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INTERNAL SPIN STRUCTURE OF THE NUCLEON*

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We present the status of experimental studies of the nucleon spin structure from the polarized deep inelastic scattering. We give an overview of results on polarized structure functions g_1 and on spin distributions of valence and sea quarks. The Bjorken and the Ellis–Jaffe sum rules for the first moments of the structure functions g_1 are discussed. The Bjorken sum rule is well confirmed experimentally. The Ellis–Jaffe sum rule significantly disagrees with data and its violation can be interpreted as due to negative polarization of the strange sea. The spin structure function of the proton, $g_1^p(x)$, is positive and the neutron, $g_1^n(x)$, is negative for $x < 0.1$ and positive elsewhere. The first semi-inclusive results from CERN indicate that the difference between g_1^p and g_1^n for low x can be related to different signs of polarization of valence *up* and *down* quarks. It is found that the overall spin carried by the valence *up* quarks in the proton is positive and amounts to unity. The valence *down* quarks are polarized in the opposite direction. Spin of non-strange sea quarks is consistent with zero over the full experimentally accessible range $0.003 < x < 0.7$.

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Polarized deep inelastic scattering (PDIS) of leptons on nucleons is used to study the inner spin structure of the nucleon and to test Quantum Chromodynamics (QCD) [1]. At present there is wealth of high quality experimental data [2–10] and commonly accepted theory of QCD [11] to interpret them. Further experimentation is in planning and new data are expected from current and future experiments [12, 13].

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Two inclusive asymmetries are measured in PDIS experiments. The first is the asymmetry of cross sections for PDIS of charged lepton polarized antiparallel and parallel to the spin of the target nucleon. The second is for cross sections on transversally polarized target with azimuthal angles different by 180°. These asymmetries are related to the virtual photon asymmetries

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}, \qquad A_2 = \frac{\sigma_{TL}}{\sigma_{1/2} + \sigma_{3/2}}, \tag{1}$$

where $\sigma_{1/2\,(3/2)}$ are the virtual photon — nucleon absorption cross sections for antiparallel (parallel) total spin projection in the direction of photon[1] and σ_{TL} is the spin-flip term in the forward photon — nucleon Compton scattering. The asymmetries (1) can be expressed in terms of spin-dependent structure functions g_1 and g_2 (*cf. e.g.* [3]). Within the quark parton model (QPM) the structure function g_1 can be interpreted as a sum over flavours of quark spin distributions

$$g_1(x,Q^2) = \tfrac{1}{2}\sum_{i=1}^{n_f} e_i^2 \Delta q_i(x,Q^2)\,, \tag{2}$$

where $\Delta q_i = q_i^+ - q_i^-$ and $q^{+(-)}$ are distributions of quarks with spins parallel (antiparallel) to the nucleon spin. The structure function g_2 depends on quark-gluon correlations and can be written in terms of Wilczek–Wandzura term and twist-3 contribution [9]. In the naive QPM $g_2 = 0$.

For the difference of first moments of g_1 of the proton and the neutron, $\Gamma_1^p - \Gamma_1^n$, the fundamental QCD sum rule, derived by Bjorken [14], predicts

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_{NS}^1, \tag{3}$$

and for $\Gamma_1^{p(n)}$ separately the Ellis–Jaffe sum rule [15] states

$$\Gamma_1^{p(n)} = C_{NS}^1\left[\pm\frac{1}{12}\left|\frac{g_A}{g_V}\right| + \frac{1}{36}(3F-D)\right] + \frac{1}{9}C_S^1(3F-D). \tag{4}$$

The Ellis–Jaffe sum rule was derived under the assumptions that the strange sea is unpolarized and that SU(3) symmetry is valid for the baryon octet decays. In (3) and (4) $g_{A(V)}$, F and D are known from weak decays of

[1] For deuteron target the indices $_{1/2}$ and $_{3/3}$ should be replaced by $_0$ and $_2$.

the neutron and Σ and Ξ. The coefficient $C^1_{S(NS)}$ is the flavour singlet (non-singlet) expression presently known up to 3rd order in α_s [16].

