Eur Phys J A (2005) **24**, s2, 11–14
DOI: 10.1140/epjad/s2005-04-002-6

EPJ A direct
electronic only

Strange and gluonic contributions to the nucleon spin

Jean-Marc Le Goff

CEA-Saclay, DAPNIA SPhN, France

Received: 15 October 2004 / Published Online: 8 February 2005

Abstract. Inclusive deep inelastic scattering (DIS) experiments lead to a small contribution of the quark spins to the nucleon spin and a negative contribution from strange quarks. Historically this triggered the interest in measuring strange form factors. However, the result of these inclusive experiments has to be reinterpreted taking into account the axial anomaly in QCD, which depends on the gluon contribution to the nucleon spin. The COMPASS experiment at CERN and experiments at RHIC are going to measure this gluonic contribution.

PACS. 13.60.Hb Total and inclusive cross sections (including deep-inelastic processes) – 13.60.Le Meson production

1 Introduction

In 1989 the EMC experiment [1] at CERN concluded that the contribution $\Delta\Sigma$ of the quark spins to the nucleon spin was compatible with zero and that the strange contribution Δs was significantly negative, triggering the so-called spin crisis. This meant that the strange axial matrix element of the nucleon was non-zero, which raised the issue whether the strange vector matrix elements could also be non-zero and motivated a large experimental program to study strange form factors through Parity Violation experiments. Here we present an overview of the spin of the nucleon, for a full review see [2].

2 Strange quark and total quark contributions

The spin of the nucleon can be decomposed in the contributions from its constituents as

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g \qquad (1)$$

where Δg is the contribution from the spins of the gluons and L_q and L_g are the contributions from orbital angular momenta of quarks and gluons. What do we know about $\Delta\Sigma$ from a theoretical point of view ? On the one hand we have the quark model which provides us with a large part of our understanding of hadrons. It gives $\Delta\Sigma \approx 0.75$. On the other hand we are not able to use QCD to compute $\Delta\Sigma$ from first principles, but using results from hyperon β decay experiments and assuming a strange quark contribution $\Delta s = 0$, we get $\Delta\Sigma \approx 0.6$. We then have a qualitative agreement between Quark Model and QCD.

In inclusive deep inelastic experiments (DIS) a lepton is scattered off a nucleon and only the scattered lepton is observed. Only two Lorentz invariants enter the problem. They can be chosen as the mass of the virtual photon, $Q^2 = -q_\mu^2$, which gives the resolution of the probe, and $x_{bj} = Q^2/2M(E-E')$ which is the fraction of the nucleon momentum carried by the quark which absorbed the virtual photon. DIS corresponds to the limit of large Q^2 at fixed x_{bj}. The cross section involves structure functions which depend only on the two Lorentz invariants. However, because the lepton scatters on a quark, which is a point-like particle, the Q^2 dependence vanishes, at least to leading order in QCD, a property known as scaling. In the unpolarized case we have two structure functions F_1 and F_2. They can be expressed in terms of the parton distribution function (pdf) as $F_1(x) = \frac{1}{2}\left[\frac{4}{9}u(x) + \frac{4}{9}\bar{u}(x) + \frac{1}{9}d(x) + \frac{1}{9}\bar{d}(x) + \frac{1}{9}s(x) + \frac{1}{9}\bar{s}(x)\right]$ and $F_2(x) = 2xF_1(x)$, where $u(x)$ for instance, is the probability to find inside the nucleon a quark of flavor u and a fraction x of the nucleon momentum. In the polarized case we have in addition g_1 and g_2; $g_1(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u(x) + \frac{1}{9}\Delta d(x) + \frac{1}{9}\Delta s(x)\right]$ with $\Delta u(x) = u^+(x) - u^-(x) + \bar{u}^+(x) - \bar{u}^-(x)$, where the polarized pdf $u^+(x)$ is the probability to find inside the nucleon a quark of flavor u with a fraction x of the nucleon momentum and a spin parallel to the nucleon spin. The integral $\Delta u = \int_0^1 \Delta u(x)dx$ is the total contribution of spins of quark of flavor u to the nucleon spin. We then have $\Delta\Sigma = \Delta u + \Delta d + \Delta s$, where the contribution of heavier flavors (c, b and t) is negligible.

