PROCEEDINGS OF SCIENCE

Nucleon Structure Overview

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Status of the research on the nucleon structure is reviewed from an experimental point of view with an emphasis on the nucleon spin problem. Following introduction, current status of the experimental studies on the helicity distributions, transverse spin effects and GPD is presented.

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1. Introduction

In order to study the nucleon structure in parton level, its spin structure is quite important. The spin of the nucleon, 1/2 is distributed to quark spin, gluon spin and their orbital angular momentum(OAM). This is expressed by the equation $1/2 = (1/2)\Delta\Sigma + \Delta G + L_z$ where $\Delta\Sigma$ is the contribution of the spin of all quarks and anti-quarks, ΔG is that of gluon spin and L_z is that of OAM of quarks and gluons. In naive quark model, the $\Delta\Sigma$ has been considered to be 100 %. However, the situation had drastically changed when EMC claimed in 1987 that the $\Delta\Sigma$ is consistent with 0 by measuring the spin structure function g_1 in low x region. This led to the nucleon spin crisis and activated extensive measurements and discussions. Recent precise measurements give $\Delta\Sigma \sim 0.3$. The value is not zero but rather small. Thus sizable contribution due to gluon spin or angular momentum of quarks and gluons is expected to restore the nucleon spin. One of the main goals of the study on the nucleon spin structure is to answer to a question such as "How does each parton share the nucleon spin?"

2. DIS and semi-inclusive-DIS

The research has been historically conducted by deep inelastic scattering (DIS) in which a lepton is scattered by a nucleon target by exchanging a virtual photon. In the inclusive DIS experiments so far only scattered leptons are detected. The process is described by the momentum transfer Q^2 and the virtual photon's energy ν in the laboratory system. A quantity, called Bjorken's x, is defined as $x = Q^2/2M\nu$ where M is the nucleon rest mass. It corresponds to the momentum fraction of the struck quark in the Bjorken limit. The struck quark fragments into a hadron with the energy of E_h. E_h divided by the virtual photon energy ν gives the variable z. In recent DIS experiments final state hadrons are detected as well as the scattered leptons. In this case, the process is called semi-inclusive-DIS (SI-DIS).

3. Major Experiments

Recently accomplished and ongoing major spin experiments are HERMES at DESY, COMPASS at CERN, a set of the experiments at JLab and the RHIC spin experiments at BNL (STAR and PHENIX). HERMES is a DIS experiment with a polarized electron beam at 27 GeV circulating in HERA and a polarized gaseous internal target. The detector has a capability to identify hadrons so that SI-DIS events are studied. Unfortunately, it terminated data taking due to shut down of HERA. COMPASS is a currently running experiment using a 160GeV polarized muon beam delivered from SPS and a polarized solid target. Thanks to its multi-purpose spectrometer, SI-DIS events are also measured. At Jlab, a 6GeV polarized electron beam with a high intensity is available. Using several types of polarized targets, various DIS experiments are performed. The beam will be upgraded up to 12 GeV soon. Aside from the DIS experiments, the polarized proton-proton collider RHIC at $\sqrt{s} \sim 200$ GeV gives complementary approach to study the polarized nucleon structure.

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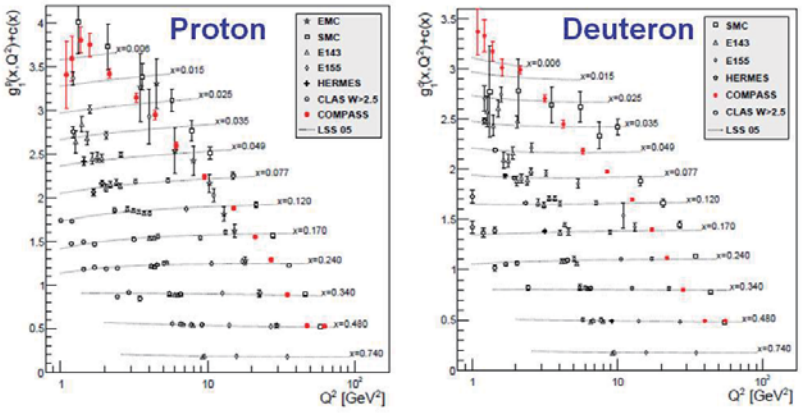

Figure 1: The spin structure function g_1 measured for proton and deuteron.

