Polarized Parton Distributions: Theory and Experiments

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Abstract

We have extracted the constituent contributions to the spin of the proton from recent data at CERN, SLAC and DESY. The valence, sea quark and antiquark spin-weighted distributions are determined separately. The data appear to imply a small to moderate polarized gluon distribution, so that the anomaly term is not significant in determining these contributions. We have analyzed the consistency of the results obtained from various sets of data and the Bjorken Sum Rule. All data are consistent with the sum rule, but they differ in the contribution of the strange sea to proton spin. This and the remaining uncertainty in the polarized gluon distribution pose unanswered questions about hadronic spin. Only further experiments which extract information about the polarized gluon and sea will reconcile these differences. We suggest specific experiments which can be performed to determine the size of the polarized sea and gluons.

Introduction

One of the goals of high energy spin physics is to determine the contributions of quarks and gluons, as well as the effect of the orbital motion, to nucleon spin. Significant interest in high energy polarization was generated when the European Muon Collaboration (EMC)\textsuperscript{1} analyzed polarized deep-inelastic lepton-hadron scattering (DIS) data, which implied that the Bjorken sum rule (BSR) of QCD\textsuperscript{2} was satisfied and the Ellis-Jaffe sum rule\textsuperscript{3} based on a simple quark model was violated. Recently, the Spin Muon Collaboration (SMC) group from CERN\textsuperscript{4}, the experimental groups from SLAC\textsuperscript{5} and the HERMES group at DESY\textsuperscript{6} measured the polarized structure functions $g_1^p$ to low $x$ and have added the corresponding neutron and deuteron structure functions $g_1^n$ and $g_1^d$. They also improved statistics and lowered the systematic errors from the EMC data.

An advantage to using spin in probing hadronic structure is that the theoretically calculated spin-weighted parton distributions are related to the experimentally measured cross sections by the polarized structure functions, $g_1$. The

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measured asymmetry in deep-inelastic lepton-hadron scattering (DIS) is given by:

\[
A = \left[ \frac{\sigma(\rightarrow\rightarrow) - \sigma(\rightarrow\leftarrow)}{\sigma(\rightarrow\rightarrow) + \sigma(\rightarrow\leftarrow)} \right] \tag{1}
\]

\[
= D(A_1 + \eta A_2).
\]

The spins of the target and beam are aligned or anti-aligned with the momentum of the interaction in measuring these cross sections. The terms \(D\) and \(\eta\) are known kinematic factors for each experiment. The structure function \(g_1\) is normally extracted from the asymmetry \(A_1\) by using the approximation

\[
g_1^p(x, Q^2) \approx \frac{A_1(x) F_2(x, Q^2)}{2x(1 + R)}, \tag{2}
\]

where \(F_2\) is the corresponding unpolarized singlet structure function and \(R = \sqrt{\sigma_L/\sigma_T}\), the ratio of the cross sections for absorbing longitudinal and transverse virtual photons. It is assumed that the transverse part of the asymmetry \(A_2^p\) is small and that \(A_1\) is relatively independent of \(Q^2\), which has been implied by these experiments.

The integrated polarized structure function, \(I^{p(n)} \equiv \int_0^1 g_1^{p(n)}(x) \, dx\), is related to the polarized quark distributions by

\[
I^{p(n)} = \frac{1}{18}(1 - \alpha_{s}^{corr})([4(1)\Delta u_v + 1(4)\Delta d_v + 4(1)(\Delta u_s + \Delta \bar{u}) + 1(4)(\Delta d_s + \Delta \bar{d})
\]

\[
+ (\Delta s + \Delta \bar{s})]). \tag{3}
\]

