# POLARIZATION OF VALENCE AND SEA QUARKS IN THE PROTON

**Wojciech Wiślicki**
on behalf of **the Spin Muon Collaboration**
Laboratory for High Energy Physics
Soltan Institute for Nuclear Studies
Hoża 69
PL-00-681 Warsaw
email: wislicki@na47sun05.cern.ch

**Abstract**

Analysis was performed of semi-inclusive and inclusive spin asymmetries determined from the polarized deep inelastic scattering by the Spin Muon Collaboration. Combined analysis of data for polarized deuterium and hydrogen targets allows for separate determination of spin carried by valence $u$ and $d$ quarks and non-strange sea quarks as a function of $x_{Bj}$ in the range $0.006 < x_{Bj} < 0.6$. It was found that polarization of valence $u$ quarks is positive and of valence $d$ quarks is negative, whereas the sea polarization is small and consistent with zero within errors.

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The result of the EMC[1], that integrated spin distribution of quarks in the proton is far below $\frac{\hbar}{2}$, has provoked intensive further experimentation and theoretical activity. Recent experiments at CERN[2,3] and SLAC[4] determined spin-dependent structure functions $g_1$ of the deuteron, the neutron and the proton thus allowing tests of sum rules for their integrals and re-evaluation of the total spin carried by quarks in the nucleon.

One of the hot problems in nucleon structure is the origin of nucleon spin. In particular, it still remains a mystery how spin is shared among valence quarks, sea quarks, gluons and orbital momentum of nucleon constituents. Experimentally these questions can not be answered by using inclusive observables only. Separation of spin valence and sea components is possible when struck quark is tagged by the final state hadron. For this study, performed within the quark-parton model (QPM), one has to assume the $SU(2)$ isospin symmetry, charge invariance and factorization of fragmentation functions. Our analysis aims towards determination of polarization of valence and non-strange sea quarks in the nucleon.

We used the polarized muon deep inelastic data from polarized deuterium and hydrogen targets, collected by the Spin Muon Collaboration (SMC) at CERN in 1992 and 1993. Our experiment determines spin-dependent cross section asymmetries. The set up consists of three major elements: the polarized target, the spectrometer and the polarimeter.

Polarized $\mu^+$ beam of two energies, 100 GeV and 190 GeV, was used. Polarization was measured from the shape of the energy spectrum of positrons from the muon decay and was found to be $-0.820 \pm 0.061$ and $-0.803 \pm 0.035$ for 100 GeV and 190 GeV, respectively[5].

The target consists of two cells filled with butanol or deuterated butanol and are polarized by dynamic nuclear polarization in opposite directions. Typical values are about 40% for deuterons and over 80% for protons. Polarization is determined with accuracy better than 3% by measuring the NMR signals with a Q-meter circuits[6]. The data are taken simultaneously from both cells and periodically reversing polarization, so that the beam fluxes and detector acceptances cancel out in measured asymmetries.

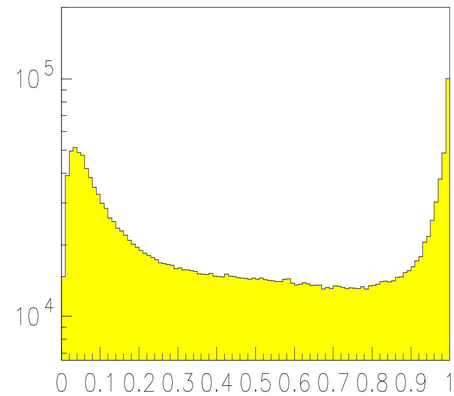


Figure 1: $E_{em}/(E_{em}+E_{had})$

Particles are detected and measured in the forward spectrometer[7]. Scattered muon is defined as a particle penetrating the iron wall and giving a signal in streamer tubes behind it. All charged particles are tracked in about 150 planes of proportional and streamer chambers and used to determine the interaction vertex. Their momenta are measured by using the bending magnet. High energy electrons from conversion of radiative photons can occasionally fit to the $\vec{\mu}\vec{N}$ interaction vertex. A calorimeter was used to discard such electrons thus avoiding their misidentification as final state hadrons. The hadron is operationally defined as a particle fulfilling acceptance requirements of the calorimeter, for which the ratio of energy loss in the electromagnetic part

