Summary of the Working Group on Spin Physics

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Abstract

A summary is given of the experimental and theoretical results presented in the working group on spin physics. New data on inclusive and semi-inclusive deep-inelastic scattering, combined with theoretical studies of the polarized distribution functions of nucleons, were presented. Many talks addressed the relatively new subjects of transversity distributions and generalized parton distributions. These distributions can be studied by measuring single spin asymmetries, while partonic intrinsic motion and models of new spin dependent distribution and fragmentation functions are needed to obtain the corresponding theoretical description. These subjects are not only studied in deep-inelastic lepton scattering, but also in polarized proton-proton collisions at RHIC. A selection of results that have been obtained in these experiments together with several associated theoretical ideas are presented in this paper. In conclusion, a brief sketch is given of the prospects for experimental and theoretical studies of the spin structure of the nucleon in the coming years.

1 Introduction

Experimental studies of the spin structure of the proton and the theoretical interpretation of the obtained results, are mostly aimed at identifying the various carriers of angular momentum inside the proton, and measuring their individual contributions to its total spin. In the past most studies were based on inclusive spin-dependent deep-inelastic lepton scattering experiments, which showed, in the QCD parton model interpretation, that the spin of the quarks can only account for about 30% of the spin of the nucleon [1]. In recent years many more probes of the spin structure of the nucleon have become available: semi-inclusive deep-inelastic scattering to study the polarization of individual quark flavors, photon-gluon fusion...
to measure the gluon polarization, exclusive processes giving (indirectly) access to possible orbital angular momentum contributions, and single spin asymmetries to investigate the transverse spin distribution. This rich variety of possible probes of the nucleon spin is reflected by the many experiments underway or in preparation that (will) provide experimental data on this subject. At this workshop data from HERMES at DESY, COMPASS at CERN, Hall A and B at JLab, and STAR and PHENIX at RHIC were presented, thus illustrating the expansion of the field.

A parallel effort has been made on the theoretical side. Starting a long time ago from the unexpected data of Ref. [1] (the so-called 'proton spin crisis'), our understanding of the spin structure of the nucleon has by now greatly improved, stressing the role of quark and gluon polarization, intrinsic partonic motion and orbital angular momentum. New generalized QCD analyses of structure functions and spin effects involving parton transverse motion, and (among others) quark-gluon correlations have been proposed, which open the way to a new interpretation of existing data and suggestions for new measurements of spin observables. More in particular, the increased experimental efforts to study the spin structure of the nucleon partly follow two such theoretical developments:

• The (re-)introduction of generalized parton distributions (GPDs) for the description of partonic correlations provides a unified framework for the description of a wide range of different experiments. By taking the first moment of a combination of certain GPDs, for example, information can be obtained on the total angular momentum $J_q$ of the quarks in the nucleon [2]. By comparing measured values of $J_q$ to the total spin carried by quarks $\Delta \Sigma_q$, information might be obtained on the orbital motion of quarks in the nucleon.

• It is predicted by both the chiral-soliton (instanton) model [3] and lattice gauge calculations [4] that the tensor charge of the nucleon ($\delta \Sigma_q$), which can be derived from the transversity distribution function $h_1(x)$ of the nucleon, is considerably larger than the longitudinal quark spin contribution $\Delta \Sigma_q$, which is derived from data on the longitudinal spin-dependent structure function $g_1(x)$. The difference between $\delta \Sigma_q$ and $\Delta \Sigma_q$ is caused by the absence of gluon-splitting contributions in the transverse case, which is also expected to result in a relatively weak $Q^2$ dependence of $h_1(x)$. Unfortunately, inclusive deep-inelastic scattering cannot be used to measure $h_1(x)$ as it is a chirally odd quantity. In semi-inclusive DIS information on $h_1(x)$ can be obtained if a process is identified that is governed by a chirally odd fragmentation function [5].

At the workshop many talks were devoted to first results and/or new plans to measure either the generalized parton distributions or the transversity distribution.

Given all these developments the presentations submitted to the working group on spin physics were split in the following categories:

1. Inclusive spin structure & QCD analyses
2. Semi-inclusive DIS & spin-flavor decompositions
3. Gluon polarization & charm production
4. Exclusive reactions & generalized parton distributions
5. Transversity & (single) spin asymmetries

The same five categories are used in the next section, where the experimental and theoretical results presented in the working group are summarized. In the final section of the paper some perspectives for spin physics are sketched.

