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QCD Spin Physics: Theoretical Overview

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Abstract

We give an overview of some of the current activities and results in QCD spin physics. We focus on the helicity structure of the nucleon, where we highlight the results of a recent first global analysis of the helicity parton distributions, and on single-transverse spin asymmetries.

Key words: Nucleon spin structure, QCD, Parton distributions
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1. Introduction

For many years now, spin has played a very prominent role in QCD. The field of QCD spin physics has been driven by the hugely successful experimental program of polarized deeply-inelastic lepton-nucleon scattering, and by a simultaneous tremendous progress in theory. A new milestone has now been reached with the advent of RHIC, the first polarized proton-proton collider. In the present article, we briefly describe some important recent theoretical achievements. The paper has two parts. The first one discusses the helicity structure of the nucleon. Here we mostly focus on current efforts to determine the polarized parton, in particular gluon, distributions of the nucleon. In the second part, we address another topic on which major theoretical breakthroughs have been made in recent years: single-transverse spin asymmetries.

2. Nucleon helicity structure

The helicity structure of the nucleon is foremost described by its twist-two helicity parton distribution functions,

$$\Delta f(x, Q^2) \equiv f^+(x, Q^2) - f^-(x, Q^2) \qquad (f = u, d, s, \bar{u}, \bar{d}, \bar{s}, g) \ , \tag{1}$$

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f^+ (f^-) denoting the number density of partons with same (opposite) helicity as the nucleon's, as a function of momentum fraction x and scale Q. QCD predicts the Q^2-dependence of the densities through the spin-dependent evolution equations [1]:

$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta q\\ \Delta g\end{pmatrix}(x,Q^2)=\begin{pmatrix}\Delta P_{qq}(\alpha_s,x) & \Delta P_{qg}(\alpha_s,x)\\ \Delta P_{gq}(\alpha_s,x) & \Delta P_{gg}(\alpha_s,x)\end{pmatrix}\otimes\begin{pmatrix}\Delta q\\ \Delta g\end{pmatrix}(x,Q^2)\ , \tag{2}$$

where $\otimes$ denotes a convolution, and the ΔP_{ij} are known as "splitting functions" [1–4] and are evaluated in QCD perturbation theory.

The partons in the nucleon have to provide the nucleon spin. One can derive a "proton spin sum rule" [5]:

$$\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta G(Q^2)+L_q(Q^2)+L_g(Q^2)\ , \tag{3}$$

where

$$\Delta\Sigma\equiv\int_0^1\left(\Delta u+\Delta\bar{u}+\Delta d+\Delta\bar{d}+\Delta s+\Delta\bar{s}\right)(x,Q^2)dx\equiv\Delta\Sigma_u+\Delta\Sigma_d+\Delta\Sigma_s \tag{4}$$

is the quark and anti-quark spin contribution, $\Delta G(Q^2)=\int_0^1\Delta g(x,Q^2)dx$ is the gluon spin contribution, and the $L_{q,g}$ correspond to orbital angular momenta of quarks and gluons. Unlike $\Delta\Sigma$, ΔG and $L_{q,g}$ depend on the resolution scale Q^2 already at lowest order in evolution. Two decades have passed since the European Muon Collaboration (EMC) at CERN discovered that the spins of the quarks and anti-quarks in the proton provide only an unexpectedly small fraction, today known to be about 25%, of the proton's spin [6]. This finding, which became famously known as the "proton spin crisis", implies that the spins of the gluons or orbital angular momenta [7] of the partons must contribute significantly to the proton spin, or both. To determine how the proton spin is carried by the proton's constituents' spins and orbital angular momenta, remains the central goal of the field.

The helicity parton distributions may be probed in spin asymmetries for reactions at large momentum transfer. The probes used so far are inclusive and semi-inclusive deep-inelastic lepton scattering (DIS and SIDIS, respectively), and *pp* scattering at large transverse momentum. Polarized DIS and SIDIS experiments have been carried out at SLAC, CERN, DESY and the Jefferson Laboratory [8] and mostly constrain the quark and anti-quark helicity distributions. RHIC at BNL [8–10] is the first polarized proton-proton collider. The measurement of gluon polarization in the proton is a major focus and strength of RHIC [11].

The basic theoretical concept that underlies much of spin physics is the factorization theorem. It states that large momentum-transfer reactions may be factorized into long-distance pieces that contain the desired information on the spin structure of the nucleon in terms of its *universal* parton densities, and parts that are short-distance and describe the hard interactions of the partons. The latter can be evaluated using perturbative QCD.

