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THE NUCLEON SPIN IN PERSPECTIVE*

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In the twentieth anniversary of the "proton spin crisis", a review of the nucleon spin structure is presented.

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1. Introduction

I think you and Uhlenbeck have been very lucky to get your spinning electron published and talked about before Pauli heard of it. It appears that more than a year ago Kronig belived in the spinning electron and worked out something; the first person he showed it to was Pauli. Pauli ridiculed the whole thing so much that the first person became also the last and no one else heard anything of it. Which all goes to show that the infallibility of the Deity does not extend to his self-styled vicar on earth. (Letter of B.L. Thomas to S. Goudsmit (1926), [1].)

Born with troubles, spin has for the first time manifested itself experimentally as a new and non-classical quantity in the Stern–Gerlach experiment ("good experiment for the wrong theory") in 1921, before the birth of the modern quantum mechanics and essentially before (what is being accepted as) the spin discovery. The history of spin, [2], and its predictable future, [3], are both very exciting. Spin plays a central role in the modern physics. We belive that it is due to the space-time symmetry and thus determines the basic structure of the fundamental interactions. With spin research programmes presently operating at BNL, CERN, JLAB and (to a certain extent) also at DESY and with prospects of an e–p collider and an e^+e^- linear collider, both working also in a polarised mode, we are witnessing a wide attempt to understand the spin, test the spin sector of QCD and possibly also use it in the search for the "new physics". For the latter spin offers a rich spectrum of concepts, like the "$g-2$" experiments (*e.g.* the last one

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recently completed at BNL), proton weak charge studies (QWEAK planned at JLAB) or the neutron electric dipole moment measurements, but it will not be discussed here. Spin is also a tool to measure observables hard to obtain otherwise, *e.g.*: the strangeness content of the nucleon and the neutron density in large nuclei are investigated using the parity-violating electron scattering (JLAB); a revolution in the nucleon electromagnetic form factor measurements was due to employing the recoil polarisation measurements (JLAB). Finally the spin is a probe to unravel the nonperturbative QCD dynamics in the nucleon, *e.g.* through its spin-dependent structure functions, the quark helicity distributions ($\Delta q(x)$ and $\Delta_{\rm T} q(x)$), gluon polarisation, $\Delta g(x_G)$, Generalised Parton Distributions, the (Generalised) Drell–Hearn–Gerasimov sum rule, single spin asymmetries, *etc.* This paper will be devoted to certain aspects of the nucleon spin structure, based on measurements of observables selected from the latter list.

Intensive studies of the nucleon spin structure have commenced after the European Muon Collaboration, 20 years ago, had published a surprising result that total quark spin constitutes a rather small fraction of the spin of the nucleon, [4]. This result has been later confirmed by several experiments using polarised electrons (muons), different polarised nucleon targets and incident energies from few to few hundred GeV and has also caused wide theoretical spin-offs. Possible other nucleon spin carriers, gluons and the parton angular momenta, should thus be investigated. The latter are presently inaccessible experimentally but the former may in principle be determined from the QCD evolution of the polarised inclusive DIS measurements. Contrary to the spin independent case and due to the limited range in the Q^2 values covered by the measurements, this method has a limited sensitivity to the gluon helicity distribution as a function of the gluon momentum fraction x_G, $\Delta g(x_G)$. Direct measurements of the gluon polarisation in the nucleon, through semi-inclusive reactions, where the final states select processes with gluons, have thus become an imperative.

The nucleon quark structure at the twist-two level and in the absence of (or after integrating over) the quark transverse momentum, $k_{\rm T}$, is fully determined by a set of quark momentum ($q(x)$), helicity ($\Delta q(x)$), and transversity ($\Delta_{\rm T} q(x)$) distributions. Helicity distribution is a difference of probabilities of quarks having spins parallel and antiparallel to the nucleon spin when the latter is oriented parallel to the virtual photon. Definition of the transversity is similar but refers to the transverse polarisation of the nucleon. Since boosts and rotations do not commute, helicity and transversity need not to be the same in the relativistic (high energy beam) case. Allowing for twists higher than two or for the non-zero $k_{\rm T}$ of quarks, results in additional 8 distributions needed to describe the quark structure of the nucleon.

