Probing Gluon Polarization through Inclusive Deep Inelastic Scattering

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- Present polarized DIS data
- From structure functions to $\Delta G$
- Reach of fixed target program at a Future Linear Collider
Nucleon Spin Structure

\[ S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle \]
A Bit of History

- First experiments: E80 and E130 at SLAC in early 1980s
  - Very active field in both theory and experiment
  - Deep-Inelastic Scattering experiments at SLAC, CERN, and DESY
  ⇒ Inclusive DIS measurements at existing facilities have reached their potential

→ Very precise measurements of longitudinal spin structure functions $g_{1}^{p,n,d}$ for Bjorken
  $x > 0.01$, $Q^{2} < 20$ GeV$^2$
  - SLAC E142, E143, E154, E155, DESY HERMES

→ SMC experiment measured $g_{1}^{p,d}$ to $x \approx 0.003$ and $Q^{2} \approx 100$ GeV$^2$
  - Precision at low $x$ is not sufficient for extracting $\Delta G$

⇒ Qualitative understanding of “spin crisis” established
  - Great success of pQCD
  - $\Delta \Sigma \sim 0.2...0.3$, $\Delta G \sim 1$ – with large uncertainty
“Known” Future Projects

- New emphasis on measuring $\Delta G$ and semi-inclusive methods
  - Parton distributions from HERMES: semi-inclusive results, open charm
  - RHIC-SPIN: Sea-quarks, gluons at moderate $x$
  - HERA-$\vec{p}$ or eRHIC (EIC?): structure function evolution

⇒ I will try to argue a case for coming back to high-precision inclusive DIS in a new kinematic regime
Polarized Deep Inelastic Lepton-Nucleon Scattering

Measure Asymmetries:

\[ A_{\parallel}(x, Q^2) = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}, \quad A_{\perp}(x, Q^2) = \frac{d\sigma^{\uparrow\rightarrow} - d\sigma^{\downarrow\rightarrow}}{d\sigma^{\uparrow\rightarrow} + d\sigma^{\downarrow\rightarrow}}. \]

Nucleon Spin Structure Functions:

\[ g_1(x, Q^2) \sim A_{\parallel}(x, Q^2) \cdot F_1(x, Q^2), \]
\[ g_2(x, Q^2) \sim A_{\perp}(x, Q^2) \cdot F_1(x, Q^2). \]
“Naive” Quark-Parton Model

- \( x \) – fraction of nucleon momentum carried by the struck parton
- \( Q^2 \) – 4-momentum transfer
  - \( \Delta q(x, Q^2) = (q^\uparrow + \bar{q}^\uparrow) - (q^\downarrow + \bar{q}^\downarrow) \)
  - \( q(x, Q^2) = (q^\uparrow + \bar{q}^\uparrow) + (q^\downarrow + \bar{q}^\downarrow) \)
- Partonic interpretation of structure functions

\[
g_1^p(x, Q^2) = \frac{1}{2} \left[ \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right]
\]
\[
F_1^p(x, Q^2) = \frac{1}{2} \left[ \frac{4}{9} \ u + \frac{1}{9} \ d + \frac{1}{9} \ s \right]
\]
Axial Current

\[ \langle p | A^q_{\mu} | p \rangle = \langle p | \bar{q} \gamma_{\mu} \gamma_5 q | p \rangle \]
\[ = \langle p | \bar{q}_R \gamma_{\mu} q_R - \bar{q}_L \gamma_{\mu} q_L | p \rangle \]
\[ = \Delta q S_\mu = \int_0^1 dx \Delta q(x) S_\mu \]

- Neutron $\beta$-decay: measure $\Delta q_3 = g_A = \Delta u - \Delta d$
- Hyperon $\beta$-decay: measure $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$
- Spin structure functions:

\[ \Gamma^p_1 \equiv \int_0^1 g^p_1(x) dx = \frac{1}{2} \left[ \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right] \]

\[ \Rightarrow \text{Extract } \Delta \Sigma = \Delta u + \Delta d + \Delta s - \text{quark spin contribution.} \]
Bjorken Sum Rule

Based on isospin symmetry

\[ \int_0^1 dx (g_1^p(x) - g_1^n(x)) = \frac{1}{6} [\Delta u - \Delta d] = \frac{1}{6} g_A, \quad Q^2 \to \infty \]