Independent information on the nucleon's helicity distributions may be obtained by using SU(2) and SU(3) flavor symmetries. The flavor non-singlet combinations turn out to be proportional to the nucleon matrix elements of the quark non-singlet axial currents,

$\langle P,S\,|\,\bar{q}\,\gamma^\mu\,\gamma^5\,\lambda_i\,q\,|\,P,S\rangle$. Such currents typically occur in weak interactions, and one may relate the matrix elements to the β-decay parameters F,D of the baryon octet. One finds

$$\begin{aligned}
&\Delta\Sigma_u - \Delta\Sigma_d = F + D = 1.267, \\
&\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s = 3F - D \approx 0.58\ .
\end{aligned} \tag{5}$$

If valid, the second relation when combined with Eq. (4) gives that $\Delta\Sigma = 0.58+3\Delta\Sigma_s$, so that a small quark spin contribution to the proton spin implies a large negative strange quark contribution.

Recently, a first *global* next-to-leading order QCD analysis of presently available spin asymmetry data from DIS, SIDIS, and *pp* scattering at RHIC has been presented [12]. The best determined distributions are– not unexpectedly– $\Delta u+\Delta\bar{u}$ and $\Delta d+\Delta\bar{d}$, which are primarily determined by the large body of DIS data and agree well with the distributions obtained in previous analyses [13–18] which typically considered only the lepton scattering data. We also note that the integrals $\Delta\Sigma_u$ and $\Delta\Sigma_d$ are in good agreement with determinations on the lattice (albeit without disconnected diagrams) [19], which may shed light on the validity of assumed extrapolations of the parton distribution functions to small x, outside the presently measured regime. We note that measurements of polarized DIS at smaller x, as well as at presently available x, but higher Q^2, will be vital for arriving at a definitive understanding of the polarized quark distributions, and of $\Delta\Sigma$ in particular. It is hoped that these will be achieved at a future polarized electron-proton collider [20].

The results of [12] for the sea and gluon distributions are shown in Fig. 1, along with estimates of their uncertainties. The shaded bands in Fig.1 show which distributions are allowed if one permits an increase of $\Delta\chi^2 = 1$ (green) or $\Delta\chi^2/\chi^2 = 2\%$ (yellow). We note that future improvements of the analysis will include a more detailed account of the experimental errors and theoretical uncertainties. As can be seen from Fig. 1, the global analysis yields very interesting results. For the first time, a strong constraint on $\Delta g(x)$ is found, thanks in large part to the RHIC data. The gluon distribution turns out to be small in the region of momentum fraction x accessible at RHIC, quite possibly having a node. At $Q^2 = 10$ GeV^2, the integral over the mostly probed x-region is found to be almost zero, $\int_{0.05}^{0.2} dx\Delta g(x) = 0.006 \pm 0.06$, while extrapolation over all x results in the gluon spin contribution $\Delta G = -0.084$. We stress, however, that this result is not yet reliable due to the large uncertainty in extrapolation. In any case, there are presently no indications of a sizable contribution of gluon spins to the proton spin. This is in line with recent theoretical expectations obtained within an effective low-energy theory of broken scale invariance of QCD [21]. We also note that a way to access Δg in lepton-nucleon scattering is to measure final states that select the photon-gluon fusion process, heavy-flavor production and $\ell p \to h^+h^-X$, where the two hadrons have large transverse momentum [8]. However, unlike at RHIC, the success of the perturbative-QCD hard-scattering description has not been established for this observable in the kinematic regime of interest here, which is why these data sets have not yet been included in the analysis [12].

The sea anti-quark distributions turn out to be better constrained now than in previous analyses, thanks to the advent of more precise SIDIS data and of a new set of fragmentation functions [22] that describes the observables well in the unpolarized case. We find that the sea appears to be far from SU(3)-flavor symmetric: the $\Delta\bar{u}$ distribution

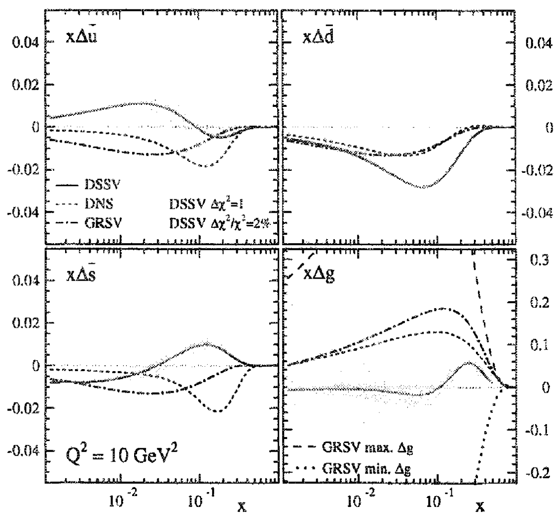

Fig. 1. Polarized sea and gluon densities of [12] compared to those in previous fits [13,17]. The shaded bands correspond to alternative fits with $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$.

