BH}|^2\)

Interference term:
- depend on a linear combination of Compton form factors
- access to GPD combinations through azimuthal asymmetries
beam helicity asymmetry

\[ A_{LU}^I(\phi) = \sum_{n=1}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi) \]

\[ A_{LU,DVCS}^{\sin \phi} \propto s_1^{DVCS} \sin \phi \]


\[ A_{LU,I}^{\sin \phi} \]

- twist-2:
  \[ \propto F_1 \text{Im} \mathcal{H} \]
  - large overall value
  - no kin. dependencies

\[ A_{LU,DVCS}^{\sin \phi}, A_{LU,I}^{\sin 2\phi} \]

- twist-3
  - overall value compatible with 0
  - no kin. dependencies

model predictions:

- overshoot the magnitude of \( A_{LU,I}^{\sin \phi} \) by a factor of 2

-Ami Rostomyan-
beam charge asymmetry

\[ A_{C}(\phi) = \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi) \]


**twist-2 GPDs:** \( A_C^{\cos \phi}, A_C^{\cos 0\phi} 

- strong \( t \)-dependence
- no \( x_B, Q^2 \) dependencies

\[ A_C^{\cos \phi} \propto F_1 \Re \mathcal{H} \]

\[ A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos \phi} \]

\( A_C^{\cos(2\phi)} \approx 0 \): twist-3 GPDs
\( A_C^{\cos(3\phi)} \approx 0 \): gluon helicity-flip GPDs

**theoretical predictions:**
- does not describe the beam-helicity data, but in good agreement with this data

-AMI Rostomyan- – p. 26
**GPDs, DVCS and HERMES**

**HERMES DVCS**

<table>
<thead>
<tr>
<th>Amplitude Value</th>
<th>Hydrogen</th>
<th>Deuteron</th>
<th>Preliminary</th>
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</thead>
<tbody>
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<td>$A_C^{\cos(0\phi)}$</td>
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<tr>
<td>$A_C^{\cos \phi}$</td>
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<tr>
<td>$A_C^{\sin(0-\phi) \sin \phi}$</td>
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</table>

![Diagram](image)

- Beam-charge asymmetry: $Re \mathcal{H}$
- Beam-helicity asymmetry: $Im \mathcal{H}$
- Transverse target-spin asymmetry: $Im( \mathcal{H} E)$
- Longitudinal target-spin asymmetry: $Im \tilde{\mathcal{H}}$
- Double-spin asymmetry: $Re \tilde{\mathcal{H}}$

Towards global fits!
longitudinal spin/momentum structure

DVCS

PDF

TMD

$A_N$

GPD

exclusive meson production

transverse spin/momentum structure
outlook