Determining Spin-Flavor Dependent Distributions

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Abstract. Many of the present and planned polarization experiments are focusing on determination of the polarized glue. There is a comparable set of spin experiments which can help to extract information on the separate flavor-dependent polarized distributions. This talk will discuss possible sets of experiments, some of which are planned at BNL, CERN, DESY and JHF, which can be used to determine these distributions. Comments will include the estimated degree to which these distributions can be accurately found.

INTRODUCTION

During the past 20 years, considerable progress has been made in understanding the nature of polarized distributions within nucleons. Various theoretical models, coupled with data from polarized deep-inelastic scattering (PDIS) have allowed extraction of polarized quark distributions. The net result is that valence distributions and the up and down sea flavors are relatively well determined, but the polarized strange sea, gluons and their corresponding orbital angular momenta are unknown. The most recent efforts have generated theoretical calculations and experiments at RHIC, HERA, and CERN, designed to determine $\Delta G$. Many of these experiments are in progress.

We now have the theoretical and experimental techniques to pursue more detail into the flavor dependence of quark spin. Future efforts should include calculations and design of experiments to determine the spin contributions of all quark (and antiquark) flavors. This paper will discuss existing theoretical models, suggest a possible set of experiments and comment on the feasibility of determining these distributions.

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THEORETICAL MODELS

Models for the spin contributions of the valence quarks are based mostly upon modifications to the constituent quark model (CQM). [1, 2] These have the basic form:

\[ \Delta u_v(x) = M(x)[u_v(x) - 2d_v(x)/3] \]
\[ \Delta d_v(x) = M(x)(-d_v(x)/3) \]

where \( M(x) \) is a modification factor to the CQM. In the Carlitz-Kaur model, \( M(x) \) is a "dilution" factor due to creation of gluons and the sea from valence quarks at small-\( x \). In the Relativistic Constituent Quark Model (Isgur), it represents a possible range of hyperfine interactions of the valence quarks with the other constituents. A statistical model, based upon the Pauli exclusion principle, [3] generates a valence distribution in a similar form,

\[ \Delta u_v = u_v - d_v \]
\[ \Delta d_v = -d_v/3. \]

These three models predict valence distributions that are qualitatively similar, but give a range of possible extrema for \( \Delta u_v \) and \( \Delta d_v \) in the valence region, which can be tested with suitable polarization measurements.

The chiral quark model (\( \chi \)QM) [4] predicts integrals of the valence distribution over \( x \), with free parameters that can be fit with data. For appropriate ranges of these parameters, this model is consistent with the integral predictions of others. Lattice calculations of the moments of up and down valence distributions are consistent with the \( \chi \)QM for \( \Delta u_v \), but considerably less negative than the \( \chi \)QM prediction for \( \Delta d_v \). The exist a number of NLO fits of quark distributions to data, with assumed parametrizations of \( \Delta u_v \) and \( \Delta d_v \). [5, 6] These make certain assumptions about the symmetry of the polarized sea and could change with more experimental information. All of these valence models are consistent with the Bjorken Sum Rule and are similar in form. However, the differences are large enough to be distinguished by experimental measurements.

There is considerably more variance in the models for sea quarks, depending upon the assumptions made about how the polarized sea is generated. Sea models can be split into two categories: those based entirely on theoretical assumptions and the models that are a phenomenological combination of theory and experimental data. We will consider models providing a completely broken SU(3) polarized sea, where each flavor of quark/antiquark is determined separately. There is considerable theoretical evidence for broken SU(3). [7, 8, 9] Lattice calculations of the moments of the up and down sea have also indicated that this asymmetry could exist.

The statistical model mentioned above [3] combinations the Pauli exclusion principle, \( F_2 \) data and axial-vector couplings, \( F \) and \( D \) to represent the polarized up quarks in terms of the unpolarized antiquarks. All other flavors are assumed to be unpolarized. This places a tight restriction on the size of the polarized sea. A light-cone model of meson-baryon fluctuations puts the intrinsic \( q\bar{q} \) pairs with the valence quarks in an energetically favored state. [10] In this model, coupling to virtual \( K^+\Lambda \) hyperons is the source of intrinsic \( s\bar{s} \) pairs. Thus, the antiquarks are unpolarized and the light flavored quarks are polarized opposite to that of the proton.
TABLE 1.  Sea flavor contributions by type of model

