The spin structure of the nucleon

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The measurements of the spin structure functions for the proton and neutron are reviewed. Recent high-precision data have allowed the Bjorken sum rule to be verified to within ca. 10% accuracy, providing a rigorous test of quantum chromodynamics, the current theory of strong interactions. The data show that there is a deficit between the spin carried by the quarks and the spin of the nucleon, as measured in deep-inelastic scattering. The theories of the deficit are discussed.

Keywords: spin structure; structure of the nucleon; deep-inelastic scattering

1. Introduction

Since the 1960s an extensive programme of studies of deep-inelastic lepton scattering has been carried out which has allowed a reasonably detailed understanding of the structure of the nucleon (Sloan et al. 1988; Cooper-Sarkar et al. 1998). In the 1980s, data from polarized beams incident on polarized targets became available, allowing the spin structure of the nucleon to be explored (Alguard et al. 1976, 1978; Baum et al. 1983; Ashman et al. 1988, 1989). The results of these measurements have led to the surprising observation that only a small fraction of the spin of the proton is carried by the quarks. The observation of this spin deficit took the world of particle physics by surprise when it was first discovered by the European Muon Collaboration (EMC) (Ashman et al. 1988, 1989), leading to many theoretical papers discussing the result.† In contrast, many static properties of baryons, e.g. their magnetic moments, can be reasonably well explained by assuming that all the spin of the baryons is carried by the quarks (Perkins 1987; Particle Data Table 1998). Since the publication of the EMC results, several experiments have produced measurements of impressive precision on both neutron and proton targets which have confirmed and extended the range of the data (Anthony et al. 1993, 1999; Adeva et al. 1998a; Abe et al. 1997, 1998; Airapetian et al. 1998; Ackerstaff et al. 1997). In this paper the polarized deep-inelastic experimental measurements are reviewed together with the possible theoretical explanations of the observed spin deficit.

2. Polarized deep-inelastic charged lepton scattering

The process of deep-inelastic scattering can be understood in the one-photon exchange approximation by the Feynman graph shown in figure 1. In this approximation

† Ashman et al. (1988, 1989) were identified as the most often cited experimental particle physics papers in the CERN Courier review (March 1996).
4-momentum = \( k \)

4-momentum = \( q \)

4-momentum = \( p \)

Figure 1. Feynman graph for deep-inelastic muon scattering in the one-photon exchange approximation. \( k \), \( q \) and \( p \) are the 4-momenta of the incident muon, exchanged photon and target proton, respectively.

the differential cross-section may be written (see Close (1979) for a review)

\[
\frac{d^2\sigma}{dx dy} = 2\pi M y \frac{\alpha^2}{Q^4} L_{\mu\nu} W^{\mu\nu},
\]

where \( L_{\mu\nu} \) is the lepton tensor and \( W^{\mu\nu} \) the hadron tensor.

The kinematic variables of deep-inelastic scattering are \( x = Q^2/2pq \), which is the fraction of the nucleon’s momentum carried by the struck quark, \( Q^2 \) the negative 4-momentum transferred to the virtual photon, and \( y = pq/pk \), where \( k \) is the 4-momentum of the incident lepton and \( p \) and \( q \) are the 4-momenta of the virtual photon and target nucleon of mass \( M \), respectively.

The hadron tensor \( W^{\mu\nu} \) can be split into two parts that are symmetric and antisymmetric under reversal of the spin of the target nucleon

\[
W^{\mu\nu} = W^{\mu\nu}_S + W^{\mu\nu}_A.
\]

(2.1)

For scattering from an unpolarized nucleon target, on averaging the spins the antisymmetric term cancels. In this case the cross-section can be expressed in terms of the usual unpolarized structure functions \( F_1 \) and \( F_2 \) for which extensive measurements exist (Sloan et al. 1988; Cooper-Sarkar et al. 1998). The cross-section can also be expressed in terms of \( F_2 \) and the related structure function \( R = \sigma_L/\sigma_T \), where \( \sigma_L \) and \( \sigma_T \) are the absorption cross-sections for longitudinal and transverse virtual photons, respectively. In the quark parton model, for spin-\( \frac{1}{2} \) quarks, \( R = 0 \) and

\[
2xF_1(x) = F_2(x) = \sum e_i^2 xq_i(x),
\]

(2.2)

where \( e_i \) and \( q_i(x) \) are the charge and density of the quark of flavour \( i \). Finite values of \( R \) are induced by the target quark transverse momentum (Altarelli & Martinelli 1978; Glück & Reya 1978).

