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Polarised quark distributions in the nucleon from semi-inclusive spin asymmetries

Spin Muon Collaboration (SMC)

B. Adeva [r], T. Akdogan [b], E. Arik [b], A. Arvidson [u,1], B. Badelek [u,w], G. Bardin [q,2], G. Baum [a], P. Berglund [h], L. Betev [m], R. Birsa [t], N. de Botton [q], F. Bradamante [t], A. Bravar [k], A. Bressan [t,3], S. Bültmann [a,4], E. Burtin [q], D. Crabb [v], J. Cranshaw [t], T. Çuhadar [b,o], S. Dalla Torre [t], R. van Dantzig [o], B. Derro [d], A. Deshpande [x], S. Dhawan [x], C. Dulya [o,5,d], S. Eichblatt [6], D. Fasching [p,7], F. Feinstein [q], C. Fernandez [r,i], S. Forthmann [g], B. Frois [q], A. Gallas [r], J.A. Garzon [r,i], H. Gilly [f], M. Giorgi [t], E. von Goeler [8], S. Goertz [c], G. Gracia [r,9], N. de Groot [o,10], M. Grosse Perdekamp [x], K. Haft [m], D. von Harrach [k], T. Hasegawa [n,11], P. Hautle [e,12], N. Hayashi [n,13], C.A. Heusch [e,14], N. Horikawa [n], V.W. Hughes [x], G. Igo [d], S. Ishimoto [n,15], T. Iwata [n], E.M. Kabuß [k], T. Kageya [n,16], A. Karev [j], H.J. Kessler [f], T.J. Ketel [o], J. Kiryluk [w], Yu. Kisselev [j], D. Krämer [a], V. Krivokhijine [j], W. Kröger [e,14], V. Kukhtin [j], K. Kurek [w], J. Kyynäräinen [a,h], M. Lamanna [t], U. Landgraf [f], J.M. Le Goff [q], F. Lehar [q], A. de Lesquen [q], J. Lichtenstadt [s], M. Litmaath [o,3], A. Magnon [q], G.K. Mallot [k], F. Marie [q], A. Martin [t], J. Martino [q], T. Matsuda [n,11], B. Mayes [i], J.S. McCarthy [v], K. Medved [j], W. Meyer [c], G. van Middelkoop [o], D. Miller [p], Y. Miyachi [n], K. Mori [n], J. Moromisato [8], J. Nassalski [w], L. Naumann [e,2], T.O. Niinikoski [e], J.E.J. Oberski [o], A. Ogawa [n,17], C. Ozben [b], H. Pereira [q], F. Perrot-Kunne [q], D. Peshekhonov [j], L. Pinsky [i], S. Platchkov [q], M. Plo [r], D. Pose [j], H. Postma [o], J. Pretz [k,o], R. Puntaferro [t], G. Rädel [e], A. Rijllart [e], G. Reicherz [c], J. Roberts [18], M. Rodriguez [u,19], E. Rondio [w,e], B. Roscherr [x], I. Sabo [s], J. Saborido [r], A. Sandacz [w], I. Savin [j], P. Schiavon [t], A. Schiller [g], E. P. Sichtermann [o], F. Simeoni [t], G.I. Smirnov [j], A. Staude [m], A. Steinmetz [k,m], U. Stiegler [e], H. Stuhrmann [g], M. Szleper [w], F. Tessarotto [t], D. Thers [q], W. Tlaczala [w,20], A. Tripet [a], G. Unel [b], M. Velasco [p,3], J. Vogt [m], R. Voss [e], C. Whitten [d], R. Windmolders [l], R. Willumeit [g], W. Wislicki [w], A. Witzmann [f,21], J. Ylöstalo [h], A.M. Zanetti [t], K. Zaremba [w,20], J. Zhao [g,22]

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[a] University of Bielefeld, Physics Department, 33501 Bielefeld, Germany [23]
[b] Bogaziçi University and Istanbul Technical University, Istanbul, Turkey [24]
[c] University of Bochum, Physics Department, 44780 Bochum, Germany [23]
[d] University of California, Department of Physics, Los Angeles, 90024 CA, USA [25]
[e] CERN, 1211 Geneva 23, Switzerland
[f] University of Freiburg, Physics Department, 79104 Freiburg, Germany [23]
[g] GKSS, 21494 Geesthacht, Germany [23]
[h] Helsinki University of Technology, Low Temperature Laboratory and Institute of Particle Physics Technology, Espoo, Finland
[i] University of Houston, Department of Physics, Houston, 77204-5506 TX, USA [25,26]
[j] JINR, Dubna, RU-141980 Dubna, Russia
[k] University of Mainz, Institute for Nuclear Physics, 55099 Mainz, Germany [23]
[l] University of Mons, Faculty of Science, 7000 Mons, Belgium
[m] University of Munich, Physics Department, 80799 Munich, Germany [23]
[n] Nagoya University, CIRSE and Department of Physics, Furo-Cho, Chikusa-Ku, 464 Nagoya, Japan [27]
[o] NIKHEF, Delft University of Technology, FOM and Free University, 1009 AJ Amsterdam, The Netherlands [28]
[p] Northwestern University, Department of Physics, Evanston, 60208 IL, USA [25,26]
[q] C.E.A. Saclay, DAPNIA, 91191 Gif-sur-Yvette, France [29]
[r] University of Santiago, Department of Particle Physics, 15706 Santiago de Compostela, Spain [30]
[s] Tel Aviv University, School of Physics, 69978 Tel Aviv, Israel [31]
[t] INFN Trieste and University of Trieste, Department of Physics, 34127 Trieste, Italy
[u] Uppsala University, Department of Radiation Sciences, 75121 Uppsala, Sweden
[v] University of Virginia, Department of Physics, Charlottesville, 22901 VA, USA [25]
[w] Soltan Institute for Nuclear Studies and Warsaw University, 00681 Warsaw, Poland [32]
[x] Yale University, Department of Physics, New Haven, 06511 CT, USA [25]