Information about valence quark spin can not be obtained from inclusive measurement of electromagnetic currents. Non-singlet spin-dependent structure function $g_3 \sim (\Delta u_v + \Delta d_v)$ [17] contributes to weak PDIS only, for which there is no experimental data at present. In order to overcome this limitation for electromagnetic probes hadrons from the final state can be used for tagging of the struck quark. In addition to the inclusive asymmetries (1) one can define, in a similar way, semi-inclusive asymmetries of the spin-dependent virtual photon cross sections for positive (negative) hadrons $A_1^{+(-)}$ [2]. In the framework of the QPM these asymmetries can be expressed in terms of valence and sea quark spin distribution functions, unpolarized quark distribution functions and quark fragmentation functions $D_q^h(z,Q^2)$ [18, 19]

$$A_1^{+(-)}(x,z,Q^2) = \frac{\sum_{q,h} e_q^2\, \Delta q(x,Q^2)\, D_q^h(z,Q^2)}{\sum_{q,h} e_q^2\, q(x,Q^2)\, D_q^h(z,Q^2)}. \tag{5}$$

Since $D_q^h \neq D_{\bar q}^h$ the weights of q and $\bar q$ are different and quarks can be separated from antiquarks. By using the proton and deuteron targets one can extract separately the x-dependent valence and sea components of the nucleon spin.

TABLE I

PDIS experiments

	CERN NA47	SLAC E142, E143
Beam	μ	e
Energy	100, 190 GeV	10, 16, 30 GeV
x range	$0.003 \div 0.7$	$0.03 \div 0.8$
Q^2 range	$1 \div 60$ GeV^2	$1 \div 10$ GeV^2
$\langle Q^2 \rangle$	4, 10 GeV^2	2, 3 GeV^2
Beam polarization	$81 \pm 3\%$	$83 \pm 2\%$
Target size	2×60 cm	3 cm
Target material and polarization	butanol (p): $86 \pm 3\%$ d-butanol (d): $47 \pm 3\%$	^{3}He (n): $39 \pm 2\%$ $^{15}NH_3$ (p): $70 \pm 3\%$ $^{15}ND_3$ (d): $25 \pm 4\%$
Statistics	p: 4.5×10^6 d: 10^7	much higher

[2] In the formula (1) for semi-inclusive asymmetries $A_1^{+(-)}$ the cross sections denote the spin-dependent virtual photon cross sections for positive (negative) hadrons $\sigma^{+(-)}_{1/2\,(3/2)}$ for proton and $\sigma^{+(-)}_{0\,(2)}$ for deuteron.

In experiments the asymmetries are determined from numbers of deep inelastic events (inclusive) or numbers of hadrons (semi-inclusive) for different beam-target spin configurations [3]. Basic characteristics of the NA47 experiment at CERN and E142 and E143 experiments at SLAC are given in Table I. Experiments at CERN are using the muon beam at higher energy and cover wider kinematic range than SLAC experiments but the statistical precision of electron data at SLAC is higher.

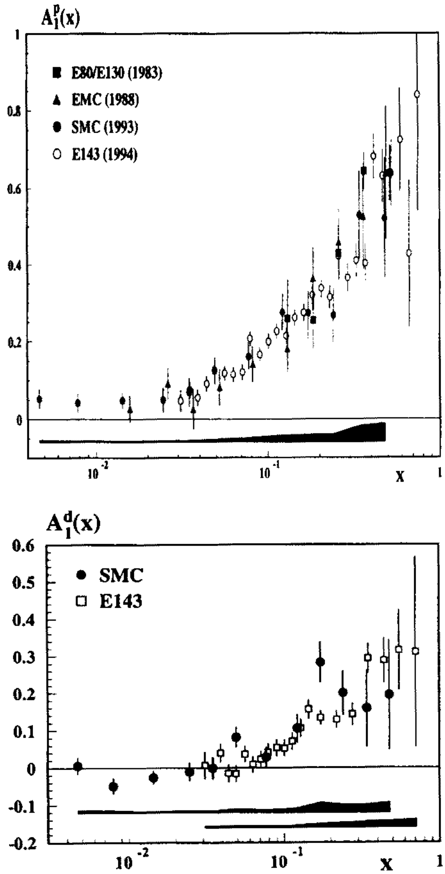


Fig. 1. Virtual photon asymmetries for the proton $A_1^p(x)$ and deuteron $A_1^d(x)$. Points are at measured values of Q^2. Errors are statistical and shaded belts represent systematic uncertainties.