In this paper the following subjects will be discussed: spin experiments and observables (Section 2), the longitudinal spin structure of the nucleon (Section 3), the polarisation of gluons in the nucleon (Section 4), the transversity effects (Section 5), the nucleon spin decomposition and the parton angular momentum in the nucleon (Section 6) and finally the future spin projects and the outlook (Section 7).

2. Experiments and observables

A list of the recently accomplished and ongoing spin experiments comprise: a set of completed electroproduction measurements at SLAC (E142, E143, E154, E155, E156) and DESY (HERMES), both at the electron energy around 30 GeV, a rich spin programme carried on at the 6 GeV CEBAF machine at JLAB, three generations of ∼200 GeV muon beam experiments at CERN (EMC, SMC and the presently running COMPASS) and finally the proton–proton collider experiments at BNL (STAR, PHENIX, BRAHMS), now running at $\sqrt{s} \approx 200$ GeV with a goal of $\sqrt{s} \approx 500$ GeV.

In fixed-target experiments there is a strong correlation between the low x and low Q^2 regions. The latter usually means values below 1 GeV^2, *i.e.* the nonperturbative region, unless a variable different from Q^2 is used in the perturbative QCD series. The range of Q^2 values covered at low x is usually narrow, at most equal to one decade in x.

Electron and muon measurements are complementary: the former offer lower beam energies but very high beam intensities and thus their kinematic acceptance is limited to low values of Q^2 and moderate values of x; the latter, with much higher energy of beams, extend to higher Q^2 and to lower values of x (an important aspect in the study of sum rules) but due to limited beam intensities the data taking time has to be long to ensure satisfactory statistics. On the other hand, electron beam experiments have to deal with substantial contribution of radiative processes.

The collider experiments boost the centre-of-mass energy more than an order of magnitude, permit studies of the jet, π meson and photon production, and, in the case of the planned electron–ion collider, will permit a deep insight into the large parton density ("low x") region.

A nontrivial technical challenge is a preparation of highly polarised beams and targets, the latter of large volumes which also maintain a constant polarisation for periods at least of the order of 1000 hours and permit to reverse it periodically without losses. Another issue is a permanent and precise monitoring of the polarisation, especially at colliders.

Spin-dependent cross-sections are only a small contribution to the total electroproduction cross-section. Therefore they can best be determined by measuring the cross-section asymmetries in which the spin-dependent contributions cancel. Direct result of the electroproduction measurements is thus the cross-section asymmetry obtained from the (longitudinally) polarised lepton — (longitudinally or transversally) polarised nucleon scattering. The asymmetry may be determined either for the inclusive- or for the semi-inclusive reaction channels. In the former only an incident and scattered leptons are registered; in the latter additionally one or more hadrons are detected. After corrections for dilution and depolarisation effects and after inclusion of necessary input information like the spin-averaged structure functions, those asymmetries lead to determination of the $\Delta q(x)$, $\Delta_{\mathrm{T}} q(x)$ and $\Delta g(x_G)$ distribution functions. Particularly important are asymmetries due to the Collins and Sivers mechanisms, the former being due to the combined effect of $\Delta_{\mathrm{T}} q$ and a chirally-odd spin-dependent fragmentation function and the latter to a correlation between the intrinsic transverse momentum of a quark and the transverse polarisation of the nucleon.

3. Longitudinal spin structure of the nucleon: inclusive and semi-inclusive measurements

More than 40 years long studies of the spin-averaged deep inelastic scattering provided a wealth of precise data on the nucleon structure functions $F_i (i = 1, 2, 3)$. For the F_2 and in the perturbative region, $Q^2 > 1$ GeV^2, they extend to $Q^2 \sim 10^5$ GeV^2 and cover a wide range in x, $x > 3 \times 10^{-5}$. The QCD analysis of those data results in a precise determination of parton distributions and reveals that about 50% of the proton momentum is carried by gluons. The measurements extend deeply into nonperturbative region, $Q^2 \ll 1$ GeV^2, and result in detailed studies of its dynamics.