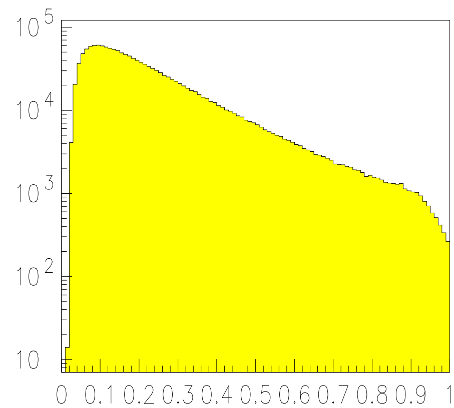


Figure 2: $z_{had} = E_h/\nu$

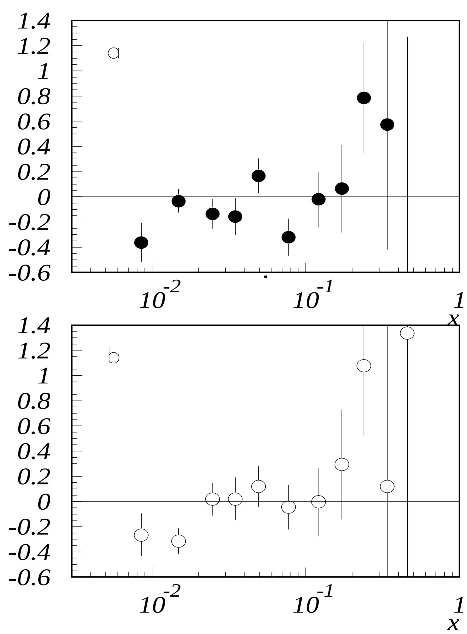


Figure 3: *Semi-inclusive asymmetries of spin-dependent cross sections for muoproduction of positive (a) and negative (b) hadrons on deuterons at 100 GeV*

($E_{em}$) to the total energy deposited in electromagnetic and hadronic ($E_{had}$) parts does not exceed 80%. The spectrum of this ratio is displayed in fig. 1. Although the kinematically accessible region of $x_{Bj}$ is somewhat wider for 190 GeV data than for 100 GeV, the combined analysis is possible in the overlap range of $0.006 < x_{Bj} < 0.6$. For both samples $Q^2 > 1$ GeV$^2$ was required. Due to limited angular acceptance of our spectrometer we poorly accept hadrons with $z_{had} = E_h/\nu$ below 0.1 (cf. fig. 2). In this analysis a cut on $z > 0.2$ was applied. This choice is a compromise between the most effective tagging of the struck quark for semi-inclusive asymmetries and non-dramatic statistics loss. After applying kinematic and geometric cuts we are left with comparable samples of $4.5\times10^6$ deep inelastic events for each, 100 GeV deuterium and 190 GeV hydrogen data set, where $\langle Q^2 \rangle$ was equal to 4.6 and 10 GeV$^2$, respectively. Corresponding hadron samples amount to $1.6 \times 10^6$ and $1.4 \times 10^6$ charged hadrons. Spin asymmetries are measured for virtual photon deep inelastic scattering cross section on polarized proton (p) and deutron (d), $A^{\mu}_{d(p)}$, and for muoproduction of charged positive (+) or negative (-) hadrons, $A^{+(-)}_{d(p)}$,

$$A^{\mu(+(-))}_{d(p)} = \alpha \frac{\sigma^{\mu(+(-))}_{d(p)_{1/2}} - \sigma^{\mu(+(-))}_{d(p)_{3/2}}}{\sigma^{\mu(+(-))}_{d(p)_{1/2}} + \sigma^{\mu(+(-))}_{d(p)_{3/2}}}, \qquad (1)$$

where indices 1/2 and 3/2 refer to the total spin projection in the direction of virtual photon. For deuteron the cross sections in (1) are assumed to be the average of proton and neutron cross sections. The factor $\alpha = 1 - \frac{3}{2}\omega_D$ accounts for $\omega_D \simeq 0.06$ probability of deuteron to be in D-state and for the proton $\alpha = 1$. The cross sections depend on polarized and unpolarized quark distributions and, for semi-inclusive asymmetries, on quark fragmentation functions.

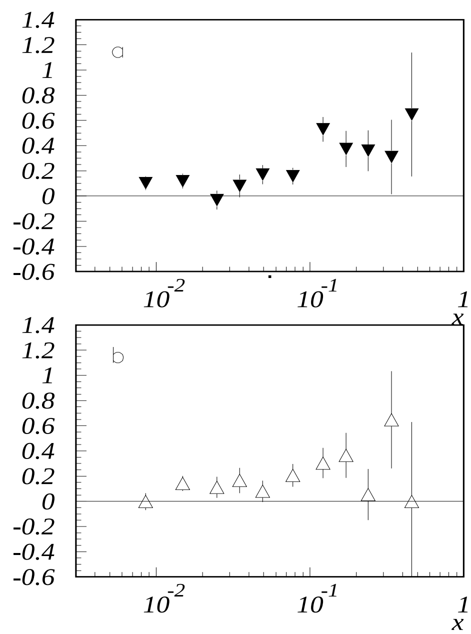


Figure 4: *Semi-inclusive asymmetries of spin-dependent cross sections for muoproduction of positive (a) and negative (b) hadrons on protons at 190 GeV*

