A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

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The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured over a large x range ($0.01<x<0.7$). The spin-dependent structure function $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114\pm0.012\pm0.026$, in disagreement with the Ellis–Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of g_1 for the neutron. These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

Deep inelastic scattering of polarised charged leptons from polarised targets provides a method of studying the internal spin structure of the nucleon [1–6]. The important quantity obtained from the measurements is the virtual photon–nucleon spin dependent asymmetry A_1 from which the spin-dependent nucleon structure function g_1 can be derived. The asymmetry A_1 is $(\sigma_{1/2}-\sigma_{3/2})/(\sigma_{1/2}+\sigma_{3/2})$ where $\sigma_{1/2}$ ($\sigma_{3/2}$) is the photoabsorption cross section when the projection of the total angular momentum of the virtual photon–nucleon system along the virtual photon direction is 1/2 (3/2). In the quark–parton model the structure function $g_1(x)$ is related to the difference of the quark distributions for quarks with helicities parallel and antiparallel to the nucleon spin.

The measured asymmetry (A) from scattering longitudinally polarised leptons by longitudinally polarised nucleons is defined as

$$A=\frac{\mathrm{d}\sigma^{\uparrow\downarrow}-\mathrm{d}\sigma^{\uparrow\uparrow}}{\mathrm{d}\sigma^{\uparrow\downarrow}+\mathrm{d}\sigma^{\uparrow\uparrow}}\,, \qquad (1)$$

where $\mathrm{d}\sigma^{\uparrow\uparrow(\uparrow\downarrow)}$ is the cross section when the lepton and nucleon spins are parallel (antiparallel). In the single-photon exchange approximation, A is related to the virtual photon–nucleon asymmetries A_1 and $A_2=\sigma_{\mathrm{TL}}/\sigma_{\mathrm{T}}$ by

$$A=D(A_1+\eta A_2)\,. \qquad (2)$$

Here $\sigma_{\mathrm{T}}=\frac{1}{2}(\sigma_{1/2}+\sigma_{3/2})$ is the total transverse cross section and σ_{TL} is the contribution to the cross section resulting from the interference of the transverse and longitudinal amplitudes. D is the depolarisation factor of the virtual photon given by $y(2-y)/[y^2+2(1-y)(1+R)]$ and η is $2(1-y)\sqrt{Q^2}/[Ey(2-y)]$. The standard kinematic variables of deep inelastic scattering are used in these formulae. The incident lepton energy is E; ν and $-Q^2$ are the energy transfer in the laboratory frame and the four-momentum transfer, respectively, and $y=\nu/E$. $R=\sigma_{\mathrm{L}}/\sigma_{\mathrm{T}}$ is the ratio of the longitudinal to transverse virtual photoabsorption cross sections and is small in the energy range of this experiment [7]. See refs. [5,8] for a review of the notation. The asymmetries A_1 and A_2 are bounded by positivity limits to be $|A_1|\leqslant 1$ and $|A_2|\leqslant\sqrt{R}$ [9]. Since both R and η are small in the kinematic range of the experiment, A_1 is the dominant contribution to the measured asymmetry A.

The asymmetries A_1 and A_2 are related to the spin-dependent nucleon structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$ by

$$A_1=\frac{2x(1+R)}{F_2}\,[g_1-(2Mx/Ey)g_2]\,,$$

$$A_2=\frac{2x(1+R)}{F_2}\,(2Mx/Ey)^{1/2}(g_1+g_2)\,, \qquad (3)$$

where M is the nucleon mass, $x=Q^2/2M\nu$ and F_2 is the spin averaged nucleon structure function (the explicit (x, Q^2) dependence of the structure functions

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has been omitted, for brevity). Hence g_1 is given by

$$g_1 = \frac{F_2}{2x(1+R)} [A_1 + (2mx/Ey)^{1/2} A_2]$$
$$\simeq \frac{F_2 A_1}{2x(1+R)} . \quad (4)$$

In the quark–parton model (in the scaling limit) g_1 is given by [2,10]

$$g_1(x) = \tfrac{1}{2} \sum e_i^2 [q_i^+(x) - q_i^-(x)] , \quad (5)$$

where e_i is the charge of the quark flavour i and $q_i^{+(-)}(x)$ is the distribution function for a quark of momentum fraction x having the same (+) or opposite (−) helicity to that of the nucleon.

