Experimental Results and Perspectives of Polarized Lepton-Nucleon Scattering

Michael Düren

Universität Erlangen-Nürnberg, Erwin-Rommel-Str. 1,
D-91058 Erlangen, Germany

Abstract. The spin structure of the nucleon and its spin puzzle is introduced in this paper, followed by a summary of the recent results on polarized lepton nucleon scattering. The spin structure functions of the proton and neutron have been measured and their first moments have been determined. The recent experiments confirm that the Ellis-Jaffe sum rule is violated, whereas the Bjorken sum rule is valid within the precision of the measurement. Results are reported about the flavor decomposition of the quark polarization, a first direct measurement of a positive gluon polarization, the observation of a double-spin asymmetry in diffractive ρ^0 production, the polarization of Λ hyperons, the observation of transverse single-spin asymmetries and the measurement of the Gerasimov-Drell-Hearn sum rule. Prospects of future fixed target and collider facilities are discussed.

1 Introduction

The fact that the nucleon has a large anomalous magnetic moment proves that it is not a fundamental spin-1/2 Dirac particle. The approximate agreement of the measured magnetic moments of the members of the baryon multiplets with predictions of the $SU(3)_f \times SU(2)$ symmetric quark-parton model is an important confirmation of the quark model approach. Additional predictions about the spin structure of the nucleon were the Bjorken [1] and Ellis-Jaffe [2] sum rules, which however were not experimentally accessible in the first two decades of the quark model. In 1987 the EMC collaboration published a measurement of the spin structure function $g_1^p(x)$ of the proton and of its first moment, the Ellis-Jaffe sum [3]. The observed violation questioned our understanding of the spin structure of the nucleon in terms of the quark-parton model. It caused intense discussion in the community and demanded experimental and theoretical clarification.

Since then a series of new spin experiments has been performed at SLAC, CERN and DESY as summarized in [4]. They became feasible by improved experimental techniques to polarize beams and targets. At CERN and SLAC the improved figure of merit, which is the product of luminosity and the squared values of the polarization of beam and target, allowed for a precision measurement of the inclusive spin structure functions. The HERMES experiment [5] uses a completely novel method, a polarized internal storage cell target in a storage ring with longitudinally polarized electrons. The HERMES storage cell is a 40 cm long elliptical tube around the stored electron beam. Polarized atoms

are continuously injected into the storage cell and leave the cell only after an average of a few hundred wall bounces. The main advantage of the storage cell technique is the ability to use pure, highly polarized atomic species (H, D, ^{3}He) in contrast to solid state targets where only a small fraction of the atomic species is polarizable.

The HERMES experiment is dedicated to semi-inclusive measurements, i.e. measurements which detect final state hadrons in coincidence with the scattered lepton. By tagging certain final state hadrons with different flavor content, the spin contributions $\Delta u, \Delta d, \Delta s$ of the up, down and strange quark flavors can be disentangled.

The inclusive as well as the semi-inclusive results show that only a fraction of the nucleon spin is due to the spin contribution $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ of the quarks. The rest is due to the contribution ΔG of the gluon spin and due to angular momentum contributions L_q and L_G of quarks and gluons moving with high speed in the nucleon. Current experiments show first evidence of a non-zero contribution by the gluon spin, however further experiments are needed to disentangle and understand all the contributions of the nucleon's spin $s_z^{\mathcal{N}}$, which are summarized in the helicity sum rule

$$s_z^{\mathcal{N}} = \frac{1}{2} = \frac{1}{2}\left(\Delta u + \Delta d + \Delta s\right) + L_q + \Delta G + L_G. \tag{1}$$

To improve our understanding of the spin structure of the nucleon, in future not only the collinear spin contributions have to be measured, but more emphasis has to be given to investigate transverse spin components, twist-3 contributions, spin-dependent off-forward parton distributions and spin effects in fragmentation.

