

# POLARIZED PARTON DISTRIBUTIONS AND THE POLARIZED GLUON ASYMMETRY

GORDON P. RAMSEY\*

Physics Department, Loyola University Chicago, 6525 N. Sheridan  
Chicago, IL 60626, USA

and

High Energy Physics Division, Argonne National Laboratory  
Argonne, IL 60439, USA

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## Abstract

The flavor-dependent valence, sea quark and antiquark spin distributions can be determined separately from theoretical assumptions and experimental data. We have determined the valence distributions using the Bjorken sum rule and have extracted polarized sea distributions, assuming that the quarks and anti-quarks for each flavor are symmetric. Other experiments have been proposed which will allow us to completely break the SU(3) symmetry of the sea flavors. To create a physical model for the polarized gluons, we investigate the gluon spin asymmetry in a proton,  $A_G(x, Q^2) = \frac{\Delta G(x, Q^2)}{G(x, Q^2)}$ . By assuming that this is approximately  $Q^2$  invariant, we can completely determine the  $x$ -dependence of this asymmetry, which satisfies constituent counting rules and reproduces the basic results of the Bremsstrahlung model originated by Close and Sivers. This asymmetry can be combined with the measured unpolarized gluon density,  $G(x, Q^2)$  to provide a prediction for  $\Delta G(x, Q^2)$ . Existing and proposed experiments can test both the prediction of scale-invariance for  $A_G(x, Q^2)$  and the nature of  $\Delta G$  itself. These models will be discussed along with suggestions for specific experiments which can be performed at energies typical of HERA, RHIC and LHC to determine these polarized distributions.

## 1 Introduction

One of the important questions in high energy physics is how the quark and gluon constituents contribute to nucleon spin. Significant interest in high energy polarization was generated when the European Muon Collaboration (EMC)[1] analyzed polarized deep-inelastic scattering (DIS) data which implied that the Bjorken sum rule (BSR) of QCD[2] was satisfied and the Ellis-Jaffe sum rule[3] based on a simple quark model was violated. Since then, the Spin Muon Collaboration

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\*E-mail address: gpr@hep.anl.gov. Talk given at SPIN 2001, Beijing, China.

(SMC)[4], experimental groups from SLAC[5] and the HERMES group[6] have measured  $g_1$  to lower  $x$  with improved statistics and have lowered the systematic errors from the original data.

Our general approach has been to split the polarized quark distributions into valence and sea components, and to use theoretical constraints and data to determine these distributions.[7] Theoretical constraints include the Bjorken sum rule, the quark counting rules at large  $x$  and positivity at leading order (LO). The structure functions  $g_1$  for the proton, neutron and deuteron can be extracted from the corresponding polarized DIS asymmetries  $A_1$ , by assuming that the structure functions  $g_2$  are small and that  $A_1$  is relatively independent of  $Q^2$ . Additional experimental information is extracted from hyperon decay data. The  $Q^2$  dependence of the distributions is generated by next-to-leading order (NLO) evolution.

The purpose of this paper is to outline present polarized quark models, introduce a gluon model and discuss how these can be determined with experiments planned at the major accelerators. The talk is outlined as follows: (1) models of the polarized valence and sea quark distributions are summarized, (2) means by which we can extract information about the polarized quark distributions from experiments are discussed (3) a physical model for the polarized gluons via the asymmetry  $\Delta G/G$  is presented and (4) a set of experiments is suggested, which would distinguish the quark and gluon contributions to the proton spin.

## 2 Quark Distributions

### 2.1 Valence quarks

There have been two models proposed for construction of the valence quark distributions. The original Carlitz-Kaur[8] model, based upon a modified SU(6) quark configuration and the Isgur[9] model, constructed from hyperfine splitting of the constituent quark model.

The original Carlitz-Kaur model constructed the polarized valence quark distributions from the unpolarized ones by starting with a modified 3-quark model based on an SU(6) proton wave function. From this, the valence quark distributions can be written as:

$$\begin{aligned}\Delta u_v(x, Q^2) &= \cos \theta_D [u_v(x, Q^2) - \frac{2}{3}d_v(x, Q^2)], \\ \Delta d_v(x, Q^2) &= -\frac{1}{3} \cos \theta_D d_v(x, Q^2),\end{aligned}\tag{1}$$

where  $\cos \theta_D$  is a "spin dilution" factor which vanishes as  $x \rightarrow 0$  and becomes unity as  $x \rightarrow 1$ , characterizing the valence quark helicity contribution to the proton.[8] Since the spin dilution factor is not derived from first principles, it is adjusted to satisfy the Bjorken sum rule, which is considered to be a fundamental test of QCD. This enables us to determine the valence distributions explicitly.

