Vol. 37 (2006) ACTA PHYSICA POLONICA B No 3

SPIN DEGREE OF FREEDOM IN THE NUCLEON * **

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(Received December 20, 2005)

The short review of the spin structure of the nucleon (longitudinal) is given and some new experimental results are presented.

PACS numbers: 13.60.Hb, 13.88.+e, 14.70.Dj

1. Theoretical introduction

After 40 years of deep inelastic experiments unpolarized structure of the nucleon seems to be reasonably well understood. The two unpolarized structure functions: F_1 and F_2 (and F_3 in addition in the case of neutrino parity violating DIS) are expressed in terms of unpolarized quark's distributions *e.g.*:

$$F_1(x,Q^2) = \frac{1}{2}\sum_{i=1}^{n_{\rm f}} e_i^2 q_i(x,Q^2). \tag{1}$$

The QCD improved parton model (QPM) together with the evolution equations (DGLAP, BFKL *etc.*) allow to describe the unpolarized nucleon structure in terms of quarks and gluons. The QCD Q^2 evolution in NLO and NNLO approximation [1] are now available. The very precise DIS data and the large Q^2 range (5 orders of magnitude) show that NLO contributions are needed to describe the data.

To understand the spin structure of the nucleon in terms of quarks and gluon in the frame of QPM is a natural extension of the research program in DIS type experiments. The polarized beams as well as polarized targets are needed to measure the asymmetry of spin-dependent cross sections. The new polarized structure functions: g_1 and g_2 have to be added to describe

* Presented at the PHOTON2005 Conference, 31 August–4 September 2005, Warsaw, Poland.

** This work is partially supported by SPUB 621/E-78/SPB/CERN/P-03/DWM 576/2003-2006.

the spin structure of the nucleon. The g_1 structure function has similar meaning as F_1:

$$g_1(x,Q^2) = \frac{1}{2}\sum_{i=1}^{n_\mathrm{f}} e_i^2 \Delta q_i(x,Q^2)\,, \tag{2}$$

where $\Delta q_i(x,Q^2)$ is equal to $q_i^+(x,Q^2) - q_i^-(x,Q^2)$ and $\pm$ refers to helicity of quarks with respect to spin projection of the nucleon. In contrast to g_1–g_2 structure function is a very nontrivial object and has no simple interpretation in the frame of QPM.

The structure function g_2 can be decomposed into two parts: twist-2 Wandzura–Wilczek part, related to g_1 via the following relation:

$$g_2^{\mathrm{WW}}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}\,, \tag{3}$$

and true twist-3 part — nontrivial correlation between quarks and gluons. However the g_1 structure function is simply expressed in terms of quarks helicity distributions $\Delta q_i(x,Q^2)$, the g_1 measurement interpretation in the context of the fraction of helicity carried by quarks inside nucleon also touches the nontrivial aspect of the theory. The famous EMC spin asymmetry measurement [2] and the naive interpretation of the results with help of Ellis–Jaffe sum rule [3] have introduced to the Particle Physics the so-called "spin crisis": quarks carried only small fraction of the nucleon's helicity. A lot of theoretical work has been done to understand spin crisis in frame of QCD, *e.g.* higher order corrections calculated to Ellis–Jaffe sum rule [4] .

The quarks helicity distributions $\Delta q_i(x,Q^2)$ are related to vector-axial quark current which is not conserved due to the Adler–Bell–Jackiw anomaly. This fact allows explaining the spin crisis by changing the interpretation of the measurement: instead of quark spin contents $\Delta\Sigma = \int_0^1 \sum_{i=1}^{n_\mathrm{f}} q_i(x,Q^2)dx$ the combination $\Delta\Sigma - \frac{3\alpha_s}{2\pi}\Delta G$ is measured, where ΔG is a gluon polarization 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 a "driving force" in preparation a series of new polarized DIS type experiments related to direct measurement of ΔG: HERMES in DESY, SMC and COMPASS at CERN, STAR and PHOENIX at RHIC.

