Towards an understanding of nucleon spin structure: 
from hard to soft scales

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Abstract

The workshop The Helicity Structure of the Nucleon (BNL June 5, 2006) was organized as part of the 2006 RHIC & AGS Users' Meeting to review the status of the spin problem and future directions. The presentations can be found at [1]. Recent data suggest small polarized glue and strangeness in the proton. Here we present a personal summary of the main results and presentations. What is new and exciting in the data, and what might this tell us about the structure of the proton?
1 Introduction

It is nearly 20 years since the European Muon Collaboration (EMC) published their polarized deep inelastic measurement of the proton’s $g_1$ spin dependent structure function and the flavour-singlet axial-charge $g_A^{(0)}|_{pDIS}$ [2]. Their results suggested that the quarks’ intrinsic spin contributes little of the proton’s spin. The challenge to understand the spin structure of the proton [3, 4, 5] has inspired a vast programme of theoretical activity and new experiments at CERN, DESY, JLab, RHIC and SLAC.

Where are we today?

We start by recalling the $g_1$ spin sum-rules. These are derived starting from the dispersion relation for polarized photon-nucleon scattering and, for deep inelastic scattering, the light-cone operator product expansion. One finds that the first moment of the $g_1$ structure function is related to the scale-invariant axial charges of the target nucleon by

\[
\int_0^1 dx \, g_1^p(x, Q^2) = \left( \frac{1}{12} g_A^{(3)} + \frac{1}{36} g_A^{(8)} \right) \left\{ 1 + \sum_{\ell \geq 1} c_{NS\ell} \alpha_s^\ell(Q) \right\} + \frac{1}{9} g_A^{(0)}_{\text{inv}} \left\{ 1 + \sum_{\ell \geq 1} c_{S\ell} \alpha_s^\ell(Q) \right\} + O(\frac{1}{Q^2}) - \beta_1(Q^2) \frac{Q^2}{4M^2}. \tag{1}
\]

Here $g_A^{(3)}$, $g_A^{(8)}$ and $g_A^{(0)}_{\text{inv}}$ are the isovector, SU(3) octet and scale-invariant flavour-singlet axial charges respectively. The flavour non-singlet $c_{NS\ell}$ and singlet $c_{S\ell}$ Wilson coefficients are calculable in $\ell$-loop perturbative QCD [6]. The term $\beta_1(Q^2) \frac{Q^2}{4M^2}$ represents a possible subtraction constant from the circle at infinity when one closes the contour in the complex plane in the dispersion relation [3, 7]. If finite, the subtraction constant affects just the first moment sum-rule. For a leading-twist subtraction: $\beta_1(Q^2) = O(1/Q^4)$ as $Q^2 \to \infty$. The first moment of $g_1$ plus the subtraction constant, if finite, is equal to the axial-charge contribution. The subtraction constant corresponds to a real term in the spin-dependent part of the forward Compton amplitude.

If one assumes no twist-two subtraction constant ($\beta_1(Q^2) = O(1/Q^4)$) then the axial charge contributions saturate the first moment at leading twist. The isovector axial-charge is measured independently in neutron beta-decays ($g_A^{(3)} = 1.2695 \pm 0.0029$ [8]) and the octet axial charge is extracted from hyperon beta-decays ($g_A^{(8)} = 0.58 \pm 0.03$ [9]). From the first moment of $g_1$, polarized deep inelastic scattering experiments have been interpreted to imply a small value for the flavour-singlet axial-charge:

\[
g_A^{(0)}|_{pDIS} = 0.15 - 0.35 \tag{2}
\]

– considerably less than the value of $g_A^{(8)}$. In the naive parton model $g_A^{(0)}|_{pDIS}$ is interpreted as the fraction of the proton’s spin which is carried by the intrinsic spin
Figure 1: Recent data on $g_1^d$ from COMPASS [13].

of its quark and antiquark constituents. When combined with the octet axial charge this value corresponds to a negative strange-quark polarization $\Delta s = \frac{1}{3}(g_A^{(0)}|_{\text{DIS}} - g_A^{(8)})$:

$$\Delta s = -0.10 \pm 0.04$$  \hspace{1cm} (3)

− that is, polarized in the opposite direction to the spin of the proton. Relativistic quark models generally predict values $g_A^{(0)} \sim 0.6$ with little polarized strangeness in the nucleon [3, 10].

