A short review is given of QCD spin physics and its major aims: obtaining the polarized gluon density, the transversity distribution and understanding single spin asymmetries. The importance of the Drell-Yan process, the role of electron-positron colliders and the use of polarization to probe other, not spin specific physics are emphasized.

1 Polarized structure functions and parton densities

The polarized structure functions $g_1$ and $g_2$ of Deep Inelastic Scattering (DIS) of polarized electrons off polarized protons (or other spin-1/2 hadrons), i.e. $\vec{e}\vec{p} \rightarrow e'X$, appear in the parametrization of the hadronic part of the cross section, given by the hadron tensor

$$W_A^{\mu\nu} = \frac{i e^{\mu\nu\rho\sigma} q_\rho}{P \cdot q} \left[ S_\sigma g_1(x_B, Q^2) + \left( S_\sigma - \frac{S \cdot q}{P \cdot q} P_\sigma \right) g_2(x_B, Q^2) \right],$$

with hadron momentum $P$ and spin vector $S$, photon momentum $q$, $x_B = Q^2/2P \cdot q$ and $Q^2 = -q^2$. The definition of structure functions is independent of the constituents of the hadron. The pQCD improved parton model allows one to go to the quark-gluon level, such that the polarized structure functions are expressed in terms of parton distribution functions. This exemplifies the goal of QCD spin physics, namely to understand the spin structure of hadrons in terms of quarks and gluons. For the longitudinal spin or helicity the (leading twist) parton distributions are $\Delta q$, $\Delta \bar{q}$, $\Delta g$ and for transverse spin $\delta q$, $\delta \bar{q}$ ($\delta g = 0$ due to helicity conservation).

One sub-goal is to complete the spin sum rule. The sum of the contributions to the proton spin have to add up to 1/2:

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + L_z \quad \left( = \frac{1}{2} \Delta \Sigma + L_q + J_g \right),$$

where $\Delta \Sigma = \Delta u + \Delta d + \Delta s$ is the total contribution of the spin of the quarks, $\Delta g$ that of the gluons and $L_z$ is the orbital angular momentum of the quarks and the gluons together ($L_q$ stands for the orbital angular momentum of the quarks alone and $J_g$ for the total angular momentum of the gluons). A still open problem is whether $L_z = L_q + L_g$? (or equivalently, $J_g = \Delta g + L_g$?)

Here one requires that the individual quantities should be separately measurable and defined in a gauge invariant, process independent way, cf. Ref. [1] and references therein.

Only lightcone momentum fraction ($x$) integrated information enters in the sum rule: $\Delta q = \int_0^1 dx \left[ (q_+ - q_-) + (\bar{q}_+ - \bar{q}_-) \right]$ and $\Delta g = \int_0^1 dx \left[ g_+ - g_- \right]$ (where $\pm$ stands for the helicity of the proton). Experiments find that $\Delta \Sigma \sim 0.3$ and $\Delta s \sim -0.1$. Such statements ought to be
accompanied by the renormalization scheme and scale at which these numbers hold, but here we only want to mention that such small numbers for $\Delta \Sigma$ and such relatively large values of $\Delta s$ were completely unexpected and viewed as a ‘spin crisis’ or ‘spin puzzle’. In the near future the $\Delta g$ piece of the puzzle will be determined experimentally and then the relative importance of the orbital angular momentum is determined implicitly.

But of course one is not only interested in the decomposition of $1/2$. One also wants an accurate description of $\Delta g(x), \Delta \bar{g}(x), \delta q(x)$ as they appear in processes like DIS, Drell-Yan, etc., namely as function of $x$. In other words, one wants to obtain a complete map of the spin structure of the proton (as function of $x$ and $Q^2$). At leading twist this entails: knowing $\Delta q(x)$ and $\delta q(x)$ for all quark flavors and knowing $\Delta g(x)$.

