STRUCTURE FUNCTIONS AND THE SPIN OF THE NUCLEON: FROM HERMES TO COMPASS

F.H. HEINSIUS (for the HERMES and COMPASS collaborations)
Fakultät für Physik, Universität Freiburg,
79104 Freiburg, Germany

The HERMES and SMC experiments have determined the contribution of different quark flavors to the nucleon spin in a large range of Bjorken-x via semi-inclusive deep inelastic scattering. The main goal of the COMPASS experiment is to measure the gluon polarization in the nucleon. In all experiments a polarized lepton is scattered off a polarized nucleon. Latest results from HERMES and perspectives for COMPASS running in 2001 and beyond are presented.

1 Spin of the Nucleon

The spin of the nucleon is known to be $1/2\hbar$ (in the following: $\hbar$=1). However, the EMC-experiment has found that the spin of the quarks contribute only by a small fraction to the proton spin. Ever since it has been a longstanding problem how the nucleon spin is divided among the quarks and gluons. All possible contributions are summarized in a sum rule, which splits the total spin of the nucleon into the contributions from quarks, $\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\overline{u} + \Delta\overline{d} + \Delta\overline{s}$, from gluons ΔG, and the orbital angular momentum of quarks and gluons, L_q and L_g, respectively:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g \tag{1}$$

The spin density contribution of the quarks to the nucleon spin $\Delta\Sigma$ can be probed in deep inelastic scattering. The latest result [1] obtained by the HERMES collaboration is $\Delta\Sigma = 0.30 \pm 0.04 \pm 0.09$, clearly showing that the other contributions to the nucleon spin are needed.

The gluon spin density ΔG can be probed in the photon-gluon fusion process as planned in the COMPASS experiment. It has been suggested that the orbital angular momentum L_q of the quarks can be probed through a measurement of the total angular momentum of the quarks $J_q = \frac{1}{2}\Delta\Sigma + L_q$ using the framework of generalized parton distributions. [2]

Non-relativistic quark models, where no distinction is made between constituent and current quarks, yield $\Delta\Sigma = 1$. This is clearly incompatible with the data. In bag models the quarks have (small) current-quark masses, so relativistic effects have to be taken into account. This leads also to orbital contributions to the angular momentum. Jaffe and Manohar estimated for this case a quark spin contribution of about $\Delta\Sigma \approx 0.65 - 0.75$.[3] Note that these models do not contain any gluon contributions. A major step forward towards a QCD based understanding was reached in a QCD sum rule approach by Balitski and Ji.[4] By defining a gauge invariant definition of the total angular momentum contributions from quarks and gluons in the nucleon they estimated: $J_q = \frac{1}{2}\Delta\Sigma + L_q = 0.15$ and $J_g = \Delta G + L_g = 0.35$.

Recently a full (non-quenched) lattice QCD calculation has succeeded to evaluate the contributions of separated quark flavors to the nucleon spin[5]: $\Delta u = 0.62(7), \Delta d = -0.29(6), \Delta s = -0.12(7)$. These numbers are, within their fairly large errors, compatible with present data. Another approach is based on the chiral soliton model (instanton model). It predicts a flavor asymmetry of the polarized antiquark distribution.[6] This awaits confirmation by the experiments.

Experimentally the polarization of the partons in the nucleon are probed in spin-dependent deep inelastic scattering (DIS). In inclusive DIS the asymmetry in the lepton nucleon scattering cross section is measured for the spin of the nucleon in the same and opposite direction to the lepton helicity:

$$A_1(x) = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} \approx \frac{g_1(x, Q^2)}{F_1(x, Q^2)} \tag{2}$$

with $F_1(x, Q^2) = \frac{1}{2}\sum_f e_f^2 q_f(x, Q^2)$ and $g_1(x, Q^2) = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x, Q^2)$ being the unpolarized and polarized structure function in the quark parton model, respectively, $\Delta q_f(x, Q^2) = q_f^{\uparrow}(x, Q^2) - q_f^{\downarrow}(x, Q^2)$, Q^2 the negative 4-momentum transfer squared of the photon, and x the Bjorken scaling variable. In semi-inclusive DIS a hadron is detected in coincidence with the scattered lepton. This allows to tag the flavor of the struck quark by the identification of the fragmentation products. For example, a π^+ is predominantly produced from an u quark.

2 HERMES results

The HERMES experiment, located at the HERA storage ring at DESY, has taken inclusive and semi-inclusive deep inelastic scattering data off positrons on ^{1}H, ^{2}H and ^{3}He targets.[7] The measured inclusive asymmetries[1], together with the asymmetries of positive and negative hadrons, allow to extract the flavor dependent polarization of the up quarks, down quarks and the sea quark contribution (Fig. 1).

