THE STRUCTURE OF THE NUCLEON

M. DUIREN

HERMES Collaboration, DESY, D-22603 Hamburg, Germany

Abstract

The spin and flavor structure of quarks and gluons in nucleons and nuclei is more complicated than expected in the original naive quark model. Recent results which show some of the key failures of the naive picture are summarized here with emphasis on recent results from the HERMES experiment. Some future options to study the quarks structure in exclusive processes in electroproduction, photoproduction and $p\bar{p}$ annihilation are presented.

1 Introduction

About 30 years ago deep inelastic scattering revealed the partonic substructure of the nucleon. Since then, deep inelastic scattering has been used extensively to study the quark and gluon content of proton and neutron, but we are still far away from understanding the ‘non-pertubative’ substructure of the nucleon in detail. As written in any textbook, the proton contains up, down and strange (anti)quarks and gluons. The valence quark distributions $u$, and $d$, are defined by subtracting quark and antiquark distributions: $u - \bar{u} = u_v, d - \bar{d} = d_v$. Their first moments obey sum rules: $\int_0^1 u_v \, dx = 2, \int_0^1 d_v \, dx = 1$. Usually it is assumed that the difference of the quark and antiquark distributions vanishes for strange quarks: $s - \bar{s} = 0$ as strange quarks are produced from gluons in pairs. As we will see later, $\bar{u}$ and $\bar{d}$ are different, and there is also no reason why $s$ and $\bar{s}$ need to be identical, except for their first moments. To measure the quark distributions from inclusive electron and neutrino scattering experiments, it is essential to assume isospin invariance as this enables the extraction of the various functions from differences on proton and neutron targets. In practice, isospin invariance implies relations like: $u_p = d_n, \bar{u}_p = \bar{d}_n, \ldots$

Semi-inclusive scattering experiments like HERMES offer the unique possibility to separate various flavor distributions by ‘tagging’ specific types of hadrons ($\pi^+, \pi^-, K^+, K^-, \ldots$) (see Figure 1 (left)). If a quark of a certain flavor is struck, the probability to produce a hadron with large energy fraction $z$ is much higher for hadrons that contain the struck quark than for those hadrons which do not contain the struck quark.
Figure 1: Left: An electron scatters off a proton by the exchange of a virtual photon. The struck quark fragments into a hadron which contains with high probability the struck quark. The identification of the type of hadron allows conclusions about the flavor type of the struck quark. If beam and target are polarized, the polarization of the quarks can be extracted separately for each flavor. Right: There are more down quarks than up quarks in the sea of the proton as shown by HERMES and E866 data.

2 Flavor asymmetry of the light quark sea

A long lived prejudice has been that the light sea is flavor symmetric: $\bar{u} = \bar{d}$. The argument was that, as QCD is flavor blind, quark-antiquark pairs are generated from gluons with equivalent rates regardless of their flavor:

$$g \rightarrow u\bar{u} \quad \text{equivalent} \quad g \rightarrow d\bar{d}.$$  

Only recently, the experiments E866 and HERMES have proven that the light sea is not flavor symmetric [1, 2]. The down sea exceeds the up sea in the proton: $\bar{d} > \bar{u}$ as shown in Figure 1 (right).

On a second glance, this result is not really surprising as non-perturbative effects do not have to be flavor symmetric. In a naive picture one can understand it as follows:

$$p + g \rightarrow \begin{cases} uud \quad u\bar{u} \to p + \pi^0, \\ \Delta^++ + \pi^- \\ uud \quad d\bar{d} \to p + \pi^0, \\ n + \pi^+ \end{cases} \tag{1}$$

Even though the production rates of $u\bar{u}$ and $d\bar{d}$ pairs from gluons are equivalent, the simplest final states from these quark combinations are different: as there is no spin-1/2 $uuu$ baryon due to the Pauli principle, the generation is suppressed as compared to the ‘$uud$ $u\bar{u}$’-state. This explains naively the
suppression of $\bar{n}$ compared to the $\bar{d}$ quarks in the proton. More sophisticated models are needed to understand the mechanism quantitatively [3].

