Spin structure of the nucleon

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1 The spin degree of freedom

Spin is a fundamental degree of freedom originating from space-time symmetry and plays a critical role in determining the basic structure of fundamental interactions. Spin also provides an opportunity to probe the inner structure of composite systems like a nucleon. After more than 20 years of measurements of the spin-dependent structure functions of the nucleon the third generation of precise polarized experiments is now running and new data are analyzed. Although our knowledge about the spin decomposition in the frame of quark parton model (QPM) and QCD is now more complete and the polarized parton distribution functions (polarized PDFs) are better constrained by data, the driving question for QCD spin physics still has no answer: where does the nucleon spin come from? The famous EMC spin asymmetry measurement [1] and the naive interpretation of the results with help of EllisJaffe sum rule [2] have introduced the so-called spin crisis to Particle Physics : quarks carry only a small fraction of the nucleon helicity. A lot of theoretical work has been done to understand the spin crisis in frame of QCD, e.g. higher order corrections calculated to the EllisJaffe sum rule [3].

The quark helicity distributions $\Delta q_i(x,Q^2)$ are related to the vector-axial quark current which is not conserved due to the AdlerBellJackiw anomaly. This fact allows to give an explanation of the spin crisis by changing the interpretation of the measurement: instead of the quark spin content $\Delta\Sigma = \int_0^1 \sum_{i=1}^{n_f} \Delta q_i(x,Q^2)dx$ the flavor-singlet axial current matrix element $a_0 = \Delta\Sigma - \frac{3\alpha_S}{2\pi}\Delta G$ is measured, where ΔG is a gluon helicity inside the nucleon. The spin crisis and the violation of the Ellis-Jaffe sum rule can be then avoided if ΔG is large enough. This interpretation was the driving force in the preparation of a series of new polarized DIS type experiments related to - among others - direct measurements of gluon polarization: HERMES in DESY, SMC and COMPASS at CERN, STAR and PHENIX at RHIC. In the light of the new measurements of the gluon polarization the role of the axial anomaly seems to be marginal as data prefer the gluon contribution to the nucleon's spin to be rather small.

To complete the picture, beside the quark helicities and the gluon polarization also an orbital angular momentum of quarks and gluons can build the longitudinal nucleon spin structure. The definition of the angular momentum of quarks and gluons (orbital as well as total one) is very delicate and nontrivial subject. It should be gauge invariant and expressed in terms of local QCD well defined operators built from quark and gluon fields. This problem was announce to be solved very recently [4].

Complementary measurements to the longitudinal spin structure of the nucleon are performed on transversely polarized targets. The two basic effects which can be accessed with transversely polarized targets are the Collins and the Sivers effect. A new polarized distribution function called "transversity" which is a difference between quark (antiquark) distributions for two different spin orientations relative to the transversely polarized target are associated with such a "transverse" spin proton structure.

Transversity probes the relativistic nature of quarks. For non-relativistic quarks there is no difference of the helicity and transversity distributions because boosts and rotations commute. Relativistic quarks make a difference which can be easily calculated in relativistic models. The good "textbook" example is MIT bag model (for references and calculations see e.g.[5]). The model explains why the naive expectation that $\Delta\Sigma = 1$ is reduced to ~ 0.6 in the helicity case while for transversity the reduction factor is about 0.83. The nucleon spin decomposition in the case of transversity does not contain gluons; there is no transversity analog of gluon helicity distribution.

In contrast to helicity distributions measured via double-spin asymmetries transverse single-spin asymmetries are be studies to extract information about transversity distribution. Due to the fact that tranversity is a C-odd and chiral-odd distribution it cannot be accessed in inclusive DIS experiments. The Collins effect [6] uses the spin-dependent part of the hadronization process as a "polarimeter". The Collins chiral-odd and T-even fragmentation function is associated with the correlation between the transverse momentum of the fragmenting quark, the produced hadron and the transversely oriented spin. The Sivers effect [7] is associated with the intrinsic quark transverse momentum in a transversely polarized nucleon. In this case final state interactions produce an asymmetry before the active quark fragments. The Sivers distribution is chiral-even and T-odd and is not universal because it is generated due to final state interactions for DIS and initial state interactions for Drell-Yan process. The Sivers effect requires a correlation of the two QCD amplitudes where two different transverse nucleon spin states produce the same final state. To produce a T-odd effect both amplitudes should have different phases and cannot appear in the so-called tree level approximation. In addition, the two different nucleon spin state amplitudes can give a non-zero correlation if there is non-zero orbital momentum of the quarks inside the nucleon (see [5] and references therein). The challenge is to disentangle these two effects from the experimental data.