The Bjorken sum rule [1,11] relates the integral of $g_1(x)$ to the ratio of the axial and vector coupling constants G_A and G_V measured in nucleon β decay. After correction for QCD radiative effects [12], this fundamental sum rule is given by

$$\int_0^1 dx [g_1^p(x) - g_1^n(x)] = \tfrac{1}{6} |G_A/G_V| (1 - \alpha_s/\pi)$$
$$= 0.191 \pm 0.002 \quad \text{for } \alpha_s = 0.27 \pm 0.02 . \quad (6)$$

Separate sum rules for the proton and neutron have been derived by Ellis and Jaffe [13] using SU(3) current algebra with the assumption of an unpolarised strange quark sea. These sum rules are given by

$$\int_0^1 g_1^{p(n)}(x) dx$$
$$= \frac{1}{12} \left|\frac{G_A}{G_V}\right| \left(+(-)1 + \frac{5}{3} \frac{3F/D - 1}{F/D + 1} \right) . \quad (7)$$

Again after correcting for QCD radiative effects [14] the integrals have values 0.189 ± 0.005 and -0.002 ± 0.005 for the proton and neutron respectively, using the current values of the ratio of the SU(3) couplings $F/D = 0.632 \pm 0.024$ [15] and the value $G_A/G_V = 1.254 \pm 0.006$. Because of the x in the denominator of eq. (4), the small x region is expected to make a large contribution to the integrals.

This paper reports the results of an experiment in which A_1 was measured using high energy polarised muons and a polarised proton target, where the range of x extended from 0.01 to 0.7 and that of Q^2 from 1.5 to 70 GeV^2. The experiment was performed in the M2 muon beam of the CERN SPS accelerator. The muon beam polarisation can be chosen by selecting a specific ratio of the parent pion to decay muon momenta. The polarisation was calculated using a Monte Carlo simulation [16] to be $(82 \pm 6)\%$ at 200 GeV where the error comes mainly from the uncertainty in the pion beam phase space. This calculation is in good agreement with a previous measurement [17] of the polarisation of the same beam.

Data were collected in eleven separate experimental running periods at beam energies of 100, 120 and 200 GeV. Scattered muons and forward produced charged hadrons were detected and measured in the EMC forward spectrometer [18], modified [19] to run at the higher beam intensities necessary for this experiment.

The polarised target has been described in detail elsewhere [20]. The target consisted of two sections, each of a length 360 mm, which were polarised simultaneously in opposite directions. The two sections were separated by a gap of length 220 mm, chosen such that reconstructed vertices from each section could be clearly separated. The target material was irradiated ammonia, chosen because of its relatively high free proton content and its resistance to radiation damage. Peak proton polarisations of more than 80% were obtained with typical values in the range 75–80%, measured with an accuracy ±5%.

The asymmetry A is obtained from the measured asymmetry Δ by

$$\Delta = \frac{N_1 - N_2}{N_1 + N_2} = P_T P_B f A , \quad (8)$$

where N_1, N_2 are the numbers of events from the two target halves, P_T, P_B are the target and beam polarisations, respectively, and f is the fraction of the events originating from the polarised free protons in the target. Here, f is a function of x since it depends on the neutron-to-proton cross section ratio. The value of Δ is less than 2% over most of the kinematic range of the experiment, requiring strict control of systematic effects to measure it. This was the reason for having a split target which ensured identical beam fluxes and apparatus conditions for both orientations of polarisation.

To compensate for the slightly differing geometric acceptances of the two target halves, the polarisation directions were reversed during each data taking period, and the values of Δ obtained for each configuration were averaged. Hence the only systematic effects remaining were due to possible changes in the ratio of the acceptances of the two target halves before and after polarisation reversal. These effects were studied by splitting the data in different ways into two samples, one of which was expected to suffer much more acceptance changes. The consistency of the results obtained from the two samples showed no indication of residual systematic effects beyond the statistical errors.

The cuts applied to the data were similar to those used in previous EMC analyses [7]. The muon scattering angle cut was increased to $1°$ to ensure good resolution of events coming from the two target halves. A total of 1.2×10^6 events survived these cuts.

Corrections to the dilution factor f were applied for the smearing of events into the target halves which originated in the unpolarised material around the target ($\sim 6\%$) and kinematic smearing due to the intrinsic resolution of the track measurements ($<3\%$), using a Monte Carlo simulation of the experiment. Corrections ($\sim 1.5\%$) were also applied for the slight polarisation of the nitrogen nucleus [21], and for higher order radiative effects [22,23] (2–20%). The contribution to the asymmetry from electroweak interference was calculated and found to be negligible.