3 Where does the proton spin come from?

The proton spin (1/2) is composed from the spin of the quarks, the spin of the gluons, and the orbital angular momentum of quarks and gluons:

$$\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + \Delta G + L_q + L_g$$  \hspace{1cm} (2)

Here, the quantities $\Delta q$ (with $q$ either $u$, $d$ or $s$) denote the integrated polarized distribution functions of quarks and antiquarks: $\Delta q = \int_0^1 (\Delta q + \Delta \bar{q}) \, dx$. There are predictions based on SU(2) and SU(3)$_f$ flavor symmetry considerations which relate these integrals to the hyperon decay coupling constants $F$ and $D$:

$$\Delta u - \Delta d = F + D$$ \hspace{1cm} (3)

$$\Delta u + \Delta d - 2\Delta s = 3F - D$$ \hspace{1cm} (4)

The upper relation corresponds to the famous Bjorken sum rule [4]. The lower one was the basis for the Ellis-Jaffe sum rule [5]. Both relations are modified by QCD corrections which are not shown here. In the eighties it was measured by EMC that the Ellis-Jaffe sum rule is violated [6]. For that reason, people seriously questioned the validity of the quark-parton model and our understanding of the spin structure of the nucleon. Since then the reason for the failure of the Ellis-Jaffe sum rule has remained unclear. Besides equation (4), the sum rule is based on the assumption that the strange quarks do not significantly contribute to the spin of the proton: $\Delta s = 0$.

One main aim of the HERMES experiment is to measure the polarization of the up, down and strange quarks separately, and to understand the spin structure of the nucleon in more detail. The experimental technique is quark flavor tagging in polarized semi-inclusive deep inelastic scattering as schematically illustrated in Figure 1 (left). First precision results of the inclusive spin structure function $g_1(x)/F_1(x)$ (see Figure 2 (left)) show good agreement between the results from SLAC, SMC and HERMES [7]. Figure 2 (right) shows preliminary results of the most recent analysis for the flavor decomposition of the quark polarization [8]. The up quarks are positively polarized with a polarization up to 50% at large $x$, the down quarks are negatively polarized, and the sea quarks are compatible with being unpolarized. The sea polarization has been extracted in this preliminary result under the assumption that the
sea polarization is the same for all flavors. In the new HERMES data, a RICH detector allows a positive identification of pions and kaons and this will enable HERMES to measure the polarization of the $\bar{u}$, $\bar{d}$ and strange sea separately. Only then will it be known whether the violation of the Ellis-Jaffe sum rule is due to a violation of the SU(3)$_f$ symmetry or due to a large negative strange sea. In addition, HERMES will be able to investigate whether the polarization of the up and down sea is the same or not.

![Graph](image)

**Figure 2:** Left: Measurements of the spin structure function $g_1/F_1$ are shown as a function of the Bjorken scaling variable $x$. The results of the three data sets displayed are in agreement, even though the mean value of $Q^2$ is different by a factor of 10 (see left bottom figure). Right: The polarization of up, down and sea quarks as a function of Bjorken $x$.

## 4 The polarization of gluons

In DIS, the measurement of the gluon polarization is more difficult than the measurement of the quark polarization as the virtual photon does not directly couple to the gluon. There are basically two ways to measure the gluon polarization in DIS: one method is based on the QCD evolution equations which make it possible to indirectly derive the polarized gluon distribution function.
\( \Delta G(x) \) from precision measurements of the spin structure functions at different \( Q^2 \). The more direct way is to observe events that can be associated with the Photon-Gluon Fusion (PGF) process in polarized DIS. The latter method has been explored at HERMES by measuring the spin asymmetry of hadron pairs with opposite and large transverse momentum. According to a Monte-Carlo calculation the event sample contains an enhanced fraction of PGF events which made it possible to derive for the first time a (positive) value for the gluon polarization \([9]\). More precise data are expected from the COMPASS experiments which is favored for this measurement due to its larger beam energy.

