Helicity dependent parton distributions

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The helicity dependent parton distributions describe the number density of partons with given longitudinal momentum $x$ and given polarization in a hadron polarized longitudinally with respect to its motion. After the discovery, more than 70 years ago, that the proton is not elementary, the observation of Bjorken scaling in the late 1960s lead to the idea of hadrons containing almost pointlike constituents, the partons. Since then, Deep Inelastic Scattering (DIS) has played a crucial role in our understanding of hadron structure. Through DIS experiments it has been possible to link the partons to the quarks, and to unveil the presence of other pointlike constituents, the gluons, which lead into a dynamical theory of quarks and gluons - quantum chromodynamics (QCD). Polarized DIS, i.e. the collision of a longitudinally polarized lepton beam on a polarized target (either longitudinally or transversely polarized), provides a complementary information regarding the structure of the nucleon. Whereas ordinary DIS probes simply the number density of partons with a fraction $x$ of the momentum of the parent hadron, polarized DIS can partly answer the question as to the number density of partons with given $x$ and given spin polarization in a hadron of definite polarization, either parallel or transverse with respect to the motion of the hadron. In here, the phenomenology associated with DIS off longitudinally polarized targets, and the present theoretical understanding of the dynamics involved, are described.
Understanding the spin structure of the proton is one of the most challenging problems in nowadays subatomic physics. The story of the proton spin dates back to the measurement, in 1933, of its anomalous magnetic moment, $\kappa_p \approx 1.79$ Bohr magnetons, revealing that the proton has an internal structure. We now understand the proton as a bound state of three confined valence quarks of spin $1/2$, interacting in a complicated manner through spin-1 colored gluons. How is the proton built up from its constituents, quarks and gluons, and how is its spin distributed among them, are the questions that polarized DIS experiments and their theoretical interpretation aim to answer. DIS has always played a crucial role in our understanding of the structure of hadrons. The observation of Bjorken scaling (Bjorken and Paschos, 1969 [1]) in the DIS experiments in the late 1960s (Breidenbach et al., 1969 [2]) lead to the idea that hadrons contain almost point like constituents, the partons. Later, through DIS experiments, it was possible to link the partons to the quarks, and to discover the existence of electrically neutral constituents, the gluons, which lead into a dynamical theory of quarks and gluons - quantum chromodynamics (QCD)(Fritzsch et al., 1973 [3]; see also H.D. Politzer, 1974 [4]). As a matter of facts, the study of the evolution with the momentum transfer of DIS observables represents probably the most direct test of the perturbative aspects of QCD.

Polarized DIS, involving the collision of a longitudinally polarized lepton beam on a polarized target (either longitudinally or transversely polarized) provides a complementary and important insight into the structure of the nucleon. Whereas ordinary DIS probes simply the number density of partons with a fraction $x$ of the momentum of the parent hadron, polarized DIS can partly answer the more sophisticated question as to the number density of partons with given $x$ and given helicity, in a hadron of definite polarization, either parallel or transverse to its motion. The polarized DIS cross section is described by two spin dependent structure functions, $g_1$ and $g_2$. The study of the longitudinal polarization structure function $g_1$ for a long time remained comfortably at the level of partons. In 1988, the proton data of the European Muon Collaboration (EMC)(Ashman et al., 1988 [5]), which differed significantly from naive theoretical predictions, were published. Those results were argued to imply that the sum of the spins carried by the quarks in a proton was consistent with zero, rather than with $1/2$, the non-relativistic quark model.
value, suggesting a spin crisis in the parton model. In the following, the phenomenology associated with DIS off longitudinally polarized targets, and the present theoretical understanding of the dynamics involved, are described. At the end, the interested reader will find an extended bibliography of up to date professional reviews, and a series of links to web pages, where he can satisfy his quest for knowledge and detail, and find the original references.

# 2 Polarized Parton Distributions

High-energy lepton scattering off the nucleon, i.e. the process $\ell N \rightarrow \ell' X$, illustrated in Fig.1, is called Deep ($-q^2 = Q^2 >> M^2$) Inelastic ($W^2 >> M^2$) Scattering (DIS). The filled circle in this figure represents the internal structure of the nucleon which can be expressed in terms of structure functions.