The values of A_1 are given in table 1, where ηA_2 has been neglected so that $A_1 \simeq A/D$. These values were obtained by statistically combining the results from the 11 data taking periods. The consistency of the various periods is shown by the χ^2 to the mean value, given in table 1. These values of χ^2 follow a reasonable statistical distribution, showing that time dependent systematic effects were well controlled. The systematic errors given in table 1 include the uncertainties in the value of R (50% of its value) which was taken to be the value calculated from QCD [24,25], the uncertainty in neglecting A_2 in eqs. (2) and (4) (taking $A_2 = \pm\sqrt{R}$), the uncertainty in f arising from the error in the measured neutron-to-proton cross section ratio and nuclear effects on the structure function F_2 in nitrogen, and the error due to radiative corrections. They also include an estimate of the possible systematic error, as described above, arising from time dependent acceptance changes.

The results for A_1^p are plotted in fig. 1 together with those of previous SLAC experiments [26,27], which are in good agreement with our results in the region of overlap. The prediction of the model of Carlitz and Kaur [28] is also shown. This model gives a good representation of the data at large x but fails to reproduce it for $x<0.2$. In fig. 2 values of A_1^p in several x are plotted versus Q^2 to search for scaling violations. These are expected to be small [6,29], and we conclude that within errors the data are consistent with scaling. This justifies combining the data from periods with different beam energies. A good fit to the data in fig. 1 is given by

$$A_1^p(x) = 1.04x^{0.16}[1-\exp(-2.9x)] .$$

The spin-dependent structure function $g_1^p(x)$ was obtained from $A_1^p(x)$ using eq. (4), setting R to the value calculated from QCD. The values of F_2^p were

Table 1
Results for A_1 in x bins. There is a further 9.6% normalisation error on A_1 due to uncertainties in the beam and target polarisations.

x range	$\langle x\rangle$	$\langle Q^2\rangle$ $(\mathrm{GeV}/c)^2$	$A_1 \pm$ stat. $\pm$ syst.	χ^2/DOF
0.01–0.02	0.015	3.5	0.021±0.035±0.017	6.8/10
0.02–0.03	0.025	4.5	0.087±0.043±0.022	9.7/10
0.03–0.04	0.035	6.0	0.013±0.054±0.024	5.3/10
0.04–0.06	0.050	8.0	0.094±0.048±0.028	4.0/10
0.06–0.10	0.078	10.3	0.139±0.049±0.037	4.3/10
0.10–0.15	0.124	12.9	0.169±0.063±0.045	19.8/10
0.15–0.20	0.175	15.2	0.360±0.087±0.057	14.9/10
0.20–0.30	0.248	18.0	0.469±0.088±0.065	13.3/10
0.30–0.40	0.344	22.5	0.517±0.141±0.068	9.8/10
0.40–0.70	0.466	29.5	0.657±0.175±0.065	8.4/10

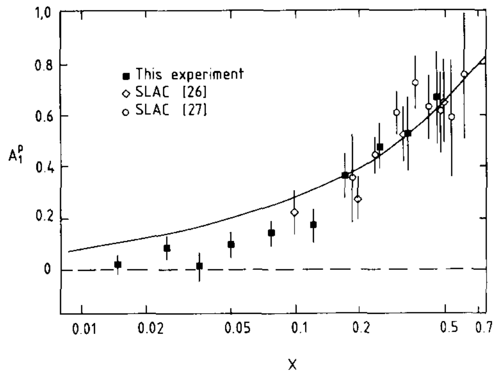

Fig. 1. The asymmetry A_1^p plotted versus x together with results from previous experiments [26,27]. The curve is from the model of ref. [28].

taken from ref. [7] but corrected from the value $R=0$ assumed in that paper to the QCD value of R. Fig. 3 shows $xg_1^p(x)$ as a function of x. The solid curve is

