CONF-8910121--4

Received by OSTI

MAY 0 9 1990

ANL-HEP-CP--89-120

DE90 010545

EXPERIMENTAL TESTS OF PROTON SPIN MODELS * †

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Abstract

We have developed models for the spin-weighted quark and gluon distribution in a longitudinally polarized proton. The model parameters are determined from current algebra sum rules and polarized deep-inelastic scattering data. A number of different scenarios are presented for the fraction of spin carried the constituent parton distributions. A possible long-range experimental program is suggested for measuring various hard scattering processes using polarized lepton and proton beams. With the knowledge gained from these experiments, we can begin to understand the parton contributions to the proton spin.

*Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.

†Talk given at the IUCF Topical Conference on Physics with Polarized Beams on Polarized Targets, McCormick's Creek State Park, IN; October 16-18, 1989

I. INTRODUCTION

This is a summary of work I have done with J.-W. Qiu, D. Richards and D. Sivers.

The measurement of spin-related observables in processes involving polarized protons provides an outstanding opportunity to enhance our knowledge of QCD. Within the framework of the QCD-aided parton model, the well-known spin structure of various hard-scattering subprocesses can be used to probe correlation between the proton spin and the spin of its constituents. Several papers[1-4] have provided phenomenological estimates for spin-weighted inclusive scattering processes based on simple models for the parton spin densities. The measurement of the longitudinal spin-spin asymmetry in deep inelastic leptoproduction[5] has recently been extended to small values of the Bjorken x variable by the European muon collaboration (EMC).[6] These results suggest a strong negative polarization for the sea of $q\bar{q}$ pairs and have generated a number of theoretical papers.[7-14] This attention emphasizes the importance of understanding how the spin of the proton is shared among the spin of its constituents and orbital angular momentum. Many of the possibilities discussed raise new experimental possibilities. It is important to assign a high priority to a comprehensive experimental program involving polarized beams and targets aimed at answering the many questions raised by these new results.

In planning new polarized beam and target experiments, it is useful to have models for the spin transfer densities which encompass a reasonable range of variation. These models will allow experimenters to assess the precision required to extract the necessary information. For this purpose we have constructed simple model distributions for the polarization of the valence quarks, the gluons and the sea. We have used existing leptoproduction data plus some simple assumptions to constrain the distribution functions.

Definitions

At this point we establish our definitions and conventions for the spin-weighted quark and gluon distributions. We consider only longitudinal polarization, where the proton is polarized along its direction of motion and we neglect the transverse momentum of the quarks and gluons so that their momenta are aligned with the proton's spin. We also neglect quark mass parameters so that helicity is conserved.

For the purpose of comparing contributions from different constituents it is convenient to distinguish between the "valence" and the "sea" quarks of the proton. For the up and down quark number densities, we will therefore write

$$\begin{aligned} u(x,Q^2) &= u_v(x,Q^2) + u_s(x,Q^2) \\ d(x,Q^2) &= d_v(x,Q^2) + d_s(x,Q^2), \end{aligned} \tag{1.1}$$

where the valence densities are normalized so $\int_0^1 dx\, u_v(x,Q^2) = 2$ and $\int_0^1 dx\, d_v(x,Q^2) = 1$. All other flavor components will be included in the sea. In general, these distributions will be denoted by their flavor quantum numbers; $\bar{u}(x,Q^2)$, $\bar{d}(x,Q^2)$, $s(x,Q^2)$, $\bar{s}(x,Q^2)$, etc. When an equation is valid for all flavors, we will use the distribution $q^i(x,Q^2)$. For a proton with its spin aligned in the $+z$ direction (along its momentum), we define the spin-weighted distribution as

$$\Delta q^i(x,Q^2) = q^i_+(x,Q^2) - q^i_-(x,Q^2), \tag{1.2}$$

where $q^i_\pm$ indicates a parton whose helicity is aligned (+) or anti-aligned (−) with that of the proton. We adopt a process-independent set of definitions for the spin-weighted quark and gluon distributions. The factorization prescription will be specified by initially demanding that the distributions evolve in Q^2 with the lowest-order Altarelli-Parisi kernels.[15] In general, the connection of these process-independent distributions to the distributions "measured" in a specific hard-scattering process will involve a correction factor calculable in perturbative QCD.[16]

Taking a broken SU(6) picture of the valence quark structure, we assume that

$$\begin{aligned} \Delta u_v(x,Q^2) &= \cos\Theta_D(x,Q^2)\left(u_v(x,Q^2) - \frac{2}{3}d_v(x,Q^2)\right) \\ \Delta d_v(x,Q^2) &= -\frac{1}{3}\cos\Theta_D(x,Q^2) d_v(x,Q^2). \end{aligned} \tag{1.3}$$

where the valence spin-dilution angle, Θ_D, measures the deviation of the observed valence spin-weighted distributions from the SU(6) ideal. This spin dilution term, which approaches 1 at large x, was first introduced by Carlitz and Kaur[17] who hypothesized a specific form for it. We have an alternative approach to the valence spin-dilution angle which emphasizes its connection to a possible nonperturbative polarization of the sea and glue. To account for these effects, we use

$$\cos\Theta_D = \left[1 + R(Q^2)\cdot x \cdot G(x,Q^2)\right]^{-1} \tag{1.4}$$

which is well-behaved at small x. For the unpolarized gluon distribution occurring in this spin dilution factor, there is a wide range of uncertainty, especially at small-x. Since the spin-flip model dilution factor contains the gluon distribution, which is large at small-x, we can more closely match the data by adjusting the power of x in $G(x, Q^2)$. This power is subject to constraints in the unpolarized data used to determine the gluon distribution at the appropriate Q_0^2. We choose the unpolarized gluon distribution to be parametrized as

$$G(x, Q^2) = A_g x^{-\alpha_g}(1 + \gamma_g x)(1 - x)^{\beta_g}. \tag{1.5}$$

Then, at small-x, our spin dilution factor has the form:

$$\cos\Theta_D = \left[1 + R \cdot A_g \cdot x^{1-\alpha_g}\right]^{-1} \simeq \frac{1}{R \cdot A_g} \cdot x^{\alpha_g - 1}. \tag{1.6}$$

The Carlitz-Kaur form for $\cos\Theta_D$ is numerically equivalent to choosing $\alpha_g = 1.5$ when using the EMC data to fix the sea parameters. If this value is decreased, as has been suggested by other models,[18] the theoretical values may match the data very well at all x. See figure 1.