4. Parton Distribution Functions

The nucleon structure can be described at leading order with only three parton distribution functions(PDF), namely, number density q, helicity distribution Δq and transversity $\Delta_T q$, when one neglects transverse momentum of partons. The number density and the helicity distribution are relatively well known. On the contrary, less information has been given for the transversity. When one takes account of the transverse momentum k_t, additional functions called transverse momentum dependent PDFs (TMD-PDFs) are necessary. Some of them are Sivers function, Boers-Mulders function and Prezelosity. The Sivers function which may be the most notable and attracts attention because it is related to orbital angular momentum (OAM) of quarks and related data have been already accumulated.

5. Helicity Distributions

Thanks to polarized inclusive DIS experiments so far, the spin structure function g_1 is available in wide kinematic range as shown in Figure 1. The g_1 is described with the helicity distributions for all quark flavors. With the complementary information, namely, weak decay constants, one can evaluate $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ as is recently determined to be $0.33 \pm 0.33(stat.)$ [1].

Not only the inclusive-DIS asymmetries, but also SI-DIS asymmetries are available for identified hadrons for proton and deuteron targets by COMPASS and HERMES as shown in Figure 2. Both groups carried out flavor decomposition of helicity distributions with a help of fragmentation functions [2]. Using all the available data from various experiments, global analyses have been performed. One of the recent ones is made by [3] as shown in Figure 3. In their analysis, u- and d-quark distributions are well determined. Sea distributions are found to be small although they give larger uncertainties. They are also studied at RHIC by measurements of single spin asymmetry for Weak boson production although currently the statistics is not enough to choose models. However, luminosity upgrade is expected in future programs, so that it will be improved.

In the global analysis, gluon helicity distribution is obtained as shown in Figure 3. However, it shows a large uncertainty and even its sign has not been determined, yet.

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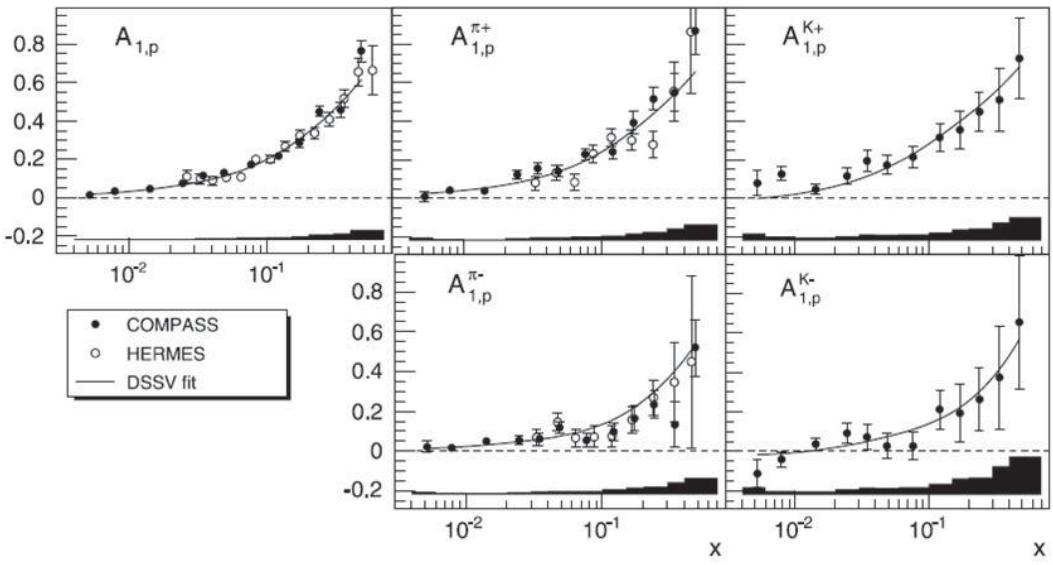

Figure 2: Double spin asymmetries for Inclusive DIS and SI-DIS for identified hadrons for proton target measured by COMPASS and HERMES.