The up quark polarization $(\Delta u + \Delta\overline{u})/(u + \overline{u})$ is positive, the down quark polarization $(\Delta d + \Delta\overline{d})/(d + \overline{d})$ is slightly negative. Their absolute values are largest at large x and remain different from zero in the sea region. The sea quark polarization $\Delta q_s/q_s$ is compatible with zero in the measured range. In the extraction of the polarizations it was assumed that the polarizations of the sea quarks are flavor independent. New data taken on a deuterium target will allow a much better constraint on the down quark polarization. Better pion-kaon separation, due to the recently installed RICH detector, will allow a flavor decomposition of the sea quarks.

From the inclusive deep inelastic scattering data the structure function $g_1(x, Q^2)$ can be extracted. It is defined in the quark parton model as

$$g_1(x, Q^2) = \sum_{f=q,\overline{q}} e_f^2 \Delta q_f(x, Q^2). \tag{3}$$

An analysis of data taken below $Q^2 = 1$ GeV^2 extends the HERMES x range to $0.0021 < x < 0.021$. The HERMES data[8] together with SMC data show a first hint on scaling violations in

$g_1^p(x,Q^2)$, as are already well-known in the unpolarized structure function $F_1(x,Q^2)$. These data are important to determine the quark spin contributions at small x. This region has currently the largest contribution to the error in the determination of $\Delta\Sigma$.

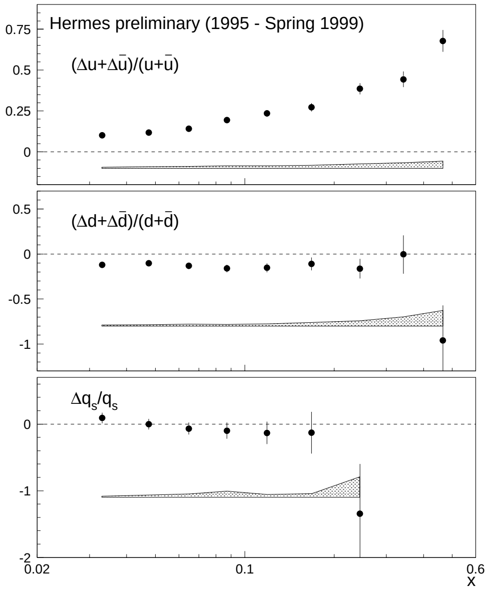

Figure 1: Polarization of up, down and sea quarks in the proton as measured by the HERMES experiment. The sea polarization is assumed to be flavor independent. All error bars shown are statistical errors, and the bands indicate the systematic uncertainties.

The inclusive deep inelastic scattering data have also been used to attempt a determination of the gluon spin contribution to the nucleon spin. A QCD fit to the world data on the structure function $g_1(x,Q^2)$ has been performed by the SMC collaboration. [9] Through the evolution with Q^2 one gets access to the singlet $\Delta\Sigma$ and non-singlet Δq_{NS} quark contributions to the nucleon spin as well as to the gluon contribution:

$$g_1(x,Q^2) = \frac{1}{9}(C_{NS}\otimes\Delta q_{NS} + C_\Sigma\otimes\Delta\Sigma + 2N_f C_g\otimes\Delta G) \tag{4}$$

Here C_{NS}, C_Σ and C_g are splitting functions calculated in NLO QCD. While the quark singlet spin contribution is determined very well ($\Delta\Sigma = 0.38^{+0.03+0.03+0.03}_{-0.03-0.02-0.05}$), this procedure does not put large constraints on the gluon contribution to the spin ($\Delta G = 0.99^{+1.17+0.42+1.43}_{-0.31-0.22-0.45}$). A determination of the gluon spin contribution through evolution requires measurements over a larger range of Q^2 and lower x values. These will only be available at collider energies. Therefore other possibilities are pursued in current experiments.

The first direct exploration of the gluon polarization has been performed by the HERMES collaboration. [10] The analysis of high-p_T hadron pairs yielded a value of $\Delta G/G = 0.41 \pm 0.18(\text{stat}) \pm 0.03(\text{syst})$ at an average fraction of the nucleon momentum carried by the struck gluon of $< x_G >$=0.17. However, this determination is model dependent as a Monte Carlo simulation is needed to determine the relative importance of the photon-gluon fusion and the QCD Compton contributions to the yield.

3 COMPASS prospects

The COMPASS [11] (Fig. 2) experiment at CERN consists out of a two-stage magnetic spectrometer with particle identification over a large kinematical range. A 100-200 GeV muon beam on ^{6}LiD and NH_3 targets will yield five times the luminosity compared to the SMC experiment. High statistics measurements are made possible by the design of quasi dead-time free readout electronics and event rates of up to 100 kHz. The primary physics goals of the COMPASS experiment are the measurement of the gluon polarization in the nucleon and the determination of the longitudinal and transverse quark spin distribution functions for small x. In addition a rich program of hadron spectroscopy with hadron beams is foreseen.