2 The cross-section longitudinal asymmetry A_1 and g_1 structure function

The longitudinal cross-section asymmetry can be decomposed into the virtual photon-deuteron asymmetries A_1 and A_2 as follows:

$$A_{LL} = D(A_1 + \eta A_2) \simeq DA_1, \tag{1}$$

where the photon depolarization factor D (as well as η), depends on the event kinematics. All factors which contain A_2 are usually neglected since they are very small in the kinematical range covered by most DIS experiments. However for the JLAB experiments the effects related with A_2 and g_2 are very important and are precisely measured [8]. The spin-dependent structure function g_1 is related to the asymmetry A_1 as follows:

$$g_1 \simeq \frac{F_2}{2x(1+R)} A_1 \tag{2}$$

where F_2 and R are unpolarized (spin independent) structure functions.

The longitudinal cross-section asymmetry and the g_1 structure function have been measured by many experiments. Here, I will concentrate on the new results from COMPASS, HERMES and - as an example of a very precise measurement from the JLAB facility - new results for the helium spin structure function measured by the E97-110 collaboration at Hall A will be flashed.

The details of the results from the COMPASS experiment can be found in [12] for small Q^2 region and in [13] (large Q^2). The experiment was using a 160 GeV polarized muon beam (75% polarization) from the SPS at CERN scattered off a polarized ^{6}LiD target (polarization: 50%).

The asymmetry and the g_1 structure function for small Q^2 have been calculated for events with $Q^2 < 1$ (GeV/c)^2 and small x ($0.00004 < x < 0.02$). The data collected in the years 2002-2003 result in a final sample of 300 million events. Systematic errors are mainly due to false asymmetries. The results are consistent with zero in the considered x range. The statistical precision of A_1^d and g_1^d of COMPASS is ten times higher than that of the SMC measurement [10]. The SMC and the COMPASS results are consistent in the region of overlap.

The large Q^2 data collected during the years 2002-2004 result in a sample of 90 million events. The measured A_1^d asymmetry for $Q^2 > 1$ (GeV/c)^2 (DIS domain) as a function of Bjorken x as measured in COMPASS and superposed to results of previous experiments at CERN [11], DESY [14] and SLAC [15, 16] is shown in figure 1. The result is consistent with zero for $x < 0.03$.

In figure 2 the g_1 structure functions for the proton and the deuteron obtained by HERMES collaboration are presented [17] and compared to results of others experiments. The HERMES experiment was using 27.5 GeV electron (positron) beam

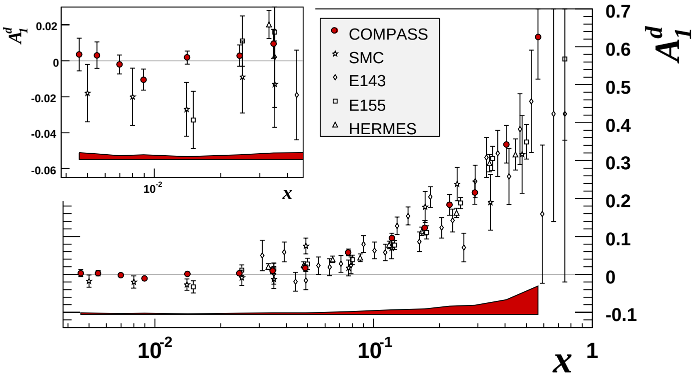


Figure 1: The asymmetry $A_1^d(x)$ for $Q^2 > 1$ (GeV/c)^2. Only statistical errors are shown with a data points. The COMPASS systematic errors are marked by shadowed areas.

with polarization 53% on several polarized gas targets (He, H, D). A result for the neutron g_1^n structure function has been recently published by HERMES [17]. Also a very high precise measurement of the "effective neutron" structure functions g_1^n and g_2^n performed on ^3He target has been reported by E97-110 collaboration [8]. The results are presented in figure 3. Note the very precise data also for g_2 and the fact that the measurement is done not in DIS but in the resonance and small Q^2 kinematical regime.