In QCD, one specifies a factorization prescription which separates the "hard" perturbative process from the "soft" hadronic dynamics. We define the "chiral" distributions $\Delta q_c^s(x, Q^2)$ and $\Delta\bar{q}_c(x, Q^2)$ (suppressing the flavor index i) for sea quarks and antiquarks, which obey the lowest-order Altarelli-Parisi equations. Then, the net helicity of the quarks and antiquarks in the sea, do not evolve with Q^2. A more physical definition of these distributions which we label $\Delta q_5^s(x, Q^2)$ and $\Delta\bar{q}_5^s(x, Q^2)$ involves the observable axial current, at least to leading order in α_s. Then the relationship between these distributions, can be written (for each flavor)

$$\Delta q_5^s(x, Q^2) = \Delta q_c^s(x, Q^2) - \frac{\alpha_s(Q^2)}{4\pi}\hat{\gamma}(x) \otimes \Delta G(x, Q^2) \tag{1.7a}$$

$$\Delta\bar{q}_5(x, Q^2) = \Delta\bar{q}_c(x, Q^2) - \frac{\alpha_s(Q^2)}{4\pi}\hat{\gamma}(x) \otimes \Delta G(x, Q^2), \tag{1.7b}$$

where $\hat{\gamma}(x)$ is convention-dependent and a choice of renormalization prescription for α_s must be made.[19] Here we have denoted the unpolarized gluon distribution in a proton as $G(x, Q^2)$ and the difference

$$\Delta G(x, Q^2) = G_+(x, Q^2) - G_-(x, Q^2), \tag{1.8}$$

represents the polarized gluon distribution in the same manner as the $\Delta q^i(x,Q^2)$ for the quarks. A number of prescription choices are possible but physical observables are more directly related to Δq_5^s or $\Delta\bar{q}_5$ than to their "c" counterparts.

Defining $\langle\Delta G(Q^2)\rangle$ to be the integral of ΔG over x, the polarized gluon distribution relates the measured spin densities to the chiral densities by

$$\sum_i(\langle\Delta q_5^i\rangle - \langle\Delta q_c^i\rangle) = \frac{N_f\alpha_s(Q^2)}{2\pi}\langle\Delta G(Q^2)\rangle \equiv \Gamma(Q^2). \tag{1.9}$$

Equations (1.7a and 1.7b) above show that the polarized gluon density can affect the relationship between the "observable" quark and antiquark spin densities $\Delta q_5^s(x,Q^2)$ and $\Delta\bar{q}_5(x,Q^2)$ and the densities $\Delta q_c^s(x,Q^2)$ and $\Delta\bar{q}_c(x,Q^2)$ which have simple chiral properties in the limit $m_q \to 0$. The QCD evolution equations suggest that $(4\pi)^{-1}\alpha_s(Q^2)\Delta G(x,Q^2)$ need not be small at large Q^2.[1,10,14] The suggestion has been made[14] that a large contribution from polarized gluons in (1.7a and 1.7b) would help reconcile the EMC data with certain theoretical ideas for proton structure based on the quark model. It is therefore important to attempt to measure $\Delta G(x,Q^2)$ in some process.

Constraints

For unpolarized distributions, there exists a large amount of experimental knowledge concerning the various parton densities.[20] The range of difference between the parameterizations of the unpolarized distributions is quite small (a few percent) compared to the uncertainties in the spin-weighted distributions discussed here. For our valence quark distributions, we use the *unpolarized* parton distributions given by Gluck, Hoffmann and Reya, [20] evaluated at $Q_0^2 = 10.7$ GeV^2:

$$\begin{aligned} xu_v(x,Q_0^2) &= 1.39x^{0.419}(1-x^{1.94})^{3.40} \\ xd_v(x,Q_0^2) &= 0.65x^{0.361}(1-x^{1.94})^{5.11}. \end{aligned} \tag{1.10}$$

We can then evolve the polarized distributions via the Altarelli-Parisi equations.

The first of three sum rules we will use to fix some of the model parameters is the Bjorken sum rule:[21]

$$A_3 = \int_0^1 dx\left[\Delta u_v(x,Q^2) - \Delta d_v(x,Q^2)\right]_c = 1.258 \pm 0.004 \tag{1.11}$$

The value of A_3 is determined from neutron beta decay. The second sum rule we use involves an SU(3) rotation of the Bjorken Sum Rule which involves hyperon decay and relates the valence quark integrals to the strange quarks in the sea. A traditional SU(3) analysis of hyperon decays determines two empirical constants $D = 0.795 \pm 0.009$ and $F = 0.466 \pm 0.009$,[22] and gives

$$A_8 = \int_0^1 dx \left[\Delta u_{tot} + \Delta d_{tot} - 2\Delta s_{tot}\right]_c = 3F - D \simeq 0.60 \pm 0.02. \tag{1.12}$$

Since the anomaly terms cancel in the differences, the distributions in A_3 and A_8 can be either the measured or the chiral ones. The third sum rule represents the total spin carried by all quarks and antiquarks and is just the matrix element of the singlet current A_0, given in terms of the chiral distributions by

$$(A_0)_c = \int_0^1 dx \left[\Delta u_v + \Delta d_v + \Delta u_s + \Delta d_s + \Delta\bar{u} + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right]_c . \tag{1.13}$$