If the lepton and target nucleon are polarized, the differences in cross-sections become sensitive to the antisymmetric part of the hadron tensor and the symmetric part cancels. This difference with the lepton and nucleon spins parallel and antiparallel is

\[
\frac{d^2\sigma^{\uparrow\downarrow}}{dx dQ^2} - \frac{d^2\sigma^{\uparrow\uparrow}}{dx dQ^2} = a g_1(x, Q^2) + b g_2(x, Q^2),
\]

(2.3)

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and when the lepton and nucleon spins are perpendicular, the cross-section difference is

\[
\frac{d^2\sigma^\uparrow\downarrow}{dx dQ^2} - \frac{d^2\sigma^\uparrow\uparrow}{dx dQ^2} = a' g_1(x, Q^2) + b' g_2(x, Q^2). \tag{2.4}
\]

Here the terms \(a, b, a', b'\) are calculable from quantum electrodynamics (QED) while the structure functions \(g_1, g_2\) carry the information on the spin structure of the nucleon. In order to determine these structure functions, the virtual photon asymmetries \(A_1\) and \(A_2\) are measured. The asymmetries given in equations (2.3) and (2.4) can be written

\[
\begin{align*}
\frac{d\sigma^\downarrow\downarrow}{dx} - \frac{d\sigma^\uparrow\uparrow}{dx} &\propto D(A_1 + \eta A_2), \\
\frac{d\sigma^\uparrow\downarrow}{dx} - \frac{d\sigma^\uparrow\uparrow}{dx} &\propto D[A_2 - \gamma(1 - \frac{1}{2}y)]A_1,
\end{align*}
\tag{2.5}
\]

where again the terms \(D, \eta\) and \(\gamma\) arise from QED,\(^\dagger\) whereas the asymmetries \(A_1\) and \(A_2\) are the virtual photon asymmetries, which depend on the details of the target structure. In terms of the virtual photon cross-sections the asymmetries are given by

\[
A_1 = \frac{\sigma_1/2 - \sigma_3/2}{\sigma_1/2 + \sigma_3/2}, \tag{2.6}
\]

where \(\sigma_{1/2}\) and \(\sigma_{3/2}\) are the photoabsorption cross-sections with the total photon–proton angular momentum in the \(J_z = \frac{1}{2}\) and \(\frac{3}{2}\) states, respectively. The asymmetry \(A_2\):

\[
A_2 = \frac{\sigma_{TL}}{\sigma_T} \leq \pm \sqrt{R}, \tag{2.7}
\]

where \(\sigma_{TL}\) is a cross-section arising from the interference of the transverse and longitudinal amplitudes. For spin-\(\frac{1}{2}\) quarks with zero transverse momentum the interference cross-section \(\sigma_{TL} = 0\), and hence the asymmetry \(A_2\) should be zero. Finite values of the longitudinal amplitudes, and hence of \(A_2\), can be induced by the target quark transverse momentum (Altarelli & Martinelli 1978; Glück & Reya 1978).

In the quark parton model, neglecting the effects of quark transverse momenta and the quark masses, the virtual photon can only be absorbed by a quark when the total photon–quark angular momentum is \(J_z = \pm \frac{1}{2}\). It is not absorbed from the \(J_z = \pm \frac{3}{2}\) state due to the conservation of angular momentum and the conservation of the quark helicities in the scattering process. Thus, \(\sigma_{1/2}\) and \(\sigma_{3/2}\) are proportional to the probability of the photon being absorbed by quarks parallel and antiparallel to the nucleon spin, respectively:

\[
\sigma_{1/2} \propto \sum_i e_i^2 q_i^+(x) \quad \text{and} \quad \sigma_{3/2} \propto \sum_i e_i^2 q_i^-(x). \tag{2.8}
\]

Here the plus (minus) implies quarks spinning parallel (antiparallel) to the nucleon spin, as illustrated in figure 2.

