Polarized lepton nucleon scattering — summary of the experimental spin sessions at DIS 99

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This paper summarizes the contributions to the experimental sessions on polarized lepton nucleon scattering at the DIS 99 workshop. 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. OVERVIEW

Exciting and even unexpected results have been presented in the sessions about polarized lepton nucleon scattering, at the DIS 99 workshop. Most striking are the presentations of the *flavor decomposition of the quark polarization*, the first direct observation of a *positive gluon polarization* in the nucleon and the observation of a *double-spin asymmetry in diffractive ρ^0 production*. First results on the Gerasimov-Drell-Hearn (GDH) sum rule have been reported. The interesting and new fields of polarization phenomena related to transversity, leading twist-3 distributions and fragmentation came into the reach of experimentalists this year. Promising results were announced about azimuthal pion asymmetries and the polarization of Λ hyperons in the final state.

2. INCLUSIVE SPIN PHYSICS

Spin structure functions have been measured for many years, and an impressive, precise data set has been collected by the experiments at SLAC, by SMC and by HERMES [1]. At all three sites the spin structure function $g_1(x, Q^2)$ was measured for the proton and the neutron and consistent results were obtained that agree with the Q^2 evolution as predicted by QCD. The experiment E155x at SLAC is running in spring 1999 with the aim to provide 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}.

The situation of the spin sum rules has not changed significantly since the last DIS meeting. The Ellis-Jaffe sum rule is found to be violated and all results support the Bjorken sum rule. 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 [2]. A measurement of the high x region at low energies is planned at Jefferson Lab [3].

2.1. Gerasimov-Drell-Hearn sum rule

The 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. Fig. 1 shows a preliminary analysis of a small subset of the data. For the integral a number of $230 \pm 20\ \mu$b was reported, which accounts for most of the GDH prediction of 204 μb [4]. The remaining difference might be due to contributions at higher energies which are planned to be measured at Bonn.

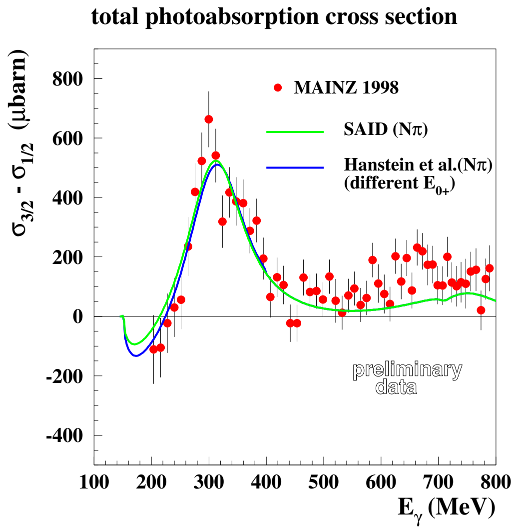

Figure 1. The spin dependent part of the total photoproduction cross section as a function of the photon energy as measured at Mainz.

The GDH sum rule can be generalized for electroproduction. Data have been recently published by the HERMES collaboration [5] and a new measurement in the important resonance region was performed in spring 1999 as experiment E94-010 at Jefferson Lab [3]. First raw data of this experiment have been shown at this conference.

3. SEMI-INCLUSIVE DIS

3.1. Flavor decomposition

The violation of the Ellis-Jaffe sum rule, which was first reported by EMC [6], was interpreted as evidence for the fact that only a fraction of the nucleon spin can be attributed to the quark spins and that the strange quark sea seems to be negatively polarized [7]. This caused the so-called *spin crisis*. This interpretation is based on the assumption that the spin structure of the baryon multiplets is $SU(3)_f$ flavor symmetric.

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

$$\sigma^h(x, Q^2, z) \propto \sum_f e_f^2 q_f(x, Q^2) D_f^h(z, Q^2). \qquad (1)$$

In the target rest frame, E_h is the energy of the hadron, $\nu = E - E'$ and $-Q^2$ are the energy and the squared four-momentum of the exchanged virtual photon, $E(E')$ is the energy of the incoming (scattered) lepton and e_f is the quark charge in units of the elementary charge. The Bjorken variable x is calculated from the kinematics of the scattered lepton according to $x = Q^2/2M\nu$ with M being the nucleon mass. 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

$$A_1^h(x, Q^2, z) = C_R \frac{\sum_f e_f^2 \Delta q_f(x, Q^2) D_f^h(z, Q^2)}{\sum_f e_f^2 q_f(x, Q^2) D_f^h(z, Q^2)} \qquad (2)$$

where $\Delta q_f(x, Q^2) = q_f^{\uparrow\uparrow}(x, Q^2) - q_f^{\uparrow\downarrow}(x, Q^2)$ is the polarized quark distribution function and $q_f^{\uparrow\uparrow(\uparrow\downarrow)}(x, Q^2)$ is the distribution function of quarks with spin orientation parallel (anti-parallel) to the spin of the nucleon. The unpolarized quark distribution functions are defined by F_2 (and not by F_1):

$$F_2 = \sum_f e_f^2 x q_f(x, Q^2) \tag{3}$$

and they include therefore a longitudinal component of the photon absorption cross section. The term