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Abstract

We present a measurement of semi-inclusive spin asymmetries for positively and negatively charged hadrons from deep inelastic scattering of polarised muons on polarised protons and deuterons in the range $0.003 < x < 0.7$ and $Q^2 > 1$ GeV^2. Compared to our previous publication on this subject, with the new data the statistical errors have been reduced by nearly a factor of two. From these asymmetries and our inclusive spin asymmetries we determine the polarised quark distributions of valence quarks and non-strange sea quarks at $Q^2 = 10$ GeV^2. The polarised u valence quark distribution, $\Delta u_v(x)$, is positive and the polarisation increases with x. The polarised d valence quark distribution, $\Delta d_v(x)$, is negative and the non-strange sea distribution, $\Delta\bar{q}(x)$, is consistent with zero over the measured range of x. We find for the first moments $\int_0^1 \Delta u_v(x) \mathrm{d}x = 0.77 \pm 0.10 \pm 0.08$, $\int_0^1 \Delta d_v(x) \mathrm{d}x = -0.52 \pm 0.14 \pm 0.09$ and $\int_0^1 \Delta\bar{q}(x) \mathrm{d}x = 0.01 \pm 0.04 \pm 0.03$, where we assumed $\Delta\bar{u}(x) = \Delta\bar{d}(x)$. We also determine for the first time the second moments of the valence distributions $\int_0^1 x \Delta q_v(x) \mathrm{d}x$.

[1] Now at Gammadata, Uppsala, Sweden.
[2] Deceased.
[3] Now at CERN, 1211 Geneva 23, Switzerland.
[4] Now at University of Virginia, Department of Physics, Charlottesville, 22901 VA, USA[24]
[5] Now at CIEMAT, Avda Complutense 22, 28040, Madrid, Spain.
[6] Now at Fermi National Accelerator Laboratory, Batavia, 60510 IL, USA.
[7] Now at University of Wisconsin, USA.
[8] Permanent address: Northeastern University, Department of Physics, Boston, 02115 MA, USA.
[9] Now at NIKHEF P.O.B. 41882, 1009 DB Amsterdam, The Netherlands.
[10] Now at SLAC, Stanford 94309 CA USA.
[11] Permanent address: Miyazaki University, Faculty of Engineering, 889-21 Miyazaki-Shi, Japan.
[12] Permanent address: Paul Scherrer Institut, 5232 Villigen, Switzerland.

Measurements of spin asymmetries in polarised deep inelastic scattering provide information about the spin structure of the nucleon. In particular detailed information can be obtained from polarised semi-inclusive deep inelastic scattering, $\vec{\mu} + \vec{N} \to \mu + X + h$, where in addition to the scattered lepton hadrons (h) are also detected. In this paper we present new results on semi-inclusive asymmetries from SMC data including those published in [1]. We analyse these asymmetries together with the inclusive asymmetries in the framework of the quark parton model (QPM) and determine the polarised quark distributions of the valence quarks and of the non-strange sea quarks. This is only possible due to the semi-inclusive data.

Our experimental setup at the CERN muon beam consists of three major components: a polarised target, a magnetic spectrometer and a muon beam polarimeter. A detailed description of the experiment and the analysis of the inclusive data can be found in Refs. [2,3]. Positive muons of a nominal energy of 100 and 190 GeV were used. Most of the data were taken at 190 GeV. The muon beam polarisation P_B was determined from measured spin asymmetries in muon-electron scattering and for the 190 GeV data in addition from the energy spectrum of positrons from muon decays. It was found to be -0.795 ± 0.019 [33] (-0.81 ± 0.03) for an average beam energy of 187.4 GeV (99.4 GeV). The target consisted of two cells filled with butanol, deuterated butanol or ammonia. The two cells were polarised in opposite directions by dynamic nuclear polarisation. The average polarisations P_T were approximately 0.90 for protons and 0.50 for deuterons with a relative error $\Delta P_T/P_T$ of 3%. The determination of semi-inclusive asymmetries requires the separation of hadrons from electrons which originate mainly from photon conversions. For this purpose we used a calorimeter [4] which consists of an electromagnetic and a hadronic part. The electromagnetic part amounts to 20 radiation lengths which is sufficient to contain electromagnetic showers. The total thickness of the calorimeter is 5.5 nuclear interaction lengths. For each shower the ratio of the energy deposited in the electromagnetic part to the total deposited energy is calculated. Electrons are eliminated by requiring this ratio to be smaller than 0.8. There was no hadron identification, only the charge of the hadron is known.

The asymmetries of the spin-dependent virtual photon absorption cross sections for production of positive (negative) hadrons are defined as

$$A_1^{+(-)} = \frac{\sigma_{\uparrow\downarrow}^{+(-)} - \sigma_{\uparrow\uparrow}^{+(-)}}{\sigma_{\uparrow\downarrow}^{+(-)} + \sigma_{\uparrow\uparrow}^{+(-)}}, \qquad (1)$$

where the indices $\uparrow\downarrow$ and $\uparrow\uparrow$ refer to the relative orientation of the nucleus (proton or deuteron) and photon spins. Contributions from the asymmetry A_2 are neglected. The cross sections $\sigma^{+(-)}$ refer to the

[13] Permanent address: The Institute of Physical and Chemical Research (RIKEN), wako 351-01, Japan.
[14] Permanent address: University of California, Institute of Particle Physics, Santa Cruz, 95064 CA, USA.
[15] Permanent address: KEK, Tsukuba-Shi, 305 Ibaraki-Ken,Japan.
[16] Now at University of Michigan, Ann Arbor MI48109, USA.
[17] Now at Penn. State University, 303 Osmond Lab, University Park, 16802 PA, USA.
[18] Permanent address: Rice University, Bonner Laboratory, Houston, TX 77251-1892, USA.
[19] Permanent address: University of Buenos Aires, Physics Department, 1428 Buenos Aires, Argentina.
[20] Permanent address: Warsaw University of Technology, Warsaw, Poland.
[21] Now at F.Hoffmann-La Roche Ltd., CH-4070 Basel, Switzerland.
[22] Now at Los Alamos National Laboratory, Los Alamos, NM 87545, USA.
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number of produced hadrons, i.e. all hadrons detected in one event are counted. The extraction of the semi-inclusive asymmetries from the counting rates is described in [1].

