QCD Spin Physics: Theoretical Overview

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Exploring the nucleon: a fundamental quest

Know what we are made of!

Explore and Understand QCD:
- Confinement
- Lattice Models

Test our ability to use QCD:
- Asymptotic Freedom
- Factorization

Nucleon as tool for discovery:
- RHIC Heavy Ions
- LHC, ...
• How do quarks and gluons carry the proton spin?
• longitudinal vs transverse nucleon polarization:
Outline:

- Nucleon helicity structure
- Transverse-spin phenomena in QCD
- Conclusions
Nucleon helicity structure
\[ \frac{1}{2} = \langle P, \frac{1}{2} | \hat{J}_z | P, \frac{1}{2} \rangle \]

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g \]

Jaffe, Manohar; Ji, Hoodbhoy; Jaffe, Bashinsky; Brodsky; Chen et al.
\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g
\]

- it is known how to access the \( q \) and \( g \) spin contributions:

\[
\Delta \Sigma = \int_0^1 dx \left[ \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \right](x)
\]

\[
\Delta q(x) = \text{Diagram}
\]

\[
\Delta G = \int_0^1 dx \Delta g(x) \quad \Delta g(x) = \text{Diagram}
\]

- do high energy scattering at large momentum transfer!
\[
\Delta q(x) = \frac{1}{4\pi} \int dy^- e^{-iy^-xP^+} \langle P, S | \bar{\psi}_q(0, y^-, 0_\perp) \gamma^+ \gamma_5 \psi_q(0) | P, S \rangle
\]

\[Q_0^2 < Q^2\]

**DGLAP evolution:**

\[
\mu^2 \frac{d}{d\mu^2} \left( \begin{array}{c} \Delta q(x, \mu^2) \\ \Delta g(x, \mu^2) \end{array} \right) = \int_x^1 \frac{dz}{z} \left( \begin{array}{cc} \Delta P_{qq} & \Delta P_{qg} \\ \Delta P_{gq} & \Delta P_{gg} \end{array} \right) \left( \begin{array}{c} \Delta q \\ \Delta g \end{array} \right) \left( \begin{array}{c} x/z \\ \mu^2 \end{array} \right)
\]
The probes of nucleon helicity structure:

**DIS**

$$\Delta \sigma = \sum_{f=q,\bar{q},g} \int dx \Delta f(x, Q^2) \Delta \hat{\sigma}^f(xP, \alpha_s(Q^2)) + \ldots$$

**SIDIS**

**pp (RHIC)**

$$\Delta \sigma = \sum_{a,b=q,\bar{q},g} \int dx_a \Delta f_a(x_a, p^2_\perp) \int dx_b \Delta f_b(x_b, p^2_\perp) \Delta \hat{\sigma}^{ab}(x_a P, x_b P', \alpha_s(p^2_\perp)) + \ldots$$

$$\Delta \hat{\sigma} = \Delta \hat{\sigma}_{LO} + \alpha_s \Delta \hat{\sigma}_{NLO} + \ldots$$
\[ pp \rightarrow \pi^0 X \quad \text{PHENIX} \]

\[ pp \rightarrow \text{jet } X \quad \text{STAR} \]

\[
\begin{align*}
\frac{d^3\sigma}{dp^3} (\text{mb GeV}^2 \text{c}^{-3}) & \quad \text{NLO pQCD (by W. Vogelsang)} \\
& \quad \text{CTEQ6M PDF; KKP FF} \\
& \quad \mu = p_T/2, p_T, 2p_T \\
\end{align*}
\]

\[
\begin{align*}
9.7\% \text{ normalization uncertainty} & \quad \text{is not included} \\
\end{align*}
\]

\[
\begin{align*}
\Rightarrow < 80\% \text{ gg+qq} \\
\end{align*}
\]
Long history of QCD analyses of helicity parton distributions in DIS:

- GRSV  Glück, Reya, Stratmann, WV
- ABFR  Altarelli, Ball, Forte, Ridolfi
- GS    Gehrmann, Stirling
- BB    Blümlein, Böttcher
- BBS   Bourrely, Buccella, Soffer
- LSS   Leader, Sidorov, Stamenov
- AAC   Hirai, Kumano, Saito
- DNS   de Florian, Navarro, Sassot
- ...