2 Inclusive Deep Inelastic Scattering

2.1 Spin Structure Functions

The spin dependent part of the inclusive deep inelastic scattering cross section $e + \mathcal{N} \to e' + X$ is characterized by two spin structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$. In the quark-parton model the Bjorken variable x is interpreted as the momentum fraction carried by the struck quark and $-Q^2$ is the squared four-momentum of the exchanged virtual photon and is related to the resolution of the scattering process. The first spin structure function $g_1(x, Q^2)$ is interpreted as

$$g_1(x, Q^2) = \frac{1}{2}\sum_f e_f^2 \, \Delta q_f(x, Q^2) \tag{2}$$

with e_f being the charge for a quark with flavor f in units of the elementary charge and $\Delta q_f(x, Q^2) = q_f^{\uparrow\uparrow}(x, Q^2) - q_f^{\uparrow\downarrow}(x, Q^2)$ is the polarized quark distribution function. $q_f^{\uparrow\uparrow(\uparrow\downarrow)}(x, Q^2)$ is the distribution function of quarks with

spin orientation parallel (anti-parallel) to the spin of the nucleon. The second spin structure function $g_2(x,Q^2)$ is zero in the simple quark model. In general, $g_2(x,Q^2)$ contains the Wandzura-Wilczek contribution $g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 dx'\, g_1(x',Q^2)/x'$, a pure twist-3 contribution, and minor contributions from transverse parton polarizations [6].

The spin structure function g_1 has been measured since many years, and an impressive, precise data set has been collected by the experiments at SLAC, by SMC and by HERMES as shown in Fig. 1 [4]. At all three sites the spin structure function $g_1(x,Q^2)$ was measured for the proton and the neutron. The neutron spin asymmetry is obtained either from the subtraction of deuteron and proton data, or directly from a ^{3}He target. In the ^{3}He nucleus the spins of the protons are anti-parallel and do not contribute to the measured asymmetry (except for a small contribution which can be corrected). All experimental results are consistent and agree with the Q^2 evolution as predicted by QCD.

The measurement of g_2 is more difficult. Experiments at SMC and SLAC have shown that g_2 is consistent with g_2^{WW}, but data are also almost consistent with zero. The experiment E155x at SLAC ran in spring 1999 with the aim to provide more precise data on g_2 and to gain access to the interesting twist-3 component of g_2 that remains after subtraction of the Wandzura-Wilczek contribution g_2^{WW}.

2.2 Sum Rules

Using SU(3)$_f$ symmetry arguments, the first moment Γ_1 of the spin structure function $g_1(x)$ can be related to the axial couplings F and D known from baryon decays:

$$\Gamma_1^{p(n)} = +(-)\frac{F+D}{12} + \frac{3F-D}{36} + \frac{\Delta\Sigma}{9} + \text{QCD corrections terms} \qquad (3)$$

In addition, the total spin carried by quark spins can be expressed as

$$\Delta\Sigma = 3F - D + 3\Delta s. \qquad (4)$$

The Ellis-Jaffe sum rule [2] is obtained from Eq. (3) by the additional (reasonable but possibly false) assumption that the spin carried by strange quarks is negligible: $\Delta s = 0$. From this assumption follows that the total spin carried by quark spins is $\Delta\Sigma = 3F - D = 58\%$ (modulo QCD corrections at finite Q^2). Fig. 2 [7] demonstrates that the Ellis-Jaffe sum rule is violated with the consequence, that either the strange quark contribution to the proton spin is significant, or that the SU(3)$_f$ symmetry which was used to derive Eq. (3) is broken. The Bjorken sum rule [1], which is the non-singlet combination of the first moments of proton and neutron does not require these two assumptions and is experimentally verified at the 10% level (see Fig. 2). The precision of the sum rule tests is limited by theoretical uncertainties in the extrapolation of the spin structure functions at low x. Experimentally, the low x range will be accessible only by a future high energy spin experiment at a new facility as the proposed polarized HERA collider [8].

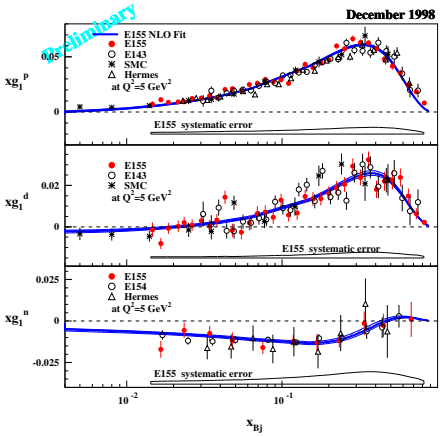

Fig. 1. Recent results for the spin structure functions $xg_1(x)$ at $Q^2 = 5$ GeV^2 for the proton, deuteron and neutron. The continuous lines are results of a QCD fit at NLO.