The Bjorken sum-rule for the isovector part of $g_1$ [11]

$$\int_0^1 dx g_1^{p-n} = \frac{g_A^{(3)}}{6} \left[ 1 - \frac{\alpha_s}{\pi} - 3.583 \left( \frac{\alpha_s}{\pi} \right)^2 - 20.215 \left( \frac{\alpha_s}{\pi} \right)^3 \right]$$  \hspace{1cm} (4)

has been confirmed in polarized deep inelastic scattering experiments at the level of 10% [12].

2 The shape of $g_1$

Deep inelastic measurements of $g_1$ have been performed in experiments at CERN, DESY, JLab and SLAC. There is a general consistency among all data sets. COMPASS are yielding precise new data on $g_1^d$ at small $x$, down to $x \sim 0.004$, shown in Fig. 1 [13]. JLab are focussed on the large $x$ region. To test deep inelastic sum-rules it is necessary to have all data points at the same value of $Q^2$. In the experiments the different data points are measured at different values of $Q^2$, viz. $x_{\text{expt.}}(Q^2)$. Next-to-leading order (NLO) QCD-motivated fits taking into account the scaling violations associated with perturbative QCD are frequently used to evolve all the data points to the same $Q^2$. In a recent fit reported at this meeting COMPASS
evolve the world $g_1$ data set to a common value $Q^2 = 3 \text{ GeV}^2$; a preliminary value was quoted [14]
\[
g_A^{(0)}|_{p\text{DIS}} = 0.25 \pm 0.02(\text{stat.}) \pm ?
\]  
where the additional error denoted "?" reflects systematics and theoretical error in the set up of the QCD-motivated fit. Even more precise data are becoming available and were reported at this meeting from COMPASS for the deuteron spin structure function $g_1^d$ [14]. The data show the remarkable feature that $g_1^d$ is consistent with zero in the small $x$ region between 0.004 and 0.02.

In contrast, the isovector part of $g_1$ is observed to rise at small $x$ ($0.01 < x < 0.1$) as $\sim x^{-0.5}$ and is much bigger than the isoscalar part of $g_1$ [3, 15]. This is in sharp contrast to the situation in the unpolarized structure function $F_2$ where the small $x$ region is dominated by isoscalar pomeron exchange. The evolution of the Bjorken integral $\int_{x_{\text{min}}}^1 dx g_1^{p-n}$ as a function of $x_{\text{min}}$ is shown for the SLAC data (E143 and E154) in Figure 2 [16]. About 50% of the sum-rule comes from $x$ values below about 0.12 and about 10-20% comes from values of $x$ less than about 0.01 [3]. The $g_1^{p-n}$ data are consistent with quark model and perturbative QCD predictions in the valence region $x > 0.2$ [17]. The size of $g_A^{(3)}$ forces us to accept a large contribution from small $x$ and the observed rise in $g_1^{p-n}$ is required to fulfill this non-perturbative constraint.

It would be interesting to extend precision measurements of the isovector $g_1^{p-n}$ to
smaller values of \( x \) to further test its low \( x \) behaviour and to observe the convergence of the Bjorken integral as a function of \( x_{\text{min}} \). Possible measurements could be made at COMPASS running on a proton target to complement the precise new deuteron-target data or with a future polarized \( ep \) collider.

The rise in \( g_1^{p-n} \) is a challenge for Regge predictions and perturbative QCD. The Regge prediction for \( g_1^{p-n} \) at small \( x \) is

\[
g_1^{p-n} \sim \sum_i f_i \frac{1}{x^{\alpha_i}}.
\]

Here the \( \alpha_i \) denote the Regge intercepts for isovector \( a_1 \) Regge exchange and the \( a_1 \)-pomeron cuts [18]. The coefficients \( f_i \) are to be determined from experiment. Soft Regge predictions for the leading \( a_1 \) intercept \( \alpha_{a_1} \) lie between -0.4 and -0.2 [19] within the phenomenological range quoted in [20]. For the value -0.2 the effective intercept corresponding to the \( a_1 \) soft-pomeron cut is \( \simeq -0.1 \). The \( a_1 \) and \( a_1 \) soft-pomeron cut alone are unable to account for the \( g_1^{p-n} \) data. Does the rise in \( g_1^{p-n} \) follow from \( a_1 \) exchange plus perturbative QCD evolution or is there a distinct hard exchange [19]? – that is, a polarized analogue of the one or two pomerons question in unpolarized deep inelastic scattering [21]! One possibility is an \( a_1 \) hard-pomeron cut, with intercept \( \simeq +0.2 \), in conjunction with QCD Counting Rules factors still at work in the measured \( x \) range.

