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Combined analysis of world data on nucleon spin structure functions

Spin Muon Collaboration (SMC)

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We analyse the proton, deuteron and neutron spin dependent structure functions at fixed $Q^2 = 5$ GeV^2. The experimental asymmetries for the proton, neutron and deuteron are compared and found to be consistent. The first moment of the neutron structure function is evaluated using all available data. We find that the Bjorken sum rule is confirmed within an experimental uncertainty of 17%. The quark spin contribution to the nucleon spin is small, and the strange quark spin content is different from zero.

Recently, experimental results on the spin dependent structure functions of the deuteron $g_1^d(x)$ [1] and of the neutron $g_1^n(x)$ [2] have been reported by the Spin Muon Collaboration (SMC) and by the E142 Collaboration. Different conclusions have been reached from the analysis of these results. The conclusions from the deuteron experiment at CERN [1] agree with those of the earlier proton experiments E80 and E130 at SLAC [3] and EMC at CERN [4]. The first moment $\Gamma_1^d = \int_0^1 g_1^d\,\mathrm{d}x$ is smaller than the prediction of the Ellis–Jaffe sum rule [5]. The fraction of the nucleon spin carried by quark spins $\Delta\Sigma$ is small and the fraction of the nucleon spin carried by strange quarks Δs is appreciable and negative. On the other hand, the results from the E142 Collaboration at SLAC [2] agree with the prediction of the Ellis–Jaffe sum rule, $\Delta\Sigma$ is large and Δs is consistent with zero (see table 1).

Both the SMC and the E142 Collaboration have tested the fundamental Bjorken sum rule [6], combining their results with those from the proton experiments. The results from the SMC analysis [1] confirm the validity of the Bjorken sum rule, while E142 [2] reports a two standard deviation difference.

These results were reanalysed in refs. [7,8], where the Q^2 dependence of the sum rules, target mass and higher-order corrections were taken into account. In the present paper, we investigate the Q^2 dependence of the data and focus our analysis on the consistency

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Table 1
Results from experiments on polarized deep inelastic lepton scattering. The quantities Γ_1, $\Delta\Sigma$, Δs are defined in the text. The statistical and systematic errors have been added in quadrature.

	Data					
	x-range	$\langle Q^2\rangle$ (GeV^2)	Q^2 range (GeV^2)	Γ_1	$\Delta\Sigma$	Δs
proton [3,4]	0.01 -0.7	10.7	1-70	0.126 ± 0.018	0.12 ± 0.17	-0.19 ± 0.06
neutron [2]	0.03 -0.6	2.0	1- 7	-0.022 ± 0.011	0.57 ± 0.11	-0.01 ± 0.06
deuteron [1]	0.006-0.6	4.6	1-30	0.023 ± 0.025	0.06 ± 0.25	-0.21 ± 0.08

of the measured cross section asymmetries. Furthermore, we discuss the effect of combining low x measurements from the proton and the deuteron to extrapolate the neutron data in the unmeasured region. From all the available data, we evaluate the Bjorken sum rule, as well as the quantities $\Delta\Sigma$ and Δs.

We compare the polarised structure functions of the proton, neutron and deuteron using the following relation:

$$g_1^d(x,Q^2) = \tfrac{1}{2}[g_1^p(x,Q^2) + g_1^n(x,Q^2)](1 - \tfrac{3}{2}\omega_D), \quad (1)$$

where ω_D accounts for the D-state admixture in the deuteron wave function. The data for $g_1^p(x)$, $g_1^d(x)$ and $g_1^n(x)$ partially overlap in x, but for each x bin the average values of Q^2 are different. Hence, to test the consistency of the different experiments, data have to be evolved to a common value of Q^2.

The structure function $g_1(x,Q^2)$ is determined from the experimental virtual photon nucleon asymmetry $A_1(x,Q^2)$ via

$$g_1(x,Q^2) = \frac{A_1(x,Q^2)F_2(x,Q^2)}{2x[1+R(x,Q^2)]}. \quad (2)$$

Thus, the Q^2 dependence of $g_1(x,Q^2)$ is determined from that of A_1, of the spin independent structure function F_2 and of the ratio R of the longitudinal to the transverse virtual photon absorption cross section.