Inclusive asymmetries A_1 for the proton and deuteron [2–5, 7, 8] are given in Fig. 1. The structure functions $g_1(x)$ of the proton and neutron [3–6, 8] are displayed in Fig. 2. As seen in Figs 1 and 2 the data are in satisfactory agreement between experiments. The A_1^p is positive in the whole measured region of x. The A_1^d is negative for low x, covered only by the SMC data, and positive elsewhere. The difference in sign is also clearly seen between g_1^p and g_1^n.

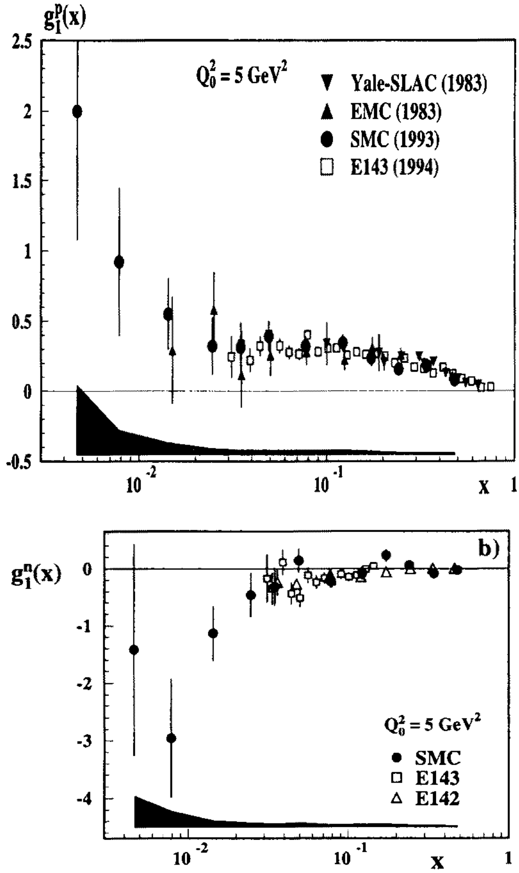


Fig. 2. Spin dependent structure functions of the proton $g_1^p(x)$ and the neutron $g_1^n(x)$ at $Q^2 = 5$ GeV^2. Errors are statistical and shaded areas are systematic uncertainties.

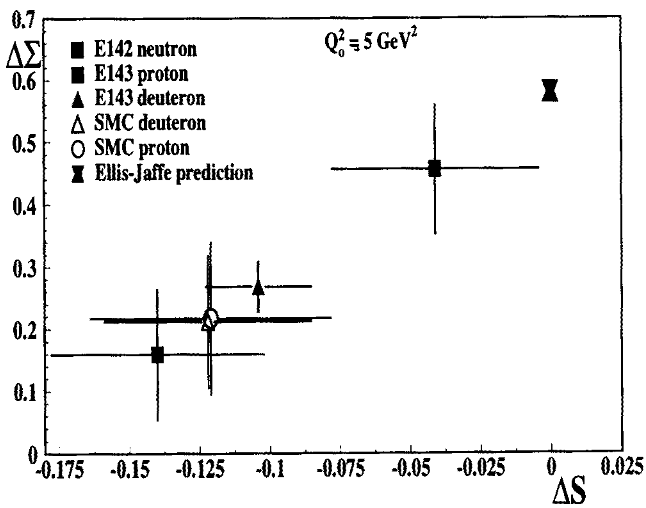
By using the first moments of g_1 (4) and the values of $g_{A(V)}$, F and D [20] we can determine total spin contents of the proton, $\Delta\Sigma = \Delta u + \Delta d + \Delta s$, and the integrated spin of strange sea Δs (*cf.* Ref. [5–8]). Experimental and theoretical values of $\Gamma_1^{p(n)}$, $\Delta\Sigma$ and Δs are displayed in Fig. 3 and summarized in Table II.