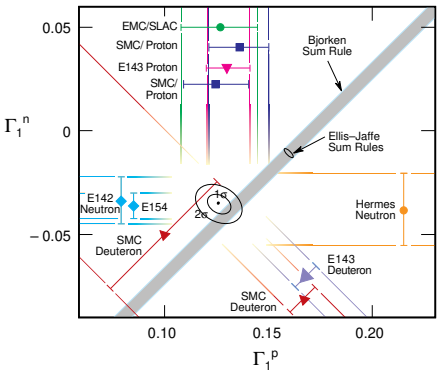

Fig. 2. The measured values of the first moments Γ_1^p and Γ_1^n of the spin structure functions g_1^p and g_1^n of the proton and neutron are in good agreement with the Bjorken sum rule, but deviate from the prediction of the Ellis-Jaffe sum rule.

A further sum rule, the Gerasimov-Drell-Hearn (GDH) sum rule, relates the polarization dependent part of the total photoproduction cross section to the anomalous magnetic moment of the nucleon. This important relation has been tested by a precision experiment at the tagged polarized photon beam of the microtron MAMI in Mainz, Germany. The energy range accessible by the experiment is 200-800 MeV. A preliminary analysis of a small subset of the data reports a number of 230 ± 20 μb, which accounts for most of the GDH prediction of $\int_{m_\pi}^{\infty} (\sigma_{3/2} - \sigma_{1/2})/\nu \, d\nu = 204$ μb [9]. The remaining difference might be due to contributions at higher energies, which are planned to be measured at ELSA/Bonn and at Jefferson Lab.

The GDH sum rule can be generalized for electroproduction. Data have been recently published by the HERMES collaboration [10], and a new measurement in the important resonance region was performed in spring 1999 as experiment E94-010 at Jefferson Lab [11].

3 Semi-inclusive Deep Inelastic Scattering

3.1 Flavor Decomposition

The observed violation of the Ellis-Jaffe sum rule made clear that the spin structure of the nucleon is not understood. More detailed experimental information is needed to disentangle the various possible contributions of quarks and gluons to the spin of the nucleon. Semi-inclusive data can be used to measure the sea polarization directly and to test $SU(3)_f$ symmetry by comparing the first moments of the flavor distributions to the $SU(3)_f$ predictions. In addition, semi-inclusive

polarized DIS experiments can determine the separate spin contributions Δq_f of quark and antiquark flavors f to the total spin of the nucleon not only as a total integral but as a function of the Bjorken scaling variable x.

Hadron production in DIS is described by the absorption of a virtual photon by a point-like quark and the fragmentation into a hadronic final state. The two processes can be characterized by two functions: the quark distribution function $q_f(x,Q^2)$, and the fragmentation function $D_f^h(z,Q^2)$. The semi-inclusive DIS cross section $\sigma^h(x,Q^2,z)$ to produce a hadron of type h with energy fraction $z = E_h/\nu$ is then given by

$$\sigma^h(x,Q^2,z) \propto \sum_f e_f^2 q_f(x,Q^2) D_f^h(z,Q^2). \tag{5}$$

It is assumed that the fragmentation process is spin independent, i.e. that the probability to produce a hadron of type h from a quark of flavor f is independent of the relative spin orientations of quark and nucleon. The spin asymmetry A_1^h in the semi-inclusive cross section for production of a hadron of type h by a polarized virtual photon is given by

$$A_1^h(x,Q^2,z) = \frac{\sum_f e_f^2 \Delta q_f(x,Q^2) D_f^h(z,Q^2)}{\sum_f e_f^2 q_f(x,Q^2) D_f^h(z,Q^2)} \cdot \frac{1+R(x,Q^2)}{1+\gamma^2}. \tag{6}$$

The term $R = \sigma_L/\sigma_T$ is the ratio of the longitudinal to transverse photon absorption cross section and appears in this formula to correct for the longitudinal component. It is assumed that R is flavor and target independent and that the contribution from the second spin structure function $g_2(x,Q^2)$ can be neglected. The term $\gamma = \sqrt{Q^2}/\nu$ is a kinematic factor which enters from the $g_2 = 0$ assumption. Eq. (6) can be used to extract the quark polarizations $\Delta q_f(x)/q_f(x)$ from a set of measured asymmetries on the proton and neutron for positively and negatively charged hadrons.