The QCD corrections, characterized by \(\alpha_{s}^{corr}\), have been calculated to \(O(\alpha_s^4)\) and are

\[
\alpha_{s}^{corr} \approx (\frac{\alpha_s}{\pi}) + 3.5833(\frac{\alpha_s}{\pi})^2 + 20.2153(\frac{\alpha_s}{\pi})^3 + 130(\frac{\alpha_s}{\pi})^4, \tag{4}
\]

where the last term is estimated. Equations (1) through (4) provide a direct means to extract information about the polarized quark distributions from the DIS experiments. There have been some recent theoretical approaches to this problem. We have done a detailed flavor dependent analysis including the QCD corrections and the effect of the gluon anomaly. It is assumed that the polarized gluon distribution is of small to moderate size and we determine the resulting polarized quark distributions for each set of data using the appropriate sum rules. The key elements of our approach are:

- determine the valence contribution to the spin using the BSR
• find sea integrated parton distributions for each flavor by breaking the SU(6) symmetry with the strange quarks and using the sum rules with data as input

• include higher order QCD corrections and the gluon anomaly for each flavor

• discuss similarities and differences between the phenomenological implications of the different experimental results, and

• suggesting a set of experiments which would distinguish the quark and gluon contributions to the proton spin.

This approach differs from that of others in that we use sum rules in conjunction with a single experimental result to extract the spin information and we break the flavor symmetric sea while including anomaly contributions.

Theoretical Background

Valence Quarks

Fundamentally, we assume that the proton is comprised of valence quarks, whose integrated polarized distribution is given by: \( \langle \Delta q_v(Q^2) \rangle \). We construct the polarized valence quark distributions from the unpolarized ones by starting with a 3-quark model based on an SU(6) proton wave function. The valence quark distributions can be written as:

\[
\Delta u_v(x, Q^2) = \cos \theta_D [u_v(x, Q^2) - \frac{2}{3} d_v(x, Q^2)],
\]

\[
\Delta d_v(x, Q^2) = -\frac{1}{3} \cos \theta_D d_v(x, Q^2),
\]

(5)

where \( \cos \theta_D \) is a “spin dilution” factor which vanishes as \( x \to 0 \) and becomes unity as \( x \to 1 \), characterizing the valence quark helicity contribution to the proton.\(^{10,11}\) The spin dilution factor is adjusted to satisfy the Bjorken Sum Rule (BSR). The BSR relates the polarized structure function \( g_1(x) \), measured in polarized deep-inelastic scattering, to the axial vector current \( A_3 \), which is measured in neutron beta decay. This sum rule is considered to be a fundamental test of QCD. In terms of the polarized distributions and our assumptions about the flavor symmetry of the \( u \) and \( d \) polarized sea, the BSR can be reduced to:

\[
\int_0^1 [\Delta u_v(x, Q^2) - \Delta d_v(x, Q^2)] \, dx = A_3(1 - \frac{\alpha_s}{\pi} + \ldots).
\]

(6)
Thus, the valence contributions are determined uniquely by this model. The valence distributions are not sensitive to the unpolarized distributions used to generate them.\textsuperscript{12,13} With our values $\langle \Delta u_v \rangle = 1.00 \pm 0.01$ and $\langle \Delta d_v \rangle = -0.26 \pm 0.01$, both the BSR and magnetic moment ratio, $\mu_p/\mu_n \approx -3/2$ are satisfied. This results in a spin contribution from the valence quarks equal to 0.74 ± 0.02. The quoted errors arise from data on $A_3 = g_A/g_V$, and the differences in choice of the unpolarized distributions.

**Sea Quarks**

The proton is also filled with a quark sea, whose lightest flavors should dominate the spin, since the heavier quarks would be significantly harder to polarize. We assume that the quark and antiquark flavors are symmetric, but break the SU(6) symmetry of the sea by assuming that the polarization of the heavier strange quarks is suppressed.\textsuperscript{10} The sea distributions are then related by:

$$\Delta \bar{u}(x, Q^2) = \Delta u(x, Q^2) = \Delta \bar{d}(x, Q^2) = \Delta d(x, Q^2)$$

$$= [1 + \epsilon]\Delta \bar{s}(x, Q^2) = [1 + \epsilon]\Delta s(x, Q^2).$$

The $\epsilon$ factor is a measure of the increased difficulty in polarizing the strange quarks. The DIS data are used to determine $\epsilon$ and the overall size of the polarized sea. Additional constraints are provided by the axial-vector current operators, $A_8$ and $A_0$.