From inclusive DIS, to be specific, from the structure function $g_1(x)$, one can only get $\Delta q(x) + \Delta \bar{q}(x)$ information and $\Delta g(x)$ only implicitly via evolution, using

$$g_1^{p/n} = \left( \frac{1}{9} \Delta \Sigma + \frac{1}{12} \Delta g_{3}^{\text{NS}} + \frac{1}{36} \Delta q_{8}^{\text{NS}} \right) \otimes \left( 1 + \frac{\alpha_s}{2\pi} \Delta C_q \right) + \sum_q e_q^2 \frac{\alpha_s}{2\pi} \Delta g \otimes \Delta C_g, \quad (3)$$

hence other processes are needed. At RHIC (BNL) polarized $pp$ collisions will be performed, in order to measure $\Delta g(x)$ and $\Delta \bar{g}(x)$ in a variety of ways (for $\delta q(x)$ see below). For $\Delta g(x)$ one can study $\vec{p} \vec{p} \to \gamma X$; jet $X$; jet jet; jet jet; $\pi^0 X$; $c\bar{c} X$; $b\bar{b} X$; $\ldots$. For $\Delta q(x), \Delta \bar{q}(x)$ one can study $\vec{p}p \to W^\pm X$. In addition, there will be more (semi-)inclusive DIS data from COMPASS (CERN), HERMES (DESY) and JLAB.

The structure function $g_2$ has also been measured (E155 Collaboration at SLAC\(^2\)), albeit with much less precision than $g_1$. The combination $g_1 + g_2 = g_T$ contains information about quark-gluon correlations inside the proton’s transverse spin. This is a higher twist effect and $g_T$ is not related to the leading twist, transverse spin (i.e. helicity flip) parton density $\delta q$.

### 2 Transversity

Transversity ($\delta q$) is completely unknown (no data). It cannot be measured in inclusive DIS (heavily suppressed). The reason is that it must be probed together with another helicity flip. There are two main routes to follow. The first is to use two transversely polarized hadrons, e.g. study $p^\uparrow p^\uparrow \to \ell \ell X$, $p^\uparrow p^\uparrow \to$ jet $X$, $e p^\uparrow \to \Lambda^\uparrow X$ or $p p^\uparrow \to \Lambda^\uparrow X$. The second route is to use the distribution of final state hadrons, which may be correlated with the transverse spin direction. For example, one can measure the transverse momentum of a final state hadron compared to the jet direction. The so-called “Collins effect”\(^3\) may correlate this transverse momentum with the transverse spin and may produce single spin asymmetries in $e p^\uparrow \to e' X$ and $p p^\uparrow \to \pi X$. Or one can measure the angular distribution of hadron pairs, where their orientation may be correlated with the transverse spin, described by the so-called two-hadron interference fragmentation functions\(^{16,17}\) and leading to asymmetries in $e p^\uparrow$ or $p p^\uparrow \to (\pi^+ \pi^-) X$.

Several of these options contain unknown fragmentation functions that have to be determined separately. For this purpose one can use off-resonance data of $B$-factories\(^8\) such as BELLE or BABAR. This would also be useful for the study of the spin structure of hyperons.

### 3 Spin asymmetries in hadron and lepton pair production

As said, the direction of produced hadrons may be correlated with the polarization of one or more particles in the collision. This is demonstrated by the large single spin asymmetries that have been observed in $p p^\uparrow \to \pi X$\(^{9,10,11}\). It is a so-called left-right asymmetry, since the pions prefer to go left or right of the plane spanned by the beam direction and the transverse spin, depending on whether the transverse spin is up or down and depending on the charge of the pions. Similar types of asymmetry have been observed in $p p \to \Lambda^\uparrow X$\(^{12}\) and $\nu_{\mu} p \to \mu \Lambda^\uparrow X$\(^{13}\).
It is expected that the underlying mechanisms of these different asymmetries are related, but it is also fair to say that single transverse spin asymmetries are not really understood, i.e. it is not clear how to explain them on the quark-gluon level. The suggested mechanisms can be roughly categorized as: semi-classical models; $k_T$-dependent distributions; higher twist.

One particularly informative observable is the single transverse spin asymmetry $A_N$ in Drell-Yan $p p \rightarrow \ell \ell X$, since mechanisms that depend solely on fragmentation effects do not contribute. To indicate that an experiment with a (few) percent accuracy can be extremely useful to narrow down the possible origins of single spin asymmetries, three predictions are summarized, each based on a fit to the same E704 $\pi$ asymmetry data $^9$ (no quantitative comparisons of the predictions are possible however, due to the different kinematics chosen).