In 1989 the EMC measured $\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$. Using $SU_f(3)$ symmetry hyperon β decays give $a_3 = \Delta u - \Delta d$ and $a_8 = \Delta u + \Delta d - 2\Delta s$. This provided 3 equations for 3 unknowns resulting in $\Delta\Sigma = 0.12 \pm 0.17$ and $\Delta s = -0.10 \pm 0.03 < 0$! This

Send offprint requests to: jmlegoff@cea.fr

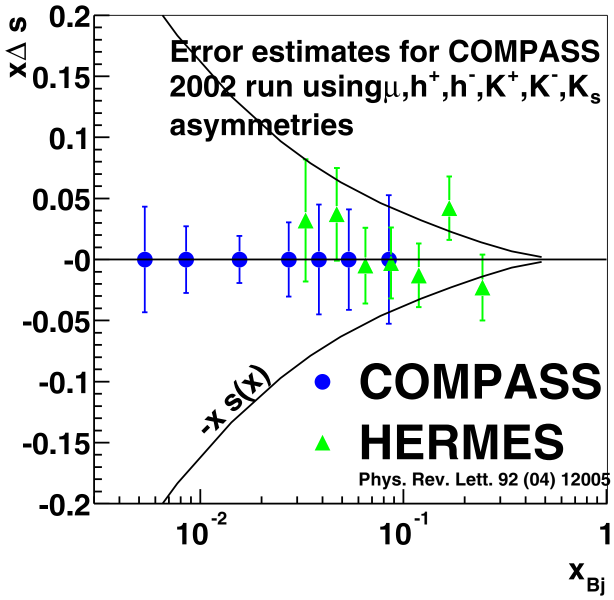

Fig. 1. Results of Hermes semi-inclusive analysis [4] and projections from COMPASS

came as a big surprise which was advertised as the spin crisis, so that the EMC paper is one of the 3 most cited experimental papers [3]. The results were confirmed by SMC at CERN, SLAC, and Hermes at DESY. The uncertainty is now dominated by the extrapolation in the low x, unmeasured region.

In order to go further and measure the x dependence of the polarized pdf one needs to perform semi-inclusive DIS, $l + p \to l' + h + X$. The spin asymmetry for this process can be written as

$$A_1^h = \frac{\sum_q e_q^2[\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)]}{\sum_q e_q^2[q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)]} \qquad (2)$$

where $z = E_h/E_{\gamma^*}$ and the fragmentation function $D_q^h(z)$ gives the probability that the fragmentation of a quark of flavor q gives a hadron h. The fact that $D_q^h(z) \neq D_{\bar{q}}^h(z)$ allows for the separation of sea from valence. Using A_1, A_1^{h+}, A_1^{h-} for proton and neutron the SMC obtained Δu_v, Δd_v, $\Delta\bar{d}$, $\Delta\bar{u}$ without using $SU_f(3)$ flavor symmetry. However, such an analysis relies on 2, which assumes that the measured hadron comes from the fragmentation of the struck quark and not from the target remnant.

In order to measure also $\Delta s(x)$ one needs to identify strange particles within the measured hadrons, either using a RICH detector, or by reconstructing the K^0 mass. Unfortunately this introduces more sensitivity to target remnants because $m_K > m_\pi$. Figure 1 presents the results obtained by the Hermes collaboration. They exhibit no indications of $\Delta s < 0$. Data down to lower x are expected from COMPASS.

Polarized pdf can also be measured through parity violating $\vec{p}\ p \to W$ at RHIC in Brookhaven [5]. The point is that $q\bar{q} \to W^\pm$ selects a given quark helicity. W^+ production is dominated by $u\bar{d} \to W^+$. If u comes from the polarized proton and $\bar{d}$ from the unpolarized one, we get a $\Delta u\ \bar{d}$ contribution. The opposite case gives $\Delta\bar{d}\ u$. The spin asymmetry for the process then reads

$$A_L^{W^+} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \qquad (3)$$

The same formula is obtained for W^- production with u and d exchanged. The nice thing with such an analysis is that it is independent of target fragmentation effects. It has, however, hardly any sensitivity to Δs.

We must go back to the inclusive case and note that EMC does not actually measure Δq but axial matrix elements $a_q = \langle N|\bar{q}\gamma_\mu\gamma_5 q|N\rangle$. Naively the axial matrix elements are identified with Δq. However, due to axial anomaly we rather have $a_0 = \Delta\Sigma - 3\frac{\alpha_s}{2\pi}\Delta g$ and $a_s = \Delta s - \frac{\alpha_s}{2\pi}\Delta g$. In addition $\Delta g \propto \ln Q^2$, so that the gluonic contribution to a_q does not go to zero at high Q^2 in spite of the α_s factor.