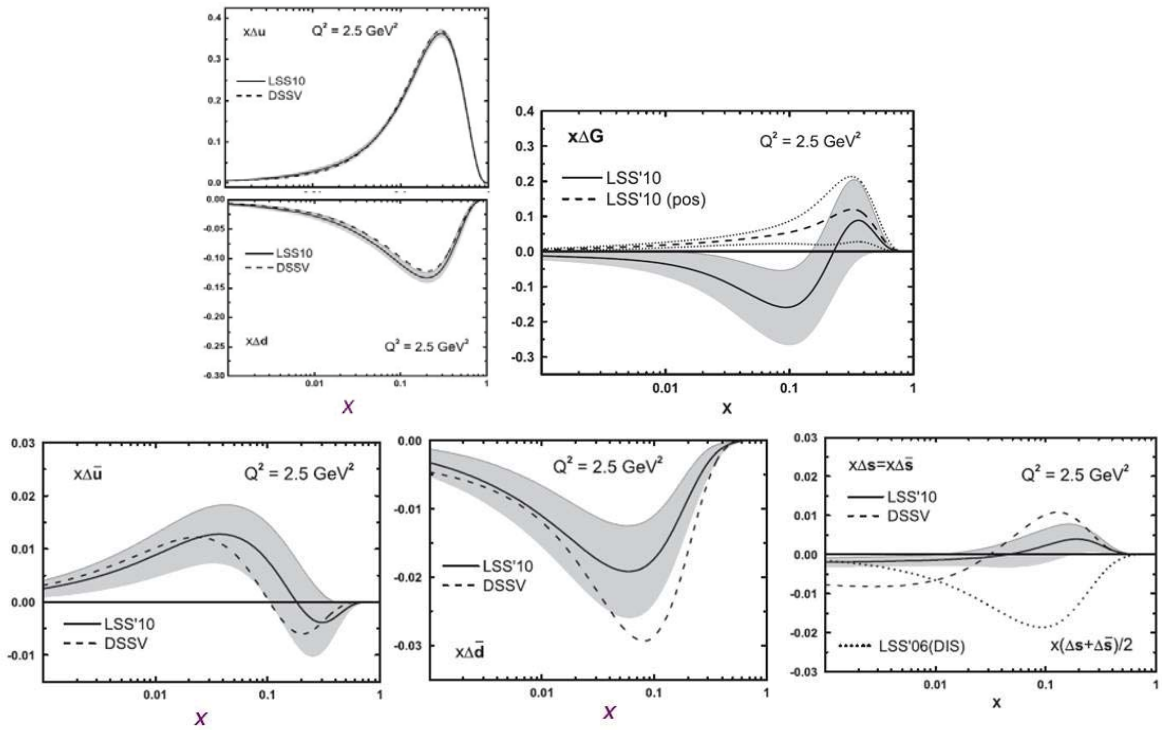

Figure 3: Helicity distributions obtained by global analysis [3].

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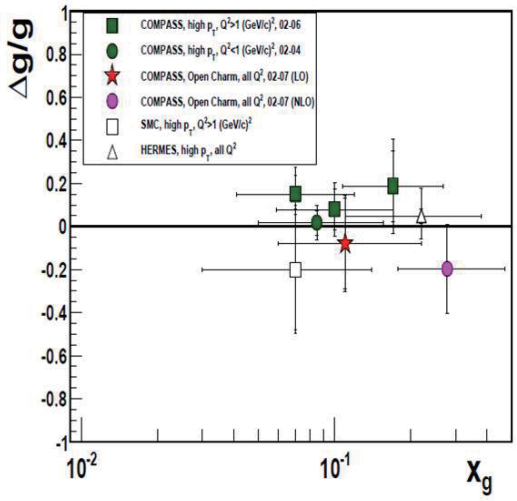

Figure 4: Gluon polarization as a function of x_g obtained by DIS experiments.