Thus

\[
A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\sum e_i^2 q_i^+(x) - e_i^2 q_i^-(x)}{\sum e_i^2 q_i^+(x) + \sum e_i^2 q_i^-(x)} = \frac{g_1(x)}{F_1(x)}, \tag{2.9}
\]

\(^\dagger\) Detailed expressions for the terms \(a, b, a', b', D, \eta\) and \(\gamma\) can be found in Hughes & Kuti (1983).
where the polarized structure function,

\[ g_1(x) = \sum e_i^2 \{ q_i^+(x) - q_i^-(x) \} \]

and the unpolarized structure function is related to the quark distributions by equation (2.2). Here we have neglected terms of order \( \eta \) and \( \gamma \), which are usually small, in order to illustrate the simple relationships between the structure functions and the virtual photon asymmetries.

### 3. History of the spin structure functions

When the quark parton model was first developed in the early 1970s (see Close (1979) for a review) there was intense interest in the spin structure of the nucleon. It was quickly realized that the static Quark Model in which all the properties of the proton are determined by the valence quarks would give a value of \( A_1 = \frac{5}{3} \) independent of \( x \). Models were then developed to allow for the dilution of this value by the sea quarks at small \( x \) and the enhancement expected at large \( x \), where the proton’s momentum is carried largely by u-quarks. At this time sum rules were also derived by Bjorken (1969, 1970) and Ellis & Jaffe (1974a, b); these are described below. An experimental programme was started at the Stanford Linear Accelerator Center (SLAC) to check these models and the measurements were found to be compatible with the quark parton model predictions in the measured range of \( x > 0.1 \) (Alguard et al. 1976, 1978; Baum et al. 1983; see also figure 3).

In 1983, a large polarized proton target (Brown et al. 1984) was installed in the EMC apparatus and a programme of measurements of the asymmetry in deep-inelastic muon scattering, with the spins of the muon and proton parallel and antiparallel, began. The positively charged muons, which originated from \( \pi^+ \) and \( K^+ \) decay, were naturally ca. 80% polarized and this polarization was calculated from the known
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The EMC (Ashman et al. 1988, 1989) and SLAC E80 and E130 (Alguard et al. 1976, 1978; Baum et al. 1983) data compared with the quark parton model prediction of Carlitz & Kaur (1977a, b) (•, EMC data; ○, SLAC E80 data; □, SLAC E130 data; ——, Carlitz & Kaur (1977a, b) model).

Figure 3. The EMC (Ashman et al. 1988, 1989) and SLAC E80 and E130 (Alguard et al. 1976, 1978; Baum et al. 1983) data compared with the quark parton model prediction of Carlitz & Kaur (1977a, b) (•, EMC data; ○, SLAC E80 data; □, SLAC E130 data; ——, Carlitz & Kaur (1977a, b) model).

The target was in two halves, each polarized in opposite directions parallel or antiparallel to the beam. The beam passed sequentially through each target half so that the asymmetry could be measured directly from the difference in count rates from scattering in each target half. The polarizations of the two target halves were measured by nuclear magnetic resonance and were typically ca. 80%. The polarizations were inverted at intervals of time and the average asymmetries taken to equalize the acceptance of the apparatus for each target half. The measured asymmetry $A_m$ is related to the virtual photon asymmetry $A_1$ by

$$A_m = \frac{d\sigma^{\perp\perp} - d\sigma^{\perp\uparrow}}{d\sigma^{\perp\perp} + d\sigma^{\perp\uparrow}} = P_B P_T D f A_1,$$

(3.1)

neglecting the term in $\eta A_2$ in equations (2.5). Here $f$ is the fraction of target nucleons which is free, polarized protons, and $P_B$, $P_T$ are the polarizations of the beam and target, respectively. Figure 3 shows the measured values of $A_1$ as a function of $x$ from the EMC measurements compared with the earlier SLAC measurements. There is good agreement between the EMC and SLAC data in the region of overlap for $x > 0.1$ and these data are consistent with the predictions from the quark parton model. One version of this model is shown by the smooth curve in figure 3 (Carlitz & Kaur 1977a, b). However, the EMC data at small $x$ were inconsistent with the models. This inconsistency caused considerable theoretical interest and led to the name ‘spin crisis’ being given to the implied deficit (see below) between the spin of the nucleon and the spin carried by its quarks, as measured in deep-inelastic scattering (Leader & Anselmino 1988).