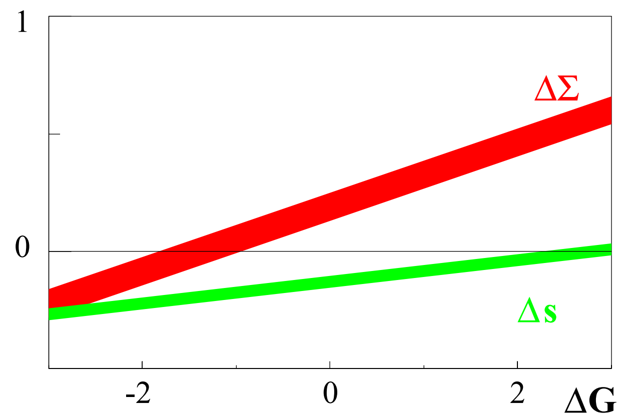

Fig. 2. $\Delta\Sigma$ and Δs as a function of the hypothesis for Δg

The actual value of $\Delta\Sigma$ and Δs now depends on the value of Δg as illustrated by Fig. 2. If $\Delta g \approx 0$ we are back to the spin crisis with a small $\Delta\Sigma$ and a negative Δs. If Δg is large and positive we may end up with the expected $\Delta s \approx 0$ and $\Delta\Sigma \approx 0.6$. Δg must be measured, both for itself and in order to extract the actual value of $\Delta\Sigma$ and Δs from inclusive experiments.

3 Gluon contribution

When Q^2 increases the resolution of the probe improves and what used to appear as a quark may start to appear as a quark and a gluon, or a gluon may appear as a quark anti-quark pair. In these conditions the variation $dq(x,Q^2)/d(\ln Q^2)$ tells us something about $g(x,Q^2)$. This is formalized in the Dokshitzer-Gribov-Lipatov-Altareli-Parisi (DGLAP) equations. Indeed, in the unpolarized case, performing a next-to-leading order QCD fit of F_2 data, from fixed target experiments and from the HERA collider, provides a good measurement of $g(x,Q^2)$. This is unfortunately not the case in the polarized case because there is no polarized lepton-proton collider. The Q^2 range for g_1 data, between SLAC or Hermes and SMC, is not large enough (at most a factor 10) to allow for a precise estimate of $\Delta g(x, Q^2)$. A direct measurement is needed.

It is difficult to probe gluons in lepton scattering because they have no electric charge. Photons can, however, interact with gluons through the photon gluon fusion (PGF) process, $\gamma^* g \to q\bar{q}$. This is a higher order process which has a small cross section relative to the leading order process, $\gamma^* q \to q$, so tagging is needed.

The first possibility consists in requiring the produced $q\bar{q}$ pair to be a $c\bar{c}$ pair. Since the intrinsic charm inside the nucleon is negligible, the observation of charm is a signature of the PGF process. The fragmentation of charm quarks produces a $D^0 = c\bar{u}$ meson in 60% of the cases. The easiest way to see the D^0 is through its decay to $K\pi$ which has a 4% branching ratio. Due to this low branching ratio, one requires to detect either the c or the $\bar{c}$ through this channel. The drawback is that in this case it is not possible to reconstruct the kinematics at the vertex and the momentum fraction of the gluon cannot be evaluated. One gets the mean value of $\Delta g(x)/g(x)$ averaged over the experimental acceptance.

A second possibility arises from the fact that in the leading order process, $\gamma^* q \to q$, all the produced hadrons are in the direction of the virtual photon, whereas in the PGF process the $q\bar{q}$ pair can be produced at any angle and the resulting hadrons may have a transverse momentum p_t with respect to the photon. So the idea is to search for pairs of hadrons with high p_t (or two high p_t jets at high energy). There is, however, a physical background, the so-called QCD Compton process, $\gamma^* q \to qg$, since in this process the final q and g both can produce a high p_t hadron. This background has to be evaluated by a Monte Carlo (MC) simulation, starting from the known polarized quark distribution functions.

This second method was already used by Hermes [6] and SMC [7]. Hermes used a 28 GeV electron beam, they did not measure the scattered electron and they were dominated by low Q^2, quasi real photons. The hard scale, for perturbative QCD to be valid, is then provided by p_t. The generator PYTHIA was used for background estimation. The difficulty in this case is that, in addition to QCD Compton, there is an important background of events where the photon is resolved into its partonic structure. In this analysis the dilution due to these events was taken into account but not their contribution to the asymmetry. SMC had a 190 GeV/c muon beam. They selected only events with $Q^2 > 1$ (GeV/c)^2, in which case the resolved photon contribution could be neglected and the pure DIS generator, LEPTO, could be used. The results obtained by the two collaborations are presented in Fig. 4. Error bars are still pretty large.