Measurements of the spin-dependent nucleon structure functions g_1 and g_2, are more scarce and thus spin-dependent parton distributions are known only with limited accuracy. The status of proton and neutron g_1 measurements is shown in Figs 1 and 2, [5]. No clear spin effects manifest themselves for $x \lesssim 0.03$. The $Q^2 < 1$ GeV^2 region for the g_1^d has been measured by COMPASS in the range of $0.00004 < x < 0.2$, Fig. 3, [6], with a statistical precision at least ten times higher than that of the SMC. The resulting structure function is consistent with zero, *i.e.* no spin effects are visible in the nonperturbative region at low x. In the region around $Q^2 = 1$ GeV^2 down to $Q^2 \sim 0.01$ GeV^2 and moderate x, a large body of precise g_1 data is provided by the CLAS Collaboration at JLAB [7]. They greatly improve the knowledge of the parton distribution functions.

Measurements of the g_2 provide meaningful information only at low energies, *e.g.* at JLAB where they are successfully performed. As an example, a precise determination of the x dependence of the g_2 at the $\Delta(1232)$ resonance region and $x \sim 0.1$, is presented in Fig. 4 [8].

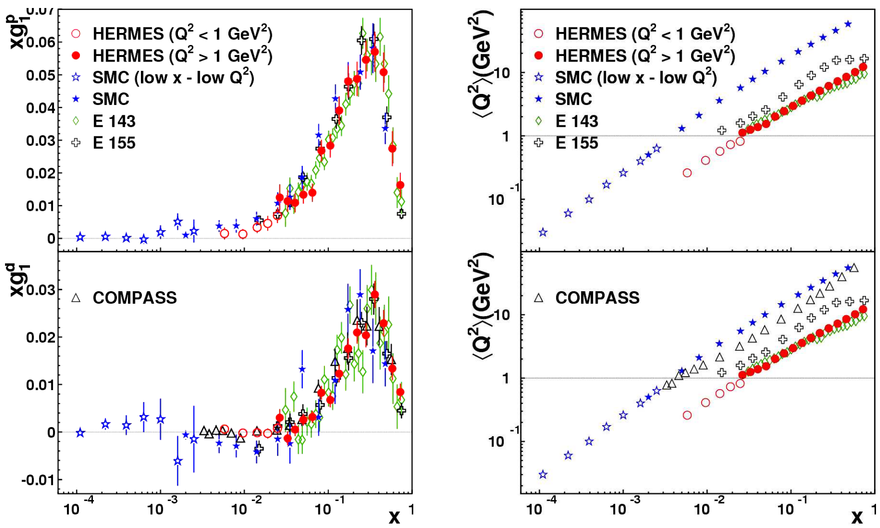

Fig. 1. HERMES results on xg_1^p and xg_1^d as functions of x compared to data of SLAC, SMC and COMPASS (left) together with corresponding values of $\langle Q^2\rangle$ (right). COMPASS results for xg_1^d at $Q^2 < 1$ GeV^2, [6], are not shown. Error bars represent the systematic and statistical uncertainties added in quadrature. Figure taken from [5].

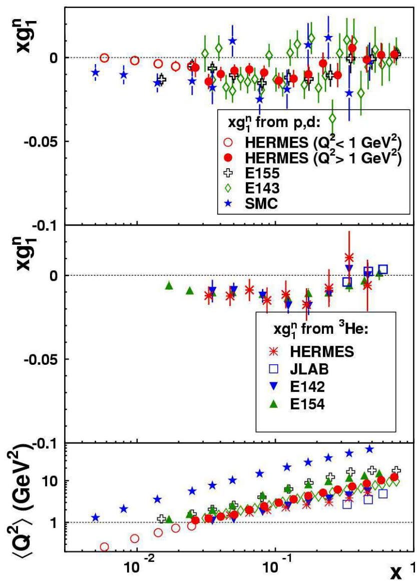

Fig. 2. HERMES results on xg_1^n as function of x compared to data of SLAC, SMC and JLAB together with corresponding values of $\langle Q^2\rangle$, [5]. Error bars represent the systematic and statistical uncertainties added in quadrature.