5 DVCS, OFPDs and the orbital angular momentum

While the quark spin and the gluon spin distributions can be measured in inclusive and semi-inclusive deep inelastic scattering, the orbital angular momentum remained inaccessible in the last decades, and there was no clue how to access it quantitatively. Only in the recent years it became clear that the so-called Off-Forward (or Skewed) Parton Distributions (OFPDs) offer a unique way to access the orbital angular momentum of the quarks, albeit indirectly \([10]\). There exist four OFPDs for each quark with flavor \( q \): \( H^q(x, \xi, t) \), \( E^q(x, \xi, t) \), \( \tilde{H}^q(x, \xi, t) \) and \( \tilde{E}^q(x, \xi, t) \). The OFPDs are generalized parton distributions which depend on the light cone momentum fractions \( x \), the ‘skewedness’ parameter \( \xi \) and on the momentum transfer \( t \). In the limit \( t \to 0 \) and \( \xi \to \infty \) the usual parton distributions are obtained:

\[
H^q(x, 0, 0) = q(x); \quad \tilde{H}^q(x, 0, 0) = \Delta q(x).
\]

First moments of the OFPDs yield the well known nucleon form factors:

\[
\int H^q(x, \xi, t) \, dx = F^q_{\text{tot}}(t); \quad \int E^q(x, \xi, t) \, dx = F^q_{\text{el}}(t).
\]

The total angular momentum, i.e. the sum of the spin and orbital angular momentum can be obtained from the OFPDs by integrating the angular momentum density \( J^q(x) \) and summing over all quark flavors \( q \). The density is given by the OFPDs as:

\[
J^q(x) = \frac{x}{2} [H^q(x, 0, 0) + \Delta q(x, 0, 0)]
\]

Various exclusive reactions allow to access certain combinations of these OFPDs. The cleanest mechanism is provided by Deeply Virtual Compton
Scattering (DVCS) as illustrated in Figure 3(a): a virtual photon is scattered off a quark inside a proton and produces a real photon in the final state while the proton stays intact. Experimentally, the observation of DVCS events requires high luminosity ($\mathcal{L} > 10^{33}/\text{cm}^2/\text{s}$), high beam energy ($E > 25$ GeV) and the identification of the exclusive channel with a proton in the final state. The latter requirement is non-trivial, as to a large probability, the final state baryon remains in an excited state.

Electroproduction is not the only class of experiments which is suitable to measure DVCS processes. Its inverted process, which we call inverse Deeply Virtual Compton Scattering (DVCS) [11] can be accessed in photoproduction (see Fig. 3(b)). In both cases the DVCS process can be accessed at the amplitude level, as it interferes with the corresponding Bethe-Heitler diagram. Charge asymmetries allow to project out the interference term. While in electroproduction this requires a run with electrons as well as positrons, in photoproduction this asymmetry comes for free from identifying the charges of the two final state leptons and comparing their azimuthal distributions.

6 Timelike Virtual Compton Scattering in $p\bar{p}$ annihilation

By crossing of the DVCS diagram, the timelike virtual Compton scattering process (TVCS) in $p\bar{p}$ annihilation is obtained as shown in Figure 4(a). Also in this case, a corresponding Bethe-Heitler diagram (Figure 4(b)) exists, which interferes with the Compton diagram and allows to access the Compton diagram at the amplitude level.

From the experimental point of view TVCS has two big advantages: As mentioned above the Compton process requires that the final state proton stays
intact, a requirement which is not trivial to meet in a high energy process, as it is likely that the nucleon is excited and a resonance is produced in the final state. In \( p\bar{p} \) annihilation, both nucleons are naturally in the ground state and the problem of nucleon resonances does not appear.

As in DVCS, the charge asymmetry (\( \mu^+ \) vs. \( \mu^- \)) allows to project out the interference term of TVCS and its corresponding Bethe-Heitler process.

Theoretically, the work on DVCS, DVCS and TVCS has only recently started, and many aspects remain to be explored. Naively one expects that TVCS gives a similar insight into the quark structure of the nucleon as DVCS does. If one requires that the invariant mass of the muon pair (which corresponds to the \( q^2 \) of the virtual photon) and the energy of the real final state photon are sufficiently large, the process involves hard scales which should allow to probe the quarks inside the proton. On the other hand, the kinematics of TVCS and DVCS are not identical and one has to carry out a dedicated theoretical study of this process before firm statements can be made. Especially the relative importance of higher-twist effects has to be studied.