If Regge intercepts are \( Q^2 \)-independent, as suggested by analyticity in \( Q^2 \) [22], the hard exchange observed in \( g_1^{p-n} \) should also contribute in the transition region and in polarized photoproduction as well as in the spin-dependent part of the proton-proton total cross-section [19]. The latter could be investigated at RHIC using Roman Pot detectors, e.g. using the pp2pp apparatus, with a spin rotator before the detector to achieve longitudinal polarization and varying over the energy range of the machine. One would be looking for a leading behaviour \( \Delta \sigma^{p-n} \sim s^{-0.5} \) to \( \sim s^{-0.8} \) instead of the simple \( a_1 \) prediction \( \sim s^{-1.4} \). The strategy would be to look for a finite asymmetry at the lowest energy and, if a signal is found, to keep measuring with increasing energy until the asymmetry disappears within the experimental uncertainties. These measurements would provide a valuable test of spin-dependent Regge theory [18, 23]. The leading non-perturbative gluon-exchange contribution in the isoscalar part of \( \Delta \sigma \) is expected to behave as \( \sim (\ln s/\mu^2)/s \) where \( \mu \sim 0.5-1 \text{ GeV} \) is a typical hadronic scale [23]. High-energy polarized photoproduction and the transition region could be investigated using a polarized electron-proton collider [24, 25] or perhaps through measurement of low \( Q^2 \) asymmetries at COMPASS using a proton target. Knowledge of spin-dependent Regge behaviour would help to constrain the high-energy part of the Gerasimov-Drell-Hearn sum-rule as well as the high-energy extrapolations of \( g_1^{p-n} \) at intermediate \( Q^2 \) that go into the JLab programme to extract information about higher-twist matrix elements in the nucleon.
There are interesting puzzles also at large $x$. Recent data from the Jefferson Laboratory Hall A Collaboration on the neutron asymmetry $A_1^n$ [26] are shown in Fig. 3. These data show a clear trend for $A_1^n$ to become positive at large $x$. The crossover point where $A_1^n$ changes sign is particularly interesting because the value of $x$ where this occurs in the neutron asymmetry is the result of a competition between the SU(6) valence structure [27] and chiral corrections [28]. Figure 3 also shows the extracted flavour-dependent asymmetries. The Hall A data are consistent with constituent quark models with scalar diquark dominance which predict $\Delta d/d \to -1/3$ at large $x$, while perturbative QCD Counting Rules predictions (which neglect quark orbital angular momentum) give $\Delta d/d \to 1$ and tend to deviate from the data, unless the convergence to 1 sets in very late.

New preliminary Hall B data were reported at this meeting [29] which appear to deviate from the Hall A measurements in the larger $x$ region, $x \sim 0.6$, and are less inconsistent with helicity Counting Rules predictions at large $x$. We look forward to the final results and their extension to higher $x$. A precision measurement of $A_1^n$ up to $x \sim 0.8$ will be possible following the 12 GeV upgrade of CEBAF and will provide valuable input to resolving these issues.

Below scaling kinematics, JLab experiments are resolving the spin structure of excited nucleon resonances and testing ideas about quark-hadron duality [29].
3 Spin and the singlet axial charge

There has been considerable theoretical effort to understand the flavour-singlet axial-charge in QCD. QCD theoretical analysis leads to the formula

$$g_A^{(0)} = \left( \sum_q \Delta q - 3 \frac{\alpha_s}{2\pi} \Delta g \right)_{\text{partons}} + C_\infty. \tag{7}$$