The resulting valence distributions are not very sensitive to the unpolarized distributions used to generate them.[7] In this model,  $\langle \Delta u_v \rangle = 0.90 \pm 0.03$  and  $\langle \Delta d_v \rangle = -.25 \pm 0.03$ , the spin contribution from the valence quarks is  $0.65 \pm 0.06$ . The errors arise from data on  $g_A/g_V$  and higher order corrections. These results are consistent with the measured magnetic moment ratio,  $\mu_p/\mu_n$ .

The Isgur model uses the hyperfine interactions of the constituent quark model to predict the valence distribution in the kinematic region  $0.3 \leq x \leq 0.9$ , where valence quarks dominate in the proton. The shape of the polarized valence distributions are slightly different from the Carlitz-Kaur model, but the essential features are the same. The minor differences are likely not distinguishable by any proposed experiments. Both models are consistent with recent SMC[10] and HERMES data.[6]

## 2.2 Sea quarks

We assume that the lightest flavors should dominate the spin of the sea, since the heavier quarks would be significantly harder to polarize. The SU(6) symmetry of the sea can be completely broken by considering the following:

- assuming that the polarization of the heavier strange quarks is suppressed,[7]
- since the unpolarized quark flavors are asymmetric and we assume that the polarized distributions depend upon these, there is reason to believe that there is flavor asymmetry in the polarized quarks,[11, 12]
- chiral quark model predictions.[13]

The sea distributions are then related by:

$$\begin{aligned}\Delta\bar{u}(x, Q^2) &= c_1\Delta u(x, Q^2) = c_2\Delta\bar{d}(x, Q^2) = c_3\Delta d(x, Q^2) \\ &= [1 + \epsilon]\Delta\bar{s}(x, Q^2) = [1 + \epsilon]\Delta s(x, Q^2),\end{aligned}\tag{2}$$

where  $\epsilon$  is a measure of the increased difficulty in polarizing the strange quarks and the  $c_i$  are due to the asymmetries in the quark and antiquark polarized distributions for each flavor. It is implicitly assumed that the strange sea is equally polarized ( $\Delta s \approx \Delta\bar{s}$ ). Since both are likely small, any differences due to meson-baryon effects in the fluctuation of the proton wave function,[14] are likely not distinguishable by polarized experiments. We also assume the the charm contribution to proton spin in this kinematic region is negligible compared to the light quark contributions.

Additional constraints are provided by the axial-vector current operators,  $A_3$ ,  $A_8$  and  $A_0$ . The coefficient  $A_8$ , determined by hyperon decay,  $A_0$  is related to the total spin carried by the quarks. Through these relations, we can extract specific information about individual contributions to the overall proton spin.

## 2.3 Extraction of quark distributions from data

There are various experiments proposed or in progress to extract the polarized quark distributions. The valence models can be tested to a rough approximation in deep-inelastic scattering[6] if certain simplifying assumptions are made about the symmetry of the polarized sea. If we wish to extract the separate flavors, independent of these assumptions, the best candidates would be differences in asymmetries measured in  $\pi^\pm$  and  $K^\pm$  production.[15] The sea distributions and dependence of the asymmetries on the fragmentation functions cancel in these differences, so that the individual valence distributions may be found. Here

$$A_p^{\pi^+} - A_p^{\pi^-} = \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}\tag{4}$$

$$A_p^{K^+} - A_p^{K^-} = \frac{\Delta u_v}{u_v}\tag{5}$$

$$A_d^{\pi^+} - A_d^{\pi^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v},\tag{6}$$

where  $p$  refers to a proton target and  $d$  to a deuteron target. The proton asymmetries would be sufficient to uniquely determine the valence distributions, but the deuteron measurement provides a good consistency check for these models.

