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TESTING PROTON SPIN MODELS WITH POLARIZED BEAMS *

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Abstract

We review models for spin-weighted parton distributions in a proton. Sum rules involving the nonsinglet components of the structure function xg_1^p help narrow the range of parameters in these models. The contribution of the γ_5 anomaly term depends on the size of the integrated polarized gluon distribution and experimental predictions depend on its size. We have proposed three models for the polarized gluon distributions, whose range is considerable. These model distributions give an overall range of parameters that can be tested with polarized beam experiments. These are discussed with regard to specific predictions for polarized beam experiments at energies typical of UNK.

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Measuring spin-observables with polarized proton beams provides an excellent opportunity to enhance our knowledge of QCD. Several papers^{1,2,3} have provided phenomenological estimates for spin-weighted inclusive scattering processes based on simple models for the parton spin densities. Recent technical developments involving polarized beams and targets will now allow hard-scattering processes to be measured in kinematic regimes where QCD perturbation theory can be valid.⁴ The results from the EMC⁵ suggest a strong negative polarization for the sea of $q\bar{q}$ pairs and have created controversy regarding reconciliation of the data with the parton model predictions. This stresses the importance of understanding how the spin of the proton is shared among the spin of its constituents and orbital angular momentum. It is crucial to assign a high priority to a comprehensive experimental program involving polarized beams and targets aimed at answering the many questions that still exist. In planning polarized beam and target experiments, it is useful to have models for the spin transfer densities which will allow experimenters to assess the precision required to extract the necessary information. We have constructed simple model distributions for the polarization of the valence quarks, the gluons and the sea using existing data on the longitudinal spin-spin asymmetry in deep-inelastic lepton-proton scattering and the sum rules involving the polarized parton distributions.

In our models, we distinguish between the “valence” and the “sea” quarks of the proton to construct the spin-weighted distributions. The polarized valence quark distributions are based on a broken SU(6) model, written in terms of the unpolarized distributions with a flavor independent factor, which is connected to a possible nonperturbative polarization of the sea and glue. These valence distributions have been discussed elsewhere in detail.¹ Coupled with the Bjorken sum rule, this model implies that the valence quarks carry about 77% of the proton’s spin, consistent with a Skyrme model approach.⁶

Recent attention to the γ_5 anomaly⁷ has allowed speculation that the polarized gluon density can affect the relationship between the “observable” quark and antiquark spin densities and those densities which have simple chiral properties in the limit $m_q \rightarrow 0$. Traditionally, this distribution was thought to be limited by the gluon’s momentum. However, analysis of the EMC data indicate that it may be significantly larger. Since the QCD evolution equations⁸ do not specify the size of $\Delta G(Q^2)$ at any particular Q^2 , it is important to attempt to measure $\Delta G(x, Q^2)$ in some processes. Possible models for ΔG fall into three basic categories. First, we can assume $\Delta G = 0$ for all x at some value of Q_0^2 . The polarization

of the gluons is generated using the spin-weighted QCD evolution equations. This model is consistent with the Skyrme approach to the proton structure. A second model assumes $\Delta G \simeq xG$ at $Q_0^2 \simeq 10.7 \text{ GeV}^2$, so that the net spin carried by gluons is approximately equal to the fraction of momentum that they carry: $\langle \Delta G(Q_0^2) \rangle \equiv \int_0^1 dx \cdot xG(x, Q^2) \simeq 0.50$. Finally, one can assume that the spin-spin forces lead to a saturation of the gluon polarization and $\Delta G \simeq G$ for $x \geq x_0$, for some chosen x_0 . This possibility is suggested by the discrepancy of the EMC data with certain theoretical estimates on the amount of sea polarization allowed. If we assume that the gluon density follows the second model for $x_0 \leq 0.04$ and saturates thereafter, then $\langle \Delta G(x) \rangle \simeq 5.0$. This last model gives considerable difference between the measured and calculated values of the spin fraction of the proton carried by quarks.