The anomaly terms do not cancel, so the difference between the chiral $(A_0)_c$ and the value of A_0 determined from the data, $(A_0)_5$ is

$$(A_0)_5 = (A_0)_c - \Gamma(Q^2), \tag{1.14}$$

with $\Gamma(Q^2)$ given by eq (1.9). To compare the theoretical models with data, we can express A_0 in terms of A_3, A_8 and the measured value of the integral of xg_1^p as follows:

$$(A_0)_c = 9\left[1 + \frac{\alpha_s}{\pi}\right] \int_0^1 dx \cdot g_1^p(x) - \frac{1}{4}A_8 - \frac{3}{4}A_3 + \Gamma. \tag{1.15}$$

From (1.13) we can relate this to the fraction of the proton's spin carried by quarks

$$(A_0)_c \equiv f_v + f_s \equiv f_v + \tilde{f}_s + \Gamma. \tag{1.16}$$

Here, f_v and f_s are the fractions of the proton spin carried by the valence and sea quarks, respectively, given by the chiral distributions. Only f_s is modified by the anomaly as $f_s = \tilde{f}_s + \Gamma$.

II. MODELS FOR THE SPIN-WEIGHTED DISTRIBUTIONS

The basic sources of information for fixing the parameters in our models are data on the longitudinal spin-spin asymmetry in deep-inelastic lepton-proton scattering and the sum rules involving the polarized parton distributions.

Since the spin-dilution angle is flavor independent, it can be determined by the Bjorken sum rule:

$$A_3 = \int_0^1 dx \Big[u_v(x, Q^2) - \frac{1}{3} d_v(x, Q^2)\Big] \cos\Theta_D(x, Q^2) = 1.258 \pm 0.004. \tag{2.1}$$

In particular, evaluating the integral at $Q_0^2 = 10.7$ GeV^2, we obtain $R = 0.18$ in our valence model. Then the fraction of the proton spin carried by the valence quarks, f_v, is about 78%.

Having determined a suitable form for the polarized valence distributions, we now consider the polarized gluon distribution. Traditionally, this distribution was thought to be limited by the gluon's momentum. However, recent attention to the γ_5 anomaly[14] has allowed speculation that the polarized gluon distribution may be significantly larger. Possible models for ΔG fall into three basic categories. In the first, we assume $\Delta G = 0$ for all x at some value of Q_0^2. One can then generate the polarization of the gluons using the Altarelli-Parisi equations. This model is consistent with the Skyrme approach to the proton structure. A second model assumes $\Delta G \simeq xG$ at $Q_0^2 \simeq 10.7$ GeV^2, so that the net spin carried by gluons is approximately equal to the fraction of momentum that they carry: $\langle \Delta G(Q_0^2)\rangle \simeq \int_0^1 dx \cdot xG(x, Q^2) \simeq 0.50$. Depending on the form for the $\Delta q_i(x, Q^2)$, this starting point is relatively stable under the Altarelli-Parisi evolution equations. This model can be compatible with either the EMC-motivated quark distributions or with theoretically motivated distributions. In this model, $\Gamma(Q_0^2)$ of equation (1.9) is about 0.06. Finally, one can assume that the spin-spin forces lead to a saturation of the gluon polarization and $\Delta G \simeq G$ at large x. This possibility is suggested by the discrepancy of the EMC data with certain theoretical estimates on the amount of sea polarization allowed. One explicit parametrization is

$$\begin{aligned} \Delta G &= \frac{x}{x_0} G \quad x < x_0 \\ \Delta G &\simeq G \quad x > x_0 \end{aligned} \tag{2.2}$$

The second model discussed above corresponds to $x_0 = 1$ here. If we choose $x_0 \simeq 0.04$ then $\langle \Delta G(x) \rangle \simeq 5.0$, which implies that $\Gamma(Q^2) \simeq 0.65$. Thus, this model for the gluon polarization gives considerable difference between the measured and calculated values of the spin fraction of the proton carried by the sea.

To complete our specification of the spin-weighted parton densities, we turn to the sea distributions. Baryon decays and the EMC data suggest strongly that the sea pairs are polarized in a direction opposite to the proton's spin. However, the experimental errors and theoretical ambiguities in the interpretation of the data leave a good deal of uncertainty concerning the magnitude of polarization.

The polarized sea distribution consists of the chiral parton distributions:

$$\Delta S(x) = \Delta u_s(x) + \Delta \overline{u}(x) + \Delta d_s(x) + \Delta \overline{d}(x) + \Delta s(x) + \Delta \overline{s}(x). \tag{2.3}$$

Since the spin-spin forces are different in $q\bar{q}$ and qq channels, we make the distinction that

$$\Delta \bar{q}(x, Q_0^2) = c(x) \Delta q_s(x, Q_0^2), \tag{2.4}$$

at some Q_0^2 for each flavor. The parameter $c(x)$ represents the enhancement of antiquarks over quarks in the sea. As a first approximation, we let $c(x)$ be constant and flavor independent. Additionally, we assume isospin invariance of the sea with respect to the up and down quarks, but a broken flavor SU(3) sea so that

$$\begin{aligned} \Delta u_s = \Delta d_s &= [1 + \epsilon(x)] \Delta s \\ \Delta \bar{u} = \Delta \bar{d} &= [1 + \bar{\epsilon}(x)] \Delta \bar{s}. \end{aligned} \tag{2.5}$$

