SPIN STRUCTURE FUNCTIONS

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The experimental status of the spin-dependent structure functions as obtained from the deep inelastic scattering experiments at CERN, SLAC, and DESY is reviewed. All data show a violation of the Ellis-Jaffe sum rule. The Bjorken sum rule is found to be valid and is tested to the 10% level.

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1 Introduction

After the discovery by the EMC that the contribution of the quark spins to the proton spin is much smaller than expected, new experiments were proposed and set up to study this "spin puzzle." First was the experiment of the Spin Muon Collaboration (SMC) at CERN, followed by the SLAC experiment and the HERMES experiment at DESY. In parallel, intensive work started on the theoretical side. The information obtained from the measurements is twofold. On one hand, the test of the Bjorken sum rule provides a sensitive test of QCD, on the other hand, the nonperturbative spin-avours structure of the nucleon is contained in the polarised parton distribution functions. The structure function data are now precise enough to perform sensible QCD analyses and to determine the parton distribution functions. However, the precision of the data is still far from the quality of the spin-averaged structure function measurements and several constraints are needed in the QCD analyses. An important aim is to understand the nucleon's spin in terms of the spins of quarks and gluons, \( \sum q^2 = u^2 + d^2 + s^2 + g^2 \), and their orbital angular momenta, \( L_q \) and \( L_g \),

\[
\frac{1}{2} = \frac{1}{2} + L_q + g + L_g.
\]

It is well known from both experiment and theory, that at high \( Q^2 \) about half of the nucleon's longitudinal momentum is carried by the gluons. Recently, it was predicted that the same sharing should apply for the total angular momentum. In the Quark Parton Model, the quark polarisations,

\[
q = q^+ + q^- + q^0 \quad ;
\]

and
are related to the spin-dependent structure function $g_1$ by

$$g_1(x; Q^2) = \frac{1}{2} \sum_f e_f^2 q_f(x; Q^2);$$

where $f$ runs over the quark flavours and $e_f$ are the electrical quark charges. The notations $q_f$ refer to parallel (antiparallel) orientation of the quark and nucleon spins.

Experimentally the spin-dependent structure functions, $g_1$ and $g_2$, are obtained from the measured event-number asymmetries, $A_k^{\text{raw}}$, for longitudinal orientation of the target and lepton spins, and $A_2^{\text{raw}}$ for transverse target polarisations. These raw asymmetries range for the proton typically from a few per cent at large $x$ to a few parts per thousand at small $x$. In the lepton-nucleon asymmetries, $A_k$ and $A_2$, the uncertainties of the raw asymmetries get amplified by the factor $1=P_b P_t f$ accounting for the incomplete beam and target polarisations, $P_b$ and $P_t$, and the dilution factor, $f$. Typical target materials contain a large fraction of unpolarisable nucleons and $f$ denotes the fraction of the total spin-averaged cross section arising from the polarisable nucleons. For the target materials used, $f$ varies from about 0.13 (butanol), over 0.17 (ammonia) to 0.3 ($^3$He). For deuterated butanol and ammonia $f$ is 0.23 and 0.3, respectively, while for the proton and deuteron gas targets of the HERMES experiment $f$ is close to unity. The neutron structure functions are either obtained from the combination of proton and deuteron data or from experiments using $^3$He targets. The deuteron asymmetries are slightly reduced from the average of proton and neutron asymmetries due to the $D$-state component in the deuteron wave function. The $^3$He asymmetry is mainly due to the unpaired neutron, however a small proton contribution has to be corrected for. Due to the cancellation of the isoscalar part in $g_1$, the measurement using deuteron targets are most sensitive to the avour-singlet part, and thus to the violation of the Ellis/Jaffe sum rule. The structure functions, $g_1$ and $g_2$, are related to the virtual-photon asymmetries, $A_1$ and $A_2$, via