In order to study the gluon distribution, DIS experiments, HERMES, SMC and COMPASS have determined the gluon polarization by measuring the double spin asymmetries for the photon gluon fusion process. The results are consistent with zero in the range of the measurements as shown in Figure 4 [4]. And they are consistent with the results of the global analysis based on the data of the DIS experiments.

The gluon polarization is studied also in RHIC, by the measurement of the double spin asymmetries for inclusive π^0 production and inclusive jet production. Their data, included in the global analysis, begin to played an important role to constrain the polarized gluon distribution.

6. Transverse Spin Effects

To study the transversity and TMD PDFs, the modulations observed in SI-DIS for transversely polarized nucleon target have been playing an important role. The angular modulation of the final hadron with respect to the nucleon spin gives asymmetries. One of them is Collins asymmetry which originates from the transversity along with Collins fragmentation function. Another is Sivers asymmetry given by Sivers function. HERMES and COMPASS have studied the modulation for proton and deuteron targets. The Collins asymmetries for proton target obtained by HERMES and COMPASS show non-zero asymmetries both for π^+ and π^- [5]. On the contrary, the asymmetries obtained by COMPASS for deuteron target are consistent with zero [6]. Based on all the available data global analyses have been carried out with a help of Collins fragmentation function obtained by BELLE [7]. They gave transversity for u and d quarks showing that they give opposite signs to each other and their shapes are similar to the helicity distributions although their intensities are slightly smaller.

The Sivers asymmetries are also available. HERMES measured the asymmetries for proton target as shown in Figure 5. The asymmetries for π^+ are clearly positive, while, those for π^- . are consistent with zero. This feature was confirmed by COMPASS. Using all the available data

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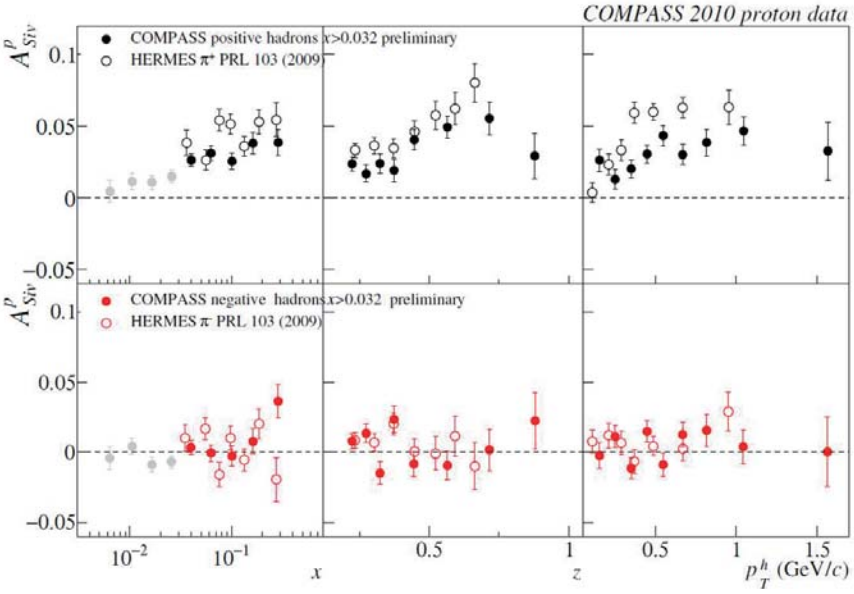

Figure 5: Sivers asymmetries for proton target measured by COMPASS and HERMES.

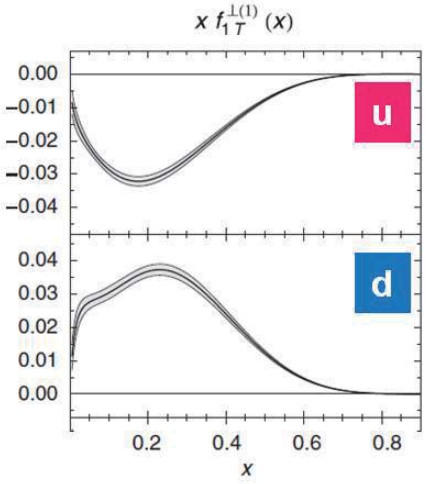

Figure 6: Sivers functions for u and d-quarks obtained by a global analysis [8].

of Sivers asymmetries, global analyses have been carried out. One of the recent analyses has been made by A.Bachetta and M.Radici [8]. Assuming the Sivers function is related to GPD-E with so called lensing function, they fit the data of Sivers asymmetries under the constraints of anomalous magnetic moments. The Sivers functions for u and d-quarks are given as shown in Figure 6. They are non-zero and opposite to each other in sign. This means the direction of k_t of the u-quark is opposite to that of d-quark with respect to the proton spin and the boost. This suggests presence of OAM of quarks.