Experimentally the asymmetries (1) are determined from the numbers of events (inclusive) or charged particle yields (semi-inclusive) taken for two beam-target spin configurations and accounting for the degree of polarization of beam and target, the amount of unpolarizable material in the target (dilution factor), virtual gamma depolarization and radiative corrections.

Inclusive asymmetries for deuteron and proton were published[2,3] and semi-inclusive asym-

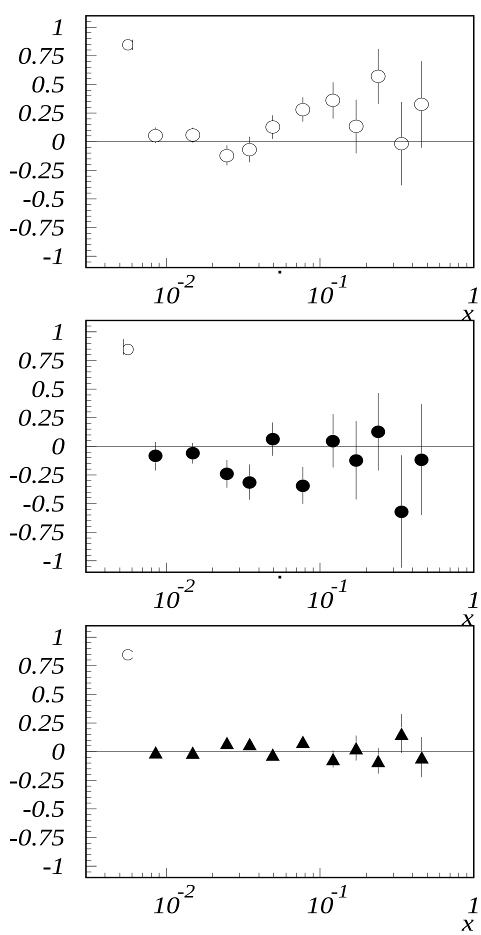


Figure 5: *Quark spin distribution functions* $x\Delta u_v(x)$ *(a),* $x\Delta d_v(x)$ *(b) and* $x\Delta\bar{q}(x)$ *(c) at* $Q^2 = 10\ GeV^2$

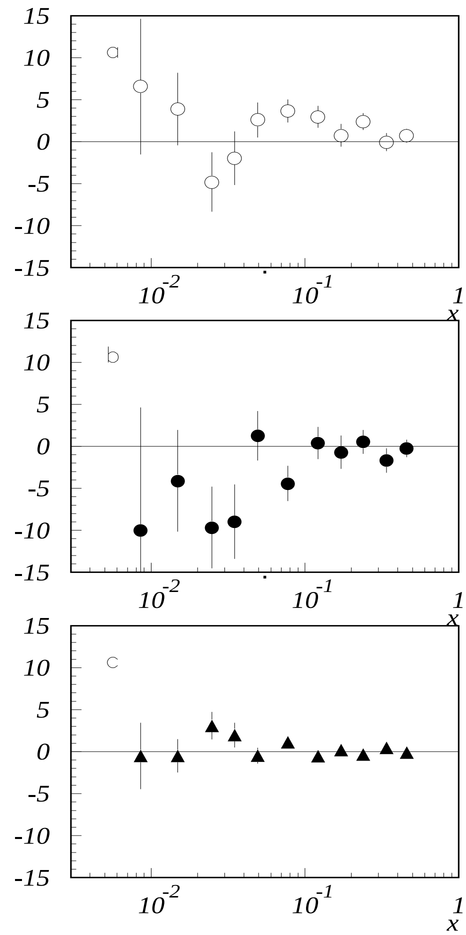


Figure 6: *Quark spin distribution functions* $\Delta u_v(x)$ *(a),* $\Delta d_v(x)$ *(b) and* $\Delta\bar{q}(x)$ *(c) at* $Q^2 = 10\ GeV^2$

metries are displayed in fig. 3 for positive and negative hadrons from the deuteron and in fig. 4 from the proton.

The errors for experimental points presented in these and the following figures are statistical only.