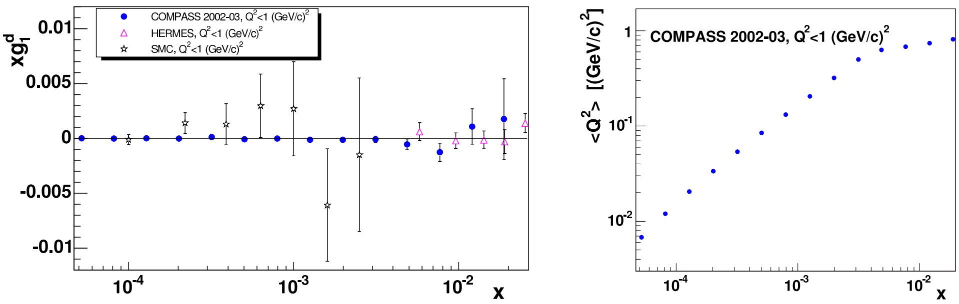

Fig. 3. COMPASS g_1^d measurements in the nonperturbative region, $Q^2 < 1$ GeV^2, compared with data of HERMES and SMC together with corresponding values of $\langle Q^2 \rangle$, [6]. Error bars represent the systematic and statistical uncertainties added in quadrature.

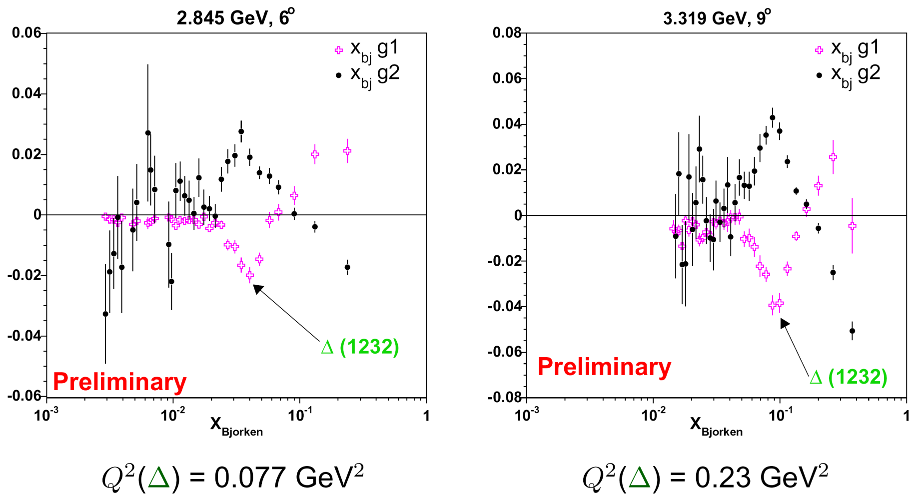

Fig. 4. Values of the xg_1 and xg_2 for the ^{3}He target as measured in the $\Delta(1232)$ resonance region by the Hall A and E97-110 experiment at JLAB, [8]. Error bars on the points show total uncertainties.

The world data on g_1 were QCD analysed at the NLO accuracy by several groups, including COMPASS [9]. An accurate evaluation of the first moment of $g_1^d(x)$, and of the matrix element of the singlet axial current, a_0 (assuming the a_8 matrix element as determined from the weak decays of hyperons) was obtained in the latter. In the $\overline{\mathrm{MS}}$ renormalisation scheme the a_0 is the same as the quark spin contribution to the nucleon spin. At $Q^2 = 3$ GeV^2 it is equal to $a_0 = 0.30 \pm 0.01$ (stat.) $\pm\, 0.02$ (evol.), in a very good agreement with the HERMES result at $Q^2 = 5$ GeV^2. With this (and a_8) value and in the $Q^2 \to \infty$ limit, the first moment of the strange quark distribution is $(\Delta s + \Delta\bar{s}) = -0.08 \pm 0.01$ (stat.) ± 0.02 (syst.). The gluon helicity distribution, $\Delta g(x_G)$ was, however, poorly constrained: two solutions with either $\Delta g(x_G) > 0$ or $\Delta g(x_G) < 0$, described the data equally well.

The recent NLO QCD analysis of world data, performed by the DSSV group [10] deserve a special attention. Apart of the complete set of the inclusive and semi-inclusive spin dependent (deep) inelastic data from EMC, SMC, COMPASS, SLAC, JLAB and HERMES, also the RHIC high-p_{T} results from STAR (jets at $\sqrt{s} = 200$ GeV) and PHENIX (π^0 at $\sqrt{s} = 62$ and 200 GeV) were for the first time included. The results were compatible with those of COMPASS, mentioned above. Also here errors on the polarisation of gluons were very large but its first moment is close to zero.