is mainly positive, while the $\Delta\bar{d}$ anti-quarks carry opposite polarization. This pattern has been predicted at least qualitatively by a number of models [13,23]. Already based on the Pauli principle one would expect that if valence-u quarks primarily spin along the proton spin direction, $u\bar{u}$ pairs in the sea will tend to have the u quark polarized opposite to the proton. Hence, if such pairs are in a spin singlet, one expects $\Delta\bar{u} > 0$ and, by the same reasoning, $\Delta\bar{d} < 0$. We note that the uncertainties in SIDIS are still quite large, and it is in particular difficult to quantify the systematic uncertainty of the results related to the fragmentation mechanism at the relatively modest energies available. Complementary and clean information on $\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}$ will come from RHIC [9,10], where one will exploit the parity-violating couplings of produced W bosons to left-handed quarks and right-handed anti-quarks. Comparisons of such data taken at much higher scales with those from SIDIS will be extremely interesting.

The strange sea quark density shows a sign change, which is due to a certain tension between the inclusive DIS data combined with the F, D baryon β-decay parameters, which demand a negative integral of Δs (see above), and the semi-inclusive DIS data, which prefer a positive Δs at medium x. As a consequence, Δs obtains its negative integral purely from the contribution from low-x. Interestingly, there are initial lattice determinations of the integral $\Delta\Sigma_s$ [24], which point to small values. It will clearly be important to better understand the strange contribution to nucleon spin structure. We stress that this is not a topic of interest just for nucleon spin structure enthusiasts: as was pointed out recently [25], the uncertainty in $\Delta\Sigma_s$ provides the single largest uncertainty in predictions of the spin-dependent elastic scattering cross sections of supersymmetric dark matter particles on protons and neutrons.

3. Single-transverse-spin asymmetries in QCD

Studies of single-transverse spin asymmetries A_N have a long history, starting from the 1970s and 1980s when large "left-right" asymmetries were observed in hadronic reactions like $p^{\uparrow}p \to \pi X$ at forward angles of the produced pion [26]. Measurements at RHIC [27,28] have shown over the past few years that large asymmetries in forward single-inclusive hadron production also persist to very high energies. It was known early on [29] that in single-inclusive processes, A_N is suppressed by an inverse power of the pion's transverse momentum, so that simple parton-model estimates would predict nearly vanishing asymmetries. The large size of the observed asymmetries therefore posed a challenge for theorists. Two mechanisms have been proposed [30–32]. The first is formulated in terms of the collinear factorization approach and twist-three transverse-spin-dependent quark-gluon correlation functions of the proton [31,32]. The other relies on the use of transverse-momentum dependent parton distributions for the transversely polarized proton. For these distributions, known as "Sivers" functions [30], the parton transverse momentum is assumed to be correlated with the proton spin vector, so that spin asymmetries naturally arise from the directional preference expressed by that correlation. The Sivers functions extend the set of "ordinary" Feynman parton distributions which only depend on a parton's light-cone momentum fraction. While the precise role of the Sivers functions for hadronic hard processes and their factorization remained yet to be understood, it was clear that the functions would contain valuable information about the nucleon, because the correlations they represent would be closely related to orbital angular momenta of partons in the proton.

Significant theoretical progress on single-spin asymmetries and the Sivers functions has been made in recent years. A breakthrough was the realization [33–35] that there is a class of single-spin observables in QCD that are not suppressed by an inverse power of the hard scale. These asymmetries are characterized by a large momentum scale Q (for example, the virtuality of the photon in DIS) and by a much smaller, and also measured, transverse momentum $q_{\perp}$. This allows a direct probe of the partons' transverse momenta in the nucleon. For some observables, rigorous QCD factorization theorems have been established [36,37] which relate the spin-dependent cross sections to parton distribution functions not integrated over the transverse momenta of the partons, among them the Sivers functions. This opened the door to clean experimental access to the Sivers functions. The "leading-twist" Sivers single-spin asymmetries emerging in this way have been studied experimentally over the past few years in DIS [8], and there are now quite solid indications that the Sivers effect indeed exists.