The cross-section for inclusive unpolarized scattering can be written

$$\frac{d^2\sigma}{dx\,dy} = \frac{4\pi\alpha^2}{x\,y\,Q^2} \left\{ xy^2 F_1(x, Q^2) + \left[ 1 - y - \frac{M^2 x^2 y^2}{Q^2} \right] F_2(x, Q^2) \right\},$$

where $F_1$ and $F_2$ are the so called unpolarized structure functions. The following notation has been used,

$$x \equiv \frac{Q^2}{2q \cdot P} = \frac{Q^2}{2M\nu}, \quad y \equiv \frac{P \cdot q}{P \cdot k} = \frac{\nu}{E}$$

where $\nu = E - E'$ is the energy of the virtual photon in the Laboratory frame and $x$ is
known as the Bjorken variable. The DIS regime occurs in the so called Bjorken limit:

\[-q^2 = Q^2 \to \infty \quad , \quad \nu = E - E' \to \infty \quad , \quad x \text{ fixed}. \quad (3)\]

The difference of the inclusive cross-sections for the lepton and the target nucleon polarized longitudinally, i.e. along or opposite to the direction of the lepton beam, is given by

\[
\frac{d^2\sigma \rightarrow \rightarrow}{dx \, dy} - \frac{d^2\sigma \rightarrow \rightarrow}{dx \, dy} = \frac{16\pi\alpha^2}{Q^2} \left[ \left( 1 - \frac{y}{2} - \frac{y^2 M^2 x^2}{Q^2} \right) g_1(x, Q^2) - \frac{2M^2 x^2 y}{Q^2} g_2(x, Q^2) \right] \quad (4)
\]

where the reversal of the nucleon’s spin direction is indicated by the double arrow. The functions \( g_1(x, Q^2) \) and \( g_2(x, Q^2) \) are called spin dependent structure functions. Another difference of cross sections, similar to Eq. (4), can be defined for transversely polarized nucleons, yielding a different combination of \( g_1(x, Q^2) \) and \( g_2(x, Q^2) \). In experiments with both longitudinal and transverse target polarization, both \( g_1 \) and \( g_2 \) can be therefore measured. In Eq. (4) it is anyway easily seen that the contribution of \( g_2(x, Q^2) \) is vanishing in the Bjorken limit, Eq. (3), and it is therefore difficult to measure it in actual DIS experiments. For this reason, only in recent years it has been possible to gather precise information on \( g_2(x, Q^2) \). In this presentation, only the longitudinal polarization structure function \( g_1(x, Q^2) \) will be discussed.

3 The parton model and QCD

The parton model was proposed by Feynman (Feynman, 1972 [6]), a few years before QCD, to explain Bjorken scaling, i.e., the fact that the structure functions in the Bjorken limit depend almost only on \( x \) and not on \( Q^2 \). The partons are pointlike constituents of the nucleon, which interact electromagnetically like leptons. The nucleon, in a frame where it is moving very fast, could be viewed as a “beam” of collinear partons. The partons are characterized as having momentum \( p = x' P \), where \( P \) is the momentum of the nucleon, and covariant spin vector \( s \). The interaction with the hard photon is then visualized as in Fig. 2, in which the lepton-parton scattering is treated analogously to elastic lepton-lepton scattering. \( S \) is the covariant spin vector of the nucleon. Requiring the final parton to be on mass shell, i.e. \( (p + q)^2 = 0 \), selects the value \( x' = x \). Thus \( x \) can be interpreted as the fraction of longitudinal momentum of the target carried by the struck parton. The partons were shown to have the quantum numbers of the current quarks, which were found to carry only a part of the nucleon momentum. The missing part was ascribed to a neutral vector particle, the gluon, which only carries color degrees of freedom, and therefore does not couple to leptons.