2 New experimental and theoretical results

In the following five subsections the most important results presented at the workshop are summarized. It is noted that unavoidable personal biases are introduced whenever a rich collection of new results has to be summarised. For a full collection of subjects and results discussed at the workshop the reader is referred to the individual contributions appearing elsewhere in these proceedings. To avoid unnecessary duplication, the figures representing the various new results are not reproduced in the subsections below.

2.1 Inclusive spin structure & QCD analyses

Following last years release of very precise $g_1^Q(x)$ data by the HERMES Collaboration, this year the collaboration presented QCD fits of all available $g_1^Q(x)$ data. Using two different techniques, fairly precise (and consistent) singlet and non-singlet parton distributions were obtained. It has also been possible to extract values for the polarized gluon distribution $x\Delta G(x)$ with relatively large margins of uncertainty. The resulting first moment $\Delta G$ of the polarized gluon distribution is still largely uncertain, ranging from about $+0.1$ to $+1.0$, but most likely positive.

Exploiting the high luminosity available at JLab, the Hall-A collaboration presented new high-$x$ data obtained in inclusive polarized electron scattering from a polarized $^3$He target. The resulting values for $A_1^n(x)$ cover the $x$-domain from $0.3$ to $0.6$ and have superior precision as compared to existing data. If such data are extended to even higher $x$-values in the future it will be possible to determine the limiting value of $A_1^n(x)$ at $x \rightarrow 1$ for which widely different predictions exist.

In the deuteron the quarks can be polarized even if the deuteron itself is unpolarized. Such a non-zero quark polarization can be caused by nuclear interaction effects, and needs to be accounted for when the spin-dependent structure function of the neutron $g_1^p(x)$ is extracted from polarized deep-inelastic scattering data on the deuteron. The effect of a possibly small quark polarization in an unpolarized deuteron target can be studied by measuring the tensor structure function $b_1^T(x)$,
which can be determined from deep-inelastic scattering experiments if a tensor polarized deuterium target is used. Such measurements were carried out for the first time by the HERMES Collaboration at DESY [8]. The data presented show that \( b_1^d(x) \) is small, being consistent with zero for \( x > 0.1 \) and slightly positive at lower values of \( x \).

From the theoretical point of view the agreement between the QCD predictions on the evolution of the polarized structure function \( g_1^p(x, Q^2) \) and the data is very good; however, the amount of available data and the explored kinematical regions, if compared with the analogous information on the unpolarized distribution functions, is still rather poor. The Bjorken sum rule on the difference between the first moment of \( g_1^p(x, Q^2) \) and \( g_1^n(x, Q^2) \) is well obeyed, while the few data on \( g_2(x, Q^2) \) do not yet allow a definite conclusion about the validity of the Burkhardt-Cottingham sum rule, although indicating its possible violation [9].

Some theoretical issues are still open concerning heavy quark and higher twist contributions, the small-\( x \) behavior, radiative corrections and modeling of polarized distribution functions. New results were presented on the twist-2 heavy quark contribution to \( g_2(x, Q^2) \) within a covariant parton model, obeying the Wandura-Wilczek and Burkhardt-Cottingham relations [10]. A model independent determination of higher-twist contributions to \( g_1(x, Q^2) \) was presented by Alexander Sidorov [11], and another study of higher-twist effects, within an infrared-renormalon model, by Andrei Kataev [12]. The small-\( x \) behaviour of the singlet \( g_1 \) function, taking into account effects due to the running of the strong coupling constant \( \alpha_s \), was obtained by Boris Ermolaev [13]. Radiative corrections were discussed by Eduard Kuraev [14] and statistical modeling of polarized distributions by Jacques Soffer [15]. Finally, the importance of the Bloom-Gilman duality when discussing inclusive polarized parton distributions was discussed by Alessandra Fantoni [16].