Following the publication of the EMC results (Ashman et al. 1988, 1989), new experiments were designed to improve and extend the EMC measurements. These experiments have produced impressive new measurements (Anthony et al. 1993, 1999; Adeva et al. 1998a; Abe et al. 1997, 1998; Airapetian et al. 1998; Ackerstaff et al.

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1997), including measurements of the structure function $g_2$, which is found to be small (Adams et al. 1994, 1997; see also Abe et al. 1998). These experiments have confirmed the original EMC measurements and the conclusion that only a small fraction of the spin of the nucleon is carried by its quarks in deep-inelastic scattering.

4. The measured spin deficit

The spin deficit is derived from the integrals of $g_1^p$ and $g_1^n$ over $x$. These integrals can be expressed as follows (Hughes & Kuti 1983):

$$\int_0^1 g_1^p(x) \, dx = \Gamma_1^p = \frac{1}{12} a_3 f(\alpha_s) + \frac{1}{36} a_8 f(\alpha_s) + \frac{1}{9} a_0 h(\alpha_s), \quad (4.1)$$

$$\int_0^1 g_1^n(x) \, dx = \Gamma_1^n = -\frac{1}{12} a_3 f(\alpha_s) + \frac{1}{36} a_8 f(\alpha_s) + \frac{1}{9} a_0 h(\alpha_s), \quad (4.2)$$

where functions $f(\alpha_s)$, $h(\alpha_s)$ represent the QCD radiative corrections, with $\alpha_s$ the strong coupling constant, which have been calculated to third order (Kodaira et al. 1979a;b;c; Larin & Vermaseren 1991; Larin et al. 1991) and estimated to fourth order (Kataev & Starshenko 1995):

$$f(\alpha_s) = 1 - \frac{\alpha_s}{\pi} - 3.5833 \left( \frac{\alpha_s}{\pi} \right)^2 - 20.215 \left( \frac{\alpha_s}{\pi} \right)^3 - \sim 130 \left( \frac{\alpha_s}{\pi} \right)^4 + \cdots, \quad (4.3)$$

$$h(\alpha_s) = 1 - \frac{\alpha_s}{\pi} - 1.0959 \left( \frac{\alpha_s}{\pi} \right)^2 - \sim 6 \left( \frac{\alpha_s}{\pi} \right)^3 + \cdots. \quad (4.4)$$

The $a_j$ in equations (4.1) and (4.2) are directly related to the proton matrix elements of the nonet of axial vector currents

$$A_j^\mu = \bar{\psi} \gamma^\mu \gamma_5 (\lambda_j/2) \psi, \quad j = 0, 1, \ldots, 8,$$

by

$$\langle P, S| A_j^\mu | P, S \rangle = 2 M a_j S^\mu,$$

where $S^\mu$ is the covariant spin vector of the proton. From isospin invariance it follows that (Bjorken 1969, 1970)

$$a_3 = g_A = F + D = 1.26, \quad (4.5)$$

where $g_A$ is the ratio of the axial vector and vector coupling constants measured in neutron $\beta$ decay. If $SU(3)_F$ is a good symmetry for describing the $\beta$ decays of the octet of hyperons, then

$$a_8 = 3F - D, \quad (4.6)$$

where $F$ and $D$ are the symmetric and antisymmetric couplings obtained from hyperon decay. There is no theoretical prediction for $a_0$.

In the quark parton model the $a_j$ are given by

$$a_0 = \Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}, \quad (4.7)$$

$$a_8 = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} - 2(\Delta s + \Delta \bar{s}), \quad (4.8)$$

$$a_3 = g_A = \Delta u + \Delta \bar{u} - \Delta d - \Delta \bar{d}, \quad (4.9)$$

where

$$\Delta q = \int_0^1 (q^+(x) - q^-(x)) \, dx$$

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for the flavours u, d and s. The term $\Delta \Sigma$ represents the total fraction of the spin of the proton carried by the quarks. Predictions for the values of the integrals in equations (4.1) and (4.2) were obtained by assuming $\Delta s + \Delta \bar{s} = 0$, taking the values of $a_3$ and $a_8$ from equations (4.5) and (4.6) and relating $a_0$ to $a_8$ by equations (4.7) and (4.8). This is the Ellis–Jaffe sum rule (Ellis & Jaffe 1974a, b).