For unpolarized DIS, one finds the scaling result expressed in terms of the number density of quarks, \( q(x) \), and antiquarks, \( \bar{q}(x) \)

\[
F_1(x) = \frac{1}{2} \sum_j e_j^2 \left[ q_j(x) + \bar{q}_j(x) \right], \quad (5)
\]
where the sum is over flavors $j$, $e_j$ is the charge of the quarks, and the Callan-Gross relation

$$F_2(x) = 2xF_1(x),$$

implies that the charged partons are spin $1/2$ particles.

For longitudinally polarized DIS one obtains

$$g_1(x) = \frac{1}{2}\sum_j e_j^2 [\Delta q_j(x) + \Delta \bar{q}_j(x)],$$

where

$$\Delta q(x) = q_\to(x) - q_\from(x),$$

are the longitudinal polarization functions, or helicity dependent parton distributions, with $q_{\to(\from)}(x)$ representing the number densities of quarks whose spin orientation is parallel (antiparallel) to the longitudinal spin direction of the proton (see Fig. 3). In terms of these, the unpolarized parton density is

$$q(x) = q_\to(x) + q_\from(x).$$

The parton model is an intuitive description, much like the impulse approximation in nuclear physics, and it appeared long before QCD. Once QCD is accepted as the theory of strong interactions, with quark and gluon as the fundamental fields, there are interaction
dependent modifications of the simple parton model results for DIS. The main impact of the QCD interactions is: i) to introduce calculable logarithmic $Q^2$ dependence in the parton densities; ii) to generate a contribution of the gluons to the structure functions, and, in particular to $g_1$, arising from the polarization of the gluons in the nucleon.

Unfortunately, these correction terms are infinite. The infinity is caused by collinear divergences which occur because of the masslessness of the quarks and which are removed through a mechanism called factorization of collinear divergences. This mechanism allows the reaction to be written as a product of a hard and a soft part (see Fig. 4), and the infinity is absorbed in the latter, which cannot be calculated in QCD. For this part either models of hadrons or parametrizations of data are used. After an elaborate calculation, $g_1$ is found to depend also on $Q^2$:

$$g_1(x, Q^2) = \frac{1}{2} \sum_{\text{flavors}} e_q^2 \left\{ \Delta q(x, Q^2) + \Delta \bar{q}(x, Q^2) \\
+ \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \{ \Delta C_q(x/y) [\Delta q(y, Q^2) + \Delta \bar{q}(y, Q^2)] \\
+ \Delta C_G(x/y) \Delta G(y, Q^2) \} \right\}$$

(10)

where $\alpha_s(Q^2)$ is the QCD running coupling constant, while $\Delta C_G$ and $\Delta C_q$ are the so called Wilson coefficients, which can be evaluated in pQCD. One can notice that the first line in the above equation represents the result obtained in QCD at leading order, while the remaining part is given by the higher-order contributions. Both the helicity dependent parton distributions and the Wilson coefficients depend on the factorization and renormalization schemes used.
4 The proton spin problem

Let us return to the parton model and write the expression of \( g_1 \), for protons \((p)\) and neutrons \((n)\), respectively, in terms of linear combinations of the helicity dependent parton distributions associated with the quark flavors \( u, d, s \):

\[
g_1^{p(n)}(x) = \frac{1}{9} \left[ \pm \frac{3}{4} \Delta q_3(x) + \frac{1}{4} \Delta q_8(x) + \Delta \Sigma(x) \right] \quad (11)
\]

where

\[
\Delta q_3 = (\Delta u + \Delta \bar{u}) - (\Delta d + \Delta \bar{d}) \quad (12)
\]

\[
\Delta q_8 = (\Delta u + \Delta \bar{u}) + (\Delta d + \Delta \bar{d}) - 2(\Delta s + \Delta \bar{s}) \quad (13)
\]

\[
\Delta \Sigma = (\Delta u + \Delta \bar{u}) + (\Delta d + \Delta \bar{d}) + (\Delta s + \Delta \bar{s}) \quad (14)
\]

These quark densities transform respectively as the third component of an isotopic spin triplet, the eighth component of an SU(3)\(_F\) octet, and a flavor singlet.