In the framework of the QPM all asymmetries can be expressed as linear combinations of polarizations of valence, $\Delta u_v$ and $\Delta d_v$, non-strange sea, $\Delta\bar{q}$, and strange, $\Delta s$, quarks,

$$A^{\mu+-}_{d,p} = c^{\mu+-}_{1_{d,p}}\Delta u_v + c^{\mu+-}_{2_{d,p}}\Delta d_v + c^{\mu+-}_{3_{d,p}}\Delta\bar{q} + c^{\mu+-}_{4_{d,p}}\Delta s, \quad (2)$$

where the $SU(2)$ isosymmetry was assumed for the non-strange sea, i.e. $\Delta\bar{u} = \Delta\bar{d} \equiv \Delta\bar{q}$, $\Delta$ being the difference between distributions of spins parallel and antiparallel to the nucleon spin. Following the usual convention all quark distributions refer to the proton; i.e. in formulae for deuteron asymmetries it was assumed that distribution of $u_v(d_v)$ in neutron is the same as $d_v(u_v)$ for proton. Coefficients $c^{\mu+-}_{i_{d,p}}$ depend on unpolarized quark distribution functions, for which the parametrizations were used[8)]. For semi-inclusive asymmetries, in addition, they depend also on quark fragmentation functions into hadrons, integrated over $z_{had}$ from 0.2 to 1, for which we used the EMC measurements[9)]. It was assumed that the fragmentation functions are invariants of charge and isospin transformations. For example, for pions, the most abundant hadrons in the final state, the favoured fragmentation functions are

$$D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} \quad (3)$$

and the unfavoured fragmentation functions are

$$D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-}. \quad (4)$$

Polarization of strange quarks can not be determined from eqns. (2), because its contribution to asymmetries is much smaller than the non-strange quarks. We assumed that the strange quark spin is distributed in $x$ in the same way as unpolarized $s(x)$ obtained from the CCFR[12] and that the integrated $\Delta s$ is equal to $-0.12$, as determined in ref. 3. The overdetermined system of 6 equations (2), consisting of semi-inclusive asymmetries for positive and negative hadrons and one inclusive asymmetry for each target, was solved by the minimum $\chi^2$ method. Resulting quark polarization distributions $x\Delta q$ are presented in fig. 5. The same result, but without momentum weight, $\Delta q$, is shown in fig. 6. Values in figs. 5, 6 are evolved to common $Q^2 = 10$ GeV$^2$. In this procedure it was assumed that asymmetries do not depend on $Q^2$, as supported by our observation[10]. Unpolarized quark distribution functions and fragmentation functions were evolved from the $\langle Q^2 \rangle$ measured in given $x$ bin to 10 GeV$^2$. Inspection of figs. 5 and 6 reveals that valence $u$ quarks are polarized in the direction of proton spin and valence $d$ quarks are polarized in opposite way. Positive polarization of $u$ quarks and negative of $d$ quarks is expected from values of the $SU(3)$ coupling constants $F$ and $D$, which constrain the integrals of $\Delta u$ and $\Delta d$[1], but the $x$-dependence of valence components is measured for the first time. It is seen from figs. 5c and 6c that the non-strange sea in the proton does not exhibit significant polarization over the measured range of $x_{Bj}$.

Behaviour of polarized structure functions below our measured $x$ is a matter of debate[11]. Since for $x < 0.04$ we do not observe any significant deviation of $\Delta q$ from a constant, neither for the valence nor for the sea, we obtained its value from a fit in the range $0.006 < x < 0.04$ and extrapolated it below $x = 0.006$, down to $x = 0$. This type of $x$-dependence is consistent with Regge behaviour $x^\alpha$ with $\alpha = 0$, as we assumed in our analysis of the $g_1$ structure functions[2,3]. Tiny amount of spin from the low-$x$ extrapolation was added to our integral, as listed in table 2.

To estimate the contribution from $x > 0.6$ a fit was performed of the function $Ax^B(1-x)^C$ for $0.1 < x < 0.6$ and extrapolation beyond $x = 0.6$ gave the values displayed in table 2.

The main contribution to the error of $\Delta\bar{q}$ comes from the region of high $x$, where statistical precision of our data is worse than for small $x$, as seen from fig. 5c. The error for $\Delta\bar{q}$, as calculated with errors on points above $x = 0.1$, is given in parentheses in lower rows of tables 1 and 3. On the other hand, we observe that all points for $x > 0.1$ are consistent with zero within one standard deviation and their mean value is zero. The integral of unpolarized sea in this region amounts to 0.035, roughly a quarter of our statistical error. Thus, we can make our conclusion about $\Delta\bar{q}$ more stringent, by assuming the maximum error for $x > 0.1$ being equal to 0.035, which gives the overall error on $\Delta\bar{q}$ equal to 0.068, as given in tables 1 and 3.