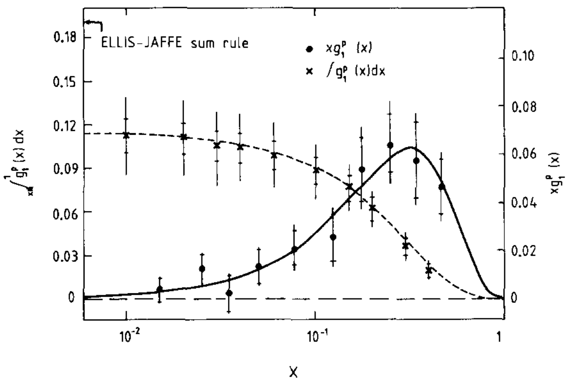

Fig. 3. The quantity $xg_1^p(x)$ (right-hand axis and solid circles) versus x. The left-hand axis and the crosses show the values of $\int_{x_m}^1 g_1^p(x)dx$ where x_m is the value of x at each lower bin edge. The inner error bars are statistical and the outer error bars are the total errors obtained by combining the statistical and systematic errors (table 1) in quadrature. The curves are described in the text.

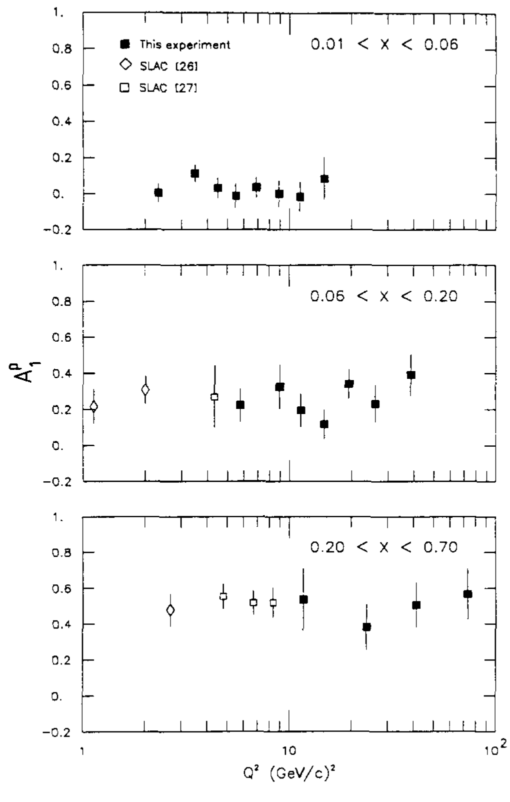

Fig. 2. A_1^p versus Q^2. The data in each x range have been corrected to the same mean x using a fit to the data as a function of x.

derived from the fitted function to $A_1^p(x)$. The integral of $g_1^p(x)$ over the measured region was found to be

$$\int_{0.01}^{0.7} g_1^p(x)dx = 0.111 \pm 0.012(\text{stat.}) \pm 0.026\ (\text{syst.})\ .$$

The convergence of this integral is also shown in fig. 3 where $\int_{x_m}^1 g_1^p(x)dx$ is plotted as a function of x_m, the value of x at the lower edge of each bin. It can be seen that the integral converges well towards $x=0$. The dashed curve is the integral of the solid curve and this was used to extrapolate to $x=0$. The data covered 98% of the value of the integral. The value obtained at a mean Q^2 of 10.7 GeV^2 was

$$\int_0^1 g_1^p(x)dx = 0.114 \pm 0.012(\text{stat.}) \pm 0.026(\text{syst.})\ .$$

Here the systematic error was obtained from the individual systematic errors, added in quadrature and includes a further uncertainty of 10% on the value of the integral to allow for possible errors on the value of F_2 for the proton. The uncertainty due to the extrapolation outside the measured range of x is small providing that $xg_1(x)$ is well behaved and approaches zero reasonably as x tends to zero. It is expected from Regge theory [30] that $xg_1(x)$

approaches zero linearly with x at small x and such behaviour is compatible with the data in the range $0.01<x<0.1$. If, however, $xg_1(x)$ approaches zero as $(1/\ln x)^2$ as predicted by an alternative Regge model [30] the value of the integral increases by 0.018 which is within the quoted systematic error. Such behaviour would imply that $g_1(x)$ diverges as x approaches zero i.e. the quarks remain strongly polarised, which seems unreasonable. This also applies to any other functional form for $xg_1(x)$ which tends to zero more slowly than linearly with x.