The coefficient $A_8$ is determined by hyperon decay and is related to the polarized quark distributions by:

$$A_8 = \langle [\Delta u_v + \Delta d_v + \Delta u_s + \Delta d_s + \Delta \bar{u} + \Delta \bar{d} - 2\Delta s - 2\Delta \bar{s}] \rangle \approx 0.58 \pm 0.02. \quad (8)$$

$A_0$ is related to the total spin carried by the quarks in the proton. We can relate these axial currents and the structure function $g_1^p$ in the anomaly-independent form:

$$A_0 = 9(1 - \alpha_s^{corr})^{-1} \int_0^1 g_1^p(x) \, dx - \frac{1}{4}A_8 - \frac{3}{4}A_3 \approx \langle \Delta q_{tot} \rangle. \quad (9)$$

**Gluons**

The gluons are polarized through Bremsstrahlung from the quarks. The integrated polarized gluon distribution is written as: $\langle \Delta G \rangle = \int_0^1 \Delta G(x, Q^2) \, dx$. We cannot determine \textit{a priori} the size of the polarized gluon distribution at a given $Q^2$. The evolution equations for the polarized distributions indicate that the polarized gluon distribution increases with $Q^2$ and that its evolution is directly related to the behavior of the orbital angular momentum.\textsuperscript{14} Thus, one assumes a
particular form for the polarized gluon distribution at a given $Q^2$ and checks its consistency with data which are sensitive to $\Delta G(x, Q^2)$ at a particular $Q^2_0$.

The model of $\Delta G$ that is used has a direct effect on the measured value of the quark distributions through the gluon axial anomaly,\textsuperscript{15} which has the form:

$$\Gamma(Q^2) = \frac{N_f \alpha_s(Q^2)}{2\pi} \int_0^1 \Delta G(x, Q^2) \, dx,$$  \hspace{1cm} (10)

where $N_f$ is the number of quark flavors. For each quark flavor, the measured polarization distribution is modified by a factor: $\langle \Delta q \rangle - \Gamma(Q^2)/N_f$. Thus, the quark spin contributions depend indirectly on the polarized gluon distribution. In a naive quark model, $\langle \Delta q \rangle = 1$ and $\Delta G$ may be quite large to be consistent with data.\textsuperscript{16} However, a reasonably sized $\Delta G$ is possible if the sea has a suitably negative polarization. We have considered two possible models for calculating the anomaly: (1) $\Delta G = xG$ (indicating that the spin carried by gluon is equal to its momentum) and (2) $\Delta G = 0$, which is an extreme case for bounding the distributions. We believe that the present data imply that anomaly effects, and thus the overall integrated polarized gluon distribution, is limited at these energies.

The polarized distributions are related to the orbital angular momentum of the constituents by the $J_z = \frac{1}{2}$ sum rule:

$$J_z = \frac{1}{2} = \frac{1}{2} \langle \Delta q_v \rangle + \frac{1}{2} \langle \Delta S \rangle + \langle \Delta G \rangle + L_z.$$  \hspace{1cm} (11)

The right hand side represents the decomposition of the constituent spins along with their relative angular momentum, $L_z$. Although this does not provide a strict constraint on either $\Delta q_{tot}$ or $\Delta G$, it does give an indication of the angular momentum component to proton spin.

**Phenomenology**

We use SMC\textsuperscript{4}, SLAC\textsuperscript{5} and DESY\textsuperscript{6} data to extract information about the flavor dependence of the sea contributions to nucleon spin. We can write the integrals of the polarized structure functions, $\int_0^1 g_1^p(x) \, dx$ in the terms of the axial-vector currents as:

$$I^p \equiv \int_0^1 g_1^p(x) \, dx = \left[ \frac{A_3}{12} + \frac{A_8}{36} + \frac{A_0}{9} \right] \left( 1 - \alpha_s^{cor} \right),$$