The symmetry breaking parameter ϵ indicates the difficulty in polarizing the strange quarks due to their larger masses. The x dependence of ϵ is most likely related to the quark masses, but we assume that ϵ is almost constant over the important kinematic range. Since we have assumed that c is flavor independent, it is reasonable to conclude that $\epsilon = \bar{\epsilon}$. Thus,

$$\Delta \bar{u} = c \Delta u_s = \Delta \bar{d} = c \Delta d_s = (1 + \bar{\epsilon}) \Delta \bar{s} = c(1 + \epsilon) \Delta s. \tag{2.6}$$

Now we can rewrite the A_8 sum rule in terms of the total polarized sea, ΔS, as

$$A_8 = \langle \Delta u_v \rangle_c + \langle \Delta d_v \rangle_c + (\frac{2\epsilon}{3 + 2\epsilon}) \langle \Delta S \rangle_c = 0.60 \pm 0.02. \tag{2.7a}$$

The Bjorken sum rule and our valence model fixes

$$\langle \Delta u_v \rangle_c + \langle \Delta d_v \rangle_c = 0.78 \pm 0.01, \tag{2.7b}$$

Thus, the A_8 sum rule requires that the total spin carried by sea of $q\bar{q}$ pairs, f_s, be negative, but allows a considerable range in the magnitude of that contribution, due to the experimental error and the theoretical uncertainty in ϵ. This estimate is independent of the EMC data and since the anomaly terms cancel in A_8 we can write

$$\frac{2\epsilon}{3+2\epsilon}\langle \Delta S \rangle_c = -0.18 \pm 0.01. \tag{2.8}$$

The first scenario we consider assumes a small $\langle \Delta G \rangle$ and uses the EMC experimental determination of $\int_0^1 dx \cdot g_1^p(x, Q^2)$ to determine the sea parameters explicitly. We choose a suitable value for the parameter c, then use the sum rules to determine ϵ and $\langle \Delta S \rangle$. The structure function $g_1^p(x, Q^2)$ is given in the QCD parton model by

$$g_1^p(x, Q^2) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x, Q^2)[1 - \frac{\alpha_s}{\pi}\tau_i(x) + \ldots] \tag{2.9}$$

where $\tau(x)$ is a calculable correction factor. Since g_1^p is measured by experiment, the parton density expansion in (2.9) is in terms of the Δq_5^i distributions. If we accept SU_3-flavor as a good symmetry for baryon decays we can use the parton model expression for the integral of g_1^p and the A_8 sum rule to set reasonable limits on the polarized gluon distribution. The latest analysis of the EMC data[22] gives a value for the integral

$$\int_0^1 dx \cdot g_1^p(x) = 0.126 \pm 0.010(\text{stat}) \pm 0.015(\text{sys}). \tag{2.10}$$

We can write the integral with the QCD correction as

$$\begin{aligned} (1 - \frac{\alpha_s}{\pi})^{-1} \cdot 2 \cdot \int_0^1 dx \cdot g_1^p(x) &= \frac{4}{9}\langle \Delta u_v \rangle + \frac{1}{9}\langle \Delta d_v \rangle + \frac{4}{9}\langle \Delta u_s + \Delta \bar{u} \rangle_5 + \frac{1}{9}\langle \Delta d_s + \Delta \bar{d} + \Delta s + \Delta \bar{s} \rangle_5 \\ &= \frac{4}{9}\langle \Delta u_v \rangle + \frac{1}{9}\langle \Delta d_v \rangle + \frac{6+5\epsilon}{9}\langle \Delta s + \Delta \bar{s} \rangle_c - \frac{2}{9} \cdot \Gamma. \end{aligned} \tag{2.11}$$

Using $\alpha_s = 0.27$ in this model, the measured spin fraction $f_v + \tilde{f}_s$ is 0.14 ± 0.18, consistent with the conjecture that the net quark contribution to the proton spin is small. Also, $\epsilon = 0.6 \pm 0.4$ and the total spin carried by each of the quark flavors including valence and sea is

$$\begin{aligned}\langle \Delta u_v \rangle + \langle \Delta u_s + \Delta \bar{u} \rangle &= 1.02 + (-0.24) = 0.78 \\ \langle \Delta d_v \rangle + \langle \Delta d_s + \Delta \bar{d} \rangle &= -0.25 + (-0.24) = -0.49 \\ \langle \Delta s + \Delta \bar{s} \rangle &= -0.15.\end{aligned} \quad (2.12)$$

The total contribution from all flavors of sea quarks in this model is -0.63 ± 0.60. If we assume that the polarized gluon distribution is large, say $\langle \Delta G \rangle \simeq 5$, then when the above results are translated into parton model language, we find that

$$f_v + f_s = f_v + \tilde{f}_s + N_f \frac{\alpha_s}{2\pi} \langle \Delta G \rangle \simeq 0.79 \pm 0.25, \quad (2.13)$$

consistent with the naive quark model. A theoretical concern with this scenario is that the spin carried by the sea quark pairs is much larger than the corresponding momentum. This is easily seen by comparing the integrals over x of the unpolarized and polarized sea. Using the EMC data, $\int_0^1 dx \Delta S = -0.81$, while $\int_0^1 dx \cdot xS \simeq 0.15$ for typical models of the unpolarized sea.[20]

To resolve this discrepancy, we introduce a theoretically motivated model in which the sea quarks obtain their spin through a localized interaction with the valence quarks. In this "Valence Dominated Model", the spin transfer densities of the sea anti-quarks and quarks are limited by $\Delta \bar{s}(x) \simeq -\frac{1}{3} x \cdot \bar{s}(x)$ and $c \cdot \Delta s(x) \simeq -\frac{1}{3} x \cdot s(x)$. Then, for the process-independent sea distributions,

$$\frac{\Delta S}{S} = \frac{(3 + 2\epsilon)(c\Delta s + \Delta \bar{s})}{5(s + \bar{s})} = -\frac{(3 + 2\epsilon)}{15} x. \quad (2.14)$$