The counting rate asymmetry A^{exp} is related to the virtual photon asymmetry A_1 by:

$$A_1 = \frac{1}{P_B P_T D f} A^{exp} . \tag{2}$$

The depolarisation factor D depends on the event kinematics and on the ratio R of longitudinal to transverse virtual photon cross sections [2]. The dilution factor f accounts for the presence of unpolarisable nuclei in addition to the protons or deuterons in the target. It can be expressed in terms of the numbers n_A of nuclei with mass number A and the corresponding total spin-independent cross sections σ_A^{tot}. Taking into account radiative effects on the nucleon [2,5] the effective dilution factor is defined as

$$f = \frac{\sigma_{p,d}^{1\gamma}}{\sigma_{p,d}^{tot}} \frac{n_{p,d}\sigma_{p,d}^{tot}}{\sum_A n_A \sigma_A^{tot}} . \tag{3}$$

Here p,d stands for proton or deuteron.

The evaluation of the dilution factor for inclusive events, f^i, is described in Ref. [2]. The main contributions to the total inclusive cross section are the one photon exchange with vertex and vacuum polarisation corrections, and the inelastic, elastic and quasielastic bremsstrahlung processes. In the elastic and quasielastic bremsstrahlung processes no hadrons are produced and therefore these processes do not contribute to the total semi-inclusive cross section. In the analysis hadrons are selected if their energy is above a certain fraction, z, of energy transfer ν. This reduces the energy available for a possible bremsstrahlung photon accompanying an inelastic event, relative to the inclusive case. The contribution from inelastic bremsstrahlung is then reduced. This reduction was estimated to be small and is included only in the systematic error of the dilution factor. We compute the dilution factor for the semi-inclusive events, f^{si}, without the elastic and quasielastic contributions in the cross section. In the inclusive case, at low x there is a large contribution of elastic bremsstrahlung from high Z nuclei in the denominator of Eq. (3). It is not present in the semi-inclusive case and therefore f^{si} is 30% larger than f^i in this region, whereas the difference is very small for $x > 0.1$. Using the QPM we compute from f^{si} the dilution factors for positive, f^+, and negative, f^-, hadrons [6,7]. For the polarised deuterated butanol target f^+ and f^- are equal to f^{si}. For the butanol and ammonia targets, where protons are polarised, the ratio $f^+/f^{si} \approx 1.07$ and $f^-/f^{si} \approx 0.88$ at $x = 0.5$ and both ratios are close to 1 at low x. The ratios differ from unity for these targets because more positive hadrons are produced on protons at large x as compared to the isoscalar unpolarised target nuclei. The correctness of the above procedure for the evaluation of the dilution factor was verified using a Monte Carlo in which radiative processes and hadron production were simulated.

Polarised radiative corrections are applied to the asymmetries as described in Refs. [2,8]. In this procedure, as for the evaluation of the dilution factor, contributions of processes where no hadron is produced are omitted.

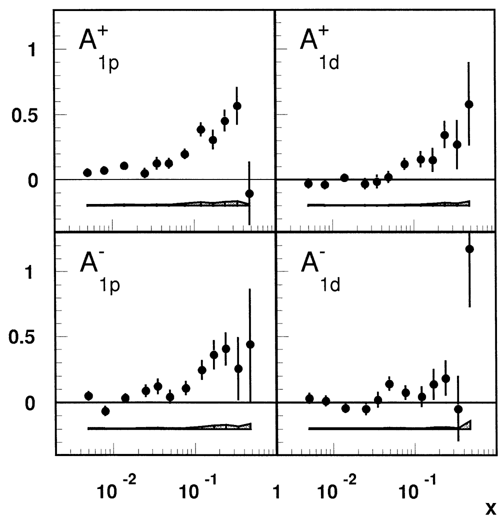

Fig. 1. Semi-inclusive spin asymmetries for the proton and the deuteron as a function of x for positively and negatively charged hadrons. The error bars are statistical and the shaded areas represent the systematic uncertainties.

Table 1
Values of semi-inclusive spin asymmetries A^+_{1p}, A^-_{1p}, A^+_{1d} and A^-_{1d}. The first error is statistical, the second one systematic.

x	A^+_{1p}	A^-_{1p}	A^+_{1d}	A^-_{1d}
0.005	$0.053 \pm 0.034 \pm 0.005$	$0.050 \pm 0.038 \pm 0.005$	$-0.030 \pm 0.039 \pm 0.005$	$0.032 \pm 0.042 \pm 0.005$
0.008	$0.070 \pm 0.034 \pm 0.007$	$-0.064 \pm 0.038 \pm 0.006$	$-0.039 \pm 0.038 \pm 0.006$	$0.013 \pm 0.042 \pm 0.005$
0.014	$0.107 \pm 0.030 \pm 0.011$	$0.036 \pm 0.034 \pm 0.004$	$0.013 \pm 0.033 \pm 0.004$	$-0.041 \pm 0.036 \pm 0.007$
0.025	$0.049 \pm 0.041 \pm 0.005$	$0.089 \pm 0.048 \pm 0.009$	$-0.033 \pm 0.044 \pm 0.006$	$-0.046 \pm 0.049 \pm 0.006$
0.035	$0.125 \pm 0.050 \pm 0.011$	$0.121 \pm 0.059 \pm 0.011$	$-0.016 \pm 0.053 \pm 0.004$	$0.020 \pm 0.060 \pm 0.005$
0.049	$0.124 \pm 0.042 \pm 0.010$	$0.042 \pm 0.052 \pm 0.005$	$0.019 \pm 0.046 \pm 0.005$	$0.142 \pm 0.053 \pm 0.012$
0.077	$0.195 \pm 0.041 \pm 0.016$	$0.109 \pm 0.054 \pm 0.009$	$0.119 \pm 0.046 \pm 0.010$	$0.076 \pm 0.055 \pm 0.008$
0.122	$0.386 \pm 0.055 \pm 0.027$	$0.244 \pm 0.075 \pm 0.018$	$0.155 \pm 0.063 \pm 0.012$	$0.045 \pm 0.077 \pm 0.007$
0.173	$0.306 \pm 0.078 \pm 0.020$	$0.361 \pm 0.112 \pm 0.027$	$0.149 \pm 0.093 \pm 0.013$	$0.138 \pm 0.116 \pm 0.014$
0.242	$0.454 \pm 0.083 \pm 0.030$	$0.405 \pm 0.126 \pm 0.032$	$0.345 \pm 0.104 \pm 0.023$	$0.183 \pm 0.133 \pm 0.016$
0.342	$0.567 \pm 0.144 \pm 0.035$	$0.256 \pm 0.238 \pm 0.021$	$0.269 \pm 0.190 \pm 0.017$	$-0.046 \pm 0.248 \pm 0.009$
0.480	$-0.106 \pm 0.245 \pm 0.011$	$0.438 \pm 0.433 \pm 0.040$	$0.578 \pm 0.320 \pm 0.032$	$1.176 \pm 0.451 \pm 0.063$