$$A_k = D (A_1 + A_2); \quad A_1 = d(A_2 - A_1);$$

$$A_1 = \frac{g_1 - 2g_2}{F_1}; \quad A_2 = \frac{g_1 + g_2}{F_1};$$

Here $F_1 = F_2 (1 + \frac{2}{Q^2})$ is the well-known spin-averaged structure function and $Q^2 = Q^2_{\text{cm}}$, and are kinematic factors, which are small in most of the kinematic domain covered by the data. The variables $Q^2$ and $q^2$ denote respectively the energy transfer and negative square of the 4-momentum transfer. The kinematic factors, $D$ and $d$, account for the incomplete transverse polarisation of the virtual photon. With longitudinal target
polarisation predominantly $g_1$ is determined, while experiments with transverse target polarisation are sensitive to $g_1 + g_2$. The virtual photon asymmetries are bounded by $\mathcal{A}_1 \frac{j_1}{R}$ and $\mathcal{A}_2 \frac{j_2}{R}$, where $R = \frac{L}{T}$ is the longitudinal-to-transverse photoabsorption cross-section ratio known, like $F_2$, from unpolarised deep inelastic scattering.

2 The Experiments

New data from the 1995 runs come from the SMC (deuteron), the HERMES experiment (³He) and the SLAC experiment E-154 (³He, preliminary). Some important parameters of these and the earlier experiments are summarised in Table 1 and the kinematic ranges of the SMC and E-143 experiments are compared in Fig. 1.

The experiments of the SMC were performed at the CERN muon beam at 190 GeV using a large, double-cell solid-state polarised target. Data with parallel and antiparallel orientation of the lepton and target spins were taken simultaneously. This technique cancels most systematic uncertainties and overcomes the problem that the natural polarisation of the muon beam cannot effectively be reversed. Average polarisations of 86% and 50% were achieved for the butanol and deuterated butanol targets used in the years 1992-1995. The opposite polarisation of the material in the two 65 cm long cells was reversed.
Table 1: Parameters of the experiments

| Experiment | Lab. | Beam | $Q^2$ | $x$ range | Targets |
|------------|------|------|-------|-----------|---------|
| E-80/130   | Slac | 22 GeV | e | 4 | 0.18 | 0.7 | p |
| EM C       | Cern | 200 GeV | x | 10.7 | 0.01 | 0.7 | p |
| SM C       | Cern | 190 GeV | e | 10 | 0.003 | 0.7 | p, d |
| E-142/143  | Slac | 29 GeV | e | 213 | 0.03 | 0.8 | $^3$He, p, d |
| E-154/155  | Slac | 48 GeV | e | 5 | 0.014 | 0.7 | $^3$He, p, d |
| HERMES     | Desy | 27 GeV | e | 3 | 0.023 | 0.6 | $^3$He, p, d |

every 5 h. In the 1996 run a proton target made of ammonia was employed. The incoming and scattered muons were analysed by magnetic spectrometers. Hadrons produced in the scattering were also detected. However, a particle identification beyond electron-hadron separation was not attempted. A dedicated spectrometer downstream of the main scattering spectrometer ensures the about 80% polarization of the muon beam by two methods. One is based on the dependence of the energy spectrum of the decay positrons on the parent muon polarization, the other uses the asymmetry in polarized muon-electron scattering from a magnetised iron foil. The domain unique to the SM C experiment is high $Q^2$ and small $x$ which is essential for the extrapolation to $x = 0$ and for QCD analyses of the structure function data.

The SLAC experiments E-142/E-143 and E-154 were performed at the SLAC electron beam in End Station A with energies up to 29 and 48 GeV, respectively. The rather low energy of the incoming electron limits the accessible kinematic range. Apart from the E-142 experiment (39%) electron polarizations of 80% were reached using strained-lattice GaAs photocathodes. The electron polarization was varied randomly on a pulse-by-pulse basis and measured by Möller scattering from thin iron magnetic foils. For the neutron experiments, E-142 and E-154, a $^3$He gas target with a pressure of 10 bar was used and polarizations of 30(40)% were reached by spin-exchange with optically pumped rubidium vapour. With the ammonia targets used in the E-143 experiment and foreseen for the E-155 experiment polarizations of 65(80)% for NH$_3$ and 25% for ND$_3$ were reached. For the E-155 experiment running in 1997 also a $^6$LiD deuteron target is foreseen. The lithium-6 nucleus can be understood as an $^4$He+$^2$H system yielding for $^6$LiD a favourable dilution factor $\alpha = 0.5$. The scattered electrons were analysed by two magnetic spectrometers placed under different scattering angles to increase the acceptance. With the intense electron beam much higher luminosities than with muon beams
can be achieved yielding smaller statistical errors. The accuracy of the results obtained from the SLAC experiments is thus systematically limited.