To extract polarized parton distribution functions for quarks and gluons a perturbative QCD analysis is performed. The idea is based on the so-called QCD evolution equations (DGLAP eqs.) which allow to find a link between the g_1 structure function measured at different Bjorken x and Q^2. Initial parameterizations of quark combinations and gluons in x at some fixed Q^2 are assumed and a minimization is performed. Many efforts in the past have been made by several groups, including also COMPASS collaboration [13]. One of the most recent one is a QCD NLO fit done by DSSV group [18]. It is the first time when RHIC proton-proton collision jet data have been included in the fit. The QCD fits allow to estimate the helicity contribution from quarks and gluons to the spin of the nucleon. The DSSV fit predicts $\Delta\Sigma$ between $0.25 - 0.3$ and gluon polarization very close to 0 however still with large error.

Using the experimental values measured by the DIS-type experiments the first moment of $g_1(x)$, Γ_1 can be calculated and - with the help of data from weak hyperon decays (a_8 matrix element in the case of deuteron), a_0 can be extracted. Recently Γ_1^d at $Q^2 = 3(\mathrm{GeV/c})^2$ has been calculated from COMPASS deuteron data [13]. The flavor-singlet axial current matrix element, a_0 has been found to be: $a_0 = 0.35 \pm 0.03(stat.) \pm 0.05(sys.)$. Here the value of $a_8 = 0.585 \pm 0.025$ from [19] has been

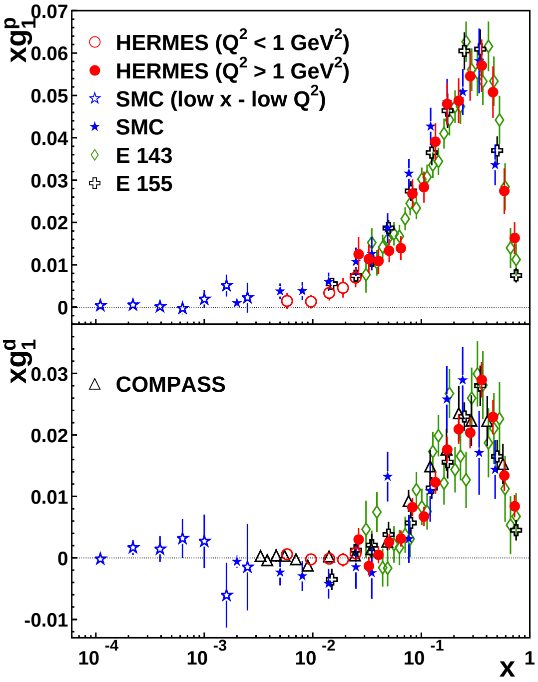


Figure 2: HERMES results on xg_1^p and xg_1^d vs x, shown on separate panels, compared to data from SMC , E143, E155, and COMPASS. The error bars represent the sum in quadrature of statistical and systematic uncertainties.

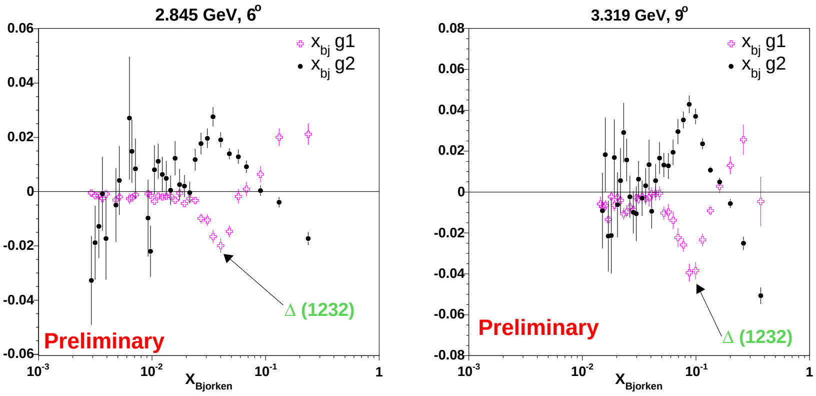
used. The obtained result is in very good agreement with HERMES result [17] at $Q^2 = 5(\mathrm{GeV/c})^2$: $a_0 = 0.35 \pm 0.011(theor.) \pm 0.025(exp.) \pm 0.028(evol.)$ and with DSSV fit. The combination of the matrix elements: $\frac{1}{3}(a_0 - a_8)$ is equal to strange quark contribution to the nucleon spin. From the COMPASS inclusive analysis $\Delta s + \Delta \overline{s} = -0.08 \pm 0.01(stat.) \pm 0.02(sys.)$ is obtained.