Results on the decomposition of the proton spin into contributions from the valence spin distributions Δu_v and Δd_v and from the sea Δq_s have been previously reported by SMC [12]. New, more precise data from HERMES have been presented recently [13]. Fig. 3 shows the polarization $\Delta q/q$ of quarks in the proton, separated into flavors. The *up* flavor has a positive polarization which reaches about 40% at large x, whereas the *down* flavor has a polarization opposite to the proton spin, in excess of 20%. In the sea region at small x the up and down polarizations do not vanish completely. The sea polarization itself is compatible with zero as shown in the lower panel. The extraction of the sea was done under the assumption that the polarization of the sea quarks is independent of their flavor.

The first and second moments of the spin distributions have been determined by HERMES. In the measured region, the results of HERMES and SMC agree within the quoted errors. A simple Regge-type extrapolation has been applied at low x to obtain the total integrals as quoted in Table 1. The HERMES results for the first and second moment of Δu_v show a significant discrepancy with

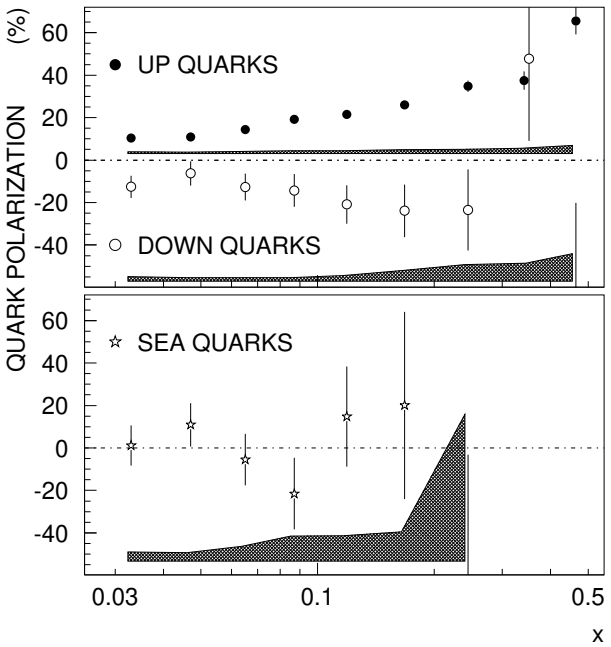

Fig. 3. The polarization of quarks in the proton has been measured by HERMES as a function of x, separately for the flavors up and down and for the sea. The error bars shown are the statistical and the bands the systematic uncertainties.

a prediction from quenched lattice QCD in Ref. [14]. The result for $\Delta u + \Delta\bar{u}$ is inconsistent with the result from the inclusive data based on $\mathrm{SU}(3)_f$ flavor symmetry as in Ref. [15]. The inconsistency of the up flavor has its counterpart in the difference which is observed in the sea results. The inclusive analysis obtains a large negative strange sea compared to the zero sea in the semi-inclusive analysis. However, the uncertainties of the sea measurements are so large that the result is not conclusive.

Table 1. The integrals of various spin distributions as measured by HERMES for $Q^2 = 2.5$ GeV^2. Note that the entry for $\Delta s + \Delta\bar{s}$ does not represent a direct measurement of the strange sea but relies on the assumption that the sea polarization is flavor independent. An uncertainty of the Regge-type extrapolation at low x is not included in the quoted error.

	total integral
$\Delta u + \Delta\bar{u}$	$0.56 \pm 0.02 \pm 0.03$
$\Delta d + \Delta\bar{d}$	$-0.25 \pm 0.06 \pm 0.05$
$\Delta s + \Delta\bar{s}$	$-0.02 \pm 0.03 \pm 0.04$
Δq_0	$0.28 \pm 0.04 \pm 0.09$
Δq_3	$0.83 \pm 0.07 \pm 0.06$
Δq_8	$0.32 \pm 0.09 \pm 0.10$
Δu_v	$0.57 \pm 0.05 \pm 0.08$
Δd_v	$-0.21 \pm 0.10 \pm 0.13$
$x\Delta u_v$	$0.12 \pm 0.01 \pm 0.01$
$x\Delta d_v$	$-0.02 \pm 0.02 \pm 0.02$