A different technique is applied in the HERMES experiment which started data-taking in 1995. The electrons in the HERA ring self-polarize by the Sokolov-Ternov effect to about 50%. Spin rotators before and after the target provide longitudinal electron polarization. A 40 cm long windowless storage cell placed in the ring is filled with up to $10^{17}$ atoms/s which are then pumped away at both ends of the cell. Thus pure polarized proton, deuteron, and $^3$He targets can be used without diluting the asymmetries by the presence of unpolarized target materials. This target technique is in particular ideal to study hadrons produced in the deep inelastic scattering process. The polarization of the hydrogen and the deuterium target can be changed within milliseconds while obtaining equilibrium in the $^3$He target takes about 20 s. With the $^3$He target employed in the 1995 run polarizations of 50% were reached. The scattered electrons are analysed in an open magnetic spectrometer. Particle identification is provided by the combined information from a TRD, a threshold Cherenkov counter, and a lead-glass calorimeter. Due to the limited energy of the HERA electron ring of 27 GeV HERMES cannot extend the kinematic range of the SM C and SLAC experiments. However, it will provide high-precision semi-inclusive data.

3 A symmetries and Structure Functions

The virtual-photon asymmetries measured by the various experiments with proton, deuteron, and neutron targets are summarized for $Q^2 > 1$ GeV$^2$ in Fig. 2. Although the SM C data were taken at an about six-times higher value of $Q^2$ than the SLAC E-143 data the agreement between the two data sets is excellent. Thus, in the region of overlap, the data are compatible with no $Q^2$ dependence of $A_1$. A symmetric for $Q^2 < 1$ GeV$^2$ were published by the E-143 Collaboration and by the SM C. However, due to higher-twist contributions they are difficult to interpret. From the asymmetries and Eqs. 1, the structure function $g_1$ is obtained as

$$g_1(x; Q^2) = \frac{F_2(x; Q^2)}{2x(1 + R(x; Q^2))} A_1(x; Q^2) + A_2(x; Q^2).$$

(6)

Usually the term $A_2$ is neglected, what is consistent with experimental results for $A_2$. In the analysis of some SLAC experiments, where $Q^2$ is larger than in the high-energy muon experiments, Eqs. 1 were solved for both, $A_1$ and $A_2$. It all analyses the parametrisations of $F_2$ by the NMC and of $R$ by SLAC were used. New $R$ data from the NMC for $x < 0.1$ agree
Figure 2: The virtual-photon asymmetry, $A_1$, as a function of $x$. The shaded bands indicate the systematic errors, from top to bottom: proton: E-143, SMC; deuteron: E-143, SMC; neutron: E-142, HERMES, E-154.

well with $R_{QCD}$, where $R_{QCD}$ is calculated in perturbative QCD using the experimental gluon distribution function. In this x region, previously basically uncorrected by experiments, the SLAC $R$ parametrization deviates somewhat from the data. Note that apart from radiative corrections and $Q^2$ extrapolations the $R$ dependence cancels in the experimental $g_1$, when the same values of $R$ were used in the $g_1$ and $F_2$ analyses. For a recent review of the unpo-
Figure 3: The structure function $g_1(x;Q^2)$ as a function of $x$ at the $Q^2$ of the individual measurements. The systematic errors are indicated by the shaded bands, from top to bottom: proton: E-143, EMC, SMC; deuteron: E-143, SMC; neutron: E-142, HERMES, E-143, E-154, SMC. The E-143 and SMC neutron data are calculated from the proton and deuteron data.