In order to interpret the results in the QPM a cut of $Q^2 > 1$ GeV^2 is applied. The current fragmentation region is selected by a cut on $z = E_{had}/\nu > 0.2$. After cuts on ν, y, the energy and the angle of the scattered muon as in Ref. [2], we obtain 32×10^6 events. After applying the z cut we obtain 5×10^6 positive and 4×10^6 negative hadrons. All of the data are in the deep inelastic region, $W > 3$ GeV, and cover the range $0.003 < x < 0.7$ with an average $Q^2 \approx 10$ GeV^2.

The asymmetries measured in different periods of data taking are compatible with each other, and thus all SMC data are combined. The semi-inclusive asymmetries $A^{+,-}_{1p,d}$ for positive and negative hadrons from the deuteron and the proton are presented in Fig. 1 and Table 1. The correlations between the asymmetries are listed in Table 2. The main contributions to systematic errors are due to the uncertainties of the target and beam polarisations, to the variation in time of the spectrometer acceptance and

Table 2
The correlation coefficients between the asymmetries. In the correlations only the dominating statistical uncertainties are taken into account. Therefore the proton and deuteron asymmetries are uncorrelated. The correlations are given by $\mathrm{cor}(A^+,A^-) = \langle n^+ n^- \rangle / \sqrt{\langle n^{+2} \rangle \langle n^{-2} \rangle}$ and $\mathrm{cor}(A,A^{+(-)}) = \langle n^{+(-)} \rangle / \sqrt{\langle n^{+(-)2} \rangle}$, where $n^{+(-)}$ is the number of positive (negative) hadrons per scattered muon.

x	Correlations					
	(A_{1p},A^+_{1p})	(A_{1p},A^-_{1p})	(A^+_{1p},A^-_{1p})	(A_{1d},A^+_{1d})	(A_{1d},A^-_{1d})	(A^+_{1d},A^-_{1d})
0.005	0.32	0.29	0.05	0.31	0.29	0.05
0.008	0.35	0.32	0.06	0.34	0.31	0.05
0.014	0.38	0.34	0.06	0.37	0.34	0.06
0.025	0.41	0.36	0.07	0.40	0.36	0.06
0.035	0.44	0.37	0.07	0.42	0.37	0.07
0.049	0.45	0.37	0.07	0.43	0.38	0.07
0.077	0.47	0.36	0.07	0.44	0.37	0.07
0.122	0.45	0.32	0.06	0.43	0.35	0.06
0.173	0.40	0.27	0.05	0.39	0.30	0.06
0.242	0.34	0.22	0.05	0.33	0.25	0.05
0.342	0.30	0.18	0.04	0.27	0.21	0.05
0.480	0.30	0.17	0.05	0.25	0.18	0.05

to the uncertainty of the dilution factor. Negligible contributions arise from secondary interactions of hadrons in the target, radiative corrections and differences in acceptance for pions, kaons and protons due to different absorptions in the target and different angular distributions.

The inclusive asymmetry A_{1p} can be expressed in terms of polarised and unpolarised structure functions:

$$A_{1p}(x,Q^2) = \frac{g_1^p(x,Q^2)}{F_1^p(x,Q^2)} = \frac{g_1^p(x,Q^2)}{F_2^p(x,Q^2)}\, 2x\left[1+R(x,Q^2)\right]. \quad (4)$$

In the QPM the structure functions can be written in terms of polarised quark distributions $\Delta q = q^{\uparrow} - q^{\downarrow}$ and unpolarised quark distributions $q = q^{\uparrow} + q^{\downarrow}$, where $q^{\uparrow}(q^{\downarrow})$ is the distribution of quarks of flavour q and spin parallel (antiparallel) to the nucleon spin. The published leading order parametrisations of the unpolarised quark distributions were obtained from experimental values of F_2^p using the relation $F_2^p(x,Q^2) = x\sum_q e_q^2\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$. The values of F_2^p were extracted from cross sections assuming non-zero values of R. Therefore the expression for A_{1p} becomes:

$$A_{1p}(x,Q^2) = \frac{\sum_q e_q^2\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]}{\sum_q e_q^2\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]} \times\left[1+R(x,Q^2)\right], \quad (5)$$

where e_q is the fractional charge of the quark q with $q = u,d,s$. For $x < 0.12$ we use a parametrisation of R measured by the NMC [9] and for higher x we use the SLAC parametrisation [10]. At our average Q^2 of 10 GeV^2 the ratio R varies from 0.15 at $x = 0.005$ to 0.07 at $x = 0.5$.

For semi-inclusive processes the asymmetries depend in addition on the fragmentation functions $D_q^h(z,Q^2)$, which represent the probability that a quark q fragments into a hadron h. Using the quantity $D_q^h(Q^2)$ defined as $D_q^h(Q^2) = \int_{0.2}^1 \mathrm{d}z\, D_q^h(z,Q^2)$ we have:

$$A_{1p}^{+(-)}(x,Q^2) = \frac{\sum_{q,h} e_q^2\left[\Delta q(x,Q^2)\, D_q^h(Q^2) + \Delta\bar{q}(x,Q^2)\, D_{\bar{q}}^h(Q^2)\right]}{\sum_{q,h} e_q^2\left[q(x,Q^2)\, D_q^h(Q^2) + \bar{q}(x,Q^2)\, D_{\bar{q}}^h(Q^2)\right]} \times\left[1+R(x,Q^2)\right], \quad (6)$$

where the summation is over π^+, K^+ and p for positive hadrons and over π^-, K^- and $\bar{p}$ for negative hadrons. We assumed the same R for positive and negative hadrons, and used the same R as for the inclusive case. It was checked that our acceptance depends only weakly on z in the region covered by the integral of the fragmentation functions. Since the fragmentation process is parity conserving and the polarisation of hadrons is not observed, the fragmentation functions do not depend on the quark helicity ($D_{q^{\uparrow}} = D_{q^{\downarrow}}$). In general $D_q^h \neq D_{\bar{q}}^h$, so the measurement of semi-inclusive asymmetries allows a separation of Δq and $\Delta\bar{q}$, whereas only the sum, $(\Delta q + \Delta\bar{q})$, can be determined from the inclusive asymmetries.