Possible explanations of these differences are that either $SU(3)_f$ is violated, which would modify the inclusive result, or that the assumption about the flavor independence of the sea is wrong, which would modify the semi-inclusive result. To test the applicability of $SU(3)_f$ and $SU(2)_f$ flavor and isospin symmetry, the semi-inclusive results for the octet combination Δq_8 and the triplet combination Δq_3 of the polarized quark distributions have been compared to the predictions $\Delta q_8 = 3F - D$ and $\Delta q_3 = F + D$ (Bjorken sum rule). Both predictions agree with the HERMES results when the appropriate QCD corrections are taken into account. For a decisive conclusion about the origin of the discrepancy, the precision has to be further improved and the sea assumption has to be tested explicitly.

A significant improvement of the precision of the $\Delta d(x) + \Delta\bar{d}$ determination is expected in the near future from HERMES using the 1999 deuterium data set. The recently installed RICH will allow a direct measurement of $\Delta s(x)$ using kaon identification.

3.2 Transverse Asymmetries

The next step in polarized DIS, beyond the understanding of the collinear part of the quark and gluon polarization in the nucleon, is the understanding of the transverse polarization components. Single-spin asymmetries in polarized hadronic reactions are interpreted as effects of *time-reversal-odd* distribution functions (Sivers mechanism) or *time-reversal-odd* fragmentation functions (Collins mechanism) [16].

SMC presented recently the first measurement of semi-inclusive DIS hadron production on a transversely polarized target [17]. Leading hadron production has been analyzed in terms of the Collins angle and indeed a non-zero asymmetry $A_N = 11\% \pm 6\%$ has been found for positive hadrons, whereas the negative hadrons yield $-2\% \pm 6\%$.

A significant result has been reported by HERMES on a related quantity [18]. HERMES measured the asymmetry of hadron production on a longitudinally polarized target. Even in this case an asymmetry is expected in the azimuthal angle between the plane which contains the produced pion and the virtual photon and the plane which contains the scattered lepton and the virtual photon. Fig. 4 shows this single-spin asymmetry as a function of the azimuthal angle for positive and negative pions. A sinusoidal fit yields an asymmetry of $A_N = 2.0\% \pm 0.4\%$ for the positive and $A_N = -0.1\% \pm 0.5\%$ for the negative pions.

4 Diffractive Asymmetries

Results on double-spin asymmetries in diffractive ρ^0-production have been reported by SMC [19] and HERMES [20]. Naively, no spin asymmetry is expected in the approach where diffraction is described by the exchange of a pomeron with vacuum quantum numbers. In this frame one should expect that diffractive ρ^0 production does not know about the spin of the target nucleon. The SMC

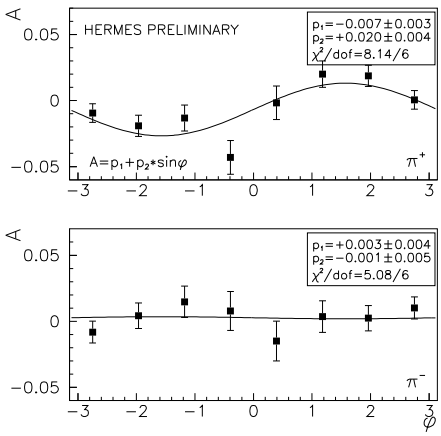

Fig. 4. Azimuthal dependence of the single-spin asymmetry in the cross section for π^+ (top) and π^- (bottom). The error bars are statistical uncertainties. The curves are sinusoidal fits to the data.

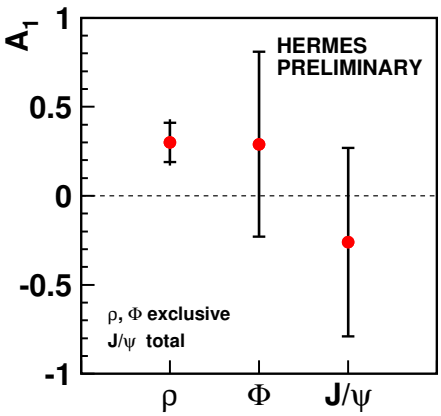

Fig. 5. Double-spin asymmetry in diffractive ρ, ϕ and J/ψ production from HERMES.

