Opportunities in nucleon spin physics

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Outline

1. Historical Remarks
2. Polarized gluon distribution $\Delta g$
4. Orbital angular momentum & GPDs
5. Transversity
6. Conclusion
Historical remarks

17 years ago, a group of experimentalists led by V. Hughes made a remarkable discovery:

A very small fraction of the proton spin is carried by the spin of the quarks!

- Put the naive but well-accepted and cherished quark model into serious questioning!
- One of the most cited papers in experimental nuclear & particle physics!
- Lunched one of the most extensive program in high-energy spin physics!
Historical remarks (cont.)

- An impressive follow-ups
  - SLAC E142,E143,E155,E156
  - SMC
  - HERMES
  - JLAB spin physics program
  - COMPASS
  - RHIC Spin
  - JLAB12 GeV Upgrade
What are we after?

- When the nucleon is polarized, how do quarks and gluons make up and/or respond to this polarization?
  - Where does the spin of the nucleon come from? *(spin decomposition)*
    - Gluon and quark helicity
    - Orbital angular momentum
  - **Interesting polarization-dependent observables**
    - Transversity *(figure this in a spin sum rule?)*
    - $G_2$ structure function
    - Sivers functions
Is this useful & fundamental?

**Useful**
- QCD accounts for the most of the visible mass in the universe.
- The proton and neutron structure is crucial for understanding nuclear physics and Higgs production!

**Fundamental**
- QCD is one of the most beautiful but yet unsolved theories ($1M prize from Clay Math Inst. Cambridge, MA$)
- String theorists have spent much of their time studying QCD in the last five years!
  - ADS/CFT correspondence
  - Twistor-string theory & multiple gluon scattering
Spin decomposition

• The spin of the nucleon can be decomposed into contributions from quarks and gluons

\[ J = 1/2 = J_q(\mu) + J_g(\mu) \]

• Decomposition of quark contribution

\[ J_q = \sum_f \left[ \frac{1}{2} (\Delta q^\nu_f + \Delta q^s_f) + L_{qf} \right] \]

• Decomposition of gluon contribution

\[ J_g = \Delta g + L_g \]
Gluon polarization

- Thought to large because of the possible role of axial anomaly!
  - 2-4 units of hbar!
- One of the main motivations for COMPASS experiment!
- Surprisingly rapid progress, but the error bars remains large
  - Scale evolution
  - HERMES Collaboration
  - COMPASS
  - RHIC Spin
Experimental progress…

PHENIX run 3+4
(Y. Fukao, hep-ph/0501049)
Current theoretical prejudices

- It shall be positive!
  - There was a calculation by Jaffe in 1996 (PRB365), claiming it is negative in NR quark and bag models.
  - However, there are two types of contributions

  ![Diagram of quark models](image)

  Barone et al., PRB431, 1998

- Recently it is shown by Ji & Toublan that it is positive-definite in quark models (to be published)
Current theoretical prejudices

It shall not be as large!

- The anomaly argument for large $\Delta g$ is controversial
  - There is also an anomaly contribution to the quark orbital motion.
  - It is un-natural for heavy quarks.

Naturalness

$$\Delta \Sigma/2 + \Delta g + L_z = \frac{1}{2}$$

If $\Delta g$ is very large, there must be a large negative $L_z$ to cancel this---(fine tuning) $\Delta g < 0.5$?

Model predictions are around 0.5 hbar.
Additional comments on gluon

- There is no known way to measure $L_g$
- In principle, one can measure the total gluon contribution through the gluon GPDs.

$$J_g = \frac{1}{2} \int dxx [H_g + E_g]$$

- Heavy-quark production & two jets
- In practice, it is easier to deduce $J_g$ from the spin decomposition if $J_q$ is known.

$$J_g = 1/2 - J_q$$
The total angular momentum is related to the GPDs by the following sum rule:

\[ J_q = \lim_{t \to 0} \frac{1}{2} \int dx x [H_q(x, t, \xi) + E_q(x, t, \xi)] \]

Thus, one in principle needs to measure GPDs \( H \) and \( E \) at a fixed \( \xi \) for the full dependence in \( t \) and \( x \).

GPD \( E \) is particularly difficult to measure because it is usually proportional to \( t/4M^2 \).
Why care about the orbital motion?

- Study of orbital motion of the Mars led to discovery of inverse squared laws: Kepler
- Study of orbital motion of the electron in H led to quantization rules: Bohr
- Quark motion in s-wave was responsible for the proposal of color! (Greenberg)
- In relativistic quark models, the orbital motion is essential, but was never put into a quantitative test!
A Key Observation

The target (transverse) spin asymmetry in vector meson production is sensitive to $E$.

$$A_{V_{L,N}} = -\frac{2|\Delta_\perp|}{\pi} \frac{\text{Im}(AB^*)/m_N}{|A|^2 (1 - \xi^2) - |B|^2 (\xi^2 + t/(4m_N^2)) - \text{Re}(AB^*) 2 \xi^2}$$

$$A_{\rho_L \rho_L}^\rho = \int_{-1}^{1} dx \frac{1}{\sqrt{2}} (e_u H^u - e_d H^d) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

$$B_{\rho_L \rho_L}^\rho = \int_{-1}^{1} dx \frac{1}{\sqrt{2}} (e_u E^u - e_d E^d) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

In a GPD model in which angular momentum fraction $J_q$ is a parameter, the asymmetry can be studied as a function of $J_q$. 