Taking the first moment of Eq. (11) yields

\[
\Gamma_1^{p(n)} \equiv \int_0^1 g_1(x)dx = \frac{1}{9} \left[ \pm \frac{3}{4} g_3^A + \frac{1}{4} g_8^A + g_0^A \right] \quad (15)
\]

where

\[
g_3^A = \int_0^1 dx \Delta q_3(x) ,
\]

\[
g_8^A = \int_0^1 dx \Delta q_8(x) ,
\]

\[
g_0^A = \int_0^1 dx \Delta \Sigma(x) .
\]

(16)

The octet of currents associated to the distributions Eqs. (12)–(14) is precisely the one that controls the weak decays of the neutron and of the octet hyperons, which implies that the values of \( g_3^A \) and \( g_8^A \) are known from \( \beta \)-decay measurements:

\[
g_3^A \equiv g_A = 1.2670 \pm 0.0035 , \quad g_8^A = 0.585 \pm 0.025 \quad (17)
\]

Hence, according to Eq. (15), a measurement of \( \Gamma_1 \) can be considered as giving the value of the flavor singlet \( g_0^A \).

In the parton model, two remarkable sum rules can be obtained. The Bjorken sum rule (Bjorken, 1970 [7]), initially derived using only the parton model and isospin invariance (see Eq. (15)), reads, to leading order in QCD:

\[
\int_0^1 dx \left[ g_3^p(x, Q^2) - g_1^p(x, Q^2) \right] = \frac{g_A}{6} . \quad (18)
\]
QCD corrections to this result have been calculated up to third order in the coupling constant (Larin et al., 1997 [8]) leading to

\[
\int_0^1 dx \left[ g_1^p(x, Q^2) - g_1^n(x, Q^2) \right] = \frac{g_A}{6} \left\{ 1 - \frac{\alpha_S}{\pi} - 3.583 \left( \frac{\alpha_S}{\pi} \right)^2 - 20.215 \left( \frac{\alpha_S}{\pi} \right)^3 \right\},
\]

a result which has been confirmed experimentally.

Besides, in the parton model

\[
g_A^0 = g_A^8 + 3(\Delta s + \Delta \bar{s}),
\]

and, if one neglects the contribution from the strange quarks in Eq. (20), i.e., from $\Delta s + \Delta \bar{s}$, the Ellis and Jaffe sum rule (Ellis and Jaffe, 1974 [9]) is obtained:

\[
g_A^0 \simeq g_A^8 \simeq 0.6 .
\]

In 1987, the EMC Collaboration performed a measurement of $g_1^p$ and $\Gamma_1^p$ and, using the known values of $g_A^3$ and $g_A^8$ in Eq. (15), obtained

\[
g_A^0 \simeq 0,
\]

a value in contradiction with the Ellis-Jaffe sum rule. This experimental result has other dramatic implications. Consider the physical significance of $\Delta \Sigma(x)$. Since $q_{\to (+)}(x)$ count the number of quarks of momentum fraction $x$ with spin component $\pm \frac{1}{2}$ along the direction of motion of the proton (say the $z$-direction), the total contribution to $J_z$ coming from the spin of a given flavor quark is

\[
\langle S_z \rangle = \int_0^1 dx \left\{ \left( \frac{1}{2} \right) q_{\to}(x) + \left( -\frac{1}{2} \right) q_{\leftarrow}(x) \right\}
\]

\[
= \frac{1}{2} \int_0^1 dx \, \Delta q(x).
\]

It follows that

\[
g_A^0 = 2\langle S_z^{\text{quarks}} \rangle,
\]

where $\langle S_z^{\text{quarks}} \rangle$ is the contribution to $J_z$ from the spin of all quarks and antiquarks. The connection between $g_A^0$ and $\langle S_z^{\text{quarks}} \rangle$, and the possible implications of the result $\langle S_z^{\text{quarks}} \rangle$ smaller than 1/2, were discussed in a paper by Sehgal [10].