Using isospin symmetry, similar expressions are obtained for the deuteron asymmetries. From the data on proton and deuteron we can separate spin contributions from u and d quarks. The spin dependent deuteron cross section is considered to be the sum of the proton and the neutron cross sections with a correction to account for the D-state probability $\omega_D = 0.05 \pm 0.01$ of the deuteron, as in Ref. [3]. We use the same R for the proton and the deuteron.

With Eqs. (5) and (6) and the corresponding relations for the deuteron our measured inclusive and semi-inclusive asymmetries can be used to evaluate the polarised quark distributions. The polarised valence quark distributions are defined as $\Delta u_v(x) = \Delta u(x) - \Delta\bar{u}(x)$ and $\Delta d_v(x) = \Delta d(x) - \Delta\bar{d}(x)$. To reduce the number of unknowns we assume a $SU(3)_f$ symmetric sea which we denote by $\Delta\bar{q}(x)$:

$$\Delta\bar{q}(x) = \Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta s(x) = \Delta\bar{s}(x). \quad (7)$$

The sensitivity of our results to this assumption will be discussed below. In particular the assumption involving $\Delta s(x)$ and $\Delta \bar{s}(x)$ has a negligible influence on our results, because our hadron sample contains mainly pions, thus $\Delta\bar{q}(x)$ provides information mainly about non strange sea quarks.

The six measured asymmetries are linear combinations of three unknowns: Δu_v, Δd_v and $\Delta\bar{q}$. Six equations for the asymmetries can thus be written in matrix form:

$$\boldsymbol{A} = \mathscr{B}\boldsymbol{\Delta q} \tag{8}$$

where $\boldsymbol{A} = (A_{1p}, A_{1p}^+, A_{1p}^-, A_{1d}, A_{1d}^+, A_{1d}^-)$ and $\boldsymbol{\Delta q} = (\Delta u_v, \Delta d_v, \Delta\bar{q})$. The elements of the matrix $\mathscr{B}$ are determined from Eqs. (5) and (6). They depend on the unpolarised quark distributions q, the fragmentation functions D_q^h, the ratio R, and ω_D.

The asymmetries were measured at average Q^2 values in each x bin varying from 1.3 GeV^2 at our lowest x to 60 GeV^2 at $x = 0.5$. No significant Q^2 dependence is observed in the inclusive data [3,11], therefore we assume the asymmetries at measured Q^2 to be equal to those at $Q^2 = 10\,\mathrm{GeV}^2$. In Eq. (8) we use parametrisations of the unpolarised quark distributions [12], of the ratio R, and of the fragmentation functions [13], all at $Q^2 = 10$ GeV^2. For the unmeasured fragmentation functions additional assumptions are made, as discussed below.

In order to determine the leading order polarised quark distributions $\Delta u_v(x)$, $\Delta d_v(x)$ and $\Delta\bar{q}(x)$ we solve Eq. (8) in every x-bin independently by minimising the quantity

$$\chi^2 = (\boldsymbol{A} - \mathscr{B}\boldsymbol{\Delta q})^T (\mathrm{Cov}_A)^{-1} (\boldsymbol{A} - \mathscr{B}\boldsymbol{\Delta q}), \tag{9}$$

where Cov_A is the covariance matrix of the asymmetries (cf. Table 2). The results are shown in Fig. 2 and Table 3. We see in the figure that the statistical error on $\Delta\bar{q}(x)$ in the region $x > 0.3$ is larger than $\bar{q}(x)$ which is an upper limit for $|\Delta\bar{q}(x)|$. In this region, in order to reduce the statistical error on $\Delta u_v(x)$ and $\Delta d_v(x)$, we set $\Delta\bar{q}(x) = 0$ before solving the system of equations. The results are shown as open circles in Fig. 2. Uncertainties due to this assumption were included in the systematic error.

We observe that $\Delta u_v(x)$ is positive while $\Delta d_v(x)$ is negative. The polarised sea quark distribution

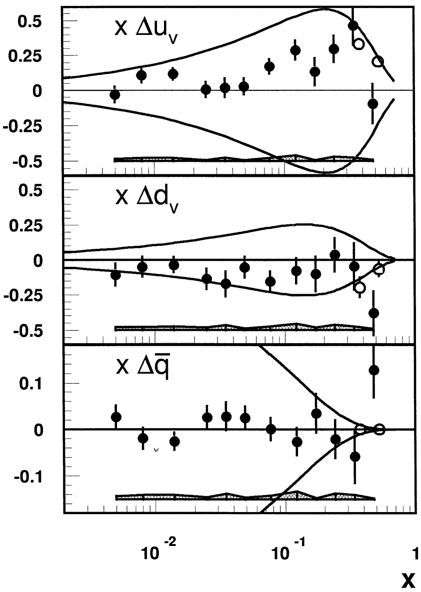

Fig. 2. The polarised quark distributions $x\Delta u_v(x)$, $x\Delta d_v(x)$ and $x\Delta\bar{q}(x)$ obtained with the assumption $\Delta\bar{u}(x) = \Delta\bar{d}(x)$. The open circles are obtained when the sea polarisation is set to zero while the closed circles are obtained without this assumption. The error bars are statistical and the shaded areas represent the systematic uncertainty. The curves correspond to the upper and the lower limits $\pm xq(x)$ from the unpolarised quark distributions [12] evaluated at $Q^2 = 10$ GeV^2. In the bottom plot the curves are $\pm x(\bar{u}(x) + \bar{d}(x))/2$.