Here, we have used the conjecture that the unpolarized strange quarks comprise about 20% of the unpolarized sea.[9] Then the total spin carried by the sea is related to the total momentum of the sea by:

$$f_s \equiv \int_0^1 dx \Delta S = -\frac{(3 + 2\epsilon)}{15} \int_0^1 dx \cdot xS. \quad (2.15)$$

Typical values of the last integral range from 0.10 to 0.15. [20] Using the larger value for this integral and the A_8 and A_0 sum rules, the value of the sea parameters become:

$$\epsilon = 12. \pm 1.8,$$
$$f_v + \tilde{f}_s = 0.56 \pm 0.07 - N_f \frac{\alpha_s(Q^2)}{2\pi} \langle \Delta G(Q^2) \rangle, \tag{2.16}$$
$$\int_0^1 dx \cdot g_1^p = 0.170 \pm 0.008 - (0.1) N_f \frac{\alpha_s(Q^2)}{2\pi} \langle \Delta G(Q^2) \rangle.$$

For a moderate sized polarized gluon distribution, the integral of g_1^p falls inside the error bars of the EMC value. The large value of ϵ implies that the strange sea is much harder to polarize, possibly due to mass differences of the quark flavors. We compare the asymmetry A_1^p vs x for both scenarios to data in figures 1 and 2. The fraction of spin carried by all quarks in this model is as much as one half of the total spin of the proton, which is significantly greater than that implied by the model which directly fits the EMC data. These conclusions are similar to other theoretical models.[24] Here, the spin carried by the quark flavors is

$$\langle \Delta u_v \rangle + \langle \Delta u_s + \Delta \bar{u} \rangle = 1.02 + (-0.10) = 0.92$$
$$\langle \Delta d_v \rangle + \langle \Delta d_s + \Delta \bar{d} \rangle = -0.25 + (-0.10) = -0.35 \tag{2.17}$$
$$\langle \Delta s + \Delta \bar{s} \rangle = -0.01.$$

The EMC motivated model, has a significantly larger negatively polarized sea and less SU(3) flavor breaking (small ϵ) than the Valence Dominated Model (VDM). It has also been suggested that the weak neutral current data νp $\rightarrow$ νp and $\bar{\nu}$p $\rightarrow$ $\bar{\nu}$p support this result by providing an estimate $\langle \Delta s + \Delta \bar{s} \rangle = -0.15 \pm 0.09$. On the other extreme, the VDM with a smaller polarized gluon contribution is more consistent with various theoretical models of the proton. Only a comprehensive experimental program in polarized beams can help to distinguish the accuracy of these theoretical models.

III. A PROSPECTIVE EXPERIMENTAL PROGRAM

We have seen that the valence quark distributions can be determined with some confidence from existing data on the longitudinal asymmetry in deep-inelastic lepton-proton scattering. Additional experimental information is needed in order to determine the spin-weighted gluon and sea distributions. Only when these distributions have been measured can we proceed to formulate tests of QCD using spin-related observables. We now outline a specific set of experiments in terms of the models introduced in Sec. II. This will enable us to estimate the sensitivity of the distributions to new experimental data. A complete set of measurements of this type will require high energy beams of polarized protons. Recent technical developments of polarized beams and targets will allow hard-scattering processes to be measured in kinematic regimes where QCD perturbation theory can be valid.[2,3,25] We shall consider in turn experiments which are sensitive to valence quark, the sea quark and, finally to the gluon distributions.

The interest generated by the measurements of the EMC group has served to emphasize the need for further precision measurements of the lepton scattering asymmetry. Measurements at small x can serve to reduce the uncertainties in the extrapolation of the integral of $g_1^p(x,Q^2)$.[8] With higher energies, the accelerators at CERN and Hamburg (HERA) could probe smaller x. In the more distant future, LEP at CERN could increase the certainty of these measurements for both proton and neutron targets. A natural extension of the work on the proton involves a measurement of A_1^{en}, which would allow an experimental test of the Bjorken sum rule. All of the models we consider treat the Bjorken sum rule as inviolate but we recognize that it is crucial to test it experimentally. In particular, various groups[26] have examined the possibility that our basic understanding of QCD may be flawed in such a way to allow a violation of the Bjorken sum rule. Measurement of en would provide significant additional information concerning nucleon structure. Predictions for A_1^{en} using both models are shown in figure 3.

The Drell-Yan process allows the most direct probe of the polarization of the antiquarks in the sea.[27] After integrating over transverse momentum, the spin-spin asymmetry for the production of lepton pairs in pp collisions can be given by

$$\frac{a_{LL}d\sigma}{dM^2dx_F} = \frac{4\pi\alpha^2}{3M^2}\cdot\frac{1}{3}\cdot\sum_q e_q^2\left[x_F^2+\frac{4M^2}{s}\right]^{-\frac{1}{2}}\left[\Delta q(x_a)\Delta\bar{q}(x_b)+\Delta\bar{q}(x_a)\Delta q(x_b)\right] \tag{3.1}$$

where

$$x_a = \frac{1}{2}[(x_F^2 + 4\frac{M^2}{s})^{\frac{1}{2}} + x_F],$$
$$x_b = \frac{1}{2}[(x_F^2 + 4\frac{M^2}{s})^{\frac{1}{2}} - x_F]. \tag{3.2}$$

To the extent that the quark spin transfer density is dominated by the valence contribution this gives a straightforward measure of the amount of polarization of the antiquarks. Figure 4 shows our model estimates for the Drell-Yan asymmetry. These measurements are sensitive to our sea parameters and will therefore allow us to constrain the SU_3 breaking (ϵ) as well as the $\bar{q}$ enhancement parameter (c).