F i g. 3: T h e s t r u c t u r e f u n c t i o n $g_1(x;Q^2)$ a s a f u n c t i o n o f $x$ a t t h e $Q^2$ o f t h e i n d i v i d u a l m e a s u r e m e n t s . T h e s y s t e m a t i c e r r o r s a r e i n d i c a t e d b y t h e s h a d e d b a n d s , f r o m t o p t o b o t t o m : p r o t o n : E-143, E M C , S M C ; d e u t e r o n : E-143, S M C ; n e u t r o n : E-142, H E R M E S , E-143, E-154, S M C . T h e E-143 a n d S M C n e u t r o n d a t a a r e c a l c u l a t e d f r o m t h e p r o t o n a n d d e u t e r o n d a t a .

L a r g e s t s t r u c t u r e f u n c t i o n s w i t h e m p h a s i s o n t h e x e d-t a r g e t e x p e r i m e n t s s e e R e f . [ 2 4 ] .

T h e s t r u c t u r e f u n c t i o n d a t a a t t h e $Q^2$ o f t h e i n d i v i d u a l m e a s u r e m e n t s a r e s h o w n i n F i g . 3 . T h e v a l u e s o f $Q^2$ v a r y f r o m a b o u t 1 G e V $^2$ f o r t h e s m a l l e s t - $x$ p o i n t o f e a c h d a t a s e t t o t y p i c a l l y 50 G e V $^2$ (10 G e V $^2$) f o r t h e l a r g e s t - $x$ p o i n t .

7
of the SM C (SLAC) data. A study of the $Q^2$ dependence of $A_1$ using the
combined SM C/EM C and SLAC data was first published by the E-143 Col-
aboration. No significant $Q^2$ dependence was found for $Q^2 > 1 \text{ GeV}^2$. For this
analysis only one SM C data point per $x$-bin at an average $Q^2$ was available. A
compilation of all now available deuteron asymmetries (SM C/E-143) is shown
in Fig. 4. The proton data are in precision and kinematic coverage similar to
the deuteron data. Still the experimental precision is not sufficient to reveal
any $Q^2$ dependence of $A_1$. It has to be noted that in the small-$x$ region, where
rather large effects are expected, the relevant $Q^2$ is very limited.

With more precise data available in a large kinematic range and after
the next-to-leading order splitting functions were calculated in 1995 QCD
analyses of the $g_1$ data start to become sensible. From these analyses
the size of the $Q^2$ dependence of $g_1$ can be estimated. Using the method and
code of Ref. 23 the SM C repeated the QCD analysis using all EM C/SM C/E-
143 proton and deuteron data (Fig. 5). Although the neutron data were not
included in the fit, the agreement is excellent (Fig. 6). A study of the system-
atic uncertainties showed that the main error sources are the choice of the
factorisation and renormalisation scales, the parametrisations of the parton
distribution functions, and the uncertainty in the strong coupling constant.
Due to these uncertainties the predicted $Q^2$ dependence in a given $x$-bin can vary considerably, in particular in the small-$x$ region where the $Q^2$
slope of $g_1$ changes sign. The systematic errors were accounted for in the evaluation
of the sum rules by the SM C. A similar study including also the E-142 and
the preliminary E-154 neutron data was performed by the authors of the
evolution code with similar results.

The data for the asymmetry $A_p^2$ and $A_d^2$ from the SM C and the E-143
Collaboration are compatible with zero in the whole covered $x$ range with a
possible exception of $A_p^2$ for $x > 0.2$ (Fig. 7). The resulting structure functions,
$g_2^{p,d}$, are shown for the SLAC data in Fig. 8. The solid line in Fig. 8 represents
the twist-2 part, $g_2^{x,w}$, which is calculable from $g_1$,

$$g_2^{x,w}(x;Q^2) = g_1(x;Q^2) + \frac{Z}{x} \int_y g_1(y;Q^2) \frac{dy}{y}$$  (7)