$\Delta\bar{q}(x)$ is compatible with zero over the full range of x. Fig. 3 shows the polarisation $\Delta q_v(x)/q_v(x)$ of the valence quarks. The average polarisation is approximately 50% for the u_v quarks and -50% for the d_v quarks. For the u_v quarks we observe a lower average polarisation of 0.18 ± 0.10 in the interval $0.003 < x < 0.06$ (first six bins) and a higher average polarisation of 0.57 ± 0.05 in the interval $0.06 < x < 0.7$ (last six bins).

The uncertainties of these results are dominated by the statistical errors. Contributions from different sources to the systematic errors on the integrals $\int_{0.003}^{0.7} \Delta q(x)\mathrm{d}x$ are listed in Table 4 and the values of the integrals in Table 5. The largest contribution is related to the assumptions made for the unmeasured fragmentation functions of s quarks. Strange quark fragmentation functions to pions were assumed to be equal to the measured unfavoured fragmentation function: $D_{s,\bar{s}}^{\pi^+,\pi^-} = D_u^{\pi^-}$. For the favoured fragmentation functions of s quarks to kaons we assumed $D_s^{K^-} = D_{\bar{s}}^{K^+} = D_d^{\pi^-}$. This is motivated by the fact that in both fragmentation processes, $s \to K^-$ and $d \to \pi^-$, a $u\bar{u}$-pair has to be produced to create the hadron. Values of the unmeasured fragmentation functions obtained with the above assumptions were varied by a factor 0.5 to 1.5 and the difference in the resulting polarised quark distributions was included in the systematic error. The uncertainty due to the unpolarised quark distributions was taken to be the difference resulting from two different parametrisations, GRV-94 (LO) [12] and CTEQ 3L (LO) [14]. The systematic error due to the assumption $\Delta\bar{q}(x) = 0$ in the last two x bins was calculated by setting $\Delta\bar{q}(x) = \pm\bar{q}(x)$ in these bins.

In the QPM, with the assumption $\Delta\bar{u}(x) = \Delta\bar{d}(x)$, the quantities $6[g_1^p(x) - g_1^n(x)]$ and $\Delta u_v(x) - \Delta d_v(x)$ are equal. The former is obtained from inclusive data only while the latter can be extracted using only the four semi-inclusive asymmetries in Eq. (8). The two quantities are generally in good agreement, as seen in Fig. 4, showing the consistency of the present analysis. The discrepancy in the last bin is mainly due to the low value of the asymmetry A_{1p}^+ in this bin. This is also reflected in Table 3 by the low χ^2 probability for this bin. It has been checked that this low value could not be caused by a false asymmetry due to a change in the spectrometer acceptance. With the constraint $\Delta\bar{q}(x) = 0$ only two unknowns, $\Delta u_v(x)$ and $\Delta d_v(x)$, have to be determined. This can be done using only the inclusive asymmetries A_{1p} and A_{1d} which have a better statistical accuracy. For this reason adding the semi-inclusive asymmetries has very little impact in the last two bins, i.e. the results for $\Delta u_v(x)$ and $\Delta d_v(x)$ from A_{1p} and A_{1d} only are almost identical with the values shown in Table 3 where all six asymmetries are used.

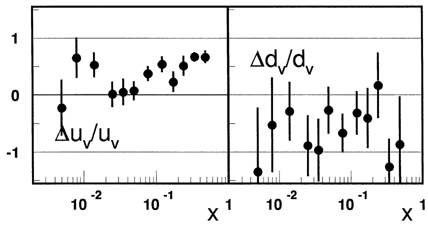

Fig. 3. The polarisation $\Delta q_v(x)/q_v(x)$ of the valence quarks. Only the statistical errors are given.

In order to calculate first moments, $\Delta q = \int_0^1 \Delta q(x) \mathrm{d}x$, of the polarised quark distributions, we need extrapolations of $\Delta q(x)$ to the unmeasured regions of x. Contributions from the unmeasured large x region $(0.7 < x < 1)$ are negligible because their upper limits given by the unpolarised distributions are small there. The low x $(0 < x < 0.003)$ extrapolation was done in several ways. Two func-

Table 3
Values of the polarised quark distributions $x\,\Delta u_v(x)$, $x\,\Delta d_v(x)$ and $x\,\Delta\bar{q}(x)$. The distributions were obtained with the assumption $\Delta\bar{u}(x) = \Delta\bar{d}(x)$. The first errors are statistical and the second ones are systematic. The values in the last two bins of x correspond to the open circles in Fig. 2. In the last two columns the value of χ^2/n and the corresponding probability p are given.

x	$x\,\Delta u_v(x)$	$x\,\Delta d_v(x)$	$x\,\Delta\bar{q}(x)$	χ^2/n	p
0.005	$-0.029 \pm 0.064 \pm 0.017$	$-0.105 \pm 0.088 \pm 0.022$	$0.027 \pm 0.027 \pm 0.007$	2.4/3	0.50
0.008	$0.107 \pm 0.059 \pm 0.023$	$-0.050 \pm 0.079 \pm 0.023$	$-0.019 \pm 0.025 \pm 0.009$	4.8/3	0.19
0.014	$0.115 \pm 0.049 \pm 0.023$	$-0.035 \pm 0.063 \pm 0.025$	$-0.025 \pm 0.021 \pm 0.009$	4.9/3	0.18
0.025	$0.004 \pm 0.063 \pm 0.007$	$-0.136 \pm 0.082 \pm 0.019$	$0.026 \pm 0.027 \pm 0.005$	2.6/3	0.46
0.035	$0.017 \pm 0.075 \pm 0.026$	$-0.170 \pm 0.097 \pm 0.035$	$0.028 \pm 0.032 \pm 0.012$	2.5/3	0.47
0.049	$0.029 \pm 0.064 \pm 0.005$	$-0.053 \pm 0.082 \pm 0.011$	$0.025 \pm 0.027 \pm 0.004$	4.2/3	0.24
0.077	$0.171 \pm 0.061 \pm 0.021$	$-0.154 \pm 0.079 \pm 0.025$	$0.002 \pm 0.026 \pm 0.008$	9.2/3	0.03
0.122	$0.287 \pm 0.076 \pm 0.040$	$-0.079 \pm 0.097 \pm 0.045$	$-0.026 \pm 0.032 \pm 0.017$	5.1/3	0.16
0.173	$0.133 \pm 0.105 \pm 0.007$	$-0.101 \pm 0.132 \pm 0.020$	$0.035 \pm 0.043 \pm 0.003$	0.6/3	0.90
0.242	$0.296 \pm 0.103 \pm 0.032$	$0.038 \pm 0.127 \pm 0.039$	$-0.021 \pm 0.043 \pm 0.013$	2.1/3	0.55
0.342	$0.332 \pm 0.041 \pm 0.025$	$-0.198 \pm 0.078 \pm 0.025$		1.8/4	0.77
0.480	$0.205 \pm 0.033 \pm 0.011$	$-0.064 \pm 0.062 \pm 0.010$		16.2/4	0.003