The production of jets and hadrons at large transverse momentum using polarized beams and targets presents a wide range of experimental opportunities. The fundamental asymmetries for the $2 \rightarrow 2$ processes are known from perturbation theory[1] and can be used to determine the polarized distributions.[2] We consider the integrated hard-scattering process[4] $\Delta\sigma_L^{jet}(pp; p_0, \sqrt{s})$, where p_0 is the momentum cutoff for defining a jet. At large CM energies, jet production is dominated by gluon-gluon scattering processes. It might be expected, therefore, that a measurement of jet production with polarized beam and target would be sensitive to the gluon polarization. Our explicit calculations show that this expectation is reasonable. In figure 5 we show estimates for the polarized jet cross section, $\Delta\sigma_L^{jet}(pp; p_0, \sqrt{s})$ at $\sqrt{s} = 14$ GeV. W[illegible]h the large and small polarized gluon distributions discussed in Sec. II and use the [illegible] and VDM models for the polarization of the sea. The predictions are very sensitive to the gluon polarization and so a measurement of $\Delta\sigma_L^{jet}$ should provide important early clues to the magnitude of $\Delta G(x, Q_0^2)$.

In order to disentangle the contribution of the gluon-gluon subprocess from those involving sea quarks and antiquarks, it is important to consider different subenergies and jet momenta. Should the polarized sea be large and negative, as suggested by the EMC data, the positive contribution to the jet cross section would be decreased. However, a large polarized gluon distribution would make the positive contribution significant. The predictions made by the curves in figure 5 can be tested with the polarized proton beam at Fermilab in 1990. Momentum cutoffs of 5 GeV could shed considerable light on the size of the polarized gluon distribution. By boosting the beam energy and measuring the cross section at $\sqrt{s} = 20$ GeV, the differences in model predictions are enhanced and the relative size of the gluon polarization could be confirmed.[4]

Perhaps the cleanest method for determining the gluon polarization is through direct photon production from a polarized beam on a polarized target. The process is expected to be dominated by the quark-gluon diagrams. The discussion of Berger and Qiu[28] shows the importance of measurements in the small-x, high p_T region where the polarized gluon distribution would be sufficiently large. The polarized proton beam at Fermilab could possibly reach the lower end of the transverse momentum (about 4 GeV) necessary to make meaningful predictions. In the future Fermilab and accelerators such as UNK could probe to larger transverse momentum to give more precise predictions concerning the polarized sea.

At this point, it seems that the immediate aim should be to do a variety of experiments to get an indication as to the size of the polarized gluon distribution and thus, the anomaly term. We should also try to gain as much information about the polarized sea as possible. With this knowledge, we may begin to understand the constituent contributions to the spin of the proton.

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FIGURE CAPTIONS

1. The proton asymmetry A_1^p as a function of Bjorken-x using the parton distributions motivated by the EMC data. The solid line corresponds to $\alpha_g = 1.5$ and the dot-dash line to $\alpha_g = 1.2$ in the valence spin dilution factor of equation (1.6).

2. The proton asymmetry A_1^p plotted as a function of x using the parton distributions obtained from the valence dominated model (VDM) discussed in the text. The α_g factors are the same as in fig. 1.

3. A prediction for the neutron asymmetry, A_1^n, from the parton distributions motivated by the EMC data (solid line) and the VDM model (dot-dash line).

4. The Drell-Yan asymmetry, A_{LL}^{DY} for $\sqrt{s} = 14$ and $x_F = 0$. The asymmetries with EMC sea distributions are represented by solid ($c = 3$) and dashed ($c = 1$) curves, while the VDM motivated asymmetries are represented by dot-dash ($c = 3$) and dotted ($c = 1$) curves, respectively.

5. The polarized jet cross section, $\Delta\sigma_L^{jet}$, as a function of momentum cutoff for distinguishing a jet, p_0 with $\sqrt{s} = 14$. Key: solid curve = EMC sea, small ΔG; dot-dash curve = VDM sea, small ΔG; dotted curve = EMC sea, large ΔG ($\langle\Delta G\rangle \simeq 5$); dashed curve = VDM sea, large ΔG.