The early SLAC measurements (Alguard et al. 1976, 1978; Baum et al. 1983) were compatible with the Ellis–Jaffe sum rule within a large error. However, the EMC measurements (Ashman et al. 1988, 1989), which covered a wider $x$ range, allowed a much more precise determination of the integral for the proton. The EMC measurements showed that $\Gamma_1^p = 0.126 \pm 0.010 \pm 0.015$, where the first error is statistical and the second error is systematic. This contradicted the value predicted from the Ellis–Jaffe sum rule. Furthermore, using the values of $F$ and $D$ from the fits at the time (Bourquin et al. 1983) and substituting this measurement of the integral into equation (4.1) allowed $a_0$ to be determined, showing that the quarks carried a fraction $12 \pm 9 \pm 14$% of the total spin of the proton. Subsequent refitting of the hyperon decay data (Close & Roberts 1993) gives values of $F$ and $D$ that cause this to rise to ca. 30%. The more recent experiments from both proton and neutron targets give similar values for this fraction. The deep-inelastic scattering data therefore indicate that the quarks carry a much smaller fraction of the proton spin than that expected from the static Quark Model of the nucleon.

5. Theories of the spin deficit in deep-inelastic scattering

Various theories have been put forward to explain the spin deficit observed in deep-inelastic scattering. One theory (Close & Roberts 1994) proposes that the structure function $g_1^p$ diverges at $x < 0.01$ so that there is a large contribution to the integral there. Such behaviour would imply that there is a significant part of the nucleon spin contained in the quark sea at very small $x$ which turns on suddenly in the unmeasured region. This would seem rather surprising. Measurements have been made by the SMC at very low $Q^2$ and $x$, in the Regge region (Adeva et al. 1999; see also Mulders & Sloan 1999). There is no sign of the divergent Regge behaviour proposed in the explanation of Close & Roberts (1994). Nevertheless, one of the areas of uncertainty in the determination of the integrals is the behaviour in the unmeasured region at very small $x$.

Another possible explanation could be that the strange sea quarks in the nucleon are polarized. Inspection of equations (4.7)–(4.9) shows that once $a_0$, $a_3$ and $a_8$ are known the equations can be solved for $\Delta u$, $\Delta d$ and $\Delta s$ (quarks and antiquarks added). The solution shows that the u-quarks are strongly polarized along the proton spin direction, the d-quarks are strongly polarized in the opposite direction and the s-quarks have a polarization of $-0.12 \pm 0.03$ (see Karliner & Lipkin (1999) and Goto et al. (2000) for a recent analysis). Experiments are currently ongoing at Jefferson Laboratory (experiment E-91-004) using electroweak interference to measure the polarization of the strange quarks in the sea. An experiment at MIT–Bates (Spyade et al. 2000), studying such electroweak interference, has reported the observation that the strange quark magnetic form factor of the proton is non-zero. However, the measured effect is of opposite sign to that expected from the polarized deep-inelastic scattering results (Manohar 2000). Hence the interpretation of this result is still unclear.

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An explanation of the effect has also been given (Brody et al. 1988; Ryzak 1989) using the Skyrme model of the nucleon in the chiral limit of massless quarks and in the leading order of the $1/N_c$ expansion. This model would imply that a large fraction of the spin of the nucleon should appear as orbital angular momentum.

Another set of models (Jaffe 1987; Efremov & Teryaev 1988; Altarelli & Ross 1988) propose that there is a further QCD radiative correction due to the Adler–Bell–Jackiw anomaly (Adler 1969; Bell & Jackiw 1969; Glück & Reya 1978) so that