TABLE II

First moments of quark distributions. In case of two errors the first is statistical and the second is systematic.

	SMC	Theory	SLAC	Theory
$\langle Q^2 \rangle$	10 GeV^2	10 GeV^2	3 GeV^2	3 GeV^2
Γ_1^p	$0.136 \pm 0.011 \pm 0.011$	0.176 ± 0.006	$0.127 \pm 0.004 \pm 0.010$	0.160 ± 0.006
Γ_1^d	$0.034 \pm 0.009 \pm 0.006$	0.070 ± 0.004	$0.042 \pm 0.003 \pm 0.004$	0.069 ± 0.004
$\Gamma_1^p - \Gamma_1^n$	0.199 ± 0.038	0.187 ± 0.003	0.163 ± 0.010	0.171 ± 0.008
$\Delta\Sigma$	0.20 ± 0.11		0.29 ± 0.05	
Δs	-0.12 ± 0.04		-0.10 ± 0.04	
Δu_v	$1.02 \pm 0.19 \pm 0.13$			
Δd_v	$-0.57 \pm 0.22 \pm 0.11$			
$\Delta\bar{q}$	$-0.020 \pm 0.089 \pm 0.030$			

Semi-inclusive asymmetries for charged hadrons [19] are shown in Fig. 4. Quark spin distributions were evaluated from semi-inclusive and inclusive asymmetries by the least-squares method and using the full covariance matrix between asymmetries [19]. Possible contribution of the gluon spin to the sea was neglected. Results are presented in Fig. 5. Integrals of quark spins over x are given in Table II. Valence *up* quarks are polarized in the direction of the proton and valence *down* quarks in the opposite way. The light quark sea spin is consistent with zero in the full measured region of x, including small x where the unpolarized sea is large.



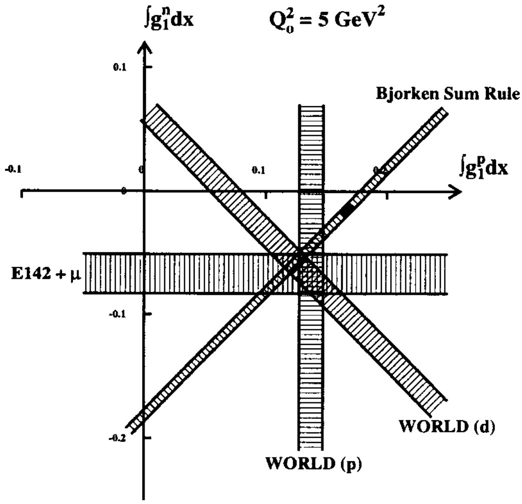


Fig. 3. Experimental results and Ellis–Jaffe prediction for $\Delta\Sigma$ vs. Δs (left) and experimental values of Γ_1^p vs. Γ_1^n and prediction of the Bjorken sum rule (right). The values are given at $Q^2 = 5$ GeV^2.