Quarks and antiquarks of the same flavour equally contribute to g_1 and thus the inclusive data do not permit to separate valence and sea contributions to the nucleon spin. Therefore additional, semi-inclusive spin asymmetries for positive and negative hadrons in the final state, h^+ and h^- are often measured, as *e.g.* in COMPASS [11], the hadrons being identified pions and kaons. Analysis based on such measurements normally requires the knowledge of the (very poorly known) fragmentation functions. However in the LO QCD, the difference asymmetry, $A^{h^+ - h^-}$ does not require this; it measures the valence quark polarisation and provides an evaluation of the first moment of $\Delta u_v + \Delta d_v$ which in [11] was found to be equal to 0.41 ± 0.07 (stat.) $\pm$ 0.06 (syst.) at $Q^2 = 10$ GeV^2. When combined with the first moment of g_1^d, this result favours a non-symmetric polarisation of light quarks, $\Delta\bar{u}(x) = -\Delta\bar{d}(x)$ at a confidence level of two standard deviations, in contrast to the often assumed symmetric scenario $\Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta\bar{s}(x) = \Delta s(x)$, Fig. 5.

The recent HERMES analysis of the kaon asymmetries on the deuteron [13] where all the necessary input information was determined from the same data, resulted in the strange sea polarisation $(\Delta s + \Delta\bar{s}) = 0.037 \pm 0.019$(stat.) $\pm\, 0.027$(syst.), at LO, and in the x range 0.02–0.6. This should be compared with the slightly negative, inclusive result of COMPASS.

4. Measurements of the gluon polarisation

They are very difficult. Due to the limited range in Q^2 at fixed x, covered by experiments, the QCD fits, *cf.* [9,10], show very limited sensitivity to the gluon helicity distribution, $\Delta g(x_G)$ and to its first moment, ΔG. The determination of $\Delta g(x_G)$ has therefore to be complemented by direct extraction from the measured semi-inclusive asymmetries. Contrary to the fits, this approach results in ΔG which is independent of any assumptions

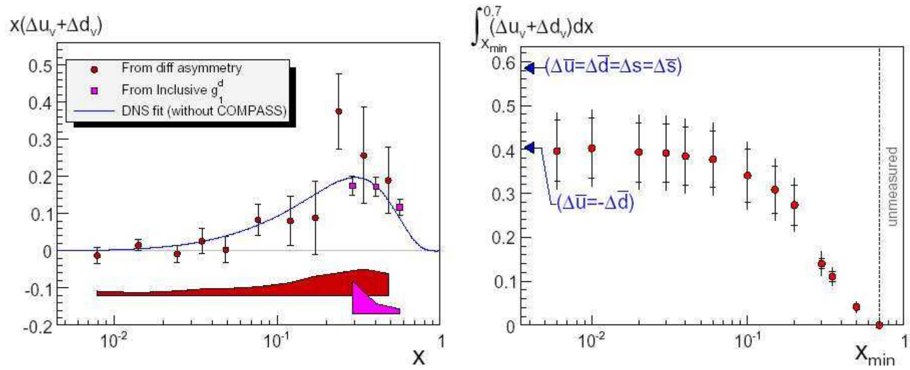

Fig. 5. COMPASS results for the polarised valence quark distribution obtained from the $A^{h^+-h^-}$ asymmetry, [11]. Left: the $x(\Delta u_v(x)+\Delta d_v(x))$ evolved to $Q^2 =$ 10 GeV^2 according to the DNS fit at LO [12] (line). Three additional points at high x are obtained from g_1^d measurements, [9]. Right: the integral of $\Delta u_v(x)+\Delta d_v(x)$ over the range $0.006 < x < 0.7$ as the function of the low x limit, evaluated at Q^2 = 10 GeV^2.

concerning the shape of the x_G dependence. However, this happens at the expense of a complicating experimental selection of a defined, gluon-initiated process. The proton–proton collisions at RHIC are a special challenge here, since the corresponding (pion, photon and jet production) asymmetries are bilinear in the parton distributions. The gluon polarisation models used to predict asymmetries are in this case validated through successful comparison of the measured, spin-averaged, cross-sections to the NLO QCD calculations.