As shown in ref. [7], we can extract values of the spin contribution of the sea quarks from deep-inelastic scattering and hyperon data, provided we assume symmetry within each flavor of the sea. Refer to Table 1 for a summary of these results. The estimated errors are based on which model of  $\Delta G$  is used and on the variations of the integrated structure functions ( $\int_0^1 g_1 dx$ ) taken from each experiment.

Table 1. Integrated Polarized Distributions

<i>Quantity</i>	<i>Range</i>	<i>Average</i>	$\Delta G$ <i>unc.</i>	<i>Exp. Var.</i>
$\langle \Delta u \rangle_{tot}$	0.80 $\rightarrow$ 0.90	0.86	$\pm 0.02$	$\pm 0.04$
$\langle \Delta d \rangle_{tot}$	-.36 $\rightarrow$ -.45	-.40	$\pm 0.02$	$\pm 0.04$
$\langle \Delta s \rangle_{tot}$	-.02 $\rightarrow$ -.12	-.06	$\pm 0.02$	$\pm 0.04$
$\langle \Delta q \rangle_{tot}$	0.23 $\rightarrow$ 0.52	0.40	$\pm 0.02$	$\pm 0.04$

From Table 1, we can draw the following conclusions:

(1) The naive quark model is not sufficient to explain the proton's spin characteristics, since the total quark contribution to proton spin falls between about  $\frac{1}{4}$  and  $\frac{1}{2}$ , with the average about  $\frac{1}{3}$ .

(2) All flavors of the sea are clearly polarized. The up and down contributions agree to within a few percent. All flavors satisfy the positivity bound [16]. However, the widest percentage variation is found in the polarized strange sea.

(3) 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.

If we are to allow a complete symmetry breaking of the sea, however, either more restrictions or different measurements are required for determination of the different distributions. One set of possibilities comes from measuring the  $g_1$  and  $g_5$  structure functions in charged current events, particularly  $W^\pm$  production.[17] Polarized lepton pair production could also yield useful information on the spin contributions from the sea.[12]

One scenario would be to extract  $g_1^+$  and  $g_5^+$  from  $W^+$  production and  $g_1^-$  and  $g_5^-$  from  $W^-$  production, in addition to the ratio of the integrated distributions,  $\Delta u_{tot}/\Delta d_{tot}$  in lepton pair production. This provides five constraints to determine the five polarized distributions:  $\Delta u_s$ ,  $\Delta d_s$ ,  $\Delta \bar{u}$ ,  $\Delta \bar{d}$  and  $\Delta s = \Delta \bar{s}$ . The only significant unknown remaining is the size and shape of the polarized gluon distribution.

### 3 The Polarized Gluon Distribution

The spin-weighted gluon density,  $\Delta G(x, Q^2)$ , is of fundamental importance in understanding the dynamics of hadron structure. Numerous experiments have been proposed[6, 15, 18] to extract this distribution. Although the polarized quark distributions are somewhat well known, the shape and size of  $\Delta G(x, Q^2)$  has not been determined. There have been phenomenological models proposed,[7] but they are not based upon strict physical models. However, the constituent quark model provides a framework for predicting an essential feature of  $\Delta G(x, Q^2)$ .

Spin observables at small  $Q^2$  conform to the non-relativistic quark model in which spin degrees of freedom are associated with constituent quarks. Thus the proton does not have a valence or "constituent" gluon polarization. At low  $Q^2 \leq m_p^2$ , a proton consists of three "valence" quarks, surrounded by radiated gluons and  $q\bar{q}$  pairs. In a variation of the Close-Sivers Bremsstrahlung model[20], gluons obtain their polarization from the valence quarks at low to medium values of  $x$  and  $Q^2$ . The QCD evolution equations can then be used to generate a prediction for the quark and gluon distributions at higher  $Q^2$ , from a  $Q_0^2$  where the constituent quark picture is applicable.

Using the assumptions from this model, we examine the gluon polarization asymmetry, defined as

$$A_G(x, t) \equiv \Delta G(x, t)/G(x, t), \quad (7)$$

where the evolution variable  $t \equiv \ln[\alpha_s(Q_0^2)/\alpha_s(Q^2)]$ . It is assumed that the same factorization prescription is used to define all of the densities in Eq. (7).