Figure 1

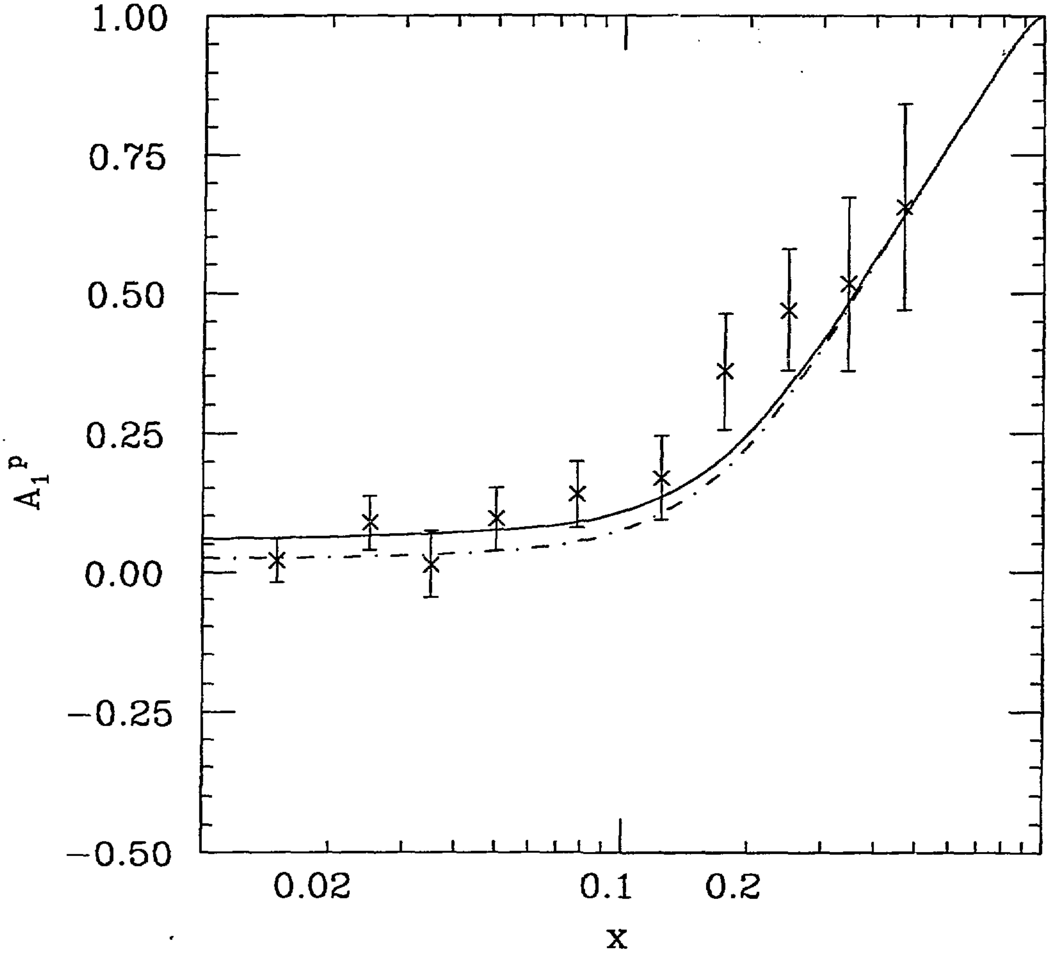

Figure 2

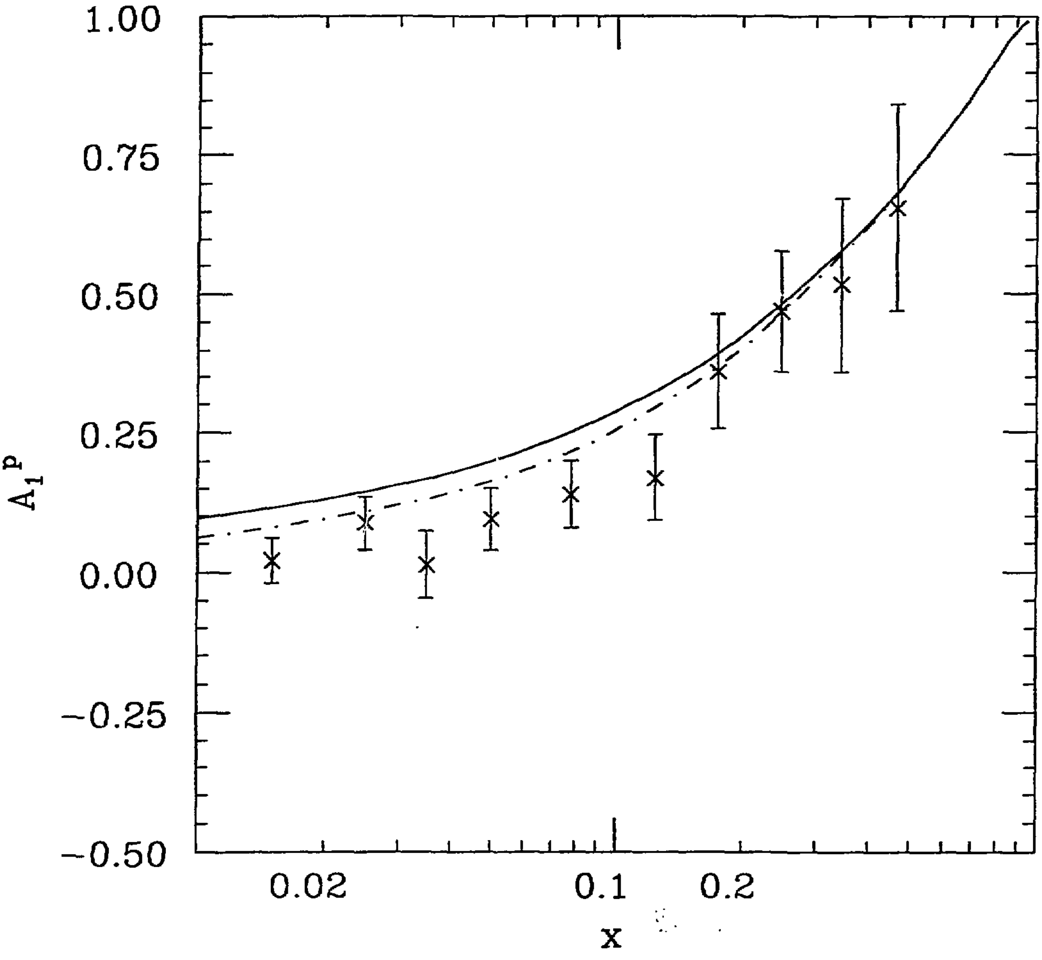