| Model     | $\Delta u$ | $\Delta \bar{u}$ | $\Delta d$ | $\Delta \bar{d}$ | $\Delta s$ | $\Delta \bar{s}$ | $\Delta c$ | $\Delta \bar{c}$ |
|-----------|------------|------------------|------------|------------------|------------|------------------|------------|------------------|
| Statistical | $\bar{u} - \bar{d}$ | $\bar{u} - \bar{d}$ | 0          | 0                | 0          | 0                | 0          | 0                |
| L-Cone    | –          | –                | $< 0$      | 0                | $< 0$      | 0                | 0          | 0                |
| $\chi_{QM}$ | 0.83      | 0                | -0.39      | 0                | -0.07      | 0                | -0.003     | 0                |
| M-cloud   | $\Delta u$ | 0                | 0          | $\Delta u$      | –          | 0                | 0          | 0                |
| CQSM      | –          | $\Delta \bar{d} - C\chi^a(\bar{d} - \bar{u})$ | –          | see $\Delta \bar{u}$ | 0          | 0                | 0          | 0                |

In the chiral quark model, [4] the polarized sea determined by chiral fluctuations of the valence quarks, creating Goldstone bosons, which result in the prediction that $\Delta \bar{q} = 0$ for all flavors. As with the valence quarks, ranges for the integrals of the polarized sea quarks are predicted. The meson cloud model is similar, with pseudo-scalar mesons replacing the Goldstone bosons. [9] In contrast to the $\chi_{QM}$, the result is that $\Delta \bar{d} = \Delta u$ and the remaining quarks are unpolarized. In a chiral quark-soliton model, [7] quark fields interact with massless pions, yielding an asymmetry for the polarized up and down quarks, related to the unpolarized up and down antiquarks. This model has been phenomenologically tested in polarized semi-inclusive processes. [8]

Most predictions of heavy quark contributions to proton spin indicate that they are likely small. The $\chi_{QM}$ prediction gives $\Delta c \approx -0.003$ and $\Delta \bar{c} = 0$. Similarly, an analysis using the operator product expansion and the axial anomaly predicts that $\Delta c = -0.0024 \pm 0.0035$, consistent with the $\chi_{QM}$. [11] Instanton models tend to predict somewhat larger contributions from the heavier quarks. [12] These range from $\Delta c = -0.012 \pm 0.002 \rightarrow -0.020 \pm 0.005$. Thus, $\Delta c$ is at most a very small fraction of the total polarized sea and will likely prove quite difficult to measure.

Table 1 contains key results from some of the models described above for comparison. The most significant differences are in the predictions for the polarization of the antiquarks. This distinction can also be carried over to the theoretically motivated phenomenological models.

Phenomenological models range from those grounded in theoretical constraints and use data to fit parameters to the ones which are primarily parametrizations determined by fits to data. Models in which the polarized sea is created by gluons, that pass polarization “information” to the quarks by the splitting process, are in the former category. [5, 13] In the GGR model, [13] the flavor asymmetry of the polarized sea is caused by the asymmetry in the unpolarized distributions. Specific forms for the parametrization of the separate distributions come from axial-vector constraints and data.

Most direct data fits [5, 6] assume minimal SU(3) breaking of the polarized sea. Similarly, LO/NLO moment fits to data [14] result in only a small amount of SU(3) breaking, but a stronger asymmetry of the sea is possible within the cited error analysis. These theoretical and phenomenological models provide a sufficient variance for experiments to be able to distinguish between their fundamental assumptions.
EXPERIMENTS

Polarized valence distributions can be fine-tuned by measuring asymmetries in pion production. By taking differences of these asymmetries for $\pi^+$ and $\pi^-$ production, the valence contributions can be extracted. This results in:

$$\Delta A^\pi_p \equiv A^\pi_p - A^\pi_{\bar{p}} \approx \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}. \quad (1)$$

In the valence models previously discussed, these asymmetries differ by 0.2 for $x < 0.5$ and by 0.1 for $0.5 \leq x \leq 0.9$. Similarly, differences in $\pi^0$ production for $p$ and $\bar{p}$ yield large asymmetries for $0.1 \leq p_T/\sqrt{s} \leq 0.3$, but high energy $\bar{p}$ beams with sufficient luminosity for good statistics are difficult to achieve.