In a non-relativistic constituent model one would naively expect all of the proton spin to be carried by the spin of its quarks. In a relativistic model one expects $2\langle S_z^{\text{quarks}} \rangle \approx 0.6$, due to the loss of normalization of the upper components, in agreement with the Ellis-Jaffe sum rule but far from the EMC result for $g_A^0$. This contradiction was labeled as the proton “spin crisis”, and it was the beginning of an impressive experimental and theoretical activity, which is still going on. From the theoretical side, a careful reanalysis both of non relativistic and relativistic models has lead to results in closer agreement to the EMC value, as we will show. Another argument has been the observation that,
even in the Bjorken limit, the gluonic version of the anomalous triangle diagram leads to
the first moment of $g_1$ (Altarelli and Ross, 1988 [11]):

$$\Gamma_1^{\text{gluons}}(Q^2) = -\frac{1}{3} \frac{\alpha_s(Q^2)}{2\pi} \Delta G(Q^2).$$

(25)

This result is of fundamental importance since it implies that the simple parton model
formula for $g_0^A$ is incomplete. Instead, one has that the quantity measured by the EMC
collaboration is

$$\tilde{g}_0^A = g_0^A - 3 \frac{\alpha_s}{2\pi} \Delta G,$$

(26)

allowing for the EJ sum rule to be fulfilled for a large enough value of $\Delta G$. However,
this result depends on the factorization scheme utilized. In schemes where $g_0^A$ has the
meaning of a spin, the small measured $\tilde{g}_0^A$ does not necessarily imply that the physically
meaningful $g_0^A$ is small. This observation was initially presented as a possible resolution of
the spin crisis, but it is now clear that it is not sufficient. As a matter of fact, to explain
the measured value of $g_0^A$, it should be $\Delta G \approx 1.7$, while the observed values are much too
small ($|\Delta G| \approx 0.29$) to resolve the spin crisis, and different analyses give even different
signs. A way out of this problem is to consider that the partons possess orbital angular
momentum.

From the experimental side, after the publication of the EMC data, an impressive
program started in several laboratories to extend the kinematical range of the EMC
experiment, to reduce the systematic errors in the measurement of $\Gamma_1^p$, and to get the
neutron information, necessary to test the fundamental Bjorken Sum Rule, Eq. (18). In
this way, it was possible to realize if the spin crisis could be ascribed to a problem of the
parton model and, in turn, of the underlying theory, QCD. The neutron measurement is
really difficult due to the lack of pure neutron targets, so that nuclear targets have to be
used and nuclear structure effects have to be carefully taken into account. Despite of these
difficulties, a reasonable amount of precise data is nowadays available for the neutron, as
it will be seen in the following.

5 Models of hadron structure

In this section, it will be shown that properly built models can help in clarifying the origin
of the so-called spin crisis. QCD is a theory of quarks (antiquarks) and gluons, as has been
shown in the asymptotic regime, where the interaction can be treated perturbatively. At
low energies, the idea that baryons are made up of three constituent quarks and mesons of
a constituent quark-antiquark pair, the naive quark model scenario, accounts for a large
number of experimental facts. The quest for a relation between the "current" quarks of
the theory and the constituent quarks of the model has an old history and this search
has been the leitmotiv of a considerable research effort. The fundamental problem one
would like to understand is how confinement, i.e. the apparent absence of color charges
and dynamics in hadron physics, is realized.
Detailed quark models of hadron structure based on the constituent quark concept have been defined in order to explain low energy properties. In order to reach the high energies of the DIS regime, the central assumption is the existence of a scale, $\mu^2_0$, where the short range (perturbative) part of the interaction is negligible, and therefore the glue and sea are suppressed, and the long range (confining) part of the interaction produces a proton composed of three (valence) quarks only. One then ascribes the quark model calculations of matrix elements to that hadronic scale $\mu^2_0$. For larger $Q^2$ their Wilson coefficients will give the evolution as dictated by pQCD. In this way quark models, summarizing a great deal of hadronic properties, may substitute "ad hoc" low-energy parameterizations. The procedure describes successfully the gross features of the DIS results.