In the absence of a ‘‘constituent’’ gluon, both  $G(x, t)$  and  $\Delta G(x, t)$  exhibit scaling violations which can be associated with radiative diagrams. Since the positive and negative helicity gluon diagrams are the same, the probability of measuring a gluon of either helicity does not depend upon  $t$ . Thus, we assume that the gluon polarization asymmetry is scale invariant:  $\partial A_G(x, t)/\partial t = 0$ , where  $t = 0$  coincides with a typical hadronic scale,  $Q^2 = m_H^2$ . Scale-invariance provides the  $x$  dependence of  $A_G(x)$ , satisfying several physical constraints:

- it obeys the constituent-counting rules,
- for large  $x$ , where quark contributions dominate the gluons, the asymmetry coincides with the original QCD-Bremsstrahlung model of Close and Sivers[20]. At other values of  $x$ , it corresponds to a natural extension of this approach by allowing for radiation from both quarks and gluons, and
- for small  $x$ , where the gluon contribution is dominant, the scale-invariant asymmetry has a natural asymptotic limit, independent of the starting point.

The asymmetry, combined with parametrizations of polarized and unpolarized distributions provides an estimate for  $\Delta G(x, Q_0^2)$  at any convenient reference scale. The requirement that  $A_G(x, t)$  has no  $t$ -dependence implies that

$$\frac{\partial A_G}{\partial t} = \frac{1}{G} \left[ \frac{\partial \Delta G}{\partial t} - A_G(x, t) \frac{\partial G}{\partial t} \right] = 0. \quad (8)$$

The  $t$ -dependence of the gluon distributions is given by the corresponding DGLAP evolution equations. Since  $\Delta G$  has not been measured, we can convert Eq. (8) into a non-linear equation for  $A_G(x)$  by inserting  $\Delta G(x, t) = A_G(x) \cdot G(x, t)$  into the convolution of the evolution equations, giving

$$A_G = \frac{\frac{\partial \Delta G}{\partial t}}{\frac{\partial G}{\partial t}} = \left[ \frac{\Delta P_{Gq} \otimes \Delta q + \Delta P_{GG} \otimes (A_G \cdot G)}{P_{Gq} \otimes q + P_{GG} \otimes G} \right]. \quad (9)$$

An equation in this form can be solved iteratively. We first observe that for a given value of  $x$ , the distributions in the DGLAP equations enter only in the range  $[x, 1]$ . Then, for a large enough  $x$  ( $x \geq 0.6$ ), the gluons can be neglected. The polarized DIS data are consistent with the constituent counting rule result that  $\lim_{x \rightarrow 1} A_1(x, Q^2) \approx \lim_{x \rightarrow 1} \Delta u_v(x, Q^2)/u_v(x, Q^2) = 1$ . Thus, we make an initial approximation

$$\lim_{x \rightarrow 1} A_G^0 = \left[ \frac{\Delta P_{Gq} \otimes \Delta u_v}{P_{Gq} \otimes u_v} \right]. \quad (10)$$

in terms of the flavor non-singlet quark distributions, valid for large  $x$ . We can then define the iterative approximation:

$$A_G^{n+1} = \left[ \frac{\Delta P_{Gq} \otimes \Delta q + \Delta P_{GG} \otimes (A_G^n \cdot G)}{P_{Gq} \otimes q + P_{GG} \otimes G} \right], \quad (11)$$

which should converge for large enough  $n$ . For the starting distributions and the iterations, we use the polarized quark distributions outlined by GGR[7] and the CTEQ4M unpolarized distributions.[21]