### 2.2 Semi-inclusive DIS & spin-flavor decompositions

In semi-inclusive deep-inelastic scattering from polarized targets a (possibly identified) hadron is observed in coincidence with the scattered lepton. The hadron serves to tag the flavour of the quark struck in the scattering process. Assuming that the fragmentation process is sufficiently well known the observed double spin asymmetries for several identified hadron species can be converted to helicity distributions for individual quark flavours. The results of such an analysis were presented by Marc Beckmann [17] with supporting information provided by Achim Hillenbrand [18] on the treatment of the fragmentation process. The data, which were derived from asymmetries measured at HERMES, demonstrated that each of the helicity densities for \( \bar{u}, \bar{d} \) and \( s \) sea quarks are consistent with zero. Also the helicity difference distribution \( \Delta \bar{u} - \Delta \bar{d} \) was shown to be consistent with zero, which is remarkable as existing calculations [19, 20] suggest a positive value for this distribution.

In the nearby future more data on flavor-separated helicity distributions can be expected from Hall-A (at high \( x \) and using some - sofar relatively strong - simplifying
assumptions \cite{2} and COMPASS \cite{21}. It is of interest to note that the polarized $p - p$ collisions at RHIC will provide a completely independent measure of the flavour-separated quark helicity distributions using the parity violating $W^+$ and $W^-$ production channels. Simulated data for the PHENIX experiment at RHIC indicate that a high statistical precision can be obtained for the spin-dependent distributions $\Delta u$, $\Delta d$, $\Delta \bar{u}$ and $\Delta \bar{d}$ \cite{22}.

2.3 Gluon polarization & charm production

Gluons are expected to play an important role in explaining the spin structure of the nucleon. At present, only a single measurement exists on the gluon polarization in the proton \cite{23}, but this measurement suffers from large statistical and systematic uncertainties. Hence, new dedicated experiments are needed to measure the gluon polarization $\Delta G$ much more precisely. At the workshop three such experiments were discussed:

- The COMPASS Collaboration \cite{21} intends to measure $\Delta G$ by identifying photon-gluon fusion processes in deep-inelastic muon scattering through charm production or the observation of high $p_T$-pairs. The COMPASS experiment was successfully commissioned in 2002, and first longitudinally polarized data have been collected, but no results on $\Delta G$ are yet available.

- The RHIC-Spin Collaboration \cite{22} will measure double spin asymmetries in polarized $p - p$ collisions. Very precise values of $\Delta G$ can be obtained if it is possible to identify prompt photons in the photon-gluon Compton process. No data have been collected yet, but it is very encouraging that it has been demonstrated to be possible to inject, ramp and maintain a polarized proton beam in RHIC.

- The SLAC E161 Collaboration \cite{24} has prepared a proposal to measure $\Delta G$ by identifying photon-gluon fusion events through open charm production. At present it is unclear when the experiment will run.

2.4 Exclusive reactions & generalized parton distributions

While a precise experimental knowledge of the Generalized Parton Distributions (GPDs) would give essentialy complete information on the structure of the nucleons, the usual inclusive structure functions and elastic form factors only provide limited information as they represent limiting cases of the GPDs. This argument explains the importance of the GPD framework, as was discussed in the introductory talk on this subject by Maxim Polyakov \cite{25}.

Access to the Generalized Parton Distributions (GPDs) is obtained by identifying exclusive reactions in high-energy lepton-induced experiments. By making
use of a variety of polarization states, targets and final-state hadrons the experiments are sensitive to different combinations of GPDs [26]. Hence, many different observables need to be extracted from the experimental data in order to be able to map the GPDs. The HERMES Collaboration [27] made a start with this effort by determining various asymmetries from their data. In the channel corresponding to exclusive photon production (or Deeply Virtual Compton Scattering) beam-spin asymmetries, beam-charge asymmetries, and target-spin asymmetries were shown. In each case non-zero asymmetries were reported, but the statistical precision in the various kinematical distributions is still rather modest. Single target-spin asymmetries were also shown for exclusive $\rho^0$ and $\pi^+$ production data [28]. Also in this case the observed asymmetries are small and the statistical precision is still limited. On the other hand, the successful determination of each of these asymmetries on the basis of the relatively low-luminosity HERMES data, implies that it is in principle possible to measure the various GPDs if in due time dedicated higher-luminosity experiments become available.

### 2.5 Transversity & (single) spin asymmetries

The transversity distribution is the only leading-twist quark distribution for which no experimental data are available. It is a chirally odd quantity and cannot be accessed in fully inclusive DIS, where it cannot be combined with a suitable chiral-odd partner to yield an observable cross section. On the other hand, it can couple, in semi-inclusive DIS or in high-energy proton-proton collisions, to other chiral-odd functions, giving rise to interesting and unexpected single spin effects [29].