In COMPASS $\Delta G/G$ will be studied via the photon-gluon fusion process, tagged either by open-charm production, or by high-p_T hadron pair production. The open-charm events will be identified by the reconstruction of D mesons from the hadronic decay products. The measurement of the spin dependent asymmetry for charm production allows the extraction of the gluon polarization $\Delta G/G$ by unfolding the known photon-gluon cross section and the gluon distribution $G(x)$. About 800 events with reconstructed D^0 mesons are expected per day. This yields an uncertainty of $\delta(\Delta G/G) = 0.11$ in 2.5 years running time. A high statistics measurement of high-p_T hadron pairs allows to measure several points of $\Delta G/G$ in the range of $x_G = 0.04 - 0.2$. However, the error is limited by systematics and is expected to be $\delta(\Delta G/G) =$

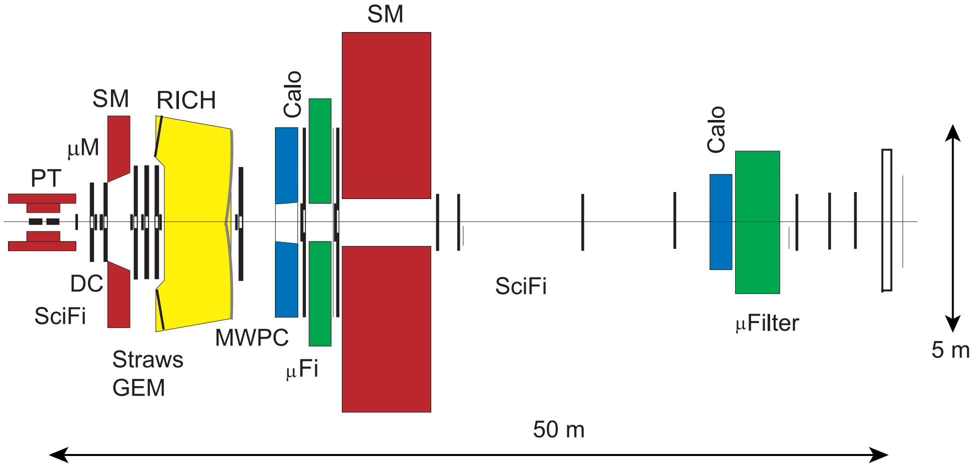

Figure 2: The COMPASS detector. Shown are the polarized target (PT), the two spectrometer magnets (SM), small angle tracking detectors (SciFi, μM, GEM), the large angle tracking detectors (DC, Straws, MWPC) and the particle identification detectors (RICH, hadron calorimeter μFilter).

0.05 after one year running time.[12] COMPASS will start to take physics data in 2001. However, due to limitations in large angle tracking it is planned to start with the measurement of g_1 at small x values, which is important for the study of possible scaling violations. In addition the experiment will gather first data on the measurement of $\Delta G/G$.

4 Future

The HERMES collaboration will continue the successful data taking in run II (2001 – 2006) with an emphasis on the measurement of the previously unknown transverse quark spin distributions $h_1(x)$. In addition further measurements of the quark and gluon polarizations are planned. To get access to exclusive scattering a recoil detector around the target is under development.

For the COMPASS experiment studies are ongoing to measure exclusive scattering reactions like deeply virtual Compton scattering (DVCS). Data on DVCS may provide information on the sofar unknown contribution of the orbital angular momentum of the quarks to the nucleon spin. To ensure the exclusivity of these reactions a recoil detector is required.

References

1. K. Ackerstaff *et al* (HERMES), *Phys. Lett.* B **464**, 123 (1999).
2. X. Ji, *Phys. Rev.* D **55**, 7114 (1997).
3. R. Jaffe and A. Manohar, *Nucl. Phys.* B **337**, 509 (1990).
4. I. Balitski and X. Ji, *Phys. Rev. Lett.* **79**, 1225 (1997).
5. S. Güsken *et al*, *Phys. Rev.* D **59**, 114502 (1999).
6. B. Dressler *et al*, *Eur. Phys. J.* C **14**, 147 (2000).
7. K. Ackerstaff *et al*, *Nucl. Instrum. Methods* **A417**, 230 (1998).
8. HERMES collaboration, to be submitted to Phys. Lett. B.
9. B. Adeva *et al*, *Phys. Rev.* D **58**, 112002 (1998).
10. A. Airapetian *et al*, *Phys. Rev. Lett.* **84**, 2584 (2000).
11. COMPASS collaboration, CERN/SPSLC 96-14 (1996).
12. A. Bravar, D. von Harrach, and A. Kotzinian, *Phys. Lett.* B **421**, 349 (1998).