To complete the picture, beside the quark's helicity $\Delta\Sigma$, and the gluon polarization ΔG also an orbital angular momentum of quarks and gluons can build the 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. The definitions in QCD should be gauge invariant and expressed in terms of local QCD well defined operators built from quark and gluon fields [5]. Moreover, the decomposition into orbital and helicity part is strictly related to the way of future experimental measurement of the angular momentum of quarks and gluons. The most promising seems to be the measurement of DVCS (Deeply Virtual Compton Scattering) which process is expressed in terms of so-called generalized parton distributions (GPD's) and related to angular momentum via Ji sum rule [6].

2. Experimental results

Below some new and interesting experimental results concerning g_2 and g_1 structure functions and gluon polarization ΔG are discussed. The very interesting new results of Gerasimov–Drell–Hearn sum rule, the semi-inclusive DIS and transversity measurements are not discussed in this paper.

2.1. g_2 structure function

The measurement of g_2 structure function is usually very complicated due to the fact that g_2 is accompanied by g_1 in the measured asymmetries and the measured effect is very small. Therefore during the years the

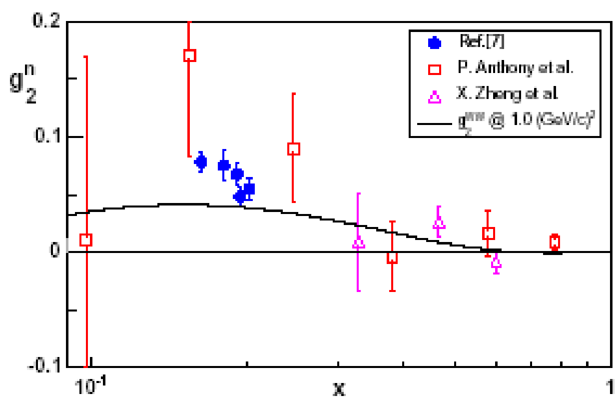

Fig. 1. Results for g_2^n as a function on x from [7] (black points). The solid black line shows g_2^{WW} taken at $Q^2 = 10\,\mathrm{GeV}^2$ without uncertainties. The open points represent data from previous experiments.

measurements were very unprecise, with large errors and practically it was impossible to say anything about nontrivial twist-3 contribution to g_2 as well as distinguish between several of theoretical models and predictions. The measurements done in Jefferson Laboratory (JLab, experiments E97-103) has changed the situation. In [7] the very precise measurement of g_2 on neutron has been reported and the results are shown in Fig. 1 (black points). An order of magnitude improvement in precision is seen as well as the fact that g_2^n is consistently higher than g_2^{WW}, Wandzura–Wilczek part of g_2. The Q^2 dependence is also discussed and presented in [7]. This result is the direct evidence of higher twist (twist-3) effects.

2.2. g_1 structure function

The new measurement of g_1 structure function on deuteron at small x and Q^2 performed by COMPASS experiment [8] confirms the previous results obtained by SMC [9], HERMES [10] and SLAC: E143 [11] and E155 [12] collaborations that g_1 is very close to 0. The very precise results of COMPASS can affect the QCD fits and maybe improve the constrains for ΔG. This aspect is not further discussed here.

The precise measurement of g_1 in high x ($x \to 1$) region gives us important information about the spin structure of nucleon. The QCD generally is not able to predict the x dependence of the parton's distribution and structure functions. However for the limit $x \to 1$ there are a lot of predictions of the behavior of g_1 given in different models, among them QCD based. Especially for u and d quark the QCD predicts $\frac{\Delta q}{q} \to 1$ in the absence of angular orbital momentum. The new, precise results obtained in JLab [13] for asymmetry A_1^n on neutron combined together with A_1^p on proton allowed to extract $\frac{\Delta u}{u}$ and $\frac{\Delta d}{d}$ with high precision. In contrast to u quark, where $\frac{\Delta u}{u}$ is large and positive the results for $\frac{\Delta d}{d}$ are negative at x around $0.4-0.6$. If the tendency will continue it could be an indirect sign that orbital angular momentum of quarks can play an important role in understanding the spin decomposition of the nucleon.