3 Semi-inclusive hadron asymmetries

Semi-inclusive measurements (at least one hadron is observed in the final state) allow to extract more information, in particular allow to separate of the flavours of quarks. The prize is that the analysis requires knowledge about fragmentation functions. However, there are very interesting observables called difference asymmetries $A^{h^+ - h^-}$ [20] which can be interpreted in LO QCD under the assumption of independent fragmentation as the ratio of polarized and unpolarized valence quark distributions:

$$A_d^{\pi^+ - \pi^-} = A_d^{K^+ - K^-} = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)}. \qquad (3)$$

Here, subscript "d" is related to deuteron target data collected by the COMPASS experiment which were already used in the recently published difference asymmetry



$Q^2(\Delta)$ = 0.077 GeV^2 $Q^2(\Delta)$ = 0.23 GeV^2

Figure 3: Neutron polarized structure functions xg_1^n and xg_2^n as a function of x from E97-110 experiment at Hall A at JLAB.

analysis [21]. Combining the first moment of the polarized valence quark distribution estimated from the difference asymmetry measurement with first moment of Γ_1^d obtained from inclusive measurements and using again a_8 from [19] it is possible to give an estimate of sea quark polarization.

Comparing the results to the so-called symmetric scenario which assumes that $\Delta\overline{u} = \Delta\overline{d} = \Delta\overline{s} = \Delta s$ and to the antisymmetric ones where $\Delta\overline{u} = -\Delta\overline{d}$ it is concluded that the COMPASS data support antisymmetric possibility [21].

The new HERMES semi-inclusive analysis of the strange quark polarization based on the measured kaon asymmetries has been very recently reported [22]. The interesting point is that for this analysis all information necessary (including kaon fragmentation functions) have been extracted from HERMES data alone. The inclusive asymmetry A_1^d and the kaon asymmetry $A_1^{d,K}$ as well as kaon multiplicities have been used. Data have been collected on a deuteron target as isoscalarity simplifies the analysis of fragmentation functions. The strange quark polarization Δs has been found to be: $\Delta s = 0.037 \pm 0.019(stat.) \pm 0.027(sys.)$ for the x range from 0.002 till 0.6. The obtained result for Δs is positive in contrast to the COMPASS result from inclusive measurement which is slightly negative.

4 The Gluon polarization

As QCD fits are not able to determine the gluon polarization with high precision so far, an alternative method is to extract polarized gluons directly from measured semi-inclusive asymmetries (HERMES, SMC, COMPASS and so-called prompt photon channel at RHIC). The precise measurements of pion and jet asymmetries from RHIC allow also to compare with models of the gluon polarization. This method is inspired by the method used in global QCD analysis and - as it was discussed above - is now used in DSSV fit. The advantage of the direct method is the possibility to determine $\Delta G/G$ without any assumption on the dependence on the momentum fraction x_G of the polarized gluon distribution, as it is done in fit-type methods. The experimental challenge is to select the data sample which allows to access gluon-originated sub-processes.

Recently two new results for the gluon polarization from direct measurements have been reported by the COMPASS collaboration. The open-charm channel is the classical way to access gluons for relatively low energies when the charm quark can be considered as heavy, not present inside the nucleon and produced only in hard processes. The measured longitudinal cross section asymmetry of charmed meson (D^* and D^0) production allows to determine $\Delta G/G$.

In the LO QCD approximation only the so-called photon-gluon fusion (PGF) process contributes. In COMPASS this channel is experimentally difficult and statistics is very limited. The new result obtained from the $2002-2006$ data is [23]: $\Delta G/G = -0.49 \pm 0.27(stat.) \pm 0.11(sys.)$ at a value of $x_G \simeq 0.11$, with an asymmetric range of $0.06 < x_G < 0.22$, and a scale $\mu^2 \simeq 13$ (GeV/c)^2.

The alternative way to select PGF events is to observe high-p_T hadron pairs in the final state. The analysis is Monte-Carlo dependent (due to physical background from hard sub-processes different from PGF) and requires very good agreement between data and MC. The big advantage is a large gain in statistics compared to the open-charm channel. The new COMPASS result for the large Q^2 ($Q^2 > 1$(GeV/c)^2) high-p_T analysis [24] is: $\Delta G/G = -0.08 \pm 0.1(stat.) \pm 0.05(sys.)$ at a value of $x_G \simeq 0.082$, with an asymmetric range of $0.06 < x_G < 0.12$, and a scale $\mu^2 \simeq 3$ (GeV/c)^2. Both presented analysis are limited to LO QCD approximation so far.