One way of obtaining information on the transversity distribution $h_1(x)$ is by measuring single target-spin asymmetries in semi-inclusive deep inelastic scattering on transversely polarized targets. Such measurements have been started both at COMPASS [30] and HERMES [31], but analysis results are not yet available. In the absence of transverse polarization data, existing longitudinally polarized data have been used to determine the single-target spin asymmetry $A_{UL}$; because of the on average non-zero lepton scattering angle the measured asymmetry can originate from a small ($\approx 15\%$) transverse spin component. At the workshop the HERMES data on $A_{UL}$ for both the proton and the deuteron were presented [32]. The measured asymmetries are well reproduced by two independent calculations that include rough estimates for $h_1(x)$ and the chiral-odd (Collins) fragmentation function $H_\perp^1$ [33, 34]. These calculations only include the Collins effect, i.e. the process sensitive to $h_1(x)$, but ignore possible contributions from the Sivers effect, i.e. the process involving the $k_\perp$-dependent structure function $f_{1T}$ in combination with the usual chiral-even fragmentation function. Transversely polarized data are needed to separate these two effects. Their relative importance has been discussed by Anatoli Efremov [35]. A general discussion on azimuthal asymmetries in semi-inclusive DIS, including model estimates of the Collins function, was presented by Karo Oganessyan [36].
A combination of the Collins and Sivers effect is also expected to be responsible for the transverse single-spin asymmetries (SSAs) observed in pion production by the E704 collaboration already some time ago. These data are now confirmed, at much higher energy, by the STAR collaboration at RHIC [37]. A discussion of SSAs in proton-proton collisions (with one proton transversely polarized), for both pion production and Drell-Yan processes, within a perturbative QCD factorization scheme including parton transverse motion, was presented by Umberto D’Alesio [38]. Jacques Soffer [39] discussed SSAs in gauge boson production and derived an inequality involving single and double transverse spin asymmetries, $A_{NN}$ and $A_N$, which might lead to a useful phenomenological bound for $A_N$.

The origin of single spin asymmetries has recently been much debated using various models for the Sivers and Collins functions, relating spin and intrinsic motion in, respectively, the distribution of quarks inside a transversely polarized proton and the fragmentation of a transversely polarized quark into a pion. In particular the Sivers effect, which was thought to violate QCD time-reversal invariance, is by now accepted as a properly defined phenomenon [40], with explicit model calculations being available [41]. Some important features of these SSA mechanisms, like the factorizability, the universality and the QCD evolution remain a challenging open problem, although considerable progress has been made; a nice discussion of many of these questions can be found in the contribution of Andreas Metz [42].

## 3 Perspectives

The field of high-energy spin physics has constantly grown both in terms of its theoretical interest, and the number of dedicated experiments and surprising results that became available in the last 15 years. As is well-known, spin is such a subtle – truly relativistic and quantum-mechanical – quantity that spin observables provide severe crucial tests of any theory or theoretical model. The QCD spin structure of the nucleon is a fascinating subject, in that the very simple perturbative QCD spin dynamics (helicity conservation) does not match most of the observed spin effects. Hence, it is clear that in due time all aspects of QCD spin have to be understood.

In the coming years many more data on the spin-structure of the nucleon will become available. The gluon polarization will be measured by both COMPASS and RHIC-spin with a fairly good precision, while various data on exclusive reactions (to study GPDs) will be produced by HERMES and JLab. The subject of transversity distributions will be addressed by both COMPASS and HERMES at two different values of $Q^2$, thus making it possible to verify the predicted weak $Q^2$ dependence by combining both data sets. Together, all these data will make it possible to quantify the role of the various carriers of angular momentum in the proton, and provide novel tests of QCD in a so-far unexplored domain.

The data will need theoretical interpretation and understanding, aiming at achieving a consistent definite dynamical picture of nucleon structure, capable of account-
ing for any spin effect. Relevant progress has been made along this line, but many more steps have to be taken: concepts like the Generalized Parton Distributions and the Transversity Distribution have to translate into quantitative experimental observations, giving the necessary initial non-perturbative input to QCD perturbation theory. QCD evolutions, universality and factorization properties have to be discussed and studied, before it can be claimed that a consistent unified picture has been obtained.

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