J. D. Bjorken (1966)

Fundamental prediction of QCD

Corrections known to \( \alpha_s^3 \), decrease with \( Q^2 \)

Low \( x \) behavior is very important

Ellis-Jaffe Sum Rule

Assuming \( \Delta s = 0 \), determine \( \Gamma_1^{p,n,d} \) from the \( \beta \)-decay data:

\[ \Gamma_1^p = 0.185, \quad \Gamma_1^n = -0.024, \quad Q^2 \to \infty \]

J. Ellis and R. Jaffe (1974)
Experiments

- Pioneer experiments of 1980’s
  - SLAC E80, E130, CERN EMC

- Second-generation experiments
  - Electron scattering experiments at SLAC: E142/3, E154/5
    - Moderate kinematic coverage, high counting rate, good control of systematic effects
  - Muon scattering: SMC at CERN
    - Wide kinematic coverage, moderate statistics
  - HERMES: “the only game in town” (right now :-)
    - Novel target technologies (gas-jet)
    - Good duty factor: ideal for coincidence measurements
Kinematics
$Q^2$ dependence: proton

December 1998

$g_1^p / F_1^p$ vs. $Q^2$ [(GeV/c)$^2$]

- E155
- E143
- SMC
- HERMES
- EMC

Preliminary

Nucleon Spin Structure a Future LC
$Q^2$ dependence: deuteron
Perturbative QCD analysis

- The data has approached the quality of unpolarized experiments – *circa* late 1980’s.
  - Sufficiently broad kinematic range
  - Precision
- Consistent treatment of data
  - $Q^2$ dependence of asymmetries
  - Low $x$ fit
- Tools exist: NLO pQCD analysis
  - Spin-dependent NLO anomalous dimensions
  - A number of analyses completed (1996-98)
Global NLO fit

- **Start with parton distributions at low** $Q^2 \approx 0.3$ GeV$^2$.

  → Need theoretical input or high-$x$ data. Example:

  $$\Delta f(x, Q_0^2) = A_f x^{\alpha_f} f(x, Q_0^2)$$

  * $f \equiv$ valence $\Delta u_V$ and $\Delta d_V$, sea, gluons
  * $f(x, Q_0^2)$ is from unpolarized measurements.

- **Evolve up to experimental** $Q^2 \geq 1$ GeV$^2$ using NLO DGLAP equations

- Constrain free parameters
Factorization at NLO

- **Factorization scheme**
  - In NLO
    \[ g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left[ C_q \otimes \Delta q + C_G \otimes \Delta G \right] \]
  - \( C_{q,G} \) – perturbative coefficients;
  - \( \Delta q \) – non-perturbative input.
  - Definition depends on renormalization procedure

- **Common schemes**
  - \( \overline{\text{MS}} \) – gluons do not contribute to the integral of \( g_1 \)
  - Adler-Bardeen – include axial anomaly contribution
    \[ \int_0^1 g_1^p(x) dx = \frac{1}{2} \left[ \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right] - \frac{\alpha_S(Q^2)}{6\pi} \Delta G \]

⇒ Perform fits in both schemes to check stability
Factorization at NLO (cont.)

- Consequence: ambiguity in definition of “quark spin” contribution:

\[ \Delta \Sigma(AB) = \Delta \Sigma(\overline{\text{MS}}) + \frac{N_f}{2\pi} \alpha_s \Delta G \]

- \( \alpha_s(Q^2) \Delta G'(Q^2) \) is independent of \( Q^2 \) to \( O(\alpha_s^2) \)

J. Kodaira (1980)

\( \Rightarrow \) \( \Delta \Sigma \) is defined up to a constant

\( \Rightarrow \) Asymptotically \( \Delta G \sim 1/\alpha_s \rightarrow \infty \)

- Angular momentum sum rule revised:

X. Ji (1996)

\[ \frac{1}{2} = \left( \frac{1}{2} \Delta \Sigma + \langle L^q_z \rangle \right) + \left( \Delta G + \langle L^G_z \rangle \right) \]

\[ = J_q(\sim 1/4) + J_G(\sim 1/4) \quad (Q^2 \rightarrow \infty) \]
Proton Structure Function