Here $\Delta g_{\text{partons}}$ is the amount of spin carried by polarized gluon partons in the polarized proton ($\alpha_s \Delta g \sim \text{constant}$ as $Q^2 \to \infty$ [30]) and $\Delta q_{\text{partons}}$ measures the spin carried by quarks and antiquarks carrying “soft” transverse momentum $k_\perp^2 \sim P^2, m^2$ where $P$ is a typical gluon virtuality and $m$ is the light quark mass [30, 31]. The polarized gluon term is associated with events in polarized deep inelastic scattering where the hard photon strikes a quark or antiquark generated from photon-gluon fusion and carrying $k_\perp^2 \sim Q^2$ [31]. $C_\infty$ denotes a potential non-perturbative gluon topological contribution [32] which is associated with the possible subtraction constant in the dispersion relation for $g_1$ [3]. If finite it would mean that $\lim_{\epsilon \to 0} \int_1^\infty dx g_1$ will measure the difference of the singlet axial-charge and the subtraction constant contribution; that is, polarized deep inelastic scattering measures the combination $g_A^{(0)}|_{\text{pDIS}} = g_A^{(0)} - C_\infty$.

Possible explanations for the small value of $g_A^{(0)}|_{\text{pDIS}}$ extracted from the polarized deep inelastic experiments include screening from positive gluon polarization [30], negative strangeness polarization in the nucleon [33], a subtraction at infinity in the dispersion relation for $g_1$ [3] associated with non-perturbative gluon topology [32], and connections to axial U(1) dynamics [34, 35].

There is presently a vigorous programme to disentangle the different contributions. Key experiments involve semi-inclusive polarized deep inelastic scattering (COMPASS and HERMES) and polarized proton-proton collisions (PHENIX and STAR at RHIC).

One would like to understand the dynamics which suppresses the singlet axial-charge extracted from polarized deep inelastic scattering relative to the OZI prediction $g_A^{(0)} = g_A^{(8)} \sim 0.6$ and also the sum-rule for the longitudinal spin structure of the nucleon

$$\frac{1}{2} = \frac{1}{2} \sum_q \Delta q + \Delta g + L_q + L_g \tag{8}$$

where $L_q$ and $L_g$ denote the orbital angular momentum contributions. The theoretical basis for spin sum-rules for longitudinal and transversely polarized targets is discussed in [36, 37].

- **NLO QCD motivated fits to $g_1$**

The first attempts to extract information about gluon polarization in the polarized nucleon used next-to-leading order (NLO) QCD-motivated fits to inclusive $g_1$ data.
Figure 4: Polarized parton distribution functions from NLO pQCD (\(\overline{\text{MS}}\)) fits at \(Q^2 = 4\) GeV\(^2\) using SU(3) flavour assumptions [38].

Similar to the analysis that is carried out on unpolarized data, global NLO perturbative QCD analyses have been performed on the polarized structure function data sets. The aim is to extract the polarized quark and gluon parton distributions. These QCD fits are performed within a given factorization scheme, e.g. the “AB”, chiral invariant (CI) or JET and \(\overline{\text{MS}}\) schemes. New fits are now being produced taking into account all the available data including new data from polarized semi-inclusive deep inelastic scattering. Typical polarized distributions extracted from the fits are shown in Fig. 4. Given the uncertainties in the fits associated in part with the ansatz chosen for the shape of the spin-dependent quark and gluon distributions at a given input scale, values of \(\Delta g\) are extracted ranging between about zero and +2. A recent COMPASS fit to the world data using the \(\overline{\text{MS}}\) scheme was reported at this meeting. Preliminary values extracted for the polarized quark and gluon spin contributions are [14]

\[
\Delta \Sigma = 0.25 \pm 0.02(\text{stat.}) \pm ? , \quad \Delta g = 0.4 \pm 0.2(\text{stat.}) \pm ? \quad (9)
\]

respectively, where the additional error denoted “?” again reflects systematics and theoretical error in the set up of the QCD motivated fit.

To go further more direct measurements involving glue sensitive observables are needed to really extract the magnitude of \(\Delta g\) and the shape of \(\Delta g(x, Q^2)\)
including any possible nodes in the distribution function.

- **Gluon polarization**

There is a vigorous and ambitious global programme to measure $\Delta g$. Interesting channels include gluon mediated processes in semi-inclusive polarized deep inelastic scattering (COMPASS) and hard QCD processes in high energy polarized proton-proton collisions at RHIC.