The measurements on the proton showed that $A_1^p(x)$ is independent of Q^2 within the experimental errors. The same conclusion can be drawn for $A_1^d(x)$, using both the SMC (deuteron) data and the combination of the E142 (neutron) and the E130 (proton) data using eqs. (1) and (2). The result is shown in fig. 1. For all bins in x, we find no evidence for a Q^2

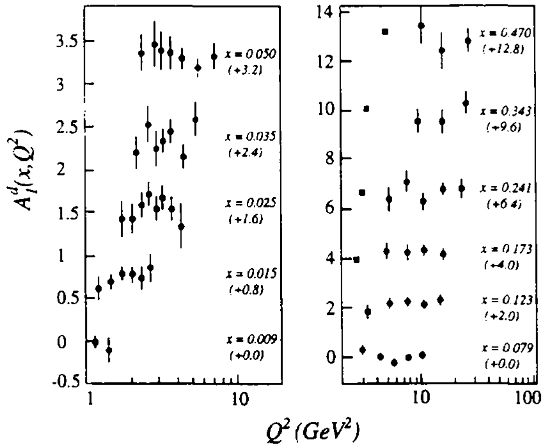

Fig. 1. A_1^d as a function of Q^2 for different values of x. The circles are SMC values. The squares are obtained from E80 + E130 and E142 data combined using eq. (3). The mean x value for each bin is shown. The numbers in parenthesis correspond to the vertical scale offset of each data set.

dependence of the experimental asymmetries.

The Q^2 evolution of the polarized structure functions can be calculated by perturbative QCD [9,10]. The parton distributions given in ref. [11] are in good agreement with the experimental values of $g_1^p(x)$ and $g_1^n(x)$. We have used the theoretical evolutions of $g_1^p(x,Q^2)$ and $g_1^n(x,Q^2)$, together with the parametrisations of $F_2(x,Q^2)$ [12] and $R(x,Q^2)$ [13] to evolve the experimental asymmetries $A_1^p(x)$ and $A_1^n(x)$ to the mean Q^2 of the SMC data in each bin of x. As a result we find that the scaling violations of A_1 predicted by this perturbative QCD calculation are small and not visible with the present experimental errors. This agrees with the results of ref. [14] where the effect of varying the gluon polarisation was investigated. Therefore, in the following discussion we assume $A_1(x)$ to be independent of Q^2 for all targets. We calculate the structure functions

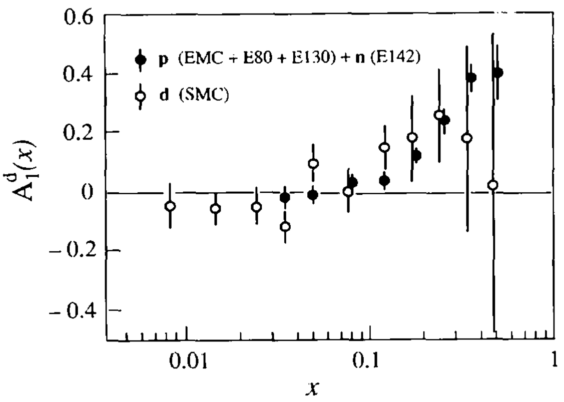

Fig. 2. A_1^d as a function of x. The open circles are SMC values. The full circles are obtained from EMC + E80 + E130 and E142 data combined using eq. (3). The corresponding x values are identical to those of SMC, but for clarity some of the data points are slightly shifted.

$g_1(x)$ and their first moments Γ_1 at a common value of $Q^2 = 5$ GeV^2.

To check the consistency among the proton, neutron and deuteron asymmetries we combine eqs. (1) and (2):

$$A_1^d = (A_1^p + A_1^n F_2^n/F_2^p)\frac{1 - \frac{3}{2}\omega_D}{1 + F_2^n/F_2^p}, \quad (3)$$

assuming $R^d = R^p = R^n$ [13,15]. We take the values for F_2^n/F_2^p from the NMC parametrisation [16] at $Q^2 = 5$ GeV^2. A χ^2 test on the consistency of the three data sets in the eight common x bins yields a value of 5.4 for 8 degrees of freedom which corresponds to a probability of 71%. Fig. 2 shows the $A_1^d(x)$ data points from SMC compared to the combination of the proton and neutron measurements using eq. (3). The data also satisfy the Kolmogorov test of compatibility at a confidence level of 75%. We conclude that the three data sets are consistent. This observation implies that the different physics conclusions derived by SMC [1] and by E142 [2] do not arise from incompatibilities in the measured asymmetries.