Present measurements of $\Delta (q + \bar{q})/(q + \bar{q})$ for the light quark flavors at HERA are providing a good start at finding the contributions of these flavors to the spin of the proton. [15] We would like to determine the individual spin contributions of each quark and antiquark flavor. For this, a combination of polarization experiments will be necessary. Charged current interactions are a useful tool in investigating kinematic dependences of both the polarized valence and sea quark distributions. The single spin asymmetries in parity-violating $W$ production ($A^{W+}_L$) can yield valuable information about the polarization of light quark flavors. [16]

$$A^{W+}_L(y) = \frac{\Delta u(x_a)d(x_b) - \Delta \bar{d}(x_a)u(x_b)}{u(x_a)d(x_b) + d(x_a)u(x_b)} \quad (2)$$

$$A^{W-}_L(y) = \frac{\Delta d(x_a)\bar{u}(x_b) - \Delta \bar{u}(x_a)d(x_b)}{d(x_a)\bar{u}(x_b) + \bar{u}(x_a)d(x_b)} \quad (3)$$

For example, at $y = 0$, $x \approx M_W/\sqrt{s}$ and the asymmetry measures combinations of $u$ and $\bar{d}$ or $d$ and $\bar{u}$. For $y = -1$, $x$ is small and the second terms in each numerator and denominator dominate, so we can separately probe $\bar{u}$ and $\bar{d}$. At $y = +1$, $x$ is of moderate value, the first terms in each numerator and denominator dominate so that both $u$ and $d$ polarizations can be measured. This would provide a more complete picture of the light quark polarizations. However, a limited kinematic range will be probed at RHIC. Therefore, this should be combined with other experiments to probe the sea polarization.

Combinations of polarized sea flavors can be investigated in a number of different experiments. For $W^\pm$ production in the HERA kinematic range, $g_5/F_1$ is extracted from the measured asymmetry. This yields the following combinations: $g_S^{W^-} = \Delta u + \Delta \bar{d} + \Delta \bar{s} + \Delta c$ and $g_S^{W^+} = \Delta \bar{u} + \Delta d + \Delta s + \Delta \bar{c}$. However, the uncertainties in the hadronic energy scale of the calorimeter are of comparable size to the asymmetries. Measurements may be difficult at RHIC as well, since these asymmetries are generally small at its kinematic range. Measurement of $g_3$ in polarized $e^+p \rightarrow \nu(\bar{\nu})X$ scattering at HERA could yield a similar combination of polarized flavors.

Parity-violating $\nu$ scattering ($p$ and $n$) measurement of $g_3$ at the proposed Japan Hadron Facility would give: $\frac{1}{2} [g_3^{\nu(p+n)} - g_3^{\nu(p-n)}] \sim \Delta s + \Delta \bar{s} - \Delta c - \Delta \bar{c}$. However, since
$g_3$ comes from $W_{\mu\nu}^\perp$, which is small, this may be difficult to distinguish.

Parity conserving double spin asymmetries in Z production $(A_{LL}^{Z0})$ provide a valuable tool in investigating the polarization of the antiquarks. This asymmetry is given by:

$$A_{LL}^{Z0}(y) \sim \Sigma_i \frac{\Delta q_i(x_a) \Delta \bar{q}_i(x_b) + \Delta \bar{q}_i(x_a) \Delta q_i(x_b)}{q_i(x_a) \bar{q}_i(x_b) + \bar{q}_i(x_a) q_i(x_b)}$$

Predicted asymmetries of $\sim 0.10$ for $\sqrt{s} = 500$ GeV could be distinguishable from zero with 400-500 events at RHIC. This would provide an excellent test of the light-cone, $\chi$QM and instanton models that predict zero polarization for antiquarks.

Polarized Drell-Yan experiments at both RHIC (at 50-100 GeV) or the proposed Japan Hadron Facility (JHF) at 50 GeV provide promising ways to extract more precise information about the polarization of the sea. At these energies, the cross sections are larger and the asymmetries are moderately sized. This makes the competing predictions easy to distinguish. The cross sections decrease rapidly with energy, so experiments at larger $\sqrt{s}$ are not good candidates for this set of measurements. The RHIC luminosity is low at 50 GeV, (the injection energy) but probably suitable at 100 GeV. Polarized beams at the JHF are quite appropriate for lepton pair production experiments and would be excellent for determining the relative size of the polarized sea. [17] These measurements in principle could distinguish the flavor dependence of the polarized sea. Combined with the experiments described above, they would give a complete picture of the sea polarization.

**CONCLUSION**

There has been considerable progress in narrowing the polarizations of the lighter quark flavors, $\Delta q_v$, $\Delta u_{tot}$ and $\Delta d_{tot}$. There exist many theoretical predictions for polarizations of the valence, sea quark and antiquark flavors. The experiments described here include most possibilities for determining the spin contributions of four quark and antiquark flavors. Many of the suggested measurements are feasible and should be done, since a combination of experiments would give the best range of information about quark spin. This opportunity opens up numerous possibilities for polarization experiments at RHIC, HERA, COMPASS and the JHF.

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