COMPASS has been conceived to measure $\Delta g$ via the study of the photon-gluon fusion process, as shown in Fig. 5. The cross section for this process is directly related to the gluon density at the Born level. The experimental technique consists of the reconstruction of charmed mesons in the final state. COMPASS also use the same process with high $p_t$ particles instead of charm to access $\Delta g$ [39]. This leads to samples with larger statistics but these have larger background contributions from QCD Compton processes and fragmentation. High $p_t$ charged particle production has been used in earlier attempts by HERMES [40] and SMC [41] to access gluon polarization. These measurements together with preliminary results reported at this meeting [14] are listed in Table 1 for $x_g \sim 0.1$. An improvement of a factor of 2 in statistics is anticipated from the 2006 COMPASS run in most channels.

RHIC Spin [5] is achieving polarized proton-proton collisions at 200 GeV centre of mass energy and $\sim 60\%$ polarization. There was additionally a brief run at 62.4 GeV this year, during which the PHENIX experiment elected to take data with longitudinally polarized collisions. A first test run at 500 GeV centre of
mass is taking place in June 2006.

The available data thus far into the RHIC spin programme and the current PHENIX detector configuration have made the double-helicity asymmetry of neutral pions the best probe of the gluon polarization in PHENIX [42, 43, 44]. Charged pion asymmetries will complement current measurements, with a significant measurement expected by 2007. Direct photons provide a theoretically cleaner probe of $\Delta g$ and are directly sensitive to its sign but require higher luminosity running. The direct photon cross section has already been measured [45], with the first asymmetry measurement expected from the 2005 data and a definitive measurement at 200 GeV anticipated by 2009. Future detector upgrades will allow access to other probes sensitive to the gluon polarization, such as open charm and jets. In particular, a silicon vertex barrel detector is planned for 2009, and a forward calorimeter ($1 < |\eta| < 3$) is planned for 2011.

An important channel at STAR providing sensitivity to the gluon is jet pro-

Table 1: Polarized gluon measurements from deep inelastic experiments

| Experiment | process | $\langle x_g \rangle$ | $\Delta g/g$ |
|------------|---------|----------------------|-------------|
| HERMES     | high $p_t$ hadrons | 0.17 | $0.41 \pm 0.18 \pm 0.03$ |
| SMC        | high $p_t$ hadrons | 0.07 | $-0.20 \pm 0.28 \pm 0.10$ |
| COMPASS    | high $p_t$ hadrons, $Q^2 < 1$ | 0.085 | $0.016 \pm 0.058 \pm 0.55$ |
| COMPASS    | high $p_t$ hadrons, $Q^2 > 1$ | 0.13 | $0.06 \pm 0.31 \pm 0.06$ (prelim.) |
| COMPASS    | charm    | 0.15 | $-0.57 \pm 0.41$ (stat.) (prelim.) |
Figure 7: Preliminary PHENIX results on $A_{LL}^{\pi^0}$ together with the predictions from various QCD fits and (right) projections for the improvement in accuracy following the 2006 run [42, 44].

Figure 8: Preliminary STAR data on the longitudinal double spin inclusive jet asymmetry $A_{LL}$ for the years 2003-04 and (right) projections for the improvement in accuracy following the 2006 run [46, 47].
duction. The 2003-2004 STAR measurement of the double-helicity asymmetry in jet production [46, 47] is expected to be greatly improved by data from 2005 and 2006. Charged pion asymmetries will provide complementary sensitivity to gluon polarization; first results are expected from 2005 data and will be further improved with 2006 data. The mid-rapidity cross section for neutral pions at STAR was recently released and is in good agreement with NLO pQCD calculations. This represents an important stepping stone for future neutral pion and direct photon asymmetry measurements at STAR, probing $\Delta g$. Photon-jet correlations will provide information on the kinematics of the partonic scattering.

The published data from COMPASS [39], HERMES [40] and SMC [41] and the preliminary data from PHENIX (05 run) [42, 44] and STAR (03-04 runs) [46, 47] shown in this meeting appear in Figs. 6, 7 and 8, together with the expectations of different NLO fits to the inclusive $g_1$ data. Figures 7 and 8 also show projections for the considerable improvement in accuracy expected in the asymmetries following the successful 2006 run at RHIC [42, 46]. In Figs. 6-8 the curves “GRSV-min” (or “$\Delta g = 0$ input”), “GRSV-std”, “GRSV-max” (or “$\Delta g = g$ input”) and “$\Delta g = -g$ input” [48] correspond to a first moment of $\Delta g \sim 0.1, 0.4, 1.9$ and $-1.8$ respectively at $Q^2 \sim 1$ GeV$^2$ [49]. Here “input” refers to the “input scale” $\mu^2 = 0.4$ GeV$^2$ in the analysis of [48].