The order of magnitude of the TVCS cross section can be estimated by comparing to the cross section of \( \gamma \gamma \rightarrow p\bar{p} \). At a center of mass energy of \( \sqrt{s} = 3 \text{ GeV} \) the cross section is \( \sigma = 0.1 \text{ nb} \) for \( \cos(\theta) < 0.6 \) (Fig. 3 in [12]). Assuming that the cross section for virtual photons is 1-2 orders of magnitude smaller than for real photons (compare Fig. 4 and 5 in [13]) and taking into account the phase space, one obtains a cross section of about 0.01 nb for virtual Compton scattering in \( p\bar{p} \). For a high luminosity machine with \( 10^{33} \text{ /cm}^2/\text{s} \) one would expect roughly 20,000 events per month of running time. This estimate shows that it is worthwhile to undertake a more detailed theoretical and experimental investigation of TVCS.
7 A first signal of DVCS at HERMES

At the HERMES experiment a first signal for DVCS has been obtained by extracting beam-spin azimuthal asymmetries from data on hard exclusive electroproduction of photons [14]. The measurement was done using a longitudinally polarized electron beam incident on an unpolarized hydrogen target. The exclusive channel has been selected by measuring a scattered lepton, a real photon and by requiring a missing mass which is close to the proton mass. A clear bump of elastic events is seen although the resolution is poor. Therefore, no distinction can be made between a proton or a $\Delta(1232)$ resonance in the final state.

From the HERMES data the azimuthal dependence of the beam-spin asymmetry has been extracted with respect to the lepton scattering plane. While the Bethe-Heitler asymmetry is expected to be weak, a $\sin(\phi)$ component is observed which is in agreement with the expectation for the DVCS process. The observed asymmetry disappears as expected in the inelastic region at large missing mass and changes sign when the helicity of the positron beam is inverted (see Figure 5 (left)). A foreseen upgrade of the HERMES detector will allow for a direct measurement of the final state proton to get rid of the background from resonance production. Dedicated high luminosity runs will be used to study hard exclusive processes not only with photons, but also with pseudoscalar and vector mesons in the final state.

8 Nuclear Effects

The discovery of EMC in the eighties, that the quark distributions of proton and neutron are modified in nuclear medium, was a big surprise to the community. Fifteen years later, another nuclear effect in DIS was observed at HERMES. An additional suppression of the DIS cross section in nuclei at low $x$ and $Q^2$ was reported and has been interpreted as a possible sign for enhanced quark-gluon correlations in nuclei [15].

Semi-inclusive DIS on nuclei is a powerful tool to study the formation of hadrons in the fragmentation process. In the nuclear medium the formation time corresponds to a formation length which, depending on the size of the nucleus and the Lorentz boost of the quark, can be either inside or partially outside the nucleus. In this sense, the nucleus acts as a ‘femto-scope’ of the process. First results from HERMES are shown in Figure 5 (right) [16]. They show a reduction of the hadron yield per DIS event at low $\nu$ in the double ratio of nitrogen divided by deuterium: $R_{MN}^{h}(z,\nu) = \frac{N_{A}^{h}(z,\nu)}{N_{h}^{A}[\nu]} \bigg/ \frac{N_{D}^{h}(z,\nu)}{N_{h}^{D}[\nu]}$. At low
energy $\nu$ of the virtual photon, the Lorentz boost is small and the hadron is formed inside the nucleus. The depletion shows that the hadron formation inside the nucleus is suppressed. While the lower plot shows that positive and negative pions give, as expected, the same depletion, the upper plot, which shows all hadrons gives different results for positive and negative particles. The interpretation is that the positive hadron sample is contaminated with protons. The protons show less depletion which means, that the formation time of protons is probably so large that they are formed outside the nucleus, even at small Lorentz boost $\nu$. In the future these results will be extended by making use of the new RICH detector at HERMES. In this way the formation length for pions, kaons and protons can be studied separately.

9 Conclusions

The naive quark model provides only a crude approximation of the structure of the proton. Surprising deviations have been presented concerning the quark structure and the spin structure of the nucleon. Hence, the nucleon should be treated as a complex relativistic many-body system of quarks and gluons. The HERMES experiment turns out to be an excellent facility to study quarks in nucleons and nuclei.
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References

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