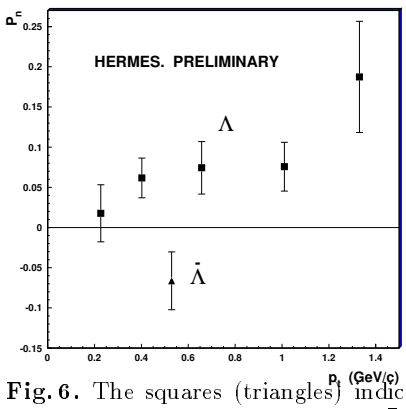

Fig. 6. The squares (triangles) indicate the transverse polarization of Λ ($\bar{\Lambda}$) in unpolarized photoproduction as function of the transverse momentum.

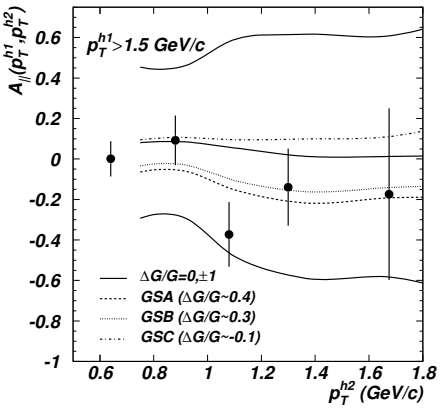

Fig. 7. Spin asymmetry in the production of hadron pairs with high p_T and opposite charge. One hadron with $p_T > 1.5$ GeV is required. The spin asymmetry is plotted as a function of the p_T of the second hadron and compared to Monte-Carlo predictions using various assumptions for the gluon polarization $\Delta G/G$.

result is in agreement with this prediction. No significant asymmetry has been observed.

HERMES reported a significant, unexpected positive asymmetry of $A_1^\rho = 0.30 \pm 0.11 \pm 0.05$ in exclusive ρ^0 production as shown in Fig. 5. The asymmetry in the production of other vector mesons, ϕ and J/ψ, was also measured, but with much less precision and is compatible with zero (see Fig. 5). The difference of the two results is possibly due to different reaction mechanisms at the different W^2

ranges of the two experiments: $W^2 \approx 225$ GeV^2 for SMC, and $W^2 \approx 25$ GeV^2 for HERMES.

4.1 Λ Polarization

Due to the parity violation of the weak decay of Λ hyperons, the angular distribution of the decay products can be used to extract the spin orientation of the Λ hyperon before its decay. This unique feature was used at HERMES to extract two interesting quantities [21].

The first one is the measurement of the polarization transfer in DIS scattering of longitudinally polarized electrons off unpolarized targets. A Λ polarization of $P_\Lambda = 0.03 \pm 0.06 \pm 0.03$ was reported, a number which however is not precise enough to distinguish between different predictions. The naive quark model which assumes 100% polarization of s-quarks in Λ hyperons predicts $P_\Lambda = 0.018$, whereas a SU(3)$_f$ symmetric model from Jaffe predicts $P_\Lambda = -0.057$, based on the measured results for the Ellis-Jaffe sum.

A much more precise result was reported concerning the transverse polarization of Λ hyperons in quasi-photoproduction off an unpolarized target:

$$\gamma^{(*)} p \rightarrow \Lambda X. \tag{7}$$

The polarization was measured with reference to the plane perpendicular to the Λ production plane. Fig. 6 shows the polarization as a function of the transverse momentum of the Λ and $\bar{\Lambda}$. A large positive polarization is observed for Λ hyperons, with the tendency to increase with their transverse momentum. The $\bar{\Lambda}$ antihyperons show a negative polarization. There is no straight-forward explanation of the observed asymmetries in QCD; however, similar polarizations have been found in hadronic collisions.

4.2 Gluon Polarization

The "most wanted" component of the nucleon spin is the polarization of gluons, as they are probably responsible for the spin deficit of the quarks. As the virtual photon does not couple directly to gluons, a measurement of the gluon polarization was up to now only very indirectly possible by using the QCD evolution equations, which relate the Q^2-dependence of the quark distributions to the gluon distribution. A QCD NLO analysis of recent data yields a gluon contribution to the proton spin of $\Delta G \approx 1.8 \pm 1.0$ [7].