The data agree well with $g_2^{x,w}$ and a possible twist-3 contribution, which relates
to quark-gluon correlations, cannot be resolved within the accuracy of the
present data.
4 Test of the Sum Rules

To evaluate the Ellis-Jaffe and Bjorken sum rules for the first moments of $g_1$,

$$Z_{1} \left(Q_0^2 \right) = \int_{0}^{1} g_1 \left(x; Q_0^2 \right) \, dx,$$  (8)
the structure functions have to be known at a fixed, preferably high, value $Q^2_0$ of $Q^2$. Experiments cannot presently provide this kind of data because $Q^2$ is limited by the incident lepton energy, $E_l$, to $Q^2 \leq 2M E_l$. Thus at small $x$ the data necessarily are obtained at small $Q^2$. Until recently the standard procedure to evaluate $g_1$ from the asymmetries was to assume scaling of either $A_1$ or of $g_1=F_1'/A_1$ and thus to account only for the $Q^2$ evolution of $F_2$ and $R$ in Eq. (6).

The second potentially dangerous step in the evaluation of $g_1$ is the extrapolation from the measured region to $x = 0$, i.e., from $x \approx 0.03$ for the SLAC and $x \approx 0.003$ for the SMC data. This extrapolation is usually performed assuming a Regge-type behaviour of the form $g_1/x^3$ with $0.5 < x < 0.1$. However, the theoretically proposed shapes vary widely, and the onset of a certain predicted behaviour is usually not well defined. Therefore it is mandatory to measure to as small values of $x$ as possible. In perturbative QCD one expects that $g_1$ turns negative at small $x$ and reasonably high $Q^2$. Such a drop is visible in the SMC neutron data and was recently confirmed by the preliminary E-154 neutron data for the region, $x > 0.014$ (Fig. 6). This $x$ behaviour is incompatible with the Regge-like behaviour of $g_1^n$ for $x < 0.03$ assumed in the analysis of the earlier E-143 data. As is obvious from Fig. 6 it
Figure 7: The asymmetry $A_2$ as a function of $x$ for the proton and the deuteron from the SMC and SLAC E-143 experiments. Also shown is the limit for the kinematics of the SMC experiments (solid line).

Figure 8: The structure function $g_2$ as a function of $x$ for the proton and the deuteron from the E-143 experiment. The solid line indicates the twist-2 part $g_2^{tw}$. The dashed and dotted lines refer to bag-model calculations of $g_2$.

is difficult to perform a sensible extrapolation to $x = 0$ from the E-154 neutron data alone. The Collaboration only quotes the integral for the measured region, $0.014 < x < 0.7$, of $0.037 - 0.011$ at $Q^2 = 5$ GeV$^2$. Assuming a power law the E-154 Collaboration found $g_1^p(x; 0) = 0.02 x^{0.8}$ corresponding to an integral of $0.043$ for $0 < x < 0.014$, which would even exceed the contribution from the measured region.

The extrapolation to $x = 1$ is uncrical due to the bound $A_1 \leq 1$ and the smallness of $F_2$ in this region. The results for the first moments of $g_1$ are summarised in Table 2 and are shown in Fig. 9.

The SMC was the first experimental group to include a full next-to-leading order QCD evolution in their analysis (Figs. 5, 6). The effect of the evolution from the $Q^2$ of the measurement, $Q^2_0$, to $Q^2$ was estimated by

$$g_1(x; Q^2) = g_1(x; Q^2_0) + g_1^\tau(x; Q^2_0) + g_1^\tau(x; Q^2),$$

(9)

where $g_1^\tau$ refers to $g_1$ as calculated from the twiss parton distribution functions. The differences of the first moments obtained with QCD evolution and with the scaling assumption for $A_1$ are small (Table 3), partly due to cancellations of contributions from different $x$ regions. The Ellis-Jaffe pre-
Table 2: Results for the Ellis-Jaeckel sum, \( Q^2_\text{rel} \)