The RHIC measurements begin to significantly constrain the gluon spin contribution. For example the PHENIX double helicity asymmetries in neutral pion production for $p_{\rm T}$ = 1 to 12 GeV are consistent with zero, and at a theory scale of 4 GeV^2 give ΔG from 0.1 to 0.2 for x_G between 0.02 and 0.3, *cf.* Fig. 6 [14]. Their future measurements will be required to measure at $x_G < 0.02$ where large uncertainty remains [10] and which may still contribute a significant amount of the proton spin (see also [15]).

The gluon polarisation in the nucleon was recently determined in two ways by COMPASS, from the cross-section asymmetry for the virtual photon–gluon fusion (PGF), $\gamma^* g \to q\bar{q}$. The PGF process was selected depending on the products of the $q\bar{q}$ pair fragmentation, either through production of hadron pairs with high transverse momenta, $p_{\rm T}$ (typically 1–2 GeV/c), with respect to the virtual photon direction, or through the open-charm production, *i.e.* when $q \equiv c$ and the $c\bar{c}$ pair fragments into a pair of the D mesons. The former process results in a very high statistics but relies on Monte Carlo generators simulating the QCD processes; the latter provides the cleanest sample of interesting events albeit at a low rate.

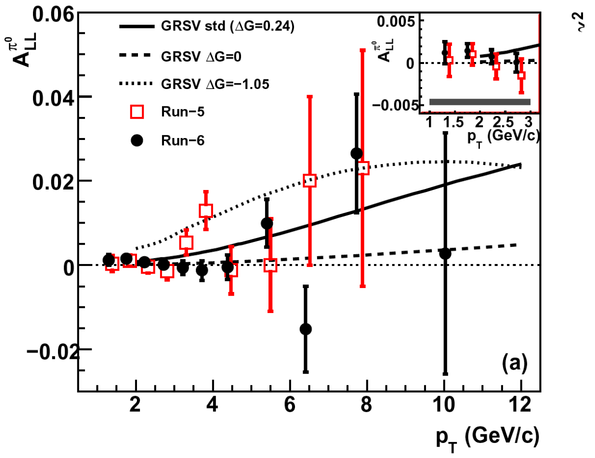

Fig. 6. PHENIX results for the asymmetry in π^0 production as a function of p_{T}, [14]. Error bars are statistical uncertainties. Curves mark different ΔG scenarios.

The production of the open charm D mesons was assumed to be dominated by the PGF mechanism (charm quark *not* pre-existing in the nucleon). The method has the advantage that in the lowest order of the α_{s} there are no other contributions to the cross-section. In the analysis the perturbative scale was set to the $4(m_c^2 + p_{\mathrm{T}}^2)$, m_c being the mass of the charm quark and p_{T} its transverse momentum with respect to the virtual photon. A leading order QCD approach gave an average gluon polarisation of $\Delta G/G = -0.49 \pm 0.27(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})$ at a scale ≈ 13 GeV^2 and at an average gluon momentum fraction $\langle x_G \rangle \approx 0.11$ $(0.06 < x_G < 0.22)$ [16]. Here G denotes the gluon momentum distribution.

Gluon polarisation has also been determined from the events with at least two high-p_{T} hadrons in addition to the incoming and outgoing muon. The cross-section helicity asymmetry for those events contains an asymmetry from the background processes in addition to the contribution from the PGF. This background asymmetry and the PGF contribution were estimated by a simulation which introduces a model dependence in the evaluation of ΔG. The $Q^2 > 1$ GeV^2 and the $Q^2 < 1$ GeV^2 events were considered separately; the new result, for $Q^2 > 1$ GeV^2, is $\Delta G/G = -0.08 \pm 0.1(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})$ at a scale ≈ 3 $(\mathrm{GeV}/c)^2$ and at $0.06 < x_G < 0.22)$ [17].

Presently all measurements of ΔG are situated around $x_G \sim 0.1$ and point towards a small gluon polarisation there, Fig. 7. This, in principle, still does not exclude a large value of the first moment of the gluon helicity distribution.