Further studies on the transverse spin effects are foreseen. COMPASS-II is planning to make a

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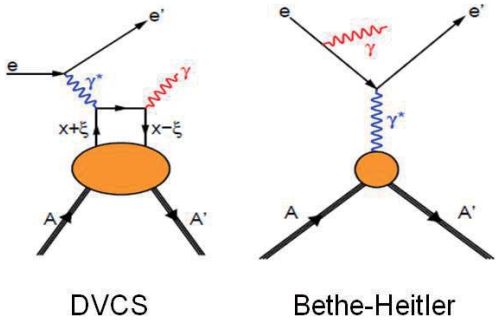

Figure 7: DVCS (left) and Bethe-Heitler(right) processes .

measurement for the π induced Drell-Yan(DY) process with a transversely polarized proton target. The azimuthal angle modulations in this process give access to the TMD functions, such as the functions of Sivers, Bore-Mulders and Pretzelosity. In the case of the Sivers function, it has naive time reversal odd character so that a sign change between DY and SI-DIS is expected as follows $f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SI-DIS)$. They are planning to confirm the relation which is a crucial test for non-perturbative QCD.

7. Generalized Parton Distribution

Generalized parton distribution (GPD), is a key concept to describe the nucleon structure. It unifies traditional notions of parton densities and elastic form factors of the nucleon. Experimentally, one can access the GPD through the deeply virtual compton scattering(DVCS) because the amplitude is described by the GPD. From the point of view of the nucleon spin structure, it is quite important because it gives total angular momentum of quarks based on the Ji's sum rule [9]. Thus, one can access the OAM through the GPD. And it is pointed out that the GPD is related to the Impact parameter dependent PDFs [10]. In other words, the quark distribution can be described as a function of transverse position and longitudinal momentntum of quarks.

HERMES and JLab experiments have made pioneering work for the DVCS measurements to extract the GPD. In their energy range, the DVCS effect appears associated with the Bethe-Heitler process which is well understood QED process as shown in Figure 7. Thus, careful analysis focusing to the interference between the DVCS and Bethe-Heitler process to extract the DVCS amplitude is necessary. The beam-spin asymmetry for the DVCS was firstly measured by HERMES in 2001 [11]. Following the measurements, they have made various measurements for DVCS including beam spin asymmetry, beam charge asymmetry, and target spin asymmetry.

The JLab experiments have been playing an important role in this field as well as HERMES. The measurements in Hall A at JLab give high accuracy in limited kinematics and those by CLAS in Hall B gives limited accuracy and in wide kinematic range. For further studies on the GPD, several measurements are planned. COMPASS-II plans to make DVCS measurements for proton with polarized $\mu^{\pm}$ at 160 GeV/c where dominant DVCS singnals are expected. In JLab after 12 GeV upgrade, several GPD experiments are proposed in Hall A and Hall B. With the already accumulated data and the data foreseen constraints on the GPD will be given in near future

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8. Conclusion

Significant progress has been achieved in the study of nucleon spin structure. Flavor decomposition of helicity distribution is carried out by HERMES and COMPASS. The global analyses of SI-DIS data gave good determination for Δu and Δd. However, the sea distributions are not well determined, yet. Polarized gluon distribution has still uncertainty although efforts for gluon polarization measurements have been made. Transversity and Sivers PDF have been extracted. The non-zero Sivers PDF suggests presence of OAM of quarks. DVCS measuments for the extraction of GPDs are in progress. Exciting future programs at COMPASS-II, RHIC and JLab-12GeV are planned.

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