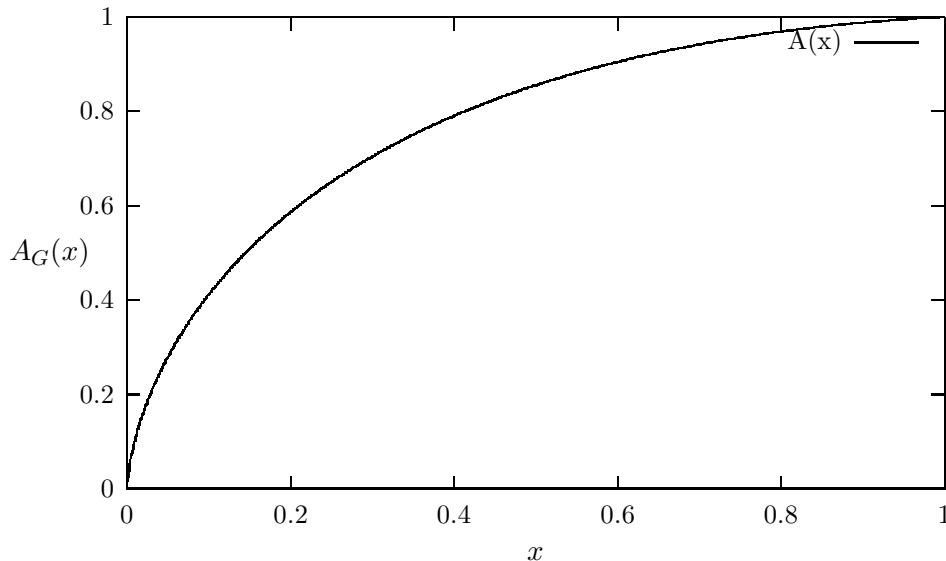


Figure 1: The gluon asymmetry  $\frac{\Delta G}{G}$  plotted as a function of  $x$

The iterations continue until a suitable convergence is reached. The spin-weighted gluon asymmetry is then determined explicitly by  $\Delta G(x, t) = A_G(x) \cdot G(x, t)$ . The resulting shape of  $A_G(x)$  is shown in Figure 1. This implies a larger polarized gluon distribution than the  $xG$  model of GGRA[7], so spin asymmetries which depend upon  $\Delta G$  are enhanced.

At small- $x$ , the argument that  $\frac{\partial A_G}{\partial t} = 0$  implies that  $A_G$  maintains its  $x$ -dependent shape asymptotically in  $t$ . Discussion can be found in ref. [19]. The uncertainties at small- $x$ , range from  $\pm 0.02$  at  $x \approx 0.20$  up to  $\pm 0.1$  below  $x = 0.05$ . These are primarily due to NLO corrections.

## 4 Experimental Program

There are many experiments either in progress or that have been proposed, to provide the means to determine the polarized distributions. These include:

- polarized lepton-hadron scattering (DIS)
- polarized lepton pair production
- jet production
- direct photon production
- $\Delta G/G$  measurements
- cc events in  $W^\pm$  production
- fragmentation in  $\pi$  and  $K$  production.

Although polarized DIS does not provide complete information on the flavor dependence of the polarized sea distributions, much can be learned from precision  $x$ -dependent measurements. These

will provide a consistency check for the separate distributions as they are determined. As discussed in ref. [22], polarized jet production and prompt photon production are the best candidates for the determination of  $\Delta G$ . The appropriate kinematic regions for STAR and PHENIX to search are also discussed in that paper. There are a number of existing and planned experiments are suitable for measuring either  $A_G(x)$  or a combination of  $\Delta G(x, Q^2)$  and  $G(x, Q^2)$ . Since this model of  $\frac{\Delta G}{G}$  implies a larger polarized gluon than the GGRA model used in ref. [22], all of the asymmetries for direct- $\gamma$  and jet production should be enhanced, making them easier to distinguish from parametrizations of  $\Delta G$ .

The HERMES experimental group at DESY has measured the longitudinal cross section asymmetry  $A_{||}$  in high- $p_T$  hadronic photoproduction.[6] From this and known values of  $\frac{\Delta q}{q}$  from DIS, a value for  $A_G(x_G)$  can be extracted. Here,  $x_G = \hat{s}/2M\nu$  is the nucleon momentum fraction carried by the gluon. Our value at  $x_G = 0.17$  is within one  $\sigma$  of the quoted value of  $A_G = 0.41 \pm 0.18$  (stat.)  $\pm 0.03$  (syst.).

The COMPASS group at CERN.[15] plans to extract  $A_G$  from the photon nucleon asymmetry,  $A_{\gamma N}^{cc}(x_G)$  in open charm muon-production, which is dominated by the photon-gluon fusion process. This experiment should be able to cover a wide kinematic range of  $x_G$  as a further check of this model. The combination of these experiments will be a good test of the assumptions of our gluon asymmetry model and a consistency check on our knowledge of the gluon polarization in the nucleon.

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