The first moments of the spin structure functions, needed to test the Bjorken sum rule, are obtained by integrating $g_1(x)$ from $x = 0$ to $x = 1$. This range includes unmeasured regions both at low and high x. The extrapolation of g_1 to high x assumes that $|A_1(x)| \leqslant 1$. For low x, following standard practice, we extrapolate the spin structure functions with a Regge-type [17] functional form $g_1(x) \propto x^{-\alpha}$. The value of α is expected [18] to be in the range $-0.5 < \alpha < 0$. Errors given below take into account the possible variations of α. Since the x value at which the Regge form becomes valid is not well known, the extrapolation should start from the data points at the smallest x. Thus, except in the extrapolation region, no assumption is made about the form of $g_1(x)$.

For the deuteron we obtain the published value $\Gamma_1^d = 0.023 \pm 0.025$ [1]. The error here and the errors throughout this paper are the quadratic sum of the statistical and systematic uncertainties.

The proton data yield in the measured region $\int_{0.01}^{0.7} g_1^p(x)\,dx = 0.122 \pm 0.017$. The extrapolations to $x = 1$ and to $x = 0$ give 0.001 ± 0.001 and 0.003 ± 0.003, respectively. The resulting first moment of the proton is $\Gamma_1^p = 0.126 \pm 0.018$ at $Q^2 = 5$ GeV^2. This value happens to be the same as that obtained by EMC at 10.7 GeV^2, using a different parametrisation for $F_2(x, Q^2)$.

We first evaluate Γ_1^n from the E142 data alone. In the measured region we obtain $\int_{0.03}^{0.6} g_1^n(x)\,dx = -0.023 \pm 0.006$. The extrapolations to $x = 0$ and to $x = 1$ amount to -0.008 ± 0.008 and 0.003 ± 0.003, respectively. We find $\Gamma_1^n = -0.028 \pm 0.012$ at $Q^2 = 5$ GeV^2, to be compared to the value published by E142, $\Gamma_1^n = -0.022 \pm 0.011$ at $Q^2 = 2$ GeV^2.

In a second step, we calculate Γ_1^n from all the available information. In addition to the E142 data, we determine the neutron structure function from the deuteron and the proton data using eq. (1). Fig. 3 shows $xg_1^n(x)$ for both the E142 data and the combined SMC + EMC data at $Q^2 = 5$ GeV^2. The two data sets on the neutron agree in the x region of overlap. We find $\int_{0.03}^{0.6} g_1^n(x)\,dx = -0.023 \pm 0.006$. This value is dominated by the high-statistics E142 data. At lower x the data from EMC and SMC yield $\int_{0.006}^{0.03} g_1^n(x)\,dx = -0.028 \pm 0.022$. To extrapolate to $x = 0$, we use the extrapolations of the muon data on g_1^d and g_1^p, since these data extend to significantly lower x values than the neutron data. This gives $\int_0^{0.006} g_1^n(x)\,dx = -0.007 \pm 0.006$. For $x > 0.6$ we take the estimated value from E142 $\int_{0.6}^{1} g_1^n(x)\,dx = 0.003 \pm 0.003$. Thus we obtain an overall $\Gamma_1^n = -0.055 \pm 0.025$ rather than $\Gamma_1^n = -0.028 \pm 0.012$ which corresponds to the E142 result evolved to $Q^2 = 5$ GeV^2.