Our value for the integral of $g_1^p(x)$ is compatible with the previously measured value of 0.17 ± 0.05 [27] where the uncertainty is dominated by the extrapolation to low x. However, it is smaller than the value 0.189 ± 0.005 expected from the Ellis–Jaffe sum rule. It is also smaller than the value 0.17 ± 0.03 derived from a calculation based on QCD sum rule methods [31] and that (0.205) expected from the model [28] of the spin structure of the nucleon. As we show later, the discrepancy with the Ellis–Jaffe sum rule could be due to a polarisation of the strange sea antiparallel to that of the proton, although a perturbative QCD calculation for the generation of the sea [32] does not predict such an effect. Another possible explanation has recently been offered by Jaffe [33] in view of the non-conservation of the U(1) axial current in QCD, a consequence of the Adler–Bell–Jackiw anomaly [34,35]. Although the precise size of the effect is currently uncalculable, Jaffe gives a lower limit for the proton sum rule of 0.113 which is compatible with the measurement presented here.

The integral of $g_1^n(x)$ was expected to be close to zero according to the Ellis–Jaffe sum rule. Using our value for the integral of $g_1^p(x)$, and assuming the validity of the Bjorken sum rule, we obtain a value of $-0.077\pm0.012(\text{stat.})\pm0.026(\text{syst.})$ for the integral of $g_1^n(x)$. Hence polarised lepton–neutron scattering should show a significant negative asymmetry over at least part of the x range.

Using the above values for the integrals of $g_1^{p(n)}(x)$, the net spin carried by the quarks in the nucleon can be deduced. Integrating the quark–parton model expression for $g_1(x)$ (eq. (5)) and including first order QCD correlations, we obtain

$$2\int_0^1 g_1^p(x)\,dx=\tfrac{4}{9}\Delta u[1-(\alpha_s/2\pi)(C_f+1)] +\tfrac{1}{9}\Delta d[1-(\alpha_s/\pi)(2C_f-1)] +\tfrac{1}{9}\Delta s[1-(\alpha_s/\pi)(2C_f-1)]\,,$$

where $C_f=(33-8f)/(33-2f)$ with f the number of quark flavours and

$$\Delta u=\int_0^1 [q_u^+(x)+q_{\bar u}^+(x)-q_u^-(x)-q_{\bar u}^-(x)]\,dx\,,$$

etc. The corresponding expression for $g_1^n(x)$ is obtained by interchanging Δu and Δd. If we assume an unpolarised strange quark sea ($\Delta s=0$) these expressions become

$$2\int_0^1 g_1^p(x)\,dx=\frac{3.82}{9}\Delta u+\frac{1.08}{9}\Delta d =0.228\pm0.024\pm0.052\,,$$

$$2\int_0^1 g_1^n(x)\,dx=\frac{1.08}{9}\Delta u+\frac{3.82}{9}\Delta d =-0.154\pm0.024\pm0.052\,.$$

Hence the mean z component of the spin, S_z, of the u flavoured quarks in a proton with $S_z=+\frac{1}{2}$ is

$$\langle S_z\rangle_u=\tfrac{1}{2}\Delta u=0.348\pm0.023\pm0.051\,,$$

and that of the d flavoured quarks is

$$\langle S_z\rangle_d=\tfrac{1}{2}\Delta d=-0.280\pm0.023\pm0.051\,.$$

Thus the mean S_z of the quarks is

$$\langle S_z\rangle_{u+d}=0.068\pm0.047\pm0.103\,.$$

Hence $(14\pm9\pm21)\%$ of the proton spin is carried by the spin of the quarks. The remaining spin must be carried by gluons or orbital angular momentum [36,37].

If we assume the discrepancy between our result and the Ellis–Jaffe sum rule prediction to be due to the polarisation of the strange quark sea we obtain

$$\langle S_z\rangle_u=0.373\pm0.019\pm0.039\,,$$

$$\langle S_z\rangle_d=-0.254\pm0.019\pm0.039\,,$$

$$\langle S_z\rangle_s=-0.113\pm0.019\pm0.039\,,$$

$$\langle S_z\rangle_{u+d+s}=0.006\pm0.058\pm0.117\,,$$

indicating that the quark spins carry $(1\pm12\pm24)\%$ of the proton spin.

In conclusion, measurements have been presented of the spin asymmetries in deep inelastic scattering of polarised muons on polarised protons. The spin-dependent structure function g_1 of the proton has also been determined. The integral $\int_0^1 g_1^p(x)dx = 0.114 \pm 0.012 \pm 0.026$ is significantly lower than the value expected from the Ellis–Jaffe sum rule. Assuming the validity of the Bjorken sum rule this result implies that the asymmetry measured from polarised neutrons should be significantly negative over at least part of its x range. In addition, the result implies that, in the scaling limit, a rather small fraction of the spin of the proton is carried by the spin of the quarks.

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