Data suggest that the sea pairs are polarized opposite to the proton's spin.⁵ However, there is still considerable uncertainty concerning the magnitude of the sea polarization. For the sea distribution, we assume that there is an enhancement of up and down quarks/antiquarks over strange quarks/antiquarks due to the difficulty of polarizing heavier flavors, and that spin-spin correlation forces tend to enhance the polarization of antiquarks over quarks in the sea. Thus, we make the distinction that

$$\Delta \bar{q}(x, Q_0^2) = c(x) \Delta q_s(x, Q_0^2), \quad (1)$$

at some Q_0^2 for each flavor. The parameter $c(x)$ represents the enhancement of polarized antiquarks over polarized quarks in the sea. 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

$$\begin{aligned} \Delta u_s &= \Delta d_s = [1 + \epsilon(x)] \Delta s \\ \Delta \bar{u} &= \Delta \bar{d} = [1 + \bar{\epsilon}(x)] \Delta \bar{s}. \end{aligned} \quad (2)$$

The symmetry breaking parameter ϵ indicates the difficulty in polarizing the strange quarks due to their larger masses. Thus,

$$\Delta \bar{u} = c \Delta u_s = \Delta \bar{d} = c \Delta d_s = (1 + \bar{\epsilon}) \Delta \bar{s} = c(1 + \epsilon) \Delta s. \quad (3)$$

One sea model uses the EMC experimental determination of $\int_0^1 dx \cdot g_1^p(x, Q^2)$ to determine the sea distributions explicitly. This and A_8 sum rule can be used to determine the polarized

sea parameters. Then, the total spin carried by each of the quark flavors including valence and sea is

$$\begin{aligned}
\langle \Delta u_v \rangle + \langle \Delta u_s + \Delta \bar{u} \rangle &= 1.02 + (-0.24) = 0.78 \\
\langle \Delta d_v \rangle + \langle \Delta d_s + \Delta \bar{d} \rangle &= -0.25 + (-0.24) = -0.49 \\
\langle \Delta s + \Delta \bar{s} \rangle &= -0.15.
\end{aligned} \tag{4}$$

The total contribution from all flavors of sea quarks in this model is -0.63 ± 0.60 . The experimental errors of determining the parameters in the sum rules are reflected in this number. 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 the total spin carried by all quarks is about 0.79 to within experimental errors, consistent with the naive quark model. A theoretical concern with this model is that the spin carried by the sea quark pairs is much larger than the corresponding momentum. In an alternate model, the spin transfer densities of the sea anti-quarks and quarks are assumed to be limited. This implies a large value of ϵ , indicating that the strange sea is much harder to polarize, due to mass differences of the quark flavors. For a small polarized gluon distribution, the fraction of spin carried by all quarks in this model is about one half of the proton spin, which is significantly greater than that implied by the EMC motivated model. Here, the spin carried by the quark flavors is

$$\begin{aligned}
\langle \Delta u_v \rangle + \langle \Delta u_s + \Delta \bar{u} \rangle &= 1.02 + (-0.10) = 0.92 \\
\langle \Delta d_v \rangle + \langle \Delta d_s + \Delta \bar{d} \rangle &= -0.25 + (-0.10) = -0.35 \\
\langle \Delta s + \Delta \bar{s} \rangle &= -0.01.
\end{aligned} \tag{5}$$

Only a comprehensive experimental program in polarized beams can help to distinguish the accuracy of these theoretical models. The valence quark distributions can be determined from existing data on the longitudinal asymmetry in deep-inelastic lepton-proton scattering. Further precision measurements of the lepton-hadron scattering asymmetry are needed at small- x to reduce the uncertainties of the polarized valence quark distributions. The accelerators at CERN and Hamburg (HERA) can probe smaller x 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.⁹ Some¹⁰ have indicated that our understanding of QCD may be flawed in such a way to allow a violation of the Bjorken

sum rule. Measurement of A_1^{en} would provide significant additional information concerning nucleon spin structure.