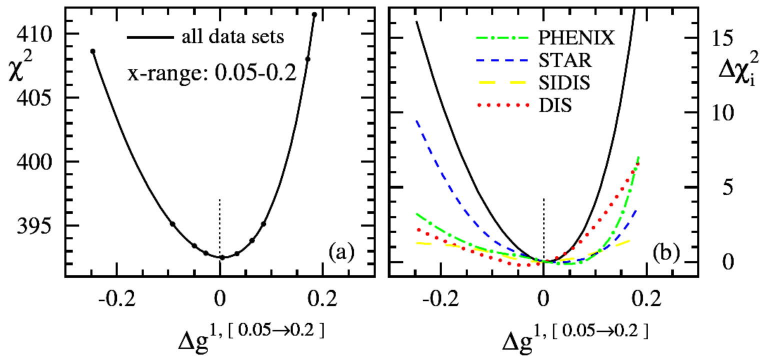

Fig. 7. The χ^2 profile (a) and partial contributions to $\Delta\chi^2$ (b) of the data sets for variations of the first moment of the gluon polarisation in the $0.05 < x_G < 0.2$ range, [10].

5. Transverse spin structure of the nucleon

To complete the nucleon quark structure at the twist-two level and neglecting the quark transverse momenta, their transversity ($\Delta_{\rm T}q(x)$) distributions need to be determined. This is accomplished through asymmetry measurements on a transversally polarised target. Particularly important are asymmetries due to the Collins and Sivers mechanisms, the former being due to the combined effect of $\Delta_{\rm T}q$ and a chirally-odd spin-dependent fragmentation function and the latter to a correlation between the intrinsic transverse momentum of a quark and the transverse polarisation of the nucleon. HERMES has found the evidence for both mechanisms, [18, 19] for its pions produced on a proton target while the corresponding asymmetries measured on the deuteron and at much higher energy by COMPASS, showed no visible effect, for any of the identified hadrons measured (charged pions ad kaons, neutral kaons), [20]. This is in line with the previously published COMPASS results for not identified charged hadrons [21], and with the expected cancellation between the u- and d-quark contributions in the deuteron.

Preliminary results obtained by COMPASS for the (part of the) data taken in 2007 with the transversely polarised proton target show a hint of a nonzero Collins asymmetry at the x values larger than 0.1. The Sivers asymmetries stay compatible with zero. These facts await confirmation with a larger statistics, *cf.* [22].

Transverse spin programme at RHIC has also come of age and provided many surprising and interesting measurements: single spin asymmetries in various reactions in mid rapidity, near $x_{\rm F} \sim 0$ (results consistent with zero) and in the forward rapidity where large asymmetries were observed in inclusive π^0 production, Fig. 8 [15, 23].

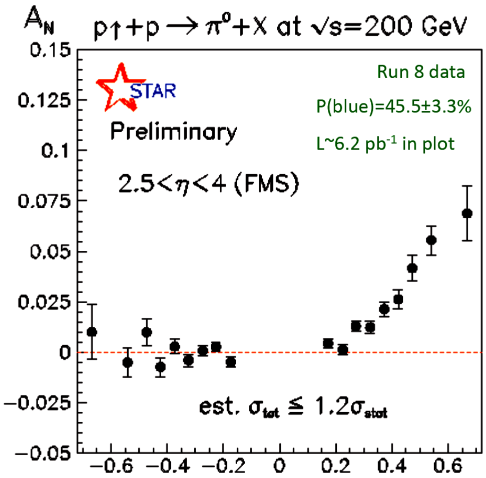

Fig. 8. Preliminary STAR results for the semi-inclusive transverse asymmetry for the π^0 production, [15].

Finally one has to mention that the first global analyses of the transverse parton distributions have already been performed and point towards small values of $\Delta_{\mathrm{T}} q$ as compared to Δq [24].

6. Nucleon spin decomposition. Angular momentum of partons

So where does the nucleon spin come from?