Goeke, Polyakov And Vanderhaghen, Prog. Nucl. Part. Phys. 2001
**Target T-spin asymmetry in DVCS**

- Unpolarized beam
- Transverse target spin asymmetry:
  \[ d\sigma_{P\uparrow} - d\sigma_{P\downarrow} \propto \left\{ \begin{array}{l} \text{Im}(F_2 H_1 - F_1 E_1) \cdot \sin(\phi - \phi_s)\cos(\phi) + \\ \frac{\sin(\phi - \phi_s)\cos(\phi)}{A_{UT}} \\ \text{Im}(F_2 \tilde{H}_1 - F_1 \tilde{E}_1) \cdot \cos(\phi - \phi_s)\sin(\phi) + \\ \frac{\cos(\phi - \phi_s)\sin(\phi)}{A_{UT}} \end{array} \right. \]

- 2D asymmetry: in $\phi$ and $(\phi - \phi_s)$
  \[ A_{UT}(\phi, \phi_s) = \frac{N_{\uparrow}(\phi, \phi - \phi_s) - N_{\downarrow}(\phi, \phi - \phi_s)}{N_{\uparrow}(\phi, \phi - \phi_s) - N_{\downarrow}(\phi, \phi - \phi_s)} \]

- $A_{UT}^{\sin(\phi - \phi_s)\cos(\phi)}$ is sensitive to parameterizations involving different $J_{\pi}$

From Aschenauer
First data from HERMES

- $A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)} \sim \text{Im}(F_2H_1 - F_1E_1)$
- $A_{UT}^{\cos(\phi-\phi_s)\sin(\phi)} \sim \text{Im}(F_2\tilde{H}_1 - F_1\tilde{E}_1)$
- $A_{UT}^{\sin(\phi-\phi_s)\cos(\phi)}$ largely independent on all model parameters but $J_{11}$
- first model dependent extraction of $J_{11}$ possible
COMPASS advantage: larger $Q^2$

- Test the accuracy of the photon production asymmetry at higher $Q$
- vector-meson production!

- Testing pQCD reaction mechanism $R \sim Q \Lambda_{QCD}$
- For $Q^2 > 2 \text{ GeV}^2$, the helicity retention works quite well!

$$R = \frac{\sigma_L}{\sigma_T}$$

[Graph showing data points and trend line]
GPD’s independent life: distributions in quantum phase space

- In the past, we only knew how to imagine quarks either in
  - Coordinate space (form factors)
  - Momentum space (parton distributions)
- GPDs provide correlated distributions of quarks and partons in combined coordinate and momentum (phase) space
  - Wigner distribution in Quantum Mechanics (1932)
**Wigner distribution**

- Define as

\[
W(x, p) = \int \psi^*(x - \eta/2) \psi(x + \eta/2) e^{ip\eta} d\eta ,
\]

A joint distribution in momentum and coordinate spaces

- When integrated over \(x\) (\(p\)), one gets the momentum (probability) density.

- Not positive definite in general (not strict density), but is in classical limit!

- Any dynamical variable can be calculated as

\[
\langle O(x, p) \rangle = \int dx dp O(x, p) W(x, p)
\]
Harmonic oscillator & squeezed light

Wigner distribution or squeezed light!

\( n=0 \)

\( n=5 \)
Wigner-type quark distribution

- GPDs depend on $x$, $\xi$, and $t$. $\xi$ and $t$ are conjugate to the 3D coordinate $r=(z,b)$

$$f_\Gamma(r^2,x) = \frac{1}{2M} \int \frac{d^3q}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} F_\Gamma(x, \xi, t) .$$

$$\frac{1}{2M} F_{\gamma^+}(x, \xi, t) = [H(x, \xi, t) - \tau E(x, \xi, t)]$$

$$+ i(\vec{s} \times \vec{q})^z \frac{1}{2M} [H(x, \xi, t) + E(x, \xi, t)] .$$

- $f(r,x)$ provides a 3D distribution of quarks with Feynman momentum $x$. 
3D images of quarks at fixed $x$

- A parametrization which satisfies the following
  *Boundary Conditions:* (A. Belitsky, X. Ji, and F. Yuan, PRD, 2004)
  - Reproduce measured Feynman distributions
  - Reproduce measured form factors
  - Polynomiaility condition
  - Positivity
Spin-dependent observables

- There are many observables depending on the spin of the nucleon, but not directly related to the angular momentum decomposition.
  - Magnetic moment
  - Transversity distribution and tensor charge
  - $g_2$-structure function & other higher-twist distributions
  - Sivers functions and other spin and transverse-momentum dependent (TMD) parton distributions.
  - Spin-dependent GPDs

Most interesting ones are related to phenomena of transverse polarization
Arguments for Transversity

- It’s one of the three twist-2 distributions.
- It describes the density of transversely polarized quarks in a transversely polarized nucleon.
- It is chirally-odd.
- It is closely related to the axial charge: the quark helicity contribution to nucleon helicity.

... Which is the killer argument?
Measurement is hard

- Many ideas have been proposed
  - In e-p scattering
    - Collins effects, two hadron production
    - Lambda production
    - Twist-3 fragmentation
    - ...
  - In pp(p-bar) scattering
    - Drell-Yan
    - ...

It will take a lot of more effort to measure the transversity distribution than other twist-2s!
Experimental progress
It is crucial to have higher energy!

- **Semi-inclusive process**
  - Generally requires higher-$Q$ to see scaling
  - Underlying parton picture: jet fragmentation, but we don’t have jets
  - Spin-dependent process generally more delicate

- **Questions**
  - Can Hermes data be interpreted in parton-physics?
  - How small an error bar can one get?
  - Can we learn something if we don’t know the corresponding chiral-odd distribution?
  - Absolute normalization?
Conclusions

- Spin physics since EMC has gone well and strong!
- We may have a rough picture of the gluon polarization quite soon.
- Get the orbital motion of the quarks!
  - Measure GPDs, please!
- Other spin-dependent observables (transversity, sivers function, …,) can potentially teach us a lot about non-perturbative QCD.