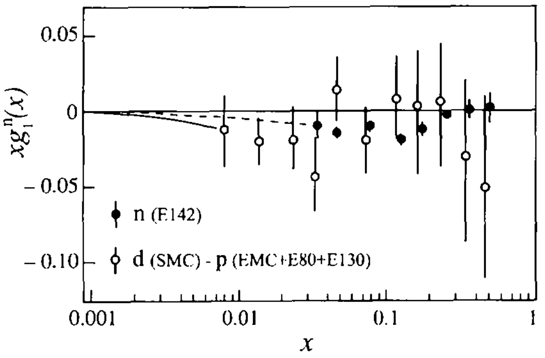

Fig. 3. Current world data on the spin dependent structure function of the neutron $xg_1^n(x)$. The full circles are data from E142. The open circles were obtained combining the SMC deuteron data and EMC + E80 + E130 proton data using eq. (1). The dashed and solid curves show the extrapolations to low x using the E142 data and using the combined data, respectively. The x values of both data sets are identical but for clarity, some of the neutron data are slightly shifted.

Table 2
First moments of the deuteron, proton and neutron spin structure functions $\Gamma_1 = \int g_1(x)\,dx$ evaluated at $Q^2 = 5\ \mathrm{GeV}^2$.

First moment	Experimental value	Experiments
Γ_1^d	$+0.023 \pm 0.025$	SMC [1]
Γ_1^p	$+0.126 \pm 0.018$	E80 + E130 [3], EMC [4]
Γ_1^n	-0.028 ± 0.012	E142 [2]
Γ_1^n	-0.055 ± 0.025	all [1-4]

Table 2 summarises the experimental results for the first moments of the polarised structure functions. The larger negative value of Γ_1^n from the combined data is due to the replacement of the E142 extrapolation by the measured low x points of the muon experiments and their extrapolation to $x = 0$. The resulting uncertainty is larger, because the assumed small error on the E142 extrapolation is replaced by the experimental errors of the muon data. The extrapolations at low x of both SMC + EMC and E142 data are compared in fig. 3. This figure shows that the E142 extrapolation does not agree well with the muon data at low x. Similarly, a continuation of the SMC/EMC extrapolation towards higher values of x would not describe well the data from E142. This indicates that

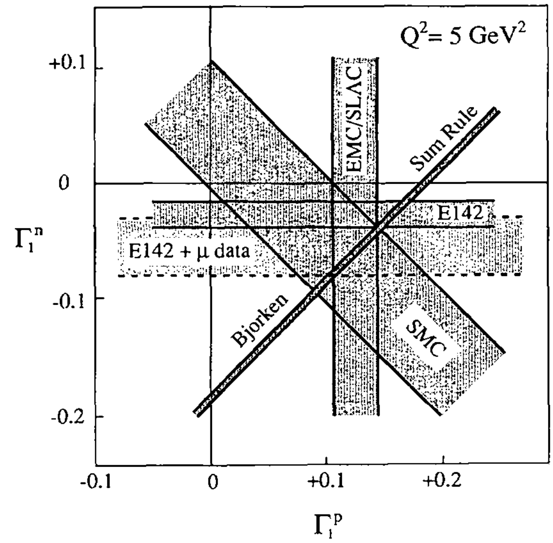

Fig. 4. The moments Γ_1^p, Γ_1^n and Γ_1^d evaluated at $Q^2 = 5\ \mathrm{GeV}^2$. The shaded areas represent the experimental uncertainties. The neutron first moment Γ_1^n calculated from all available data is indicated as (E142 + μ data). This result is correlated to those for the proton and the deuteron.

a Regge form, starting from the relatively high value of $x = 0.03$, may not be a good representation of the xg_1^n structure function in the region of small x. The difference between the value of Γ_1^n, deduced from the present analysis and the one from E142 thus emphasises the importance of the low x measurements.

The first moments of all spin structure functions determined at $Q^2 = 5\ \mathrm{GeV}^2$ are compared with the Bjorken sum in fig. 4. The theoretical value of the Bjorken sum to $\mathcal{O}(\alpha_s^3)$ [6] is

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right|\left[1 - \frac{\alpha_s}{\pi} + C_2\left(\frac{\alpha_s}{\pi}\right)^2 + C_3\left(\frac{\alpha_s}{\pi}\right)^3\right] = 0.185 \pm 0.004 \quad (4)$$

at $Q^2 = 5\ \mathrm{GeV}^2$. The coefficients $C_2 = -3.25$, and $C_3 = -13.85$ have been determined in ref. [19]. At $Q^2 = 5\ \mathrm{GeV}^2$, the higher-order corrections amount to 3%, while at $Q^2 = 2\ \mathrm{GeV}^2$ they increase to 5%. We evolve $\alpha_s(M_Z) = 0.113 \pm 0.004$ [20] to $Q^2 = 2$ and $5\ \mathrm{GeV}^2$ and obtain 0.32 ± 0.03 and 0.26 ± 0.02, respectively. Higher-twist effects contribute especially at low Q^2 [21,22] and have been estimated [14,22] to change $\Gamma_1^p - \Gamma_1^n$ by about 2%, but even this