The Drell-Yan process allows the most direct probe of the polarization of the antiquarks in the sea.¹¹ After integrating over transverse momentum, the spin-spin asymmetry for the production of lepton pairs in pp collisions can be given by

$$\frac{a_{LL}d\sigma}{dM^2dx_F} = \frac{4\pi\alpha^2}{3M^2} \cdot \frac{1}{3} \cdot \sum_q e_q^2 \left[x_F^2 + \frac{4M^2}{s} \right]^{-\frac{1}{2}} [\Delta q(x_a)\Delta\bar{q}(x_b) + \Delta\bar{q}(x_a)\Delta q(x_b)] \quad (6)$$

where $x_a = \frac{1}{2}[(x_F^2 + 4\frac{M^2}{s})^{\frac{1}{2}} + x_F]$ and $x_b = \frac{1}{2}[(x_F^2 + 4\frac{M^2}{s})^{\frac{1}{2}} - x_F]$. 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 1 shows our model estimates for the Drell-Yan asymmetry as a function of the invariant mass squared. 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.¹² The fundamental asymmetries for the $2 \rightarrow 2$ processes are known from perturbation theory¹ and can be used to determine the polarized distributions. We consider the integrated hard-scattering process $\Delta\sigma_L^{\text{jet}}(pp; p_T, \sqrt{s})$, where p_T is the momentum cutoff for defining a jet. At large CM energies, jet production is dominated by gluon-gluon scattering processes. Our explicit calculations show that a measurement of jet production with polarized beam and target would be sensitive to the gluon polarization. In figures 2 and 3 we show estimates for the polarized jet cross section, $\Delta\sigma_L^{\text{jet}}(pp; p_T, \sqrt{s})$ both as a function of $\sqrt{s}$ for $p_T = 5$ GeV and as a function of p_T at $\sqrt{s} = 75$ GeV. The predictions are very sensitive to the gluon polarization and so a measurement of $\Delta\sigma_L^{\text{jet}}$ should provide important early clues to the magnitude of $\Delta G(x, Q_0^2)$. Figure 4 shows the asymmetry A_{LL} for $pp \rightarrow \pi + X$ at $\sqrt{s} = 75$ GeV, which is also sensitive to the polarized gluon distribution, as discussed in reference 12. These predictions shown in figures 2 through 4 can be tested with the polarized proton beam at UNK. Analysis of data at various momentum cutoffs could shed considerable light on the size of the polarized gluon distribution.

An alternate 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 Qiu¹³ 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 UNK could probe transverse momenta necessary to make meaningful predictions.

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 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 Drell-Yan asymmetry, A_{LL}^{DY} for $\sqrt{s} = 75$ and $x_F = 0$ plotted as a function of the invariant mass squared. The asymmetries with EMC sea distributions are represented by solid curves, where the upper curve corresponds to ($c = 3$) while the lower to ($c = 1$). The alternate model asymmetries are represented by dot-dashed curves, with the upper ($c = 3$) and lower ($c = 1$) curves, respectively.
2. The polarized jet cross section, $\Delta\sigma_L^{jet}$, as a function of $\sqrt{s}$ for the momentum cutoff $p_T = 5$ GeV. The solid curve corresponds to the EMC motivated sea, and the dashed curve to the alternate sea model. The prominent curves correspond to a large gluon polarization, $\langle\Delta G\rangle = 5$. The other gluon models predict a much smaller jet cross section.
3. The polarized jet cross section, $\Delta\sigma_L^{jet}$, as a function of momentum cutoff for distinguishing a jet, p_t at $\sqrt{s} = 75$. Key: solid and dashed curves near the center correspond to the large ΔG model while the curves on the left to a moderate sized ΔG . The sea model designations are the same as in figure 2.
4. The asymmetry A_{LL} for $pp \rightarrow \pi + X$ plotted as a function of p_T using the distributions discussed in reference 12. Again the upper curves are predicted with the largest polarized gluon model, while the lower curves are predicted by the moderate and zero gluon models respectively, as discussed in the text. The sea distributions are designated the same as in figures 2 and 3.

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