|         | HQ \( s \) | Proton | Deuteron | Neutron | Bjorken |
|---------|------------|--------|----------|---------|----------|
| SM C    | 10         | 0.136  (16) | 0.041  (7) | 0.047  (21) | 0.183  (34) |
| SM C \( \text{scale} \) | 10         | 0.139  (17) | 0.037  (8) | 0.059  (24) | 0.198  (35) |
| E-143   | 3          | 0.127  (11) | 0.042  (5) | 0.037  (14) | 0.163  (19) |
| E-142   | 2          |         |         | 0.031  (11) |         |
| Hermes  | 2.5        |         |         |         |         |
| SM C \( \text{comb} \) | 5          | 0.142  (11) | 0.038  (6) | 0.061  (16) | 0.202  (22) |
| ABFR    | 3          | 0.114  | 0.027  | 0.056  | 0.170  |
| Sum rules | 10        | 0.171  (4) | 0.071  (4) | 0.017  (4) | 0.187  (2) |
|         | 5          | 0.165  (4) | 0.071  (4) | 0.016  (4) | 0.181  (3) |
|         | 3          | 0.166  (5) | 0.070  (4) | 0.015  (4) | 0.176  (4) |

The SM C and the ABFR \( (\text{F} \& A) \) analyses use NLO QCD evolution. In the SM C \( \text{scale} \) and the other analyses scaling of \( A_1 \) or \( g_1=F_1 \) is assumed. The SM C \( \text{comb} \) analysis includes SM C, E-143, and E-142 data. The neutron values in italics are obtained by combining proton and deuteron data. Statistical and systematic errors were added in quadrature.

dictions given in Table 2 and shown as shaded bands in Fig. 9 were calculated using QCD corrections\(^{11}\) up to order \( O \left( \frac{Q^2}{s} \right)^2 \) with three quark averages, \( s \left( M^2 \right) = 0.118 \pm 0.003 \), \( F_1 = 1.2601 \pm 0.0005 \), and \( F = D = 0.575 \pm 0.016 \).

All experiments found a violation of the Ellis-Jaeckel sum rule independent of the target material. The most significant results are obtained for the deuteron, where the violation amounts to \( 4.1 \pm 3.7 \) standard deviations for the E-143 (SM C) data. Also the re-analysed E-142 neutron data\(^{9}\) now show a violation of the sum rule, while when first published\(^{9}\) in 1993 agreement was reported.

The results for the Bjorken sum, \( \frac{P}{n} P \), are summarised in Table 3 and Fig. 14, where for comparison all experimental results were evolved to \( Q^2 = 1 \) using corrections\(^{13}\) up to order \( O \left( \frac{Q^2}{s} \right) \) and the constants given above. All results are in agreement with the Bjorken sum rule prediction, \( 0.100 \pm 0.003 \), for \( Q^2 = 1 \). The value for the E-143 data assuming scaling of \( A_1 \) instead of \( g_1=F_1 \) was taken from Ref.\(^{12}\). For the SLAC data obtained at \( Q^2 = 3 \) GeV\(^2\), the agreement improves when higher-order corrections are estimated using the technique of Padé approximants\(^{14}\). For small \( Q^2 \) this method yields a much stronger dependence of the Bjorken sum rule on \( s \) than obtained from the corrections up to \( O \left( \frac{Q^2}{s} \right) \). As a consequence the determination of \( s \) from the Bjorken sum data at small \( Q^2 \) results in a very small statistical error, \( s \left( M^2 \right) = 0.117 \pm 0.004 \). This method would yield similar small errors when applied to e.g. the CCFR data\(^{15}\) for the Gross(Llewellyn Smith) sum.
Figure 9: Results for the Ellis-Jaffe sum as a function of $Q^2$. The shaded bands indicate the theoretical prediction and its uncertainty.

The assessment of the theoretical uncertainties shown as second error for $s$ has been criticised. Using corrections to $O(\alpha^2)$ only, one obtains about three times larger uncertainties for the strong coupling constant. In this case a more significant result can be obtained from the scaling violations of $g_1$, $s(\mu^2) = 0.120^{+0.010}_{-0.008}$.