In order to produce a more quantitative description of the data, different mechanisms have been proposed: sea gluons, sea quarks and antiquarks, meson clouds, relativistic effects, etc... Some of these mechanisms appear naturally if one endows the constituent quarks with structure. In this scenario, the constituent quarks are themselves complex objects whose structure functions are described by a set of functions $\Phi_{ab}$ that specify the number of point-like partons of type $b$, which are present in the constituents of type $a$ with fraction $x$ of its total momentum. In general $a$ and $b$ specify all the relevant quantum numbers of the partons, i.e., color, flavor and spin (see Altarelli et al., 1974 [13], where this scenario has been firstly addressed. See also Hwa, 1980 [14]).

Results are shown in Figs. 5 and 6. Fig. 5 refers to the unpolarized case. The structure function $F_2(x, Q^2)$, calculated evolving the parton distributions obtained at low energy $u_o$ and $d_o$ within a semirelativistic model, describes successfully the data. Moreover, the agreement becomes impressive when compared with the analogous calculation with non-composite constituents. A qualitatively similar agreement is obtained also in the polarized case, as it is shown in Figs. 6 and 7. It should be noticed that in this framework the spin...
Figure 6: Left (Right): $xg_1(x, Q^2)$ for the proton (neutron) evolved at NLO to $Q^2 = 10 (5)$ GeV$^2$, for two different convolution models (full curves). The proton (neutron) data are from the EMC and SMC collaborations (from the E154 colaboration at SLAC). See Ref [15] for details.

...crisis, as initially presented, does not arise: the constituent quarks, the effective degrees of freedom of the model, can carry most of the proton spin, even if the measured $g_A^0$, a current quark DIS observable, is small. In this scenario, there is no need of large orbital angular momentum contributions to explain the data, once the proper structure of the constituent quarks has been taken into account.

In general, the non relativistic constituent quark models describe the nucleon by S-wave functions, or with small D-wave admixtures, once the hyperfine interaction is taken into account. Relativistic constituent quark models have a non-zero quark orbital angular momentum from the beginning and reduce the valence quark spin contributions to the nucleon spin from 1 to about 0.6. However, to reach the scale of the data, perturbative QCD evolution has to be used and the contribution of quarks and gluons to the orbital angular momentum may be of different size, and relevant at the experimental scale. However, the perturbatively generated gluon orbital angular momentum is cancelled by the gluon helicity contribution, as it can be shown by general arguments.

6 Experimental determination of the longitudinal polarization functions

A vast amount of data on the inclusive spin structure function $g_1(x, Q^2)$ has been accumulated by lepton scattering experiments at SLAC, CERN, DESY and Jefferson Lab (see Fig. 7).

Inclusive data from proton, neutron, deuteron and perturbative QCD analysis are used to extract the contributions from quark, antiquark and gluon densities with a precision that depends very strongly on that of the data. One approach to gather additional
Figure 7: World data on the polarized structure function $xg_1(x)$ for the proton, deuteron and neutron in the DIS region ($W > 2$ GeV), taken by different experiments, at several different values of $Q^2$, as compiled in Ref. [16].

Information has been to use semi-inclusive lepton scattering (SIDIS), where, in addition to the scattered lepton, one detects a leading hadron (typically a pion or kaon) in the final state. This approach was pioneered by the SMC collaboration and the most detailed data set stems from the HERMES and COMPASS collaborations (see Fig. 8). However, with SIDIS alone it is difficult to extract the sea and glue polarization. An alternate route has been employed in the polarized proton collision program at BNL, using the Relativistic Heavy Ion Collider (RHIC). One selects final state signatures like hadrons, jets or even direct photons with large transverse momentum that indicate an underlying hard interaction between two constituents from the two colliding protons. Recent analyses take into account all the data from inclusive, semi-inclusive polarized deep inelastic scattering and polarized pp scattering at RHIC, and perform all theoretical calculations at next-to-leading order of perturbative QCD to maximally constrain the extracted distributions (De Florian et al., [17]), opening the door to obtaining a better and more reliable picture of the spin structure of the nucleon.
Figure 8: World data on helicity dependent parton distributions $\Delta q(x)$ extracted from semi-inclusive DIS data, as compiled in Ref. [16].