Table 4
Contributions to the error on the integral $\int_{0.003}^{0.7} \Delta q(x)dx$. The abbreviation f.f. stands for fragmentation functions. The values of the integrals are given in Table 5.

Error source	$\int_{0.003}^{0.7} \Delta u_v(x)dx$	$\int_{0.003}^{0.7} \Delta d_v(x)dx$	$\int_{0.003}^{0.7} \Delta\bar{q}(x)dx$
Beam polarisation	0.02	0.01	0.000
Target polarisation	0.02	0.03	0.002
Dilution factor	0.02	0.01	0.002
Acceptance variation	0.01	0.03	0.002
Statistical error of f.f.	0.01	0.01	0.005
Assumptions on f.f.	0.05	0.06	0.024
Unpolarised quark distribution	0.02	0.02	0.001
$\Delta\bar{q}(x) = 0$	0.01	0.01	0.003
Total systematic error	0.07	0.08	0.03
Statistical error	0.10	0.14	0.04

tional forms of the polarised quark distributions were fitted to our semi-inclusive and inclusive asymmetries [7]. We also used parametrisations of the polarised quark distributions obtained from two different QCD analyses [15,16] of inclusive data. For every quark distribution we obtained four values for the integral $\int_0^{0.003}\Delta q(x)$ and estimated the mean value and the error. For the valence quarks these values (see Table 5) are much smaller than the upper limits given by the unpolarised distributions $|\int_0^{0.003}\Delta q_v(x)dx| \le \int_0^{0.003} q_v(x)dx$. This upper limit is 0.22 (0.17) for GRV-94,LO parametrisation of the u_v (d_v) quarks. There is no such constraint for the sea quarks. The first moments of the polarised quark distributions are

$$\Delta u_v = 0.77 \pm 0.10 \pm 0.08,$$
$$\Delta d_v = -0.52 \pm 0.14 \pm 0.09,$$
$$\Delta\bar{q} = 0.01 \pm 0.04 \pm 0.03.$$

The statistical errors are reduced by almost a factor of two compared to our previous publication [1]. The contributions to the moments from measured and unmeasured regions are detailed in Table 5.

In order to study the effect of the assumption of a $SU(3)_f$ symmetric sea in Eq. (7) we replace it by only an isospin symmetric sea, $\Delta\bar{u}(x) = \Delta\bar{d}(x) =$

Table 5
The values for the extrapolations to low x (first column), the integrals over the measured range (second column) and the first moments (third column). In the last two columns the first error is statistical, the second systematic. The upper part of the table shows the results obtained assuming $\Delta\bar{u}(x) = \Delta\bar{d}(x)$, the lower part shows the results without this assumption.

	Contributions to the first moments of the polarised quark distributions			
$\Delta\bar{u}(x) = \Delta\bar{d}(x)$	x	$0-0.003$	$0.003-0.7$	$0-1$
	Δu_v	0.04 ± 0.04	$0.73 \pm 0.10 \pm 0.07$	$0.77 \pm 0.10 \pm 0.08$
	Δd_v	-0.05 ± 0.05	$-0.47 \pm 0.14 \pm 0.08$	$-0.52 \pm 0.14 \pm 0.09$
	x	$0-0.003$	$0.003-0.3$	$0-1$
	$\Delta\bar{q}$	0.00 ± 0.02	$0.01 \pm 0.04 \pm 0.03$	$0.01 \pm 0.04 \pm 0.03$
$\Delta\bar{u}(x) \neq \Delta\bar{d}(x)$	x	$0-0.003$	$0.003-0.7$	$0-1$
	Δu_v	0.04 ± 0.04	$0.72 \pm 0.11 \pm 0.06$	$0.76 \pm 0.11 \pm 0.07$
	Δd_v	-0.05 ± 0.05	$-0.45 \pm 0.30 \pm 0.25$	$-0.50 \pm 0.30 \pm 0.25$
	x	$0-0.003$	$0.003-0.3$	$0-1$
	$\Delta\bar{u}$	0.00 ± 0.02	$0.01 \pm 0.05 \pm 0.01$	$0.01 \pm 0.05 \pm 0.02$
	$\Delta\bar{d}$	0.00 ± 0.02	$0.01 \pm 0.14 \pm 0.12$	$0.01 \pm 0.14 \pm 0.12$

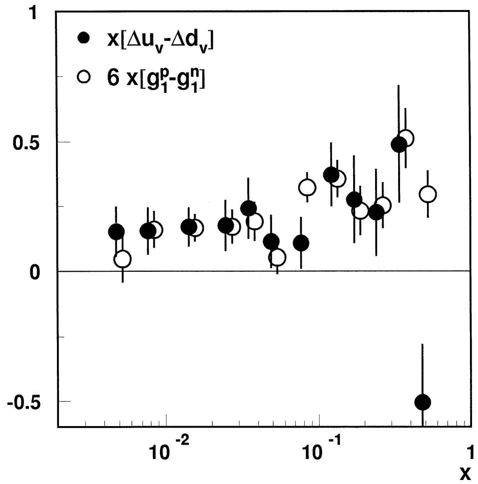

Fig. 4. The difference between the spin-dependent structure functions of the proton and the neutron, $6\,x[g_1^p(x)-g_1^n(x)]$, (open circles), and the difference between polarised *up* and *down* valence quark distributions $x[\Delta u_v(x)-\Delta d_v(x)]$, as determined with the assumption $\Delta\bar{u}(x)=\Delta\bar{d}(x)$ from SMC semi-inclusive asymmetries only (closed circles). Errors are statistical. The correlation between these two quantities is about 40%, similar to the correlation between inclusive and semi-inclusive asymmetries given in Table 2.