The SMC performed a combined analysis of the first moments at $Q^2 = 5\text{ GeV}^2$ using a next-to-leading order QCD evolution. The analysis was performed x-bin per x-bin and includes all published proton, deuteron, and neutron
Figure 10: Results for the Bjorken sum for comparison evolved to $Q^2 = 1$.

In such a procedure the SLAC extrapolations for $0.003 < x < 0.03$ are replaced by the SM C small-$x$ data. The result,

$$P^nn = 0.202 \quad 0.022 \quad \text{at} \quad Q^2 = 5 \text{ GeV}^2; \quad (10)$$

lies somewhat above the theoretical prediction of $0.181 \quad 0.003$. The combined result is larger than the individual results because the SM C data yield a larger contribution at small-$x$ than the SLAC extrapolations, while at large-$x$ the SLAC data lie slightly above the SM C data. In better agreement with the Bjorken sum rule is the integral of the fitted structure functions from the QCD analysis, which were used to evolve the data, $q_1^p q_1^n \int dx = 0.188$ at $Q^2 = 5 \text{ GeV}^2$. However, this result depends on the parametrisation of the parton distribution functions, particularly in the unmeasured region. In a similar analysis including also the neutron data the authors of the evolution code found a Bjorken integral of $0.170$ at $Q^2 = 3 \text{ GeV}^2$ ($\pm A$) also in good agreement with the Bjorken sum rule. A significant difference between the two methods is that the SM C combined analysis involves a Regge-type extrapolation, while in the integration method the fitted $g_1$ is also used in the region $x < 0.003$. 
Table 3: Results for and $s$ at $Q^2 = 1$

| Exp. | target | $p$ | $d$ | $n$ | $u$ | $d$ |
|------|--------|-----|-----|-----|-----|-----|
| SM C | p      | 0.25 (15) | 0.28 (7) | 0.22 (10) | 0.30 (5) | 0.41 (13) |
| SM C | d      | 0.28 (7) | 0.10 (10) | 0.09 (2) |
| E-143 | p      | 0.22 (10) | 0.10 (10) |
| E-143 | d      | 0.30 (5) | 0.09 (2) |
| E-142 | n      | 0.41 (13) | 0.06 (4) |
| SM C comb |     | 0.28 (6) | 0.11 (2) |
| ABFR  |       | 0.10 (7) |

The results for the avour-singlet axial-current matrix element $b$, and the polarisation of the strange quarks, $s = \int s(x) dx$, are summarised in Table 3. The values were obtained from the results for $\gamma$, using the constants given above. The dependence of the SU(3) avour symmetry assumed in the derivation of the Ellis-Jaffe sum rule is weak, while the result for $s$ strongly depends on $\gamma$. All results are given for $Q^2 = 1$. The SM C combined result:

\[ u = 0.28 \pm 0.06 \quad \text{and} \quad s = 0.11 \pm 0.02; \]

was evaluated in the same way as the combined value for the Bjorken sum and includes the SM C, E-142, and E-143 data. For the polarisation of the up and down quarks the SM C combined analysis yields $u = 0.28 \pm 0.06$ and $d = 0.42 \pm 0.02$. A much smaller value for $s$ is obtained from QCD fits to the data, due to the different treatment of the unmeasured small $x$ region. For the most significant case, the deuteron, the extrapolation from $x = 0.003$ to $x = 0$ amounts to $0.016$ for the $t$ ABFR \[^{[4]}\] in Table 3 at $Q_0^2 = 10 \text{ GeV}^2$, while aRegge-like extrapolation from the SM C deuteron data yields zero. The question of the small-$x$ behaviour of $g_1$ must eventually be settled by a measurement.