For the first time, “Global analysis” of all DIS, SIDIS, RHIC data sets:

- DSSV de Florian, Sassot, Stratmann, WV (PRL 101, 2008)
There is some additional information:

\[ \Delta \Sigma_q \equiv \int_0^1 dx \ (\Delta q + \Delta \bar{q}) (x) \propto \langle P, s \mid \bar{\psi}_q \gamma^\mu \gamma_5 \psi_q \mid P, s \rangle \]

use SU(3) to obtain non-singlet combinations from baryon decays:

\[ \Delta \Sigma_u - \Delta \Sigma_d = g_A = 1.257 \pm \ldots \]

\[ \Delta \Sigma_u + \Delta \Sigma_d - 2\Delta \Sigma_s = 3F - D = 0.58 \pm 0.03 \]

\[ \rightarrow \Delta \Sigma = \Delta \Sigma_u + \Delta \Sigma_d + \Delta \Sigma_s = 3F - D + 3\Delta \Sigma_s \]

- sizable negative strange contribution?
Spin asymmetries in inclusive DIS:

(likewise for semi-inclusive DIS)
What's the emerging picture?

- best determined: $\Delta u + \Delta \bar{u}$, $\Delta d + \Delta \bar{d}$

Comparison with:
- DNS de Florian, Navarro, Sassot
- GRSV Glück, Reya, Stratmann, WV

Similar results:
- Leader, Stamenov, Sidorov
- Blümlein, Böttcher; & HERMES
- Hirai, Kumano, Saito (AAC)
- COMPASS

$\Delta u / u \to 1$
$\Delta d / d < 0$
- on the lattice:

LHPC Collab., P. Hägler et al.

disconnected diagrams
not yet included
• light flavor sea: 

\[ \Delta \bar{u} > 0 \]

\[ \Delta \bar{d} < 0 \]

driven by SIDIS

• qualitatively:

\[ \text{Glück, Reya; ...} \]

• large-\(N_c\), chiral quark models, meson cloud

\[ \text{Thomas, Signal, Cao; Holtmann, Speth, Fässler; Diakonov, Polyakov, Weiss; Schäfer, Fries; Kumano; Wakamatsu; Bourrely, Soffer ...} \]
• strangeness:

\[ \int_{0.001}^{1} dx \Delta s(x) = -0.006 \pm 0.01 \quad (\Delta \chi^2 = 1) \]

\[ \int_{0}^{1} dx \Delta s(x) = -0.057 \pm ? \quad \text{using F,D and SU(3)} \]
• very recently: COMPASS

• lattice:

\[ \frac{1}{2} \int dx \left[ \Delta s + \Delta \bar{s} \right] = \begin{cases} -0.0061(21) \\ -0.01 \ldots 0.01 (95\% \text{CL}) \end{cases} \]

Babich et al.

Bali et al.

• perhaps: \( \Delta s \approx -\Delta \bar{s} \) ?
• this is interesting not “just” for nucleon structure enthusiasts:

\[ \mathcal{L} = \alpha_i (\bar{\chi} \chi) (\bar{q}_i q_i) + \beta_i (\bar{\chi} \gamma^\mu \gamma^5 \chi) (\bar{q}_i \gamma_\mu \gamma^5 q_i) \]

gives spin-dep. cross sec.

Ellis, Olive, Savage
• total quark and anti-quark spin contribution:

\[ \int_{0.001}^{1} dx \Delta \Sigma = 0.366 \pm 0.016 \quad (\Delta \chi^2 = 1) \]

\[ \int_{0}^{1} dx \Delta \Sigma = 0.242 \pm ? \]

• in any case, \( \Delta \Sigma \ll 1 \)

• possibly due to combination of
  -- relativistic effects
  -- one-gluon exchange between quarks
  -- pion cloud

Myhrer, Thomas
• polarized glue?

\[ \Delta G \approx 1.8 \]

“axial anomaly” Altarelli et al.

\[ \Delta \Sigma \rightarrow \Delta \Sigma - n_f \frac{\alpha_s(Q^2)}{2\pi} \Delta G(Q^2) \]

\[ pp \rightarrow \text{jet } X \]

\[ \Delta G \approx 0.4 \quad (Q^2 = 1 \text{ GeV}^2) \]

\[ \Delta G = 0 \]
there could still be significant contribution to proton spin

• gluons paired to spin-0?