For the first time a more direct measurement of the gluon polarization has been presented [22]. By selecting events with two hadrons with opposite charge and with large transverse momentum, HERMES was able to accumulate a sample of events which is enriched by photon-gluon fusion events. By requiring a large transverse momentum of 1.5 (1) GeV/c for the first (second) hadron, the subprocess, where the gluon splits into two quarks, has a hard scale and can be treated pertubatively. HERMES estimates from Monte-Carlo studies that the average squared transverse momentum of the quarks is 2.1 (GeV/c)^2. As long

as the fragmentation process is spin independent, the spin asymmetry in the production of the quark-antiquark pair is the same as the spin asymmetry of the observed final state. The measured asymmetry is however affected by background processes. The unique signature of the HERMES result is the negative sign of the asymmetry. All background processes have a positive asymmetry, as long as they are dominated by the positive polarization of the up-quarks in the proton. The observed negative asymmetry can be explained by a significant positive gluon polarization. The change of sign comes from the negative analyzing power of the photon-gluon fusion diagram. Using a specific background Monte Carlo, HERMES obtains a value of the gluon polarization of $\Delta G/G = 0.41 \pm 0.18 \pm 0.03$ at $\langle x_G \rangle = 0.17$. The quantitative result depends however critically on the detailed understanding of the background processes. Fig. 7 shows the asymmetry together with Monte-Carlo predictions using various assumptions for the gluon polarization $\Delta G/G$.

5 Future Facilities

The future of polarized DIS will consist of both, fixed target [23] and collider experiments [8,24].

5.1 Fixed target

At SLAC the fixed target inclusive era will end with the precise measurement of $g_2^{p,d}$ at E155x. At lower energies, MAMI at Mainz, ELSA at Bonn and CEBAF at Jefferson Lab will continue to do spin physics. The main future players at higher energies will be HERMES at DESY and COMPASS at CERN. Both experiments will concentrate on semi-inclusive data.

Their main aims are the measurement of the gluon polarization, the flavor decomposition of polarized quark distributions, polarized vector meson production, polarized fragmentation functions, transversity, and, in the case of COMPASS, also the angular momentum of quarks and gluons and off-forward parton distributions.

HERMES has upgraded its particle identification recently to achieve pion, kaon and proton separation in the full kinematic region, using a RICH detector. An improved muon acceptance and identification will allow for a better J/Ψ detection. A wheel of silicon detectors just behind the target cell will be installed, which improves the acceptance especially for Λ decay products. A recoil detector system is dedicated to low energy, large angle target fragments and spectator nucleons.

COMPASS will start in 2000 in the experimental area where the SMC experiment has been, however with an improved beam, improved target, high luminosity and, compared to the SMC experiment, with a much better and larger hadron acceptance and particle identification. In the final stage COMPASS will have two spectrometer magnets, two RICH detectors, two hadron and two electromagnetic calorimeters. Compared to HERMES, the high beam energy of COMPASS of

100-200 GeV enables measurements at smaller x and larger Q^2 and W^2. The large W^2 allows for charm production well above threshold and for the generation of hadrons with large transverse momentum. The production of open charm allows for a direct measurement of the gluon polarization.

A future fixed target machine is ELFE, a possible new European electron machine in the 15-30 GeV range, which is discussed in connection with the TESLA project at DESY and also at CERN as a machine which could re-use the cavities from LEP. Two further experiments, which both aimed for the measurement of the gluon polarization via charm production in photoproduction, were proposed some years ago, and are still discussed: E-156 at SLAC and APOLLON at ELFE.

5.2 Collider

Two colliders will govern the high energy part of spin physics in the future: the polarized proton collider RHIC at BNL [24], and possibly the HERA collider at DESY which may have polarized protons in future [8].

In both machines, the acceleration and storage of polarized protons is a major challenge to machine physicists. Several Siberian snakes will be needed which compensate depolarizing resonances of the beam polarization.

RHIC will start its physics program in 2000. Main points on the program are the measurement of the antiquark polarization and the gluon polarization. The antiquark polarization can be extracted using Drell-Yan production via W^+ and W^-. As W-production depends on flavor and on helicity, the experiment can extract Δu, $\Delta \bar{u}$, Δd and $\Delta \bar{d}$ separately. The gluon polarization is approached by the production of prompt photons, π^0's, jets and heavy quarks (charm).