In fig. 7 the integrals $\int_{x_{min}}^{1} \Delta q$ are displayed, and the values of integrals over the full $x$ range are denoted by asterisks . Corresponding numbers for the measured region of $x$, unmeasured region and the full range are listed in tables 1, 2 and 3.

In solving eqns. (2) we found that sensitivity of non-strange quark polarizations on $\Delta s(x)$ is negligible, because $c_4 \ll c_{1,2,3}$. We varied $\Delta s$ between 0 and $-0.12$ and we found that integrals of quark polarizations change by no more than 1.6%.

Concluding, we measured the spin distribution of the valence quarks and the non-strange sea quarks in the proton. We found that $u_v$ quarks are polarized parallel and $d_v$ quarks - antiparallel to the proton spin, whereas the non-strange sea carries small amount of spin, consistent with zero within our errors. It is highly desirable to continue the study of sharing of the nucleon spin between different degrees of freedom in present[2,3,4] and proposed[13,14,15] experiments.

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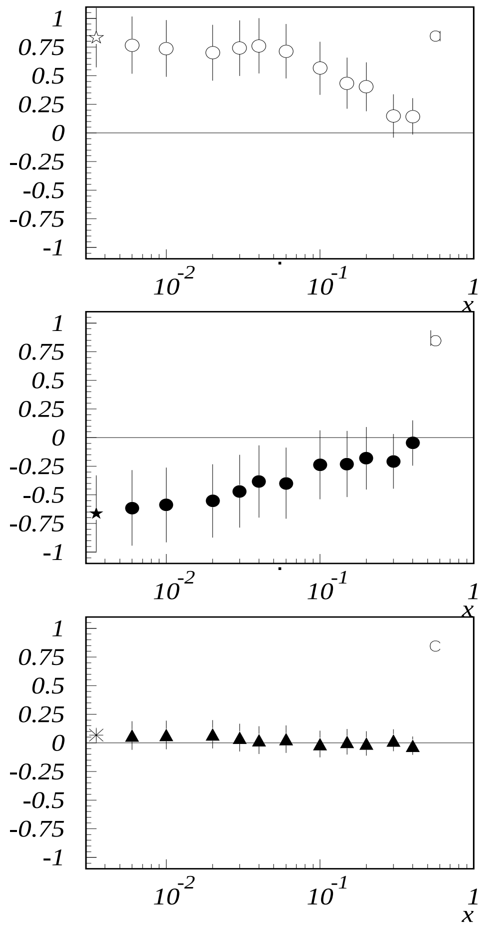


Figure 7: *The values of integrals* $\int_{x_{min}}^{1} \Delta q(x)dx$ *for* $\Delta u_v$ *(a),* $\Delta d_v$ *(b) and* $\Delta \bar{q}$ *(c). Asterisk for each figure denotes the value of the integral for* $x_{Bj}$ *from 0 to 1 and includes contribution from extrapolation to unmeasured regions. Errors are explained in the text.*

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Table 1: *Integrals of quark polarizations over measured range* $0.006 < x < 0.6$

| | $\int_{0.006}^{0.6} \Delta q(x) dx$ |
|---|---|
| $\Delta u_v$ | $0.767 \pm 0.250$ |
| $\Delta d_v$ | $-0.615 \pm 0.330$ |
| $\Delta \bar{q}$ | $0.064 \pm 0.060(0.126)$ |

Table 2: *Integrals of quark polarizations over unmeasured regions of* $x < 0.006$ *and* $x > 0.6$

| | $\int_{0}^{0.006} \Delta q(x) dx$ | $\int_{0.6}^{1} \Delta q(x) dx$ |
|---|---|---|
| $\Delta u_v$ | $0.001 \pm 0.009$ | $0.061 \pm 0.072$ |
| $\Delta d_v$ | $-0.032 \pm 0.013$ | $-0.048 \pm 0.047$ |
| $\Delta \bar{q}$ | $0.004 \pm 0.004$ | $0.001 \pm 0.106$ |

Table 3: *Integrals of quark polarizations over the range of* $0 < x < 1$

| | $\int_{0}^{1} \Delta q(x) dx$ |
|---|---|
| $\Delta u_v$ | $0.829 \pm 0.260$ |
| $\Delta d_v$ | $-0.673 \pm 0.333$ |
| $\Delta \bar{q}$ | $0.068 \pm 0.068(0.126)$ |