In QCD the nucleon spin decomposition into the quark and gluon helicites, $\Delta\Sigma$ and ΔG, and orbital angular momenta, L_q and L_g, may be expressed as follows:

$$\frac{\hbar}{2} = J_q + J_g = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + (\Delta G + L_g) \ ,$$

where each term is renormalisation scale-dependent and the $J_g = \Delta G + L_g$ decomposition is not gauge-invariant. There is no analogous sum rule involving transversity since there is no transverse analogue of the gluon helicity.

In the Quark Parton Model the nucleon spin is given by the quark spins, $\Delta\Sigma$, while ΔG and $L_{q,g}$ vanish. The quark contribution is now confirmed to be around 0.3, smaller than the expected value of 0.6 [25] which keeps the "nucleon spin puzzle" alive, 20 years after its discovery [4].

In principle however, the puzzle can still be solved by the QCD axial (or U(1)) anomaly, steming from the axial vector current nonconservation. The anomaly generates a gluonic contribution to the measured singlet axial coupling, $a_0(Q^2)$, which does not vanish at $Q^2 \to \infty$. As a result, $\Delta\Sigma(Q^2)$

becomes scheme dependent and may differ from the observable a_0 while ΔG is scheme-independent at least up to the NLO. In the Adler–Bardeen factorisation scheme, $\Delta\Sigma^{\rm AB}$ is independent of Q^2. As a consequence, the measured quantity is in fact not the $\Delta\Sigma$ but

$$a_0(Q^2) = \Delta\Sigma^{\rm AB} - \left(\frac{n_f\alpha_{\rm s}}{2\pi}\right)\Delta G(Q^2)\,.$$

Restoring the Ellis–Jaffe value of $\Delta\Sigma^{\rm AB} \sim 0.6$ (or solving the "spin crisis") would thus require a value of $\Delta G(Q^2) \approx 2$ and $L = L_q + L_g \sim -2$ at $Q^2 \approx 5$ GeV^2. If indeed the ΔG is close to zero as all the measurements seem to point to, then the axial anomaly plays only a marginal role in the nucleon spin balance. Further, if $a_0 = 0.35 \pm 0.03 \pm 0.05$ as *e.g.* the COMPASS fit at $Q^2 = 3$ GeV^2 shows [9] then the only way out is through a large orbital angular momentum contributions, $L_{q,g}$. They have to be measured precisely in order to finally settle the proton spin problem.

The L_q may in principle be accessed through the Generalised Parton Distribution functions measured in the Deeply Virtual Compton Scattering. Several DVCS data have already been taken and are being analysed; several other measurements are expected to be performed in the next few years. In particular the JLAB and HERMES results give the first determination of u- and d-quark angular momenta, albeit model dependent, [26, 27]. Preliminary conclusions together with the first results from the lattice QCD calculations [28] seem to indicate that the L_q might be close to zero even if a finite orbital momentum seems to be essential for many nucleon observables [29] and even if the perturbative QCD indicates that the orbital angular momentum must play an important role [30].

7. Outlook

During the 20 years since the "proton spin puzzle" emerged we have learned a lot about the spin degree of freedom in the nucleon. Restoration of the naive expectations of the nucleon spin content via the axial anomaly seems improbable. On the other hand significant orbital angular momentum in the proton is expected; ways of exposing it must be found.

In the near future the nucleon spin physics will be pursued at several old and new facilities: COMPASS and HERMES will continue analysing their data; COMPASS also prepares a new long-term proposal. RHIC will extend its running parameters and upgrade its detectors. Finally the JLAB, now in the course of upgrading into 12 GeV, has a rich spin programme, especially for the extensive measurements of the DVCS and transversity.

A crucial extension of the kinematic domain of the spin electroproduction will take place with the advent of the polarised Electron–Ion Collider, EIC (eRHIC/ELIC) in USA. This machine will open a field of perturbative low x spin physics where also semi-inclusive and exclusive observables will be accessible for testing the high parton density mechanisms, [31].

I am deeply indebted to Jan Kwieciński for the 18 years of the most enjoyable scientific collaboration, which included the low x spin physics. I greatly benefited from his deep knowledge, open-mindedness, enthusiasm and kindness. It was a blessing for experimentalists to have among us a theorist like Jan, untired in his efforts to understand physics, no matter — experimental or theoretical. This work was supported by the Ministry of Science and Higher Education grant number 41/N-CERN/2007/0.

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