Figure 3

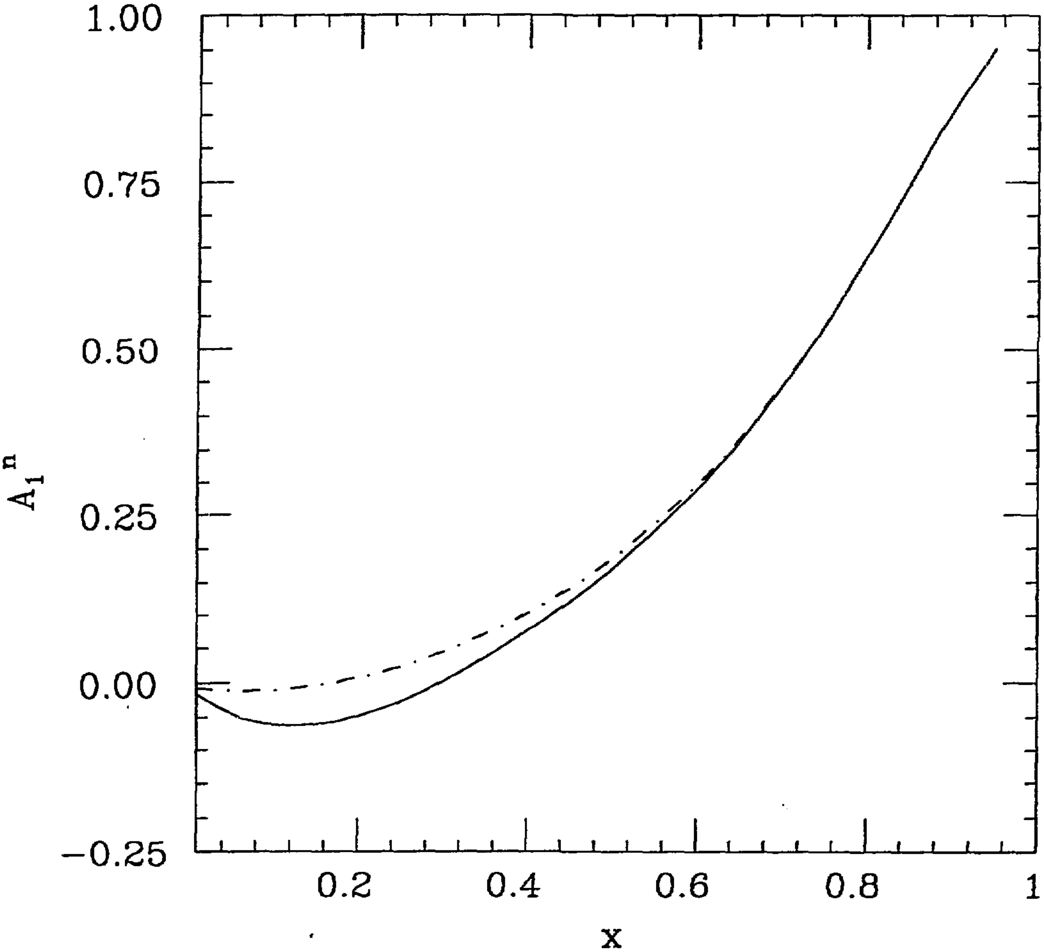

Figure 4

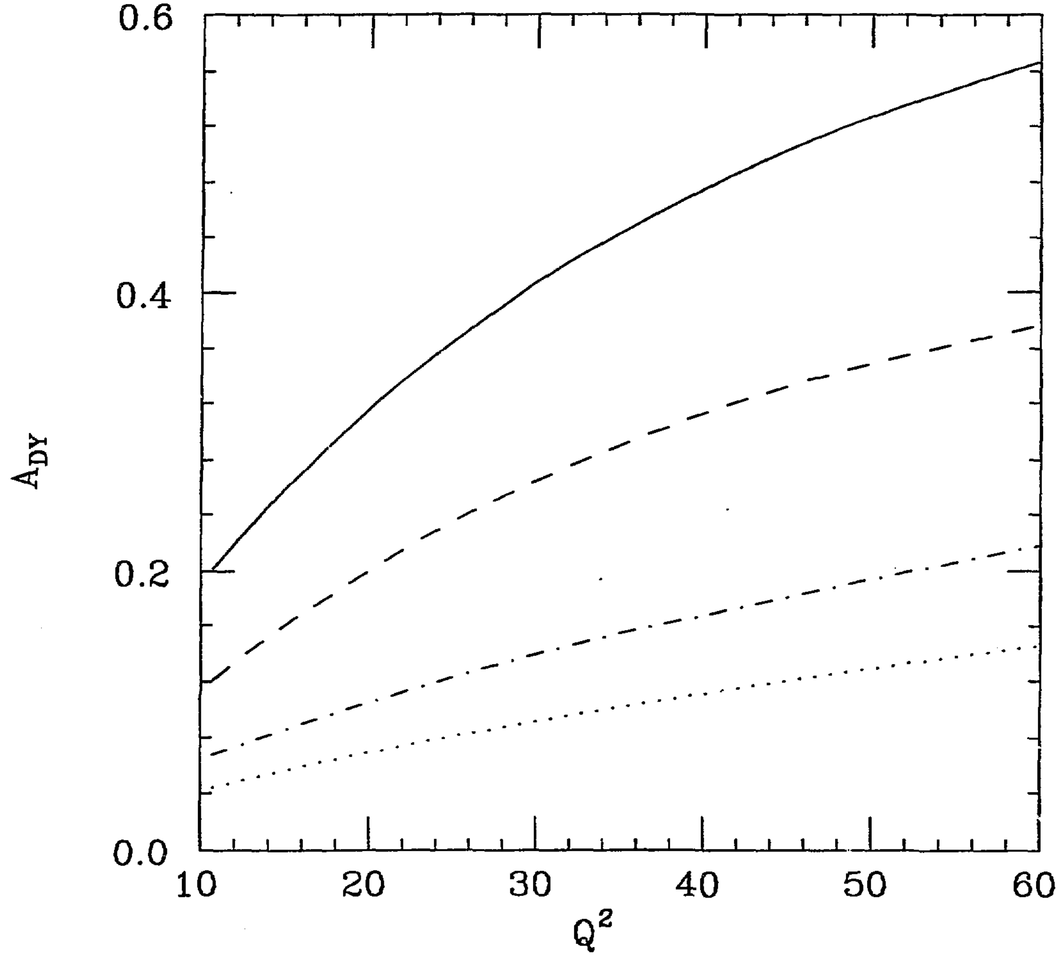

Figure 5