$$C_R = \frac{1 + R(x, Q^2)}{1 + \gamma^2}, \tag{4}$$

with $R = \sigma_L/\sigma_T$ being the ratio of the longitudinal to transverse photon absorption cross section, corrects for the longitudinal component which *a priori* is not present in the asymmetry and the polarized distribution functions. It is assumed that the ratio of longitudinal to transverse components 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. (2) 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 [8]. New, more precise data from HERMES have been presented at this workshop [9]. Fig. 2 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 polarized quark distribution functions $\Delta q_f(x)$ have been extracted by multiplying the quark polarizations $\Delta q_f(x)/q_f(x)$ with the known unpolarized distribution functions. Fig. 3 shows that the HERMES result agrees with the LO

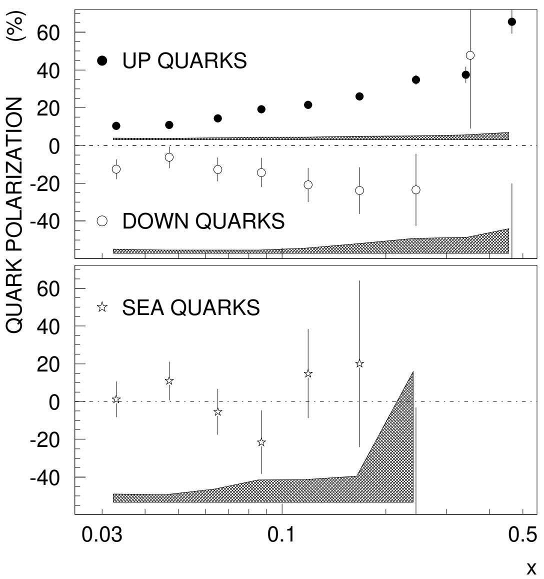

Figure 2. The polarization of quarks in the proton has been measured by HERMES as a function of x, separately for the flavors up and down and for the sea. The error bars shown are the statistical and the bands the systematic uncertainties.

parametrization of Ref. [11] of world data. However, not all LO parametrizations agree with HERMES and it seems that the parametrizations are internally inconsistent. Agreement can be achieved by dividing out a factor $(1 + R)$. The explanation is that the ratio R of the longitudinal to transverse cross section is usually set to zero in the LO fits. On the other hand experimentalists usually use the measured R, which is non-zero, to extract g_1. The result of the fit then depends on the choice of the input for the fit, either A_1 (as in Ref. [10,12]) or g_1 (as in Ref. [11]). From the relation

$$A_1 = \frac{2xg_1}{F_2} \frac{(1 + R)}{(1 + \gamma^2)}, \tag{5}$$

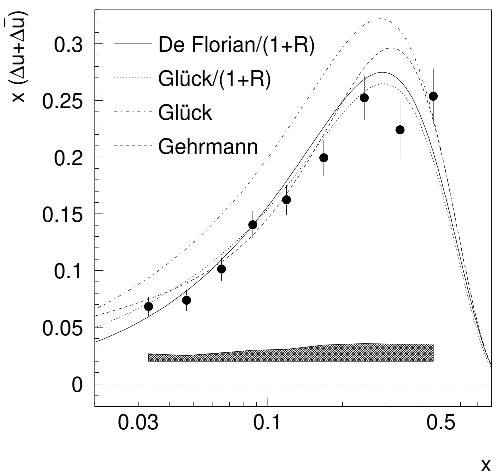

Figure 3. The quark spin distribution $x(\Delta u(x) + \Delta\bar{u}(x))$ for $Q^2 = 2.5$ GeV^2 as measured by HERMES is compared to different sets of parametrizations which correspond to the following publications: De Florian *et al.* ($0.1 < \Delta G < 0.8$, LO) [10], Gehrmann and Stirling ('Gluon A', LO) [11], and Glück *et al.* ('Standard Scenario', LO) [12]. The De Florian and Glück parametrizations are corrected by a factor $(1 + R)$ to allow for a direct comparison. The error bars shown are the statistical and the band the systematic uncertainty.

which is quoted here for the approximation that $g_2 = 0$, it follows directly that the two choices will give different results.

The first and second moments of the spin distributions have been determined by HERMES. In the measured region, the results agree between HERMES and SMC 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 a prediction from quenched lattice QCD in Ref. [13]. The result for $\Delta u + \Delta\bar{u}$ is inconsistent with the result from the inclusive data based on $SU(3)_f$ flavor symmetry as in Ref. [7]. 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. 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 Δq_8 and Δq_3 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.

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	$-0.21 \pm 0.10 \pm 0.13$
$x\Delta u_v$	$0.12 \pm 0.01 \pm 0.01$
$x\Delta d_v$	$-0.02 \pm 0.02 \pm 0.02$

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

3.2. The 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.

For the first time a more direct measurement of the gluon polarization has been announced [14]. 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 sub-process 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 $(\mathrm{GeV/c})^2$. 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 that the spin asymmetry comes out negative. 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 $x_G = 0.17$. The quantitative result depends however critically on the detailed understanding of the background processes.