The COMPASS collaboration [8] at CERN is using both methods. The muon beam intensity was increased by a factor 5 relative to SMC to provide an average luminosity of $5 \cdot 10^{32}$ cm^{-2}s^{-1}. The target is made of ^{6}LiD with a dilution factor ≈ 0.5 to be compared to 0.24 for deuterated butanol, used by SMC. The spectrometer was commissioned and first data were taken in 2002. Data were taken again in 2003 and 2004 but there will be no beam in 2005, due to LHC installation.

The 2002 data gives an asymmetry for high p_t pair production, $A^{\gamma d \to hh'} = -0.065 \pm 0.036 \pm 0.010$, including all Q^2. MC studies are going on, to take into account the contribution of resolved photons to the asymmetry. Part of these events involve a gluon in the nucleon so that their contribution to the asymmetry is proportional to $\Delta g/g$. Neglecting this fact, a statistical error $\delta(\Delta g/g) = 0.17$ should be obtained. In the same conditions, all data between 2002 and 2004 should provide $\delta(\Delta g/g) \approx 0.05$, or alternatively four bins in x_g with $\delta(\Delta g/g) \approx 0.10$ in each bin. Using only data with $Q^2 > 1$ (GeV/c)^2, should provide $\delta(\Delta g/g) \approx 0.16$.

The $D^0 \to K\pi$ open charm channel suffers from an important combinatorial background. Requiring that the D^0 comes from the disintegration $D^* \to D^0\pi \to K\pi\pi$, strongly reduces the background. The first reason is the small value of $M_{D^*} - M_{D^0} - M_\pi = 6$ MeV, which leaves little space for the background. The second reason is the excellent experimental resolution in this mass difference, better than 2 MeV, to be compared to about 25 MeV for the resolution in the D^0 mass alone. Many improvements are ongoing in terms of reconstruction, in particular in the RICH detector used to identify K. An error $\delta(\Delta g/g) \approx 0.24$ is then expected out of 2002 to 2004 data.

The gluon distribution can also be probed in polarized proton-proton collisions [5]. The golden channel is the so-called direct γ production $\overrightarrow{p}\overrightarrow{p} \to \gamma$ + jet + X. At the parton level this corresponds to $qg \to q\gamma$, where quarks from one of the protons are used to probe gluons in the other proton. So the measured asymmetry is a convolution, $\Delta g \otimes \Delta q$. There is a physics background, $q\bar{q} \to g\gamma$, which also produces γ + jet + X. Its contribution to the asymmetry, which goes like $\Delta q \otimes \Delta\bar{q}$, can be computed from the measured $\Delta q(x)$ and $\Delta\bar{q}(x)$.

Other possible channels at RHIC include jet production (or high p_t leading hadron) and heavy flavor production.

RHIC, the relativistic heavy ion collider, is used part of the time as a polarized proton-proton collider at $\sqrt{s} = 50-500$ GeV. Both PHENIX and STAR collaborations are taking data in this mode. The design polarization is 70%, using siberian snakes in RHIC and partial snakes in the AGS to eliminate depolarizing resonances. The design luminosity is $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2}s^{-1}. An integrated luminosity of 7 pb^{-1} with $P \approx 50\%$ is expected from the 2004-2005 run. The first measured leading hadron asymmetry, A^{π}_{LL}, is presented in Fig. 3. This asymmetry is sensitive to the convolution $\Delta g \otimes \Delta g$. It should then be positive unless there is a node in $\Delta g(x)$.

The expected error on $\Delta g/g$ in the golden channel for an integrated luminosity of 320 pb^{-1} with $P = 70\%$ are presented in Fig. 4. We see that a wide range of x_g is covered with an excellent accuracy. Note, however, that this is only the statistical accuracy, some systematic uncertainty will arise from background subtraction and deconvolution.

In the long term there is the EIC project [10] to build a 10 GeV polarized electron linac to collide with one of the

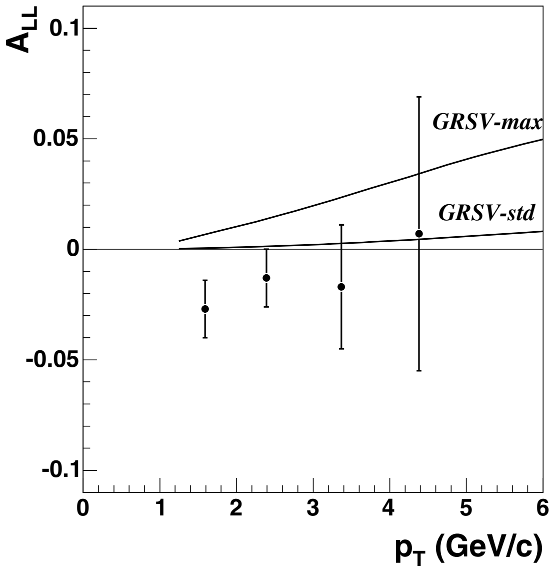

Fig. 3. Leading hadron A_{LL}^{π} asymmetry measured at RHIC by PHENIX [9], compared with prediction corresponding to the standard GRV parametrization and to a parametrization with 100% polarization at a given starting scale