Kharzeev, Levin, Tuchin
HERMES, COMPASS:

(not yet included in DSSV)
Transverse-spin phenomena
If parity conserved:

$$A_L = \frac{\sigma \rightarrow - \sigma \leftarrow}{\sigma \rightarrow + \sigma \leftarrow} = 0$$

$$p^\uparrow p \rightarrow \pi X$$

$$A_N = \frac{\sigma \uparrow - \sigma \downarrow}{\sigma \uparrow + \sigma \downarrow} = \frac{L - R}{L + R}$$

$$A_N \sim \text{Im} \left( M_+ M_+^* \right)$$

- two requirements:
  - nucleon helicity flip and phase
• simple parton model:

\[ A_N \text{ expected as } \frac{m_q}{p_\perp} \alpha_s \ll 1 \]

Kane, Pumplin, Repko '78
STAR

E704

Also: BRAHMS, PHENIX
• Do observed asymmetries arise directly from asymmetries at quark level?  

\[ [S_\perp \cdot (\hat{P} \times k_\perp)] f_q^{Sivers}(x, k_\perp) \]

“Sivers function”

• steeply falling cross sections → large effects possible

• however, there are other mechanisms:

  Efremov, Teryaev; Qiu, Sterman; Koike; Ji, Qiu, WV, Yuan

or in fragmentation:  

Collins
Where can Sivers correlation be seen directly?

- if present, should lead to azimuthal asymmetry in SIDIS, not suppressed as $1/Q$

Boer, Mulders, Tangerman
Ji, Ma, Yuan

$\sin(\phi - \phi_S)$

SMC, HERMES, COMPASS, CLAS

![Graph showing data points and lines indicating symmetry](image)
\[ \int d^2 k_\perp \frac{k_\perp}{4m_p} f_S^{\text{Sivers}}(x, k_\perp) \]

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Türk

(Goeke et al.; Yuan, WV)
Physics of the Sivers function:

- Sivers function involves parton orbital angular momentum:

\[
J^z = \pm \frac{1}{2}
\]

- Probes overlap of proton wave fcts. with \( J^z = \pm 1/2 \)

Brodsky, Hwang, Schmidt; Brodsky, Gardner; Burkardt, Schnell
- the phase? Sivers function requires “rescattering”

- corresponds to the gauge link in parton distributions:

\[ f_q(x, k_{\perp}) \sim \int dz^- d^2z_{\perp} e^{iz^- x P^+ + iz_{\perp} \cdot k_{\perp}} \langle P, s_{\perp} | \bar{\psi}_q(0) \gamma^+ U(A) \psi_q(z^-, z_{\perp}) | P, s_{\perp} \rangle \]

\[ U(A) = \mathcal{P} \exp \left( \int_{z^-}^{z_{\perp}} d\xi^\mu A_\mu \right) \]

Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman
• profound implication:

\[ f_{Dy}^{Sivers}(x, k_\perp) = - f_{DIS}^{Sivers}(x, k_\perp) \]

Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman
A lot of further recent theoretical progress:

- extension to general QCD hard scattering:

\[ qq' \rightarrow qq' \]

- gauge links in parton distributions know about full hard scattering process

- u quark pdf in \( ud \rightarrow ud \) is not the same as in \( ug \rightarrow ug \)

- ramifications also for spin-averaged case when \( k_\perp \) dependent parton distributions are used

Bomhof, Pijlman, Mulders
Boer, Bacchetta
Qiu, Yuan, WV
Collins, Qiu
• connection to GPDs / spatial distributions (within models)
  Burkardt; Diehl, Hägler; Brodsky, Gardner; Meißner, Metz, Goeke

\[
\int d^2 k_\perp k_\perp (k_\perp \times s_\perp) f_{\text{Sivers}}(x, k_\perp) \sim \int d^2 b_\perp \mathcal{I}(b_\perp) (b_\perp \times s_\perp) \frac{\partial}{\partial b^2_\perp} \mathcal{E}(x, b^2_\perp)
\]

“Lensing function”

• Suggests: spatial deformation as origin of asym.

• expected signs of \( f_{u,d}^{\text{Sivers}} \) consistent with phenomenology
• New data provide new puzzles:

$A_N$ vs. $p_T$ for $x_F > 0.4$ GeV

$\pi^+_{\text{HERMES}}, \text{arXiv:0706}$
Conclusions:

• RHIC & HERMES, COMPASS closing in on $\Delta g$: small in accessible x-region
• flavor asymmetry $\Delta \bar{u} - \Delta \bar{d} > 0$ ?
• strangeness puzzle ?
• new insights into QCD from single-spin asymmetries