[Graph showing data points and curves representing the proton structure function]
Sea and Gluon Distributions
Summary of current NLO results

- Valence distributions well constrained, sea and gluons – with large uncertainty
- Low $x$ behavior of the non-singlet distributions is well understood
  * “Regge-like” at low $Q^2$
  * Divergent at $Q^2 > 1 \text{ GeV}^2$ due to evolution
  * Powers are constrained well
- Bjorken sum rule confirmed, EJ rule violated
- $\Delta \Sigma \sim 0.2; \quad \Delta G \sim 2 \pm 1$
  $\Rightarrow$ Limited by $Q^2$ lever arm and precision at low $x$
- Future Linear Collider potential
  * Wider kinematic coverage, higher precision
  $\Rightarrow$ “SMC kinematics with E154/5 statistics”
Kinematics
Measuring $g_1^{p,n,d}(x, Q^2)$ at the NLC

- **Assumptions:**
  - 250 GeV
  - $e^-$ beam polarization 80%
  - Target polarization: 80% (p), 40% (n), 30% (d)
  - Dilution: 0.1…0.3 depending on target
  - Intensity: $10^{13}…10^{14}$ e/sec

- **Possible at NLC or TESLA**
  - Although current TESLA-N proposal focuses on low-luminosity physics
Spin Structure at the NLC (cont.)

- Complimentary to HERA-$\bar{p}$ or EIC
  - Comparable statistics achievable to $x \sim 0.002$
  - Potentially better systematics (helicity flips, nucleon polarization)
- Flavor separation through measurements of $p$, $n$, $d$ structure functions
  - Crucial for pQCD fits
  - Not readily available for HERA
  $\Rightarrow$ Goal: $\sigma(\Delta G) \sim 0.1$ in Snowmass year
Projected uncertainties
Experimental Considerations: Statistics

- Cross section smaller compared to E154/5 by a factor of $\approx 16$
  - As much luminosity as target can handle
    - Improve $^3$He targets (cf. JLAB experiments using longer targets). High polarization, low dilution a key.
    - Depolarization an issue for NH$_3$ cryogenic target
    - Conceivable to gain a factor of 2–4.
  - Run longer ($\sim$ Snowmass year per experiment)
    - Parasitic to collider program
      - Another factor of 4
  - Increase spectrometer acceptance
    - Gain a factor of 2 to be safe
Spectrometer/Detector Issues

- Maximize detector acceptance to increase counting rate
  - “Open geometry” not suitable for high-rate electron environment.
  - Double- or triple-arm spectrometers (scaled E154/5) may work, will need fine tuning
  - Quadrupoles or superconducting magnets? Beware of synchrotron radiation

- Backgrounds
  - Photons: “two-bounce” system
  - Synchrotron radiation in spectrometer magnets
    - Need some thought, avoid high gradients
  - Low-mass tracking system, multiple layers
  - Hadrons
    - “Low-energy” pions are at 50-100 GeV
    - Sounds like a TRD is needed

- Do not see show-stoppers, but detailed studies needed
Constraints on Beam Quality and the IR

- **Fixed target experiments have always been least-demanding :-)**
  - Moderate energy spread OK (1..2% full width)
  - Beam size not an issue (∼ 1 mm OK – in fact, some targets need larger spots or “rastering”)
  - Moderate requirements on jitter for these types of experiments

- **Beamline**
  - Would like to (be able to) run parasitic
  - Need access to apparatus while collider is running
  - Control synchrotron radiation
  - Need to keep longitudinal polarization
  - See also Beam Delivery/IR Working group
Detector Hall/End Station

- Low-angle scattering
  - $O(1^\circ)$ scattering angles (set by requiring $Q^2 = 1$ GeV for $y \approx 0.8$

- Long (and skinny) detector hall
  - Simple energy scaling: $O(400 \text{ m})$

- Prefer separate extraction line to exhaust beam
  - Radiation and background issues
  - Access to apparatus

- Several options discussed; need to voice our opinion!
Conclusion

- Third generation polarized DIS experiments would provide significant information on $\Delta G$
  - Evolution of structure functions probes $\Delta G$ to lowest $x$
  - Expect $\sigma(\Delta G) \approx 0.1$
  - Complimentary to other methods of measuring $\Delta G$

- Broadens LC’s horizon and community

⇒ Sound investment!