$$\Delta \Sigma \to \Delta \Sigma - \frac{\alpha_s}{2\pi} \Delta G,$$

where

$$\Delta G = \int_0^1 G^+(x) - G^-(x) \, dx$$

is the mean z-component of the spin of the gluons in the proton. Since $\alpha_s \Delta G$ is approximately constant with $Q^2$, then at low $Q^2$, where $\alpha_s$ is large, $\Delta G$ would be small and the static quark picture would prevail. Hence this model can reconcile the success of the static Quark Model and the spin deficit observed in polarized deep-inelastic scattering. There is an ongoing programme (COMPASS Proposal 1996; Saito 1995) to measure the value of $\Delta G$ in polarized deep-inelastic scattering, which should be large if this is the explanation of the spin deficit. An estimate of $\Delta G$ has been made using fits of next-to-leading-order (NLO) QCD to a wide range of measured values of the polarized structure function $g_1$ for both the proton and the neutron. These show that at $Q^2$ equal to 1 GeV$^2$,

$$\Delta G = 0.99^{+1.17+0.42+1.43}_{-0.31-0.22-0.45},$$

where the first error is statistical, the second systematic and the third is the uncertainty in the theory (Adeva et al. 1998b). This indicates, within large errors, that $\Delta G$ could be large, but the result is not conclusive. The theoretical error originates from the range in $x$ and $Q^2$ of the present data. Data over a wider range, such as would become available if polarized measurements could be made at HERA, would reduce this error considerably (Deshpande et al. 1996).

6. Checks of the Bjorken sum rule

The Bjorken sum rule can be used to rigorously check the theory of strong interactions, quantum chromodynamics (QCD). It can be seen from equations (4.1) and (4.2) that if the difference between the integrals is taken the singlet terms in $a_8$ and $\Delta \Sigma$ cancel, and with them all the theoretical uncertainties, leaving the Bjorken sum rule (Bjorken 1969, 1970):

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_A f(\alpha_s).$$

(6.1)

This is a deeply fundamental sum rule, which, if violated, implies serious consequences for QCD (Feynman 1972).

Experimental checks of the Bjorken sum rule have recently been made (see Adeva et al. (1998a), Abe et al. (1998), Airapetian et al. (1998) and Ackerstaff et al. (1997); see also Borel (1998) for preliminary results of E155) and these are shown in figure 4.†

† Corrections to the data in figure 4 have been made (in the same manner as described in Abe et al. (1998)) to the HERMES proton and E155 proton and neutron measurements for the extrapolation into the unmeasured regions.

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Figure 4. Measurements of the Bjorken sum rule integrals, $\Gamma_1^p - \Gamma_1^n$, as a function of $Q^2$ compared with the expected values. The dashed line (zeroth order) shows the value without QCD radiative corrections, the dotted line includes the first-order corrections (Kodaira et al. 1979a, b, c), while the solid line includes corrections up to third order (Larin & Vermaseren 1991; Larin et al. 1991) (Δ, HERMES data; □, SMC data; ◦, E143 data; ○, E155 (preliminary) data).

The horizontal dashed line is the value uncorrected for QCD radiative corrections (i.e. $f(\alpha_s) = 1$ in equation (6.1)). The dotted curve shows the first-order corrections represented by the first two terms of equation (4.3), and the solid curve shows the third-order corrections represented by the first four terms of equation (4.3). The data disagree with the uncorrected (zeroth-order) calculation but the agreement becomes acceptable once the corrections up to the third order in QCD are applied. In this plot we have neglected higher twist effects, which are thought to contribute at the level of $(-0.02 \pm 0.01)/Q^2$ (Balitsky et al. 1990; see also Ross & Roberts 1994).

The agreement of the measurements with the theory of QCD shows that this theory is surviving stringent checks up to its higher-order corrections. It behoves the experimenters to improve the accuracy of the measurements of this sum rule and the theoreticians to refine the calculations of the higher-order corrections to it so that higher precision checks of QCD may be made.

7. Conclusions

The data on the spin structure functions of the proton and neutron are becoming very precise. They show that there is a deficit between the spin of the proton and the total spin carried by the quarks as measured in deep-inelastic scattering. The data indicate that the deficit could be carried by the gluons and this would then be compatible with the successes of the static Quark Model. However, there are also some indications that the strange quarks in the nucleon may be polarized and we cannot yet exclude the skyrmion model. More and better data will be needed to

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locate the source of the deficit definitively. The measurements are compatible with the Bjorken sum rule once higher-order QCD radiative corrections are taken into account. This provides a strong check on the theory, and the fact that we can compute correctly such higher-order corrections attests to the depth of our understanding of the theory of QCD.

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