$$I^n \equiv \int_0^1 g_1^n(x) \, dx = \left[ -\frac{A_3}{12} + \frac{A_8}{36} + \frac{A_0}{9} \right] \left( 1 - \alpha_s^{cor} \right),$$  \hspace{1cm} (12)
\[ I^d \equiv (1 - \frac{3}{2}\omega_D) \int_0^1 g_1^d(x) dx = \left[ \frac{A_8}{36} + \frac{A_0}{9} \right] \left( 1 - \alpha_s^{corr} \right) (1 - \frac{3}{2}\omega_D), \]

where \( \omega_D \) is the probability that the deuteron will be in a D-state. Using N-N potential calculations, the value of \( \omega_D \) is about 0.058. The BSR can then be used to extract an effective \( I^p \) value from all data using the form of equation (12) above.

Since the anomalous dimensions for the polarized distributions have an additional factor of \( x \) compared to the unpolarized case, early treatments of the spin distributions assumed a form of: \( \Delta q(x) \equiv xq(x) \) for all flavors. We have compared this form of the distributions to those extracted from the recent data, using the defined ratio \( \eta \equiv \frac{\langle \Delta q_{\text{sea}} \rangle_{\text{exp}}}{\langle \Delta q_{\text{sea}} \rangle_{\text{calc}}} \) for each flavor. Any deviation from \( \eta = 1 \) would indicate that the simple model for generating the polarized distributions is inaccurate.

In order to generate the \( x \)-dependent distributions, we have used the unpolarized distributions\textsuperscript{12,13} with our extracted value of \( \eta \) and the assumption that: \( \Delta q(x) \equiv \eta xq(x) \) for each of the sea flavors. For the valence distributions, we have used equation (5) with the dilution factor of reference 10. There is no reason \textit{a priori} to suspect that a global fit to the integrated distributions should imply a satisfactory \( x \)-dependent fit to the data. However, our results indicate that this form gives very good \( x \)-dependent parametrizations for the polarized distributions.

The analysis (for each polarized gluon model) proceeds as follows:

- Extract a value of \( I^p \) from either the data directly or via the BSR in the form of equation (12),
- use equation (9) to extract \( A_0 \). Then the overall contribution to the quark spin is found from \( \langle \Delta q_{\text{tot}} \rangle = A_0 + \Gamma \).
- Use the value \( A_8 \) from the hyperon data with equations (8) and (9) to extract \( \Delta s \) for the strange sea,
- find the total contribution from the sea from \( \langle \Delta q_{\text{tot}} \rangle = \langle \Delta q_{\text{v}} \rangle + \langle \Delta S \rangle \),
- determine \( \epsilon \) and the distributions \( \langle \Delta u \rangle_{\text{sea}} = langle \Delta d \rangle_{\text{sea}} \) from equation (3) and the strange sea results.
- Finally, the \( J_z = 1/2 \) sum rule gives \( L_z \).

Results for the integrated distributions are given in Table I.
From the results in Table I, it is obvious that the naive quark model is not sufficient to explain the proton’s spin characteristics. Nor is the simple model for extracting the polarized distributions accurate. Thus, data have indicated that we must modify our initial assumptions regarding constituent contribution to proton spin. Some conclusions which can be drawn from the data are:

1. The total quark contribution to proton spin is between 1/4 and 1/2. The errors in generating these results are due mostly to experimental errors and determination of which model of the polarized gluons to use. Thus, the uncertainties related to the quark spin content and the size of ∆G are comparable.

2. Considerable discussion regarding these measurements focuses on the Ellis-Jaffe sum rule (EJSR),\(^3\) which predicts the values of \(g_1^p\) and \(g_1^n\) using an unpolarized strange sea. This differs considerably with the analysis of these data. The