Table 3
Fraction of the nucleon spin carried by all quarks ($\Delta\Sigma$) and by strange quarks (Δs).

First moment	$\Delta\Sigma$	Δs	Experiments
Γ_1^p	0.14 ± 0.17	-0.15 ± 0.06	E80 + E130 [3], EMC [4]
Γ_1^d	0.09 ± 0.25	-0.16 ± 0.08	SMC [1]
Γ_1^n	0.24 ± 0.23	-0.11 ± 0.08	all [1-4]

sign is uncertain. The theoretical value of the Bjorken sum, without the higher-twist contribution, is shown in fig. 4 together with the measured first moments.

The experimental value of the Bjorken sum $\Gamma_1^p - \Gamma_1^n$ was first determined by a fit to the measured first moments of the proton, deuteron and neutron spin structure functions (see table 2, first three lines). The result is $\Gamma_1^p - \Gamma_1^n = 0.152 \pm 0.020$. In addition, the Bjorken sum was calculated by applying the same procedure only in the region $0.03 \leqslant x \leqslant 1$ and adding at low x the quantity $\int_0^{0.03} (2g_1^p - g_1^{p+n})\,dx$ from the muon data, where $g_1^{p+n} = 2g_1^d/(1 - \frac{3}{2}\omega_D)$. The resulting value

$$\Gamma_1^p - \Gamma_1^n = 0.181 \pm 0.032 \quad (5)$$

is in good agreement with the theoretical prediction of eq. (4).

We can now determine the quark contribution $\Delta\Sigma$ to the nucleon spin. The value of $\Delta\Sigma$ is obtained from the measured first moments using the SU(3) coupling constants F and D [4,23]. We take the most recent values for $F + D = 1.257 \pm 0.003$ [20] and $3F - D = 0.575 \pm 0.016$ [8,24]. The total quark spin contribution $\Delta\Sigma$ to the nucleon spin and that of the strange quarks only Δs are given in table 3. Using these coupling constants, instead of the ones proposed in ref. [25], does not change the results significantly. Our result for Γ_1^n, which we obtain by using the muon data at low x, gives $\Delta\Sigma = 0.24 \pm 0.23$, which is lower than the value reported by E142.

In contrast to the Bjorken sum rule, perturbative QCD contributions of higher order in α_s have not been calculated separately for the proton and neutron first moments. For them they might be as large as those for the Bjorken sum rule. Higher-twist effects on Γ_1^p and Γ_1^n have been estimated [21,22] to contribute up to a few percent. Hence $\Delta\Sigma$ is more accurately determined at large values of Q^2, where the unknown contributions from perturbative QCD and higher-twist effects are smaller.

In summary, we have shown that experimental virtual photon nucleon asymmetries are compatible with no Q^2 dependence. We have evolved the spin dependent structure functions to $Q^2 = 5$ GeV^2. The data from all experiments are in good agreement. We have evaluated the proton, deuteron and neutron first moments at this common value of Q^2. Adding the information from the muon data at low x changes the first moment of the neutron by about two standard deviations compared to the previously reported result [2], but also increases the associated error. Our analysis shows that the experimental Bjorken sum agrees with the theoretical prediction, calculated with higher-order perturbative QCD contributions. The inferred quark contribution to the nucleon spin is small and the strange quark contribution is negative. The differences between the conclusions from the analyses of the SMC and E142 data alone, are not due to incompatibilities of any data on spin structure functions. They are explained by the sensitivity of the first moments to the extrapolation at low x and by higher-order QCD corrections to the Bjorken sum rule.

Future experiments planned at CERN [26], SLAC [27] and DESY [28] will provide additional important data on nucleon spin structure functions.

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