5 Sem i-inclusive A sym m etries

In unpolarised deep inelastic scattering the avour separation of the parton distribution functions is accomplished by the combination of data from charged-lepton and charged-current neutrino scattering, which weight the individual quark avours differently. Neutrino experiments require huge targets, which

\[^{[4]}\]Note that the notation corresponds to $a_0 (1)$ in e.g. Ref. [23].
are not available in the polarised case. If the HERA proton beam can be polarised, charged-current electron-proton scattering at high $Q^2$ would become possible.\footnote{Presently the only access to flavour separation is semi-inclusive scattering, where the emerging hadron carries some memory of the flavour of the initially hit quark. The fragmentation of a quark $q$ into a hadron $h$ is described by the fragmentation functions $D^h_q$. The fragmentation factorises from the hard scattering process and the differential cross section reads,

$$
\frac{1}{N} \frac{dN}{dz} = \frac{1}{N} \frac{dN}{dz} = \frac{P}{q} \frac{e_q^2 q(x;Q^2) D^h_q(z;Q^2)}{q e_q^2 q(x;Q^2)},
$$

where $N$ is the number of produced hadrons, $N$ the is the number of deep-inelastic events, $z = E_h/E_i$ is the quark’s energy fraction carried by the hadron, and $e_q$ are the quark charges. The sum runs over $q = u,d,s;u,d,s$, and $e_q$ are the quark charges.

The only data on flavour separation to date come from the SM C. The preliminary data presented here include the 1995 data set. The asymmetries for positive and negative hadrons for both proton and deuteron targets, are shown
is Fig. 11. In the analysis a cut of $z > 0.2$ was applied and the fragmentation functions were taken from EMC measurements. The HERMES Collaboration also presented hadron asymmetries for a $^3$He target. However, only together with their not yet available 1996 proton data a flavour separation can be performed. The preliminary SMC results for the valence quark distributions, $q_v$ with $q_v(x) = q(x) - \bar{q}(x)$, are shown in Fig. 12. The up valence quarks show a positive polarization over the whole $x$ range, while the down valence quarks are polarized oppositely to the proton spin. For the first moments the SMC obtains $u_v = 0.85 \pm 0.14 \pm 0.12$, $d_v = 0.58 \pm 0.16 \pm 0.11$, and $g_v = 0.02 \pm 0.06 \pm 0.03$, where $u(x) = d(x) = q(x)$ was assumed. The analysis is largely insensitive to $s(x)$, which was assumed to be proportional to $s(x)$ with a first moment as obtained from 1.

6 Conclusions and Outlook

The main goals of the experiments initiated after the discovery of the "EMC spin effect", in particular the confirmation of the EMC proton result, the extension of the measurements to smaller $x$, a measurement of the neutron or deuteron structure function and thus a test of the Bjorken sum rule are now largely achieved. The data from all experiments are in good agreement and draw a consistent picture, where the Bjorken sum rule is tested with a precision of about 10% and where is of the order of 30%. However, still the original question raised by the EMC result of how the spin of the nucleon is built up from the spins and the orbital angular momenta of quarks and gluons is unanswered. The interest has now turned to the $Q^2$ dependence of $g$, and the role of the gluon polarization, $g$, which via the axial anomaly contributes to $g$. If the violation of the Ellis-Jaffe sum rules is entirely attributed to the anomalous contribution of $g$ to $g$, a gluon polarization of $g = 2.5$ at $Q^2 = 10$ GeV$^2$ is required. QCD analyses indicate that $g$ is positive and of about this size. Also a QCD sum rule calculation indicates a large and positive value for $g$.

To make further progress in our understanding of the nucleon's spin structure a direct measurement of $g$ is indispensable. An unambiguous determination of $g$ can only be achieved studying a process where $g$ enters in leading order. The cleanest such process is the photon-gluon fusion, which can either be tagged by open charm, $g! c\bar{c}$, or $2+1$-jet production. The former is proposed for the approved COMPASS experiment at CERN while the latter is aimed at by the project to polarise the HERA proton beam. Processes using hadronic probes, like $p\bar{p}$ collisions at RHIC are in general more difficult to interpret. A detailed understanding of the nucleon's spin structure
must also include the third twist-2 structure function, the transversity h_{1}, which will be studied at HERMES, COMPASS, and RHIC.

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