3.3. 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). The numerous possible processes were discussed in the theory spin sessions [15].

SMC presented at this conference the first measurement of semi-inclusive DIS hadron production on a transversely polarized target [16]. 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 [17]. 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 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. The good statistical precision of this result is due to the hadron acceptance of the detector and the pure, highly polarized hydrogen target.

3.4. Λ polarization

A related quantity is the polarization of Λ hyperons. HERMES reported two results here [18].

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 re-

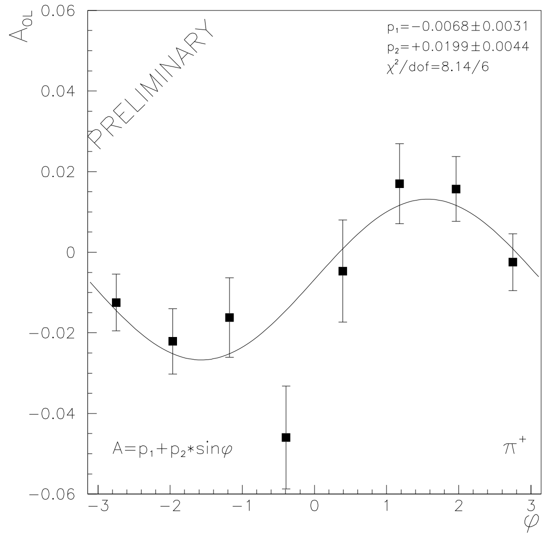

Figure 4. Azimuthal dependence of the single-spin asymmetry in the cross section for π^+. The error bars are statistical uncertainties.

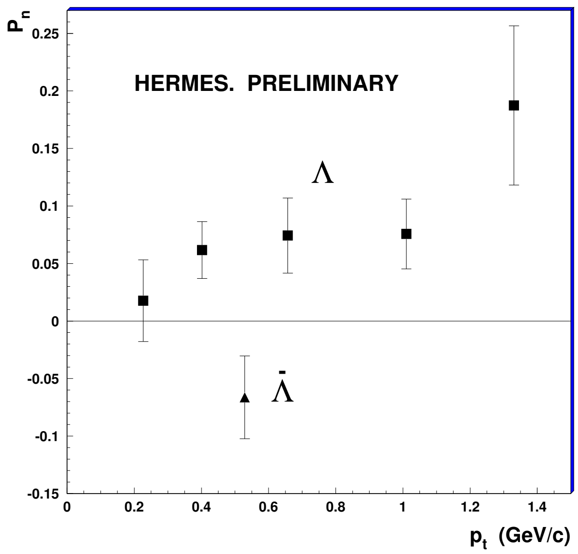

Figure 5. The squares (triangles) indicate the transverse polarization of Λ ($\bar{\Lambda}$) in unpolarized photoproduction as function of the transverse momentum.

ported, a number which is not precise enough to distinguish between different predictions. A 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 $P_\Lambda = -0.057$.

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

$$\gamma^{(*)}p \rightarrow \Lambda X. \tag{6}$$

The polarization was measured in respect to the plane perpendicular to the Λ production plane. Fig. 5 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 its 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. DIFFRACTIVE DOUBLE SPIN 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 there should be no way that the diffractive ρ^0 production knows about the spin of the target nucleon. The SMC result is in agreement with this prediction. No significant asymmetry has been observed.

HERMES reported a significant, unexpected positive asymmetry of $A_1^\rho = 0.30 \pm 0.11 \pm 0.05$. The asymmetry in the production of other vector mesons ϕ and J/ψ was also measured, but with much less precision and came out to be compatible with zero. The non-zero ρ-asymmetry can possibly be understood by comparing this process $\gamma^* + p \to p + \rho$ to the similar process $\gamma^* + p \to p + \gamma^*$ which is related to deep inelastic scattering and its well known positive asymmetry A_1^p. The difference between the HERMES and SMC result may have its reason in the different Q^2 and W^2 ranges of the two experiments.

5. FUTURE FACILITIES

The future of polarized DIS will consist of both, fixed target [21] and collider experiments [2,22].

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 results.

The main aims of the experiments 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 an upgrade program to improve particle identification with 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 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 large 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 the 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 proposed to measure 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 future: the polarized proton collider RHIC at BNL [22], and possibly the HERA collider at DESY which may have polarized protons in future [2].

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

RHIC will start its physics program in 2000. Main points on the agenda 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. As at RHIC, the gluon polarization can be extracted from the production of heavy flavors and from jet production.

6. CONCLUSIONS

Spin physics is a rich field. At this workshop an extraordinary number of results was presented, from CERN, SLAC, Jefferson Lab, Mainz and other institutions. A main source of results was the HERMES experiment at DESY which released a variety of different analyses of data taken in the last three years, some of which were exciting and unexpected. Spin physics will continue to be a rich field when the future facilities which were discussed at this workshop come into operation.

Acknowledgments: I want to thank all speakers of the spin sessions for their excellent contributions and I thank the organizers for the invitation and for the perfect support of the session conveners.

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