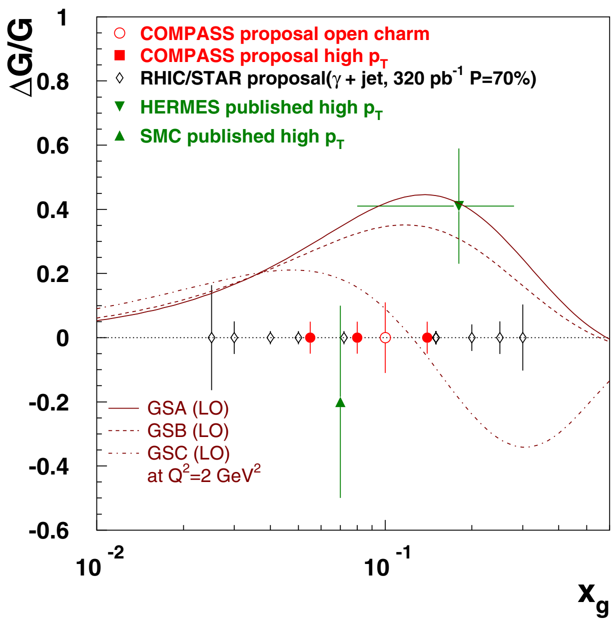

Fig. 4. Measured values of $\Delta g/g$ by Hermes and SMC, together with projections from COMPASS and RHIC

RHIC polarized proton beams with a luminosity of 10^{33} to 10^{34} cm^{-2}s^{-1} and $\sqrt{s} = 100$ GeV. The beam could start between 2012 and 2014. This would allow for:
– the measurement of g_1 down to $x = 10^{-4}$ instead of $3 \cdot 10^{-3}$ now, dramatically reducing the dominant error on $\int_0^1 g_1(x)dx$ (and then on a_0) which is due to the low x extrapolation.
– a large range of Q^2 for g_1 data and then a precise estimate of Δg from QCD NLO fit.
– a direct measurement of $\Delta g(x, Q^2)$ through hadron pairs, jet pairs and charm production.
– all in all this should give an error on the integral $\Delta g = \int_0^1 \Delta g(x)dx$ on the order of 0.03 to 0.05.

4 Conclusions and perspectives

In the reconstruction of the spin puzzle,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g \qquad (4)$$

we know the flavor singlet axial matrix element $a_0 = \Delta\Sigma - (3\alpha_s/2\pi)\Delta g = 0.27 \pm 0.13$.

The strange axial matrix element is $a_s \approx -0.10$, but this is more sensitive to possible violations of $SU_f(3)$ symmetry than a_0. The measurement of $\Delta s(x)$ in semi-inclusive DIS is delicate because it is sensitive to target fragmentation effects. There is hardly any sensitivity to $\Delta s(x)$ in $\overrightarrow{p}p$ collisions. A possible solution would be to get the integral Δs from neutrino experiments combined with parity violation experiments [11].

The first measurements of $\Delta g(x)$ by COMPASS and RHIC will appear soon. The experimental methods and the systematic errors are completely different and in addition each experiment has several channels, so this should provide a reliable measurement of $\Delta g(x)$.

In the longer term the project of a polarized electron-proton collider at RHIC would provide a much more accurate value of a_0 and Δg and then of $\Delta\Sigma$.

The contributions from orbital momentum are very difficult to access. Generalized Parton Distributions (GPD, for a review see e.g. [12]) describe at the same time the transverse position and the longitudinal momentum, which is what is needed to compute the orbital momentum. This is formalized in the Ji sum rule which relates an integral of GPDs to $J_q = \Delta\Sigma + L_q$. GPDs can be measured in DVCS experiments, $lN \to l'N'\gamma$. First DVCS measurements were performed at JLAB and HERA and plans exist at COMPASS; due to its high luminosity an electron-proton collider at RHIC would be the ideal tool for this. There is, however, a very long way before measuring the Ji sum rule.

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