7 Summary

After 30 years of dedicated experiments, a rather detailed picture of the nucleon spin structure is arising. It appears that quark helicities do contribute a significant fraction of the (longitudinal) spin of the nucleon. Most importantly, the fundamental Bjorken sum rule and its pQCD evolution are consistent with the data. None of the existing experiments show any features that would contradict perturbative QCD in its realm of applicability.

Most pQCD-based analyses of the data agree fairly well on the contribution of various quark flavors to the proton spin, although there is still some controversy on the role played by strange sea quarks. We also do not know yet whether polarized up and down antiquark densities show the same difference as the unpolarized ones. The emergent picture is one where valence quarks ($\Delta q_V \equiv \Delta q - \Delta \bar{q}$) carry roughly the expected fraction ($\approx 60\%$) of the nucleon spin, while the (on average) negative helicity of sea quarks reduces this to about 30-35 at Jefferson Lab will extend our knowledge of polarized quark densities out to $x > 0.8$ and will decisively test predictions from pQCD and QCD-inspired models.
Additional information on individual quark and antiquark flavor contributions to the nucleon spin will come from future experiments at RHIC (in particular from direct $W^\pm$ production at 500 GeV center-of-mass energy) and the new FAIR facility in Darmstadt, Germany as well as semi-inclusive measurements with COMPASS and at Jefferson Lab.

In addition to logarithmic violations of scaling, expected from pQCD, the data show some evidence for the so called higher twist contributions, i.e., non-scaling contributions to the structure function $g_1$, at intermediate $Q^2$ values. Future measurements at Jefferson Lab will improve our knowledge of higher-twist matrix elements, and of the second spin structure function, $g_2$, and its moments.

At the lower end of the $Q^2$ scale, at the real photon point, the Gerasimov-Drell-Hearn (GDH) sum rule (Gerasimov, 1966 [18]; Drell and Hearn, 1966 [19]) has been well confirmed. The transition from this point to DIS, through the region of intermediate $Q^2$, is under investigation, in particular at JLab.

One of the most important remaining open questions is where is the nucleon spin that is not carried by quark helicities. We do not know the precise magnitude and shape of the gluon contribution, and it could still be an important fraction of the total. Improved statistics from the direct measurements at RHIC and COMPASS will help dramatically.

The contribution from quark angular momentum is also an important ingredient in the total spin balance of the nucleon. While a direct measurement is not available, one can learn much about the transverse distribution and motion of quarks from semi-inclusive measurements of single spin asymmetries. This is a fairly new field, related to the transversity observable, with a very rich potential and a rapidly growing body of experimental data, but lies outside the scope of this article.

Another way to describe the nucleon spin is the study of Generalized Parton Distributions (GPDs), in particular Deeply Virtual Compton Scattering (DVCS). Moments of certain combinations of GPDs can be related to the total angular momentum (spin and orbital) carried by various quark flavors, as expressed in Ji’s sum rule (Ji, 1997 [20]). Data taken at Jefferson Lab are being analyzed and future experiments at COMPASS will clarify the situation enormously.

In summary, the description of the nucleon spin keeps being a fundamental problem of hadron structure (see Refs. [21, 22, 23, 24, 25, 26, 27] and the links in Ref [28] for further reading). An extensive and rich experimental program has been undertaken at existing facilities like CERN (COMPASS), RHIC and Jefferson Lab and much theoretical effort is being devoted to a full understanding of the nucleon spin structure.

References

[1] J.D. Bjorken and E.A. Paschos, “Inelastic Electron-Proton and γ-proton Scattering and the Structure of the Nucleon”, Phys. Rev. 185 1975, 1969.

[2] M. Breidenbach, J.I. Friedman, H.W. Kendall, (MIT, LNS), E.D. Bloom, D.H. Coward, H.C. DeStaebler, J. Drees, L.W. Mo, R.E. Taylor, “Observed Behavior of Highly Inelastic electron-Proton Scattering”, Phys. Rev. Lett. 23 935, 1969.
[3] H. Fritzsch, M. Gell-Mann and H. Leutwyler, “Advantages of the Color Octet Gluon Picture”, Phys. Lett. B47 365, 1973.