The theoretical studies have revealed an even more striking property of the Sivers functions [33,38–40]. Let us give a simple QED example that captures the essential physics [41]. In Fig. 2(a) we consider a "toy" DIS process. A transversely polarized charge-less "hadron", consisting of particles with electric charges $+1$ and -1, is probed by a highly virtual photon. In order not to be forced to vanish by time-reversal invariance, a single-spin asymmetry for the process requires the presence of an interaction phase. Such a phase may be generated by a rescattering of the struck "parton" in the field of the "hadron remnant", by exchange of a photon as shown in the figure. The amplitude with the additional exchanged photon interferes with that without the photon. More precisely, two different phases appear, the S and P-wave Coulomb phases. The difference

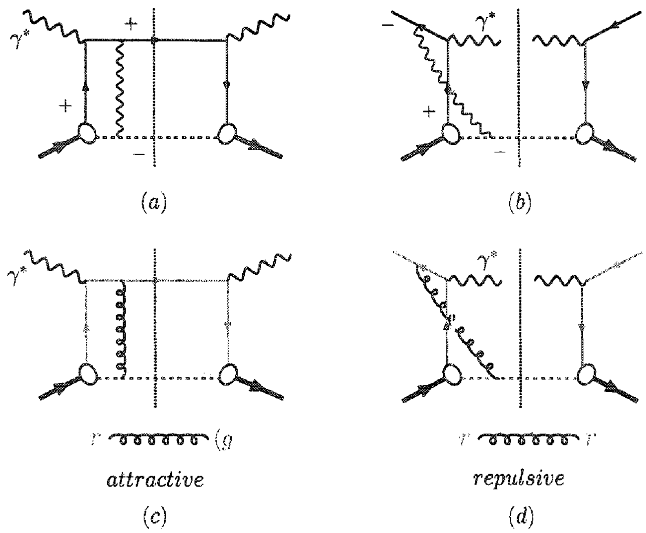

Fig. 2. *(a),(b) Simple QED example for process-dependence of the Sivers functions in DIS and the Drell-Yan process. (c),(d) Same for QCD.*

of these phases is infrared-finite and generates the single-spin asymmetry [33]. As the electric charges of the two interacting particles are opposite, this final-state interaction is *attractive.*

Now consider a similar model for the Drell-Yan process in Fig. 2(b). "Partons" of opposite charge annihilate to produce a highly virtual photon. The interaction generating the phase in this case is "initial-state" and is between the remnant of the transversely polarized "hadron" and the initial parton from the other, unpolarized, "hadron". These necessarily have identical charges, and the interaction is *repulsive.* As a result, the spin-effect in this case needs to be of opposite sign as that in DIS.

These simple models are readily generalized to true hadronic scattering in QCD, see Figs. 2(c,d). This is the essence of the – by now widely quoted – result that the Sivers functions contributing to DIS and to the Drell-Yan process have opposite sign [33,38–40]:

$$f^{\text{Sivers}}(x,k_\perp)\Big|_{\text{DY}} = -f^{\text{Sivers}}(x,k_\perp)\Big|_{\text{DIS}} \,. \tag{6}$$

In the full gauge theory, the phases generated by the additional (final-state or initial-state) interactions can be summed to all orders into a "gauge-link", which is a path-ordered exponential of the gluon field and makes the Sivers functions gauge-invariant. The non-universality of the Sivers functions is then reflected in a process-dependence of the space-time direction of the gauge-link. The crucial role played by the gauge link has given rise to intuitive model interpretations of single-spin asymmetries in terms of spatial deformations of parton distributions in a transversely polarized nucleon [42], and also to approximate relations between the Sivers functions and generalized parton distributions [43].

The process-dependence of the Sivers functions can also be tested in more complicated QCD hard-scattering. An example is the single-spin asymmetry in di-jet angular correlations [44,45], to which to lowest order all $2 \to 2$ QCD partonic processes contribute. Tremendous progress has been made recently in our understanding of the gauge links for such more general QCD observables [46]. The more involved color structure of the hard-scattering functions has profound consequences on the gauge links. As a result, the Sivers functions for this reaction differ from those in DIS by more than just a sign. In fact, universality is lost completely: the u-quark distribution in, say, the process $ud \to ud$ will differ from that in $ug \to ug$. This feature may have profound ramifications whenever transverse-momentum dependent parton distributions are relevant in hard-scattering reactions.

Single-spin observables continue to puzzle theorists. At RHIC, the STAR collaboration has recently presented data for the p_T-dependence of A_N in single-inclusive pion production [27]. Thanks to the higher-twist nature, one expects the asymmetry to fall off as $1/p_T$, a behavior that however is not at all seen in the data. Conversely, as we mentioned above, studies in lepton scattering [8] have shown single-spin asymmetries that are predicted to be leading-twist, implying that they would survive when Q^2 is increased. In its recent measurements on a proton target at higher Q^2, however, COMPASS does not see any significant asymmetry [47]. Even though the uncertainties are still large, this came as a surprise to most. Clearly, we still have a lot to learn about the origins of single-spin asymmetries in QCD.

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