| Quantity | SMC\((I^p)\) | SMC\((I^d)\) | E154\((I^n)\) | E143\((I^d)\) | HERMES \((I^n)\) |
|----------|-------------|-------------|---------------|---------------|----------------|
| \(< Δu >_{sea}\) | −.077 | −.089 | −.063 | −.068 | −.050 |
| \(< Δs >\) | −.037 | −.048 | −.020 | −.028 | −.010 |
| \(< Δu >_{tot}\) | 0.85 | 0.82 | 0.87 | 0.87 | 0.90 |
| \(< Δd >_{tot}\) | −.42 | −.43 | −.39 | −.40 | −.36 |
| \(< Δs >_{tot}\) | −.07 | −.10 | −.04 | −.06 | −.02 |
| \(η_u = η_d\) | −2.4 | −2.8 | −1.9 | −2.1 | −1.5 |
| \(η_s\) | −2.0 | −3.0 | −1.2 | −1.6 | −0.6 |
| \(ε\) | 1.09 | 0.84 | 2.10 | 1.41 | 4.00 |
| \(Γ\) | 0.06 | 0.06 | 0.08 | 0.08 | 0.07 |
| \(I^p\) | 0.136 | 0.129 | 0.134 | 0.131 | 0.135 |
| \(< Δq >_{tot}\) | 0.36 | 0.29 | 0.45 | 0.41 | 0.52 |
| \(< ΔG >\) | 0.46 | 0.46 | 0.45 | 0.44 | 0.44 |
| \(L_z\) | −.14 | −.211 | −.18 | −.15 | −.22 |

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2. Considerable discussion regarding these measurements focuses on the Ellis-Jaffe sum rule (EJSR),\(^3\) which predicts the values of \(g_1^p\) and \(g_1^n\) using an unpolarized strange sea. This differs considerably with the analysis of these data. The
up and down sea contributions seem to agree within a few percent. However, all of the proton and deuteron data imply a larger polarized sea with the strange sea polarized greater than the positivity bound.\textsuperscript{19} It is interesting to note that the results obtained from the SMC proton data are consistent with a recent lattice QCD calculation of these parameters.\textsuperscript{20} The results among the different experiments preclude us from extracting specific contributions from each flavor to the proton spin with any degree of certainty. However, the results from the various data can be categorized into distinct models, characterized by the size of the non-zero polarized sea.

(3) The values of $\eta$ deviate considerably from unity for most of the data, implying that the relation between unpolarized and polarized distributions is likely more complex than originally thought.

(4) This analysis implies that the anomaly correction is not large. If the anomaly term were larger, due to a large $\Delta G$, the strange sea would be positively polarized, while the other flavors are negatively polarized. There is no known mechanism that would allow this cross polarization of different flavors. Thus, we conclude that these data imply that the polarized gluon distribution is of small to moderate size. The key conclusions from the zero and small anomaly models are not significantly different. Further, even if there are higher twist corrections to the anomaly at small $Q^2$, the anomaly will not reconcile differences in the flavor dependence of the polarized sea.\textsuperscript{21}

(5) The orbital angular momentum extracted from data is also much smaller than earlier values obtained from EMC data.\textsuperscript{16} A point of interest is that the zero $\Delta G$ model implies a positive orbital angular momentum, while the other model gives a negative result. Thus, although $L_z$ is likely small, its sign is still in question.

(6) The extracted value for $I^p$ is comparable for all data and well within the experimental uncertainties. This implies agreement about the validity of the Bjorken Sum Rule. We have arrived at this conclusion by using the BSR to extract an effective $I^p$, in contrast to the experimental groups, which used data to extract the BSR. There is general agreement that the BSR (and thus QCD) is in tact.

Clearly, these experiments have contributed to the progress of understanding the relative contributions of the constituents to the proton spin. They have probed to smaller $x$ values, while decreasing the statistical and systematic er-
rors. This, coupled with theoretical progress in calculating higher order QCD and higher twist corrections have allowed us to narrow the range of these spin contributions. Although the flavor contributions to the proton spin cannot be extracted precisely, the range of possibilities has been substantially decreased. The main differences are the questions of the strange sea spin content and the size of the polarized gluon distribution. We stress that more experiments must be performed to determine the relative contributions from gluons and various flavors of the sea.