The COMPASS and RHIC Spin measurements suggest that polarized glue is, by itself, not sufficient to resolve the difference between the small value of $g_A^{(0)}|_{pDIS}$ and the constituent quark model prediction, $\sim 0.6$. The COMPASS data suggest that the gluon polarization is small or that it has a node in it around $x_g \sim 0.1$. The PHENIX and STAR data are consistent with modest gluon polarization. The considerable improvement in precision from the 2006 runs at COMPASS and RHIC should make it possible to resolve the different theoretical expectations. A combined NLO analysis of all the data would be valuable [50] and, so far, the COMPASS processes have been analysed only at leading order. Nevertheless, the tentative conclusion is that the gluon polarization may be small, $\ll 1$. It is interesting to note that light-cone models [51, 52] predict gluon polarizations $\Delta g \sim 0.5 - 0.6$ at 1 GeV$^2$. Further, the shape $\Delta g/g \sim x$ is expected on the basis of only QCD Counting Rules at large $x$ plus colour coherence at small $x$, with a value $\Delta g/g \sim 0.105$ at $x_g \sim 0.1$ [52] – consistent with present data from COMPASS, HERMES and SMC.

- **Sea polarization**

Semi-inclusive measurements of fast pions and kaons in the current fragmentation region with final state particle identification can be used to reconstruct the
individual up, down and strange quark contributions to the proton’s spin [53]. In contrast to inclusive polarized deep inelastic scattering where the $g_1$ structure function is deduced by detecting only the scattered lepton, the detected particles in the semi-inclusive experiments are high-energy (greater than 20% of the energy of the incident photon) charged pions and kaons in coincidence with the scattered lepton. For large energy fraction $z = E_h/E_\gamma \to 1$ the most probable occurrence is that the detected $\pi^\pm$ and $K^\pm$ contain the struck quark or antiquark in their valence Fock state. They therefore act as a tag of the flavour of the struck quark [53].

Figure 9 shows the latest results on the flavour separation from HERMES [54], which were obtained using a leading-order Monte-Carlo code based “purity” analysis. The polarizations of the up and down quarks are positive and negative respectively, while the sea polarization data are consistent with zero and not inconsistent with the negative sea polarization suggested by inclusive deep inelastic data within the measured $x$ range [48, 55]. However, there is also no evidence from this semi-inclusive analysis for a large negative strange quark polarization. For the region $0.023 < x < 0.3$ the extracted $\Delta s$ integrates to

![Figure 9: Recent HERMES results for the quark and antiquark polarizations extracted from semi-inclusive DIS. Left: (a) the flavour separation reported in [54]; Right: (b) the new preliminary results reported here [56] and in [57]. Here $\Delta Q(x) = \Delta u(x) + \Delta d(x)$.](image-url)
the value \( +0.03 \pm 0.03 \pm 0.01 \) which contrasts with the negative value for the polarized strangeness (Eq. 3) extracted from inclusive measurements of \( g_1 \). In a new analysis HERMES combine the inclusive deuteron asymmetry and semi-inclusive kaon asymmetries to make a new extraction of \( \Delta s \). The analysis uses just isospin invariance and the charge conjugation properties of the fragmentation functions. The preliminary results \([56, 57]\) are shown in Fig. 9b, and the extracted \( \Delta s \) is again consistent with zero. It will be interesting to see whether this effect persists in forthcoming semi-inclusive data from COMPASS.

For semi-inclusive hadron production experiments it is important to match the theory with the acceptance of the detector \([58]\). For example, the anomalous polarized gluon and low \( k_t \) sea contributions to \( g_A^{(0)} \) in Eq. (7) have different transverse momentum dependence. The luminosity and angular acceptance of the detector (150 mrad for HERMES) mean that these semi-inclusive measurements of \( \Delta s \) may be closer to \( \Delta s_{\text{partons}} \) in Eq. (7) than the inclusive value including the polarized gluon term.

Spin transfer reactions also have the potential to provide insight into QCD polarization phenomena. Measurements of polarized (anti-)\( \Lambda \) hyperon production are being studied at COMPASS, PHENIX and STAR as possible probes of strange quark polarization.