$\Delta\bar{q}(x)$ and allow $\Delta s(x)=\Delta\bar{s}(x)=\eta\Delta\bar{q}(x)$, varying η in the range $0.25<\eta<1.5$. The corresponding variations of the first moments are of the order of 0.01. Similar variations are observed if we use $\Delta s(x)$ as given in Ref. [15], where the integral is $\int_0^1\Delta s(x)\mathrm{d}x=-0.06$, a value consistent with the result $\int_0^1(\Delta s(x)+\Delta\bar{s}(x))\mathrm{d}x=-0.12\pm0.04$ obtained from the inclusive analysis [11]. This shows that the measurement is only sensitive to the polarisation of the non-strange sea quarks.

Releasing the constraint $\Delta\bar{u}(x)=\Delta\bar{d}(x)$ and setting $\Delta s(x)=\Delta\bar{s}(x)=(\Delta\bar{u}(x)+\Delta\bar{d}(x))/2$ leads to the results given in the lower part of Table 5. The results are consistent with those obtained with the constraint $\Delta\bar{u}=\Delta\bar{d}$. The statistical error on $\Delta u_v(x)$ practically does not change, whereas the error on $\Delta d_v(x)$ increases by a factor of two.

Polarised semi-inclusive deep inelastic scattering is presently a unique tool to measure the polarised valence and sea quark distributions. However, the corresponding first moments can be determined by other methods. With the assumption of a $SU(3)_f$ symmetric sea (Eq. (7)) and $SU(3)_f$ symmetry for the weak decays in the baryon octet, the first moments of the valence distributions can be obtained from the axial matrix elements, F and D, of baryon decays. It should be noted that the results depend strongly on these two assumptions, whereas the results from our semi-inclusive analysis are insensitive to any $SU(3)_f$ assumptions, as discussed above. With the values quoted in Refs. [17,18] one finds $\Delta u_v=2F=0.92\pm0.02$ and $\Delta d_v=F-D=-0.34\pm0.02$, which is in good agreement with our results of Table 5 obtained from deep inelastic scattering only. Our result for $\Delta\bar{q}$ is consistent with the first moment of the polarised strange quark distribution obtained from the inclusive analysis [11] quoted above.

From our polarised quark distributions we find for the second moments:

$$\int_0^1 x\Delta u_v(x)\mathrm{d}x=0.155\pm0.017\pm0.010$$

and

$$\int_0^1 x\Delta d_v(x)\mathrm{d}x=-0.056\pm0.026\pm0.011,$$

where the first error is statistical and the second is systematic. Due to the additional factor x the low x extrapolations to the unmeasured region give negligible contributions while the large x contributions remain small. A calculation of the second moments in lattice QCD [19] predicts $\int_0^1 x\Delta u_v(x)\mathrm{d}x=0.189\pm0.008$ and $\int_0^1 x\Delta d_v(x)\mathrm{d}x=-0.0455\pm0.0032$, which is in good agreement with our measured values.

To summarise, we have measured semi-inclusive spin asymmetries for positively and negatively charged hadrons from polarised protons and deuterons and we have determined the polarised quark distributions $\Delta u_v(x)$, $\Delta d_v(x)$ and $\Delta\bar{q}(x)$ of the valence and the non-strange sea quarks. The polarisation of the u_v quarks was found to be positive and to increase with x. The polarisation of the d_v quarks was found to be negative while the polarisation of the non-strange sea quarks is consistent with zero. Our results for the first moments of the polarised valence quark distributions are in good agreement with results obtained from the axial matrix elements F and D. The second moments are consistent with lattice QCD predictions.

References

[1] SMC, B. Adeva et al., Phys. Let. B 369 (1996) 93.
[2] SMC, D. Adams et al., Phys. Rev. D 56 (1997) 5330.
[3] SMC, D. Adams et al., Phys. Lett. B 396 (1997) 338.
[4] O.C. Allkofer et al., Nucl. Instr. Methods 179 (1981) 445.
[5] A.A. Akhundov et al., Fortsch. Phys. 44 (1996) 373; A.A. Akhundov et al., Sov. J. Nucl. Phys. 26 (1977) 660; 44 (1986) 988; JINR-Dubna Preprints E2–10147 (1976), E2–10205 (1976), E2–86–104 (1986); D. Bardin, N. Shumeiko, Sov. J. Nucl. Phys. 29 (1979) 499.
[6] EMC; V. Papavassiliou, Ph.D. thesis, Yale University (1988).
[7] SMC; J. Pretz, Ph.D. thesis Mainz University (1997).
[8] T.V. Kukhto und N.M. Shumeiko, Nucl. Phys. B 219 (1983) 412; I.V. Akushevich und N.M. Shumeiko, J. Phys. G 20 (1994).
[9] NMC; M. Arneodo et al., Nucl. Phys. B 483 (1997) 3.
[10] SLAC, L. Whitlow et al., Phys. Lett. B 250 (1990) 193.
[11] SMC; B. Adeva et al., Phys. Lett. B 412 (1997) 414.
[12] M. Glück et al., Z. Phys. C 67 (1995) 433.
[13] EMC, A. Arneodo et al., Nucl. Phys. B 321 (1989) 541.
[14] H.L. Lai et al., Phys. Rev. D 51 (1994) 4763.
[15] M. Glück et al., Phys. Rev. D 53 (1996) 4775.
[16] T. Gehrmann, W.J. Stirling, Phys. Rev. D 53 (1996) 6100.
[17] R.M. Barnett et al., 'Review of Particle Properties', Phys. Rev. D 54 (1996) and off-year update for the 1998 edition (URL: http://pdg.lbl.gov/).
[18] F.E. Close, R.G. Roberts, Phys. Lett. B 316 (1993) 165.
[19] M. Göckeler et al., hep-ph/9708270 and DESY 97-117, accepted in Phys. Lett. B.