- A semi-classical model calculation $^{14}$ predicts for positive $x_F$ an asymmetry that starts out at $+15\%$ at $x_F = 0$ and grows quickly to $+40\%$ for large $x_F$. This is for an invariant mass $Q$ of the lepton pair of 4 GeV and the asymmetry is slightly larger for $Q = 9$ GeV (both at $\sqrt{s} = 20$ GeV). The asymmetry is still appreciable in size for small, negative $x_F$. The transverse momentum of the lepton pair was partly integrated over.

- A recent calculation $^{15}$ using the $k_T$-dependent Sivers effect distribution function $^{16}$ predicts (at $\sqrt{s} = 200$ GeV) an asymmetry that is negligible for $x_F < 0.1$ and then grows in magnitude to become minus $10$-$30\%$ for $6 < Q < 10$ GeV and $10 < Q < 20$ GeV, respectively, $|y| < 2$, and at a particular fixed $q_T$ of the lepton pair that maximizes the asymmetry. The study nicely shows that $k_T$ dependence does not imply $1/Q$ suppression.

- A higher twist prediction $^{17}$ using the Qiu-Sterman mechanism $^{18}$ yields $|A_N^{DY}| \sim 70$ MeV/$Q$, e.g. $2\%$ at $Q = 4$ GeV ($q_T$ integrated). The power law decrease with $Q$ is a distinctive feature of higher twist. The predicted asymmetry is approximately $x_F$ independent.

4 Azimuthal spin asymmetries

Apart from the left-right asymmetries, azimuthal spin asymmetries have been observed. In semi-inclusive DIS ($e p \rightarrow e' \pi X$) the HERMES Collaboration $^{19}$ has measured a nonzero $\sin \phi$ asymmetry in $e \bar{p}$ scattering ($A_{UL}$). It is a $2\%$ asymmetry for $\pi^+$. Soon there will also be data from HERMES on $e p^\uparrow$ scattering ($A_{UT}$). The CLAS Collaboration (Jefferson Lab) has also observed $^{20}$ a nonzero $\sin \phi$, but in $\bar{e} p$ scattering ($A_{LU}$). These DIS data are at low $Q^2$ ($\langle Q^2 \rangle \sim 1 - 3$ GeV$^2$), so the interpretation of the asymmetries is far from clear. But they do demonstrate nontrivial spin effects, possibly related to the asymmetries of the $p p$ experiments.

5 Spin as a tool

An advantage of polarization is that Standard Model contributions (or at least QCD contributions) may be filtered out. One can for instance study parity violation in polarized $p p$ scattering. Asymmetries in the processes $\bar{p} p \rightarrow \text{jet } (A_L^{\text{jet}})$ and $\bar{p} p \rightarrow \text{jet } X (A_{LL}^{\text{PV}}, \tilde{A}_{LL}^{\text{PV}})$ defined as:

$$A_L^{\text{jet}} = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}, \quad A_{LL}^{\text{PV}} = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}, \quad \tilde{A}_{LL}^{\text{PV}} = \frac{\sigma_- - \sigma_-}{\sigma_- + \sigma_-},$$

are measures of parity violation. Similarly for CP violation: since the quark coupling to the $W$ has fixed helicity, certain transverse spin (helicity flip) asymmetries should be absent. For example, in $p p^\uparrow \rightarrow W X$, which may be relevant for RHIC (upgrade) or a polarized LHC.

Another example where spin can be used as a tool to study other, not spin specific physics is in the study of small $x$ effects. Polarization may offer new probes of gluon saturation. Asymmetries involving polarization dependent ($k_T$-odd) functions can be sensitive to the saturation scale $Q_s$. Recently, this was investigated theoretically for $p A \rightarrow A^\uparrow X ^{21}$.
6 Conclusions

Much experimental and theoretical work has been done on QCD spin physics over the last decades, but due to the complicated nature of QCD the understanding of the spin of the proton is not yet complete (let alone that of the neutron, Λ, ρ, etc). Accurate determinations of polarized parton distribution and fragmentation functions as function of \(x\) and \(Q^2\) are still in progress. Experimental efforts to measure new spin observables are under way at several laboratories (BNL, CERN, DESY, JLAB, SLAC, ...).

Striking single spin asymmetries have been observed (left-right asymmetries and \(\sin \phi\) azimuthal asymmetries), but are still not understood (pQCD and collinear factorization are insufficient). Especially the single transverse spin asymmetry \(A_{D}^{T}N\) in Drell-Yan offers a good opportunity to learn about the underlying mechanism(s).

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