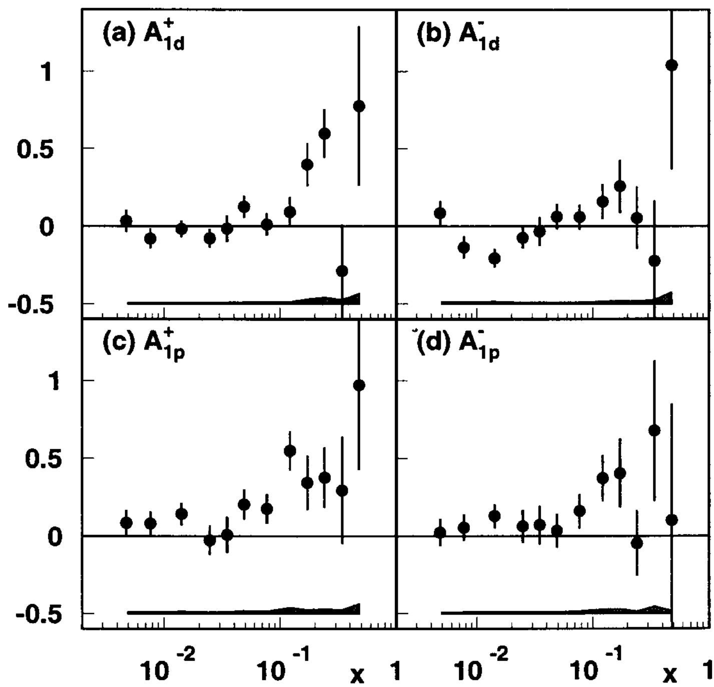


Fig. 4. Semi-inclusive asymmetries (a) $A_{1\,d}^+$, (b) $A_{1\,d}^-$, (c) A_{1p}^+ and (d) A_{1p}^-. Errors are statistical. Systematic error is given as shaded area. Points are at measured values of Q^2.

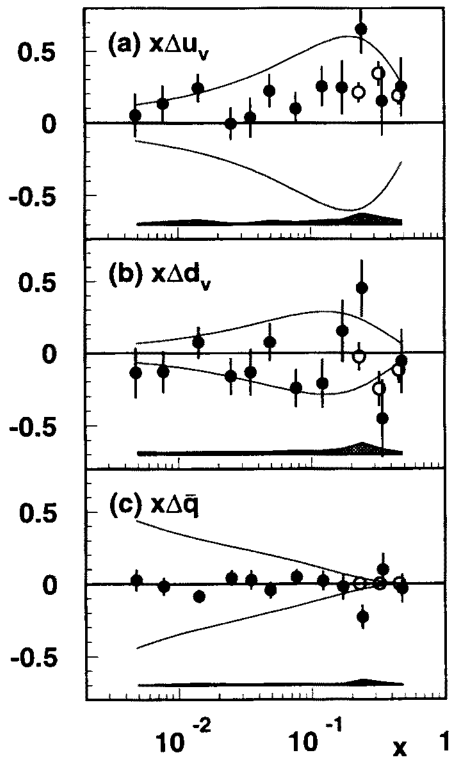


Fig. 5. Quark spin distributions (a) $x\Delta u_v$, (b) $x\Delta d_v$ and (c) $x\Delta \bar{u}$. Curves represent limits given by unpolarized distributions. Errors are statistical. Shaded belts represent systematic errors. Points are given at $Q^2 = 10$ GeV^2.

Concluding:

- Both CERN and SLAC experiments well confirm the Bjorken sum rule.
- Significant disagreement is found with the Ellis-Jaffe sum rule. If interpreted in terms of polarized strange quarks it gives $\Delta s = -0.11 \pm 0.03$.
- Total spin carried by quarks amounts to $20 \div 30\%$, tends to be higher than originally claimed by EMC [3] but is still significantly lower than the nucleon spin.
- Difference in sign is observed between the proton and neutron structure functions g_1 for small x. In view of results from semi-inclusive data it may be related to opposite polarizations of valence u and d quarks.
- The *up* valence quarks are polarized in the direction of the proton spin and *down* valence quarks are polarized in the opposite direction. Polarisations of valence quarks integrated over x are $\Delta u_v/u_v = 0.5 \pm 0.1 \pm 0.01$ and $\Delta d_v/d_v = -0.6 \pm 0.2 \pm 0.1$, where the first error is statistical and the second is systematic.

- The spin of the non-strange sea quarks is small. It is compatible to zero in the full range of x, in particular in the low-x region where the unpolarized sea is large. Its total spin amounts to $4\Delta\bar{q} = -0.08 \pm 0.36 \pm 0.12$ and it is also consistent, within errors, with the negative polarisation of strange quarks determined from Γ_1.

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