The main aims of a polarized HERA collider are the measurement of the spin structure functions at low x, which will improve the precision of the verification of the fundamental Bjorken sum rule, and the polarization of the gluon. Fig. 8 shows the anticipated precision of this measurement. As at RHIC, the gluon polarization can be extracted from the production of heavy flavors and from jet production. Fig. 9 [8] summarizes the anticipated precision of the measurement of the gluon polarization at RICH, HERA, and COMPASS. Also included is the HERA-N option, which is a proposal to scatter HERA protons off a fixed target.

References

1. J.D. Bjorken, Phys. Rev. **148** (1966) 1467; Phys. Rev. D **1** (1970) 1376.
2. J. Ellis and R.L. Jaffe, Phys. Rev. D **9** (1974) 1444; Phys. Rev. D **10** (1974) 1669.
3. EMC, J. Ashman *et al.*, Phys. Lett. B **206** (1988) 364; Nucl. Phys. B **328** (1989) 1.
4. R. Windmolders, Proc. of the 7^{th} Int. Workshop on Deep Inelastic Scattering and QCD (DIS99), Zeuthen, Germany, April 19-23, 1999, to appear in Nucl. Phys. B (Proc. Suppl.).
5. HERMES, K. Ackerstaff *et al.*, Nucl. Instr. Meth. A **417** (1998) 230.
6. W. Wandzura and F. Wilczek, Phys. Lett. B **172** (1977) 195.
7. E. Hughes in [4].

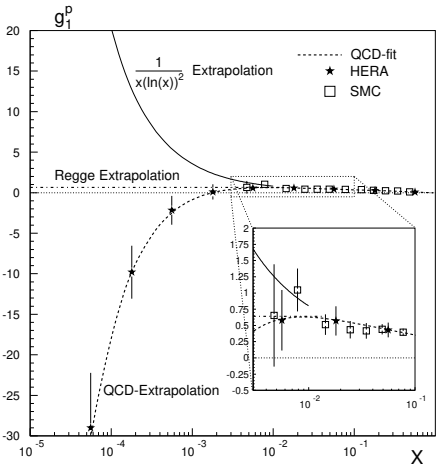

Fig. 8. The statistical uncertainty on g_1^p from possible measurements at HERA with 500 pb^{-1} is shown along with different theoretical predictions at low x. The center of the figure is expanded to show the low-x SMC points.

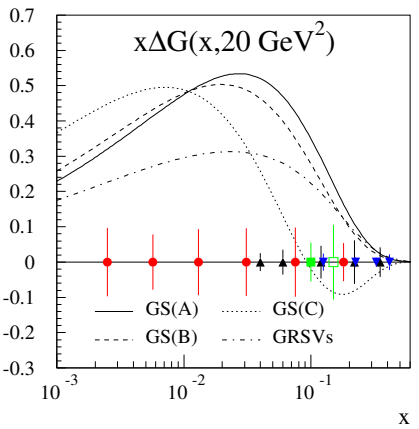

Fig. 9. Comparison of the statistical accuracy of $x\Delta G$ of the proposed future experiments as a function of x along with predictions from various theoretical models.

8. V. Hughes and D. von Harrach in [4].
9. A. Thomas in [4].
10. HERMES, K. Ackerstaff *et al.*, Phys. Lett. B **444** (1998) 531.
11. Z.-E. Meziani in [4].
12. SMC, D. Adeva *et al.*, Phys. Lett. B **420** (1998) 180.
13. HERMES, K. Ackerstaff et al., subm. to Phys. Lett.; hep-ex/9906035.
14. M. Göckeler *et al.*, Phys. Lett. B **414**, (1997) 340.
15. J. Ellis and M. Karliner, Phys. Lett. B **341** (1995) 397;
    Invited Lectures at the International School of Nucleon Spin Structure, Erice, August 1995, hep-ph/9601280.
16. J. Collins, Nucl. Phys. B **396** (1993) 161.
17. S. Bravar in [4].
18. H. Avakian in [4].
19. A. Tripet in [4].
20. F. Meißner in [4].
21. S. Belostotski in [4].
22. M. Amarian in [4].
23. E. Kabuß in [4].
24. Y. Goto and N. Saito in [4].