To illustrate the progress in precision of the RHIC measurements the π^0 longitudinal asymmetry obtained from Run 5 and new Run 6 [25] are shown in figure 4. The increasing precision is also seen in the new results from the STAR experiment from jet analysis [26] compared to the published result in [27].

The measured cross sections for different final states in STAR and PHENIX agree with the NLO QCD theoretical predictions very well. This fact justifies the theoretical approach based on QCD calculations and allows to predict asymmetries for different gluon polarization models. The predictions for different models are then compared to data.

The results presented in this section as well as the results from QCD fits point to a small value of the gluon polarization. Therefore, the role of the axial anomaly seems to be rather marginal.

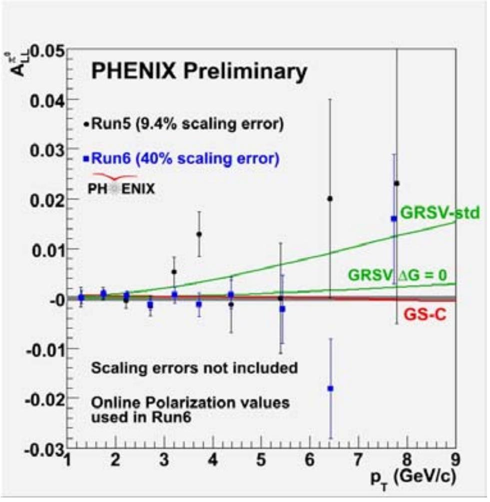


Figure 4: Preliminary Run 6 results for $\sqrt{s} = 200$ GeV for $\pi^0 A_{LL}$ asymmetry vs p_T.

5 Collins and Sivers asymmetries from HERMES and COMPASS

The single hadron spin asymmetries measured on transversely polarized targets allow to investigate the Collins and the Sivers effect. The HERMES results for asymmetries of charged pions measured on a transversely polarized proton target show that both effects are non-zero [28, 29]. These important results indicate that the Collins fragmentation function is non-zero (”polarimeter” in Collins effect) and a signature of the quark orbital angular momentum is seen (Sivers). The results from COMPASS measured on a deuteron target show that both effects are very close to zero [30, 31]. Therefore the cancellation of the effects between proton and neutron in the deuteron target is concluded. Very recently new results on charged hadron asymmetries measured on a proton target in 2007 by COMPASS have been reported [32]. The Collins asymmetries are non-zero and in a good agreement with the HERMES results while the Sivers effect is compatible with zero. This is unexpected result needs to be confirmed with larger statistics.

6 Summary

Precise measurements of the spin structure function g_1 show that quarks contribute only about 1/3 to the spin of the nucleon. This result is also confirmed by QCD fits and by a independent measurement of the valence quark polarization. Direct measurements point to a small value of the gluon polarization, however $0.2 - 0.3$ is still not excluded. Different types of asymmetries precisely measured at RHIC also indicate that the large gluon polarization scenario is rather excluded and the role of axial anomaly is small. Results for difference asymmetries measured by COMPASS support the so-called antisymmetric scenario: $\Delta\overline{u} = -\Delta\overline{d}$. A small positive polarization for strange quarks has been measured by HERMES while COMPASS results based on sum rules give a small negative polarization of the strange sea.

Collins asymmetries measured on a proton target are non-zero for large Bjorken x. The Collins and the Sivers asymmetries measured by COMPASS on deuteron target are compatible with zero what suggest a cancellation of the effect from the proton and the neutron in the deuteron. Non-zero Sivers asymmetries are observed by HERMES on a proton target while COMPASS results from proton data are compatible with zero. A non-zero Sivers effect can be related to the non-zero total orbital angular momentum of the quarks. Recent results from lattice QCD calculations predict however that the total angular momentum of quarks should be close to zero [33]. In connection with the fact that the gluon polarization seems to be small or zero this leads to a very interesting scenario: a $\sim 33\%$ of the spin of the nucleon is carried by helicity of the quarks, mainly valence ones; the missing part has to come from orbital angular momentum of gluons. A more "classical" scenario where the gluon polarization is $0.2 - 0.3$ is not yet excluded by the data and can also solve the nucleon spin decomposition problem without large total orbital angular momentum of quarks and gluons.

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