[4] H.D. Politzer, “Asymptotic freedom: an approach to strong interactions”, Phys. Rep. 14 129, 1974.

[5] J. Ashman, et al., [European Muon Collaboration], “A Measurement of the Spin Asymmetry and Determination of the Structure Function g(1) in Deep Inelastic Muon-Proton Scattering”, Phys. Lett. B206 364, 1988.

[6] R.P. Feynman, “Photon Hadron Interactions” (Benjamin, New York, 1972).

[7] J. D. Bjorken, “Asymptotic Sum Rules At Infinite Momentum”, Phys. Rev. 179:1547, 1969.

[8] S.A. Larin, T. van Rittenberg and J.A.M. Vermasseren, “The Alfa-s**3 approximation of quantum chromodynamics to the Ellis-Jaffe sum rule”, Phys. Lett B404 153, 1997.

[9] J.R. Ellis, R.L. Jaffe, “A Sum Rule for Deep Inelastic Electroproduction from Polarized Protons”, Phys. Rev. D9 1444, 1974.

[10] L. M. Sehgal, “Angular Momentum Composition of the Proton in the Quark Parton Model,” Phys. Rev. D10, 1663, 1974.

[11] G. Altarelli, G.G. Ross, “The Anomalous Gluon Contribution to Polarized Leptoproduction”, Phys. Lett. B212 391, 1988.

[12] S. Scopetta, V. Vento and M. Traini, “Towards a unified picture of constituent and current quarks”, Phys. Lett. B421 64, 1998.

[13] G. Altarelli, N. Cabibbo, L. Maiani, R. Petronzio, “The nucleon as a bound state of three quarks and deep inelastic phenomena”, Nucl. Phys. B69 531, 1974.

[14] R.C. Hwa, “Evidence for valence-quark clusters in nucleon structure functions”, Phys. Rev. D22 759, 1980.

[15] S. Scopetta, V. Vento and M. Traini, “Polarized structure functions in a constituent quark scenario”, Phys. Lett. B442 28, 1998.

[16] C. Amsler et al., Particle Data Group, Phys. Lett. B667 1, 2008.

[17] D. de Florian, R. Sassot, M. Stratmann and W. Vogelsang, “Global Analysis of Helicity Parton Densities and Their Uncertainties”, Phys. Rev. Lett. 101 072001, 2008.

[18] S.B. Gerasimov, “A Sum rule for magnetic moments and the damping of the nucleon magnetic moment in nuclei”, Sov. J. Nucl. Phys. 2 430, 1966.
[19] S. D. Drell, A. C. Hearn, “Exact Sum Rule for Nucleon Magnetic Moments”, Phys. Rev. Lett. 16 908, 1966.

[20] X. D. Ji, “Gauge invariant decomposition of nucleon spin”, Phys. Rev. Lett. 78 610, 1997.

[21] M. Anselmino, A. Efremov, E. Leader, “The theory and phenomenology of polarized deep inelastic scattering”, Physics Reports 261 1, 1995.

[22] B. Lampe, E. Reya, “Spin physics and polarized structure functions”, Physics Reports 332 1, 2000.

[23] B.W. Filippone and X. Ji, “The spin structure of the nucleon”, Advances in Nuclear Physics 26 1, 2001.

[24] S.D. Bass, “The spin structure of the proton”, Reviews of Modern Physics 77 1257, 2005.

[25] B. Foster, A.D. Martin, M.G. Vincter, “Review of structure functions”, Review of Particle Properties 2009, chapter 16.

[26] S.E. Kuhn, J.-P. Chen, E. Leader, “Spin structure of the nucleon – status and recent results”, Progress in Particle and Nuclear Physics 63 1, 2009.

[27] F. Myhrer and A.W. Thomas, “Understanding the proton’s spin structure”, Journal of Physics G. Nuclear and Particle Physics 37 023101, 2010.

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