The $x$-dependent distributions are in very good agreement with proton, neutron and deuteron data. The graphs which follow compare $x$ binned data with the polarized $x$-dependent distributions generated from results on $\eta$ and equation (3). These were found using the GRV$^{12}$ and the MRS$^{13}$ unpolarized distributions. The differences between the two sets of distributions are at small-$x$, where the data is most uncertain. More DIS experiments should be performed at small-$x$ to distinguish between models and to address the controversy regarding which contributions to $g_1$ are dominate in this kinematic region.

**Possible Experiments**

There are a number of experiments which are technologically feasible that would supply some of the missing information about these distributions. Detailed summaries can be found in references 22 and 23. The large average luminosities of these experiments and the success of Siberian Snakes makes all of the following feasible.

Deep Inelastic Scattering: The E155 experiment has been approved at SLAC. These experiments are designed to probe slightly smaller $x$ while greatly improving statistics and systematical errors. With lower error bars at small $x$, the extrapolation should achieve a more accurate value for the integrated distributions and narrow the ranges of constituent spin contributions even further.

Lepton Pair Production (Drell-Yan): The Relativistic Heavy Ion Collider (RHIC) at Brookhaven is designed so that polarized $pp$ and $p\bar{p}$ experiments can be performed at large energy and momentum transfer ranges. The energy range will be covered in discrete steps of about 60, 250 and 500 GeV, but the momentum transfer range covers $0.005 \leq Q^2 \leq 6.0$ GeV$^2$ in a fairly continuous set of steps. The PHENIX detector is suitable for lepton detection and the wide range of energies and momentum transfers could yield a wealth of Drell-Yan data over a wide kinematic range. The $x$-dependence of the polarized sea distributions could then be extracted to a fair degree of accuracy.

Jets, pions and direct photon production: The SPIN Collaboration proposes a set of experiments, which are in the kinematic region where the measurement of double spin asymmetries in jet production would give a sensitive test of the
Figure 1: The $x$-dependent structure function $g_1^P$ is compared with data as a function of $x$. 
Figure 2: The $x$-dependent structure function $g_1^n$ is compared with data as a function of $x$. The solid line represents the GRV generated distributions and the dashed line the MRS generated distributions.
Figure 3: The $x$-dependent structure function $g_1^d$ is compared with data as a function of $x$. The solid line represents the GRV generated distributions and the dashed line the MRS generated distributions.
polarized gluon distribution’s size. Naturally, this measurement has an effect on both \( \Delta G \) and the anomaly term appearing in the polarized quark distributions.\(^{24}\)

The STAR detector at RHIC is suitable for inclusive reactions involving jet measurements, direct photon production\(^ {25}\) and pion production. All of these would provide excellent measurements of the \( Q^2 \) dependence of \( \Delta G \) since all are sensitive to the polarized gluon density at differing \( Q^2 \) values. Charm production in polarized collisions are also sensitive to \( \Delta G \) and should be performed at RHIC. Should DESY proceed with plans to polarize their proton beam, many of these experiments could be performed there, complementing the kinematic regions covered by RHIC and CERN.

There has been considerable discussion about performing the COMPASS polarization experiments at the LHC at CERN. Depending on the approved experiments, there is the possibility of probing small \( x \) and doing polarized inclusive experiments to measure both sea and gluon contributions to proton spin. These could be made in complementary kinematic regions to those of the other accelerators. There are tentative plans to do polarized \( W^\pm \) production, which provides a measure of the \( x \)-dependent sea distributions. Polarized \( W^\pm \) production is also planned at SLAC and would provide useful sea information in a slightly different kinematic region than that of CERN.

Tests of the valence quark polarized distributions can be made, provided a suitable polarized antiproton beam of sufficient intensity could be developed.\(^ {26}\) This would provide a good test of the Bjorken sum rule via measurement of \( \langle \Delta q_v \rangle \) and the assumption of a flavor symmetric up and down sea. This should be an experimental priority for the spin community.

Existing data indicate that the spin structure of nucleons is non-trivial and has led to the formulation of a crucial set of questions to be answered about this structure. The experiments discussed above can and should be performed in order to shed light on the spin structure of the nucleons.

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