A direct and independent measurement of the strange quark axial-charge through neutrino-proton elastic scattering \([59, 60]\), as proposed for JPARC and FNAL, would be valuable. The axial charge measured in \( \nu p \) elastic scattering is independent of any assumptions about the presence or absence of a subtraction at infinity in the dispersion relation for \( g_1 \) and the \( x \sim 0 \) behaviour of \( g_1 \).

The W programme at RHIC will provide flavour-separated measurements of up and down quarks and antiquarks \([5]\). A 500 GeV commissioning run is planned for June 2006, and the high-energy programme is expected to start in earnest in 2009.

Future neutrino factories would be an ideal tool for polarized quark flavour decomposition studies. These would allow one to collect large data samples of charged current events, in the kinematic region \((x, Q^2)\) of present fixed target data \([61]\). A complete separation of all four flavours and anti-flavours would become possible, including \( \Delta s(x, Q^2) \).
4 Towards possible understanding

Suppose that small gluon and strangeness polarization persist in future data. Where will we be in our understanding of the (spin) structure of the proton and the small value of $g_A^{(0)}|_{p\text{DIS}}$? The two possibilities would be either a subtraction constant in the spin dispersion relation for $g_1$ or large SU(3) violation in the octet axial-charge extracted from hyperon $\beta$-decays. The assumption of good SU(3) is supported by the recent KTeV measurement [62] of the $\Xi^0 \beta$-decay $\Xi^0 \to \Sigma^+ e^- \bar{\nu}$ and by recent theoretical analysis [9, 63]. Further, a recent NLO analysis of inclusive and semi-inclusive polarized deep inelastic data which allows $g_A^{(8)}$ to float in a QCD-motivated fit reproduces the SU(3) value $g_A^{(8)} = 0.58$ up to 8% uncertainty [64].

The total proton spin sum-rule for the sum of all quark and gluon spin and orbital angular momentum contributions in Eq. (8) has to hold. Relativistic motion which tends to shift some of the valence quark total angular momentum from intrinsic spin to orbital angular momentum acts equally in the iso-singlet axial-charges $g_A^{(8)}$ and $g_A^{(0)}$ and cannot separate their values.

If there is a finite subtraction constant, polarized high-energy processes are not measuring the full singlet axial-charge: $g_A^{(0)}$ and the partonic contribution $g_A^{(0)}|_{p\text{DIS}}$ can be different. Since the topological subtraction constant term affects just the first moment of $g_1$ and not the higher moments it behaves like polarization at zero energy and zero momentum.

It is interesting to look for analogues in condensed matter physics. Is there a system where the total spin is not just the sum of the spin contributions of constituents carrying finite, non-zero, momentum? Consider Helium-3 and Helium-4 atoms. These have the same chemical structure and their properties at low temperatures are determined just by their spins – that is, the spin of the extra neutron in the nucleus of the Helium-4 atom. The proton spin problem addresses the question: Where does this spin come from at the quark level? In low temperature physics Helium-4 becomes a superfluid at 2K whereas Helium-3 remains as a normal liquid at these temperatures and becomes superfluid only at 2.6 mK with a much richer phase diagram. In the A-phase which forms at 21 bars pressure the spins of the Cooper pairs align and a polarized condensate is formed. The vacuum of the A-phase of superfluid Helium-3 behaves as an orbital ferromagnet and uniaxial liquid crystal with spontaneous magnetisation along the anisotropy axis $\hat{l}$ and as a spin antiferromagnet with magnetic anisotropy along a second axis $\hat{d}$ [65].

In low energy processes the nucleon behaves like a colour-neutral system of three massive constituent-quark quasi-particles interacting self consistently with a cloud of virtual Goldstone bosons (pions, ...) and condensates generated through dynamical chiral and axial U(1) symmetry breaking. Suppose that the singlet component of the zero momentum “condensate” in the proton is spin polarized relative to the vacuum
outside the proton with the polarization carried here by gluon topology [32]. In this case the total singlet axial-charge, as calculated in constituent quark models, would be the sum of the partonic (finite momentum) and “topological condensate” (zero momentum) contributions. The proton spin problem may be teaching us about dynamical symmetry breaking in QCD and the transition from current to constituent quarks.

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