2.3. The gluon polarization ΔG

The ΔG determination is presently performed in DIS and proton-proton collider experiments. In DIS the direct measurement is possible based on the selection of photon-gluon fusion process (PGF). In contrast in proton-proton collider (RHIC) there are a lot of subprocesses involving gluons but it is rather impossible to separate them and extract ΔG at the end. Therefore in this case experimentally measured asymmetry is compared with calculated ones. The calculations are performed in NLO QCD approximation with assumptions about polarized quarks and gluon distributions. Comparison of expected asymmetries with measurements allows to exclude some models of ΔG. The preliminary results from PHOENIX and STAR experiments at RHIC rather exclude highly polarized gluons [14].

The "golden" channel for PGF selection in DIS is a production of a heavy quark pairs like charm quarks. It is believed that charm quarks are produced outside nucleon in hard subprocesses which are PGF's in LO. NLO corrections seem to be very important but the most important subprocesses related to NLO also "probes" gluons from the nucleon. Unfortunately to measure ΔG with precision high enough requires a very large number of identified D^0 mesons what is very difficult and beam time consuming task. Such measurement is presently going on at CERN.

The alternative method of selecting PGF process for light quarks is the high p_T hadrons pair production. In this case the statistics are huge but there is a very nontrivial problem of background processes. The estimation of the background processes are performed based on Monte Carlo simulations. The most important background processes are QCD Compton (for $Q^2 > 1$ GeV^2) and resolved photon contribution for $Q^2 < 1$ GeV^2. It is clear that this analysis is a very Monte Carlo dependent and therefore sometime criticized. Having in mind the limitations of the high p_T method the latest results of the measurement of $\frac{\Delta G}{G}$ from COMPASS experiment [15] is presented in Fig. 2 together with the previous results from HERMES [16] and SMC [17].

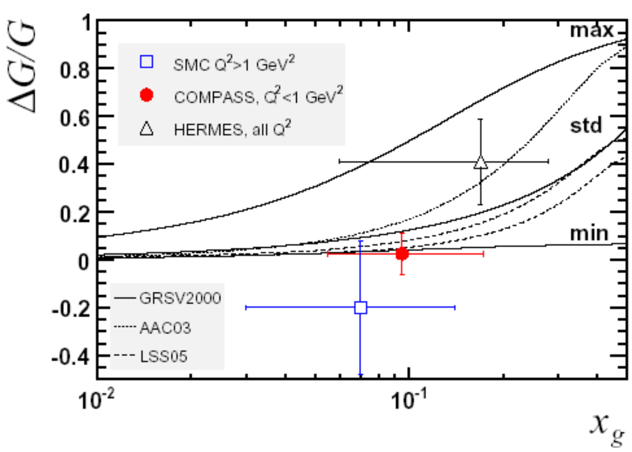

Fig. 2. The results of the $\frac{\Delta G}{G}$ measurement from COMPASS [15], SMC [17] and HERMES [16]. The horizontal bar on each point represents the range in x_g. The curves show various parameterizations from NLO fits (see details in [15]).

The results exclude the very high gluon polarization and ΔG is consistent with 0 in the measured x_g region. It is worth to note that the COMPASS result is the most precise determination of $\frac{\Delta G}{G}$ so far.

3. Conclusions

The direct observation of the higher twist effects in the precise measurement of g_2 structure function has been shown. The presented results related to measurement of g_1 structure function and the gluon polarization ΔG indirectly indicate of the importance of the angular momentum of quarks and gluons in the spin decomposition of the nucleon.

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