The 3D Structure of the Proton

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Abstract.
When Rutherford, Geiger and Marsden discovered the atomic nucleus in 1909 in Manchester, they at the same time also laid the foundations for the most successful method to study the structure of nuclei and nucleons. They found a point-like scattering centre inside the atom and identified it with the atomic nucleus and the theoretical description of this process has been known as Rutherford scattering ever since. The deviation between the theoretical description for a point-like scattering centre and experimental data has since been used to reveal information about the structure of the nucleus as well as the nucleon. There has been a continuous development from Hofstadter's experiments in the 1950s, over the SLAC experiments in the 60s and 70s to the HERA experiments at DESY and the experimental programme at Jeffersonlab. In this paper I am presenting the most recent results in Deeply Virtual Compton Scattering from the HERMES experiment at DESY, taken with a high density unpolarised target and a recoil detector in 2006/7.

1. Introduction
When Rutherford, Geiger and Marsden discovered the atomic nucleus in 1909 in Manchester, they at the same time also laid the foundations for the most successful method to study the structure of nuclei and nucleons. They found a point-like scattering centre inside the atom and identified it with the atomic nucleus and the theoretical description of this process has been known as Rutherford scattering ever since. Half a century later, in the 1950s, Robert Hofstadter used the difference between the measured results from electron scattering on nuclei and the theoretical expectation from Rutherford scattering to learn something about the structure of nuclei. The ratio between experiment and theory became known as the form factor of the nucleus, its Fourier transform corresponding to the charge distribution inside the nucleus [1]. This was quickly also extended to proton and neutron [2, 3] using the concept of electric and magnetic form factors that M. Rosenbluth had introduced already in 1950 [4]. The experiments by Taylor, Kendall and Friedman in the 1960s and 70s at SLAC then extended all of these concepts to the level of nucleons: they found point-like scattering centres, the partons (later identified with quarks), inside proton and neutron [5]. In addition to proton and neutron form factors parton distribution functions (PDFs) were introduced as functions of the momentum fraction of the partons to parameterise the new deep inelastic scattering (DIS) results.

The unpolarised quark-parton structure of the proton was mapped in great detail at DESY in deep inelastic electron-proton scattering by the HERA experiments H1 and ZEUS between 1990 and 2006 [6]. The polarised proton structure was explored in parallel at experiments at CERN [7], SLAC [8], Jeffersonlab and at the HERMES experiment at DESY. The theoretical description of the proton structure developed alongside the experimental results and an entire zoo of structure...
functions sprung up, held together in the larger, integrative framework of Generalised Parton Distributions (GPDs) [9, 10, 11].

In 2001 the first results from a new experimental process, Deeply Virtual Compton Scattering (DVCS) were published by HERMES[12] and by the CLAS experiment at Jeffersonlab[13]. DVCS is a process with a cross section three orders of magnitude smaller than DIS. The DVCS results can be interpreted in the framework of GPDs, and they allow the development of a 3-dimensional picture of the proton structure, again through a Fourier transformation, with two dimensions in momentum fraction space and one in impact parameter space.

In this paper I am presenting the most recent DVCS results from the HERMES experiment at DESY, taken with a high density unpolarised target and a recoil detector in 2006/7. I will also give an outlook on future DVCS experiments, where the picture that we have of the proton will be detailed and refined over the coming decade.

2. Generalised Parton Distributions

Generalised Parton Distributions (GPDs) encompass the familiar Parton Distribution Functions (PDFs) and nucleon Form Factors (FFs) to provide a comprehensive description of the structure of the nucleon.

GPDs depend upon four kinematic variables: the Mandelstam variable \( t = (p - p')^2 \), which is the squared momentum transfer to the target nucleon in the scattering process with \( p \) (\( p' \)) representing the initial (final) four-momentum of the proton; the average fraction \( x \) of the nucleon’s longitudinal momentum carried by the active quark throughout the scattering process; half the difference of the fractions of the nucleon’s longitudinal momentum carried by the active quark at the start and end of the process, written as the skewness \( \xi \); and the square \( -Q^2 = q^2 \) of the four-momentum of the virtual photon that mediates the lepton-proton scattering process. In the Bjorken limit of \( Q^2 \to \infty \) with fixed \( t \), the skewness \( \xi \) is related to the Bjorken variable \( x_B = -\frac{Q^2}{2p \cdot q} \) as \( \xi \approx \frac{x_B}{2-x_B} \). The results are presented as a function of \( x_B \) because there is no consensus on an experimentally observable representation of \( \xi \).

GPDs can be accessed through hard exclusive reactions, the simplest of which is Deeply Virtual Compton Scattering. The process, and the kinematic variables involved, are typically visualised through the so-called handbag diagram (cf. Fig.1).

![Figure 1. Handbag diagram for Deeply Virtual Compton Scattering.](image-url)
Exclusive leptoproduction of real photons \((e p \rightarrow e' p' \gamma)\) arises from two experimentally indistinguishable processes, the Deeply Virtual Compton Scattering (DVCS) process, i.e. the emission of a real photon by the struck quark from the nucleon, and the Bethe-Heitler process, i.e. elastic lepton-proton scattering with the emission of a Bremsstrahlung photon by the lepton. The Bethe-Heitler process is calculable in the QED framework. This process is dominant at the kinematic conditions of the HERMES experiment, but the scattering amplitudes of the two processes interfere and the large BH amplitude amplifies the contribution of the DVCS amplitude to the interference term. It is through the study of this interference term at HERMES that useful information for the constraint of certain GPDs can be obtained. A comprehensive description of the theory, including the terminology and the definition of Fourier coefficients etc. can be found in [14]. The HERMES collaboration has already published a series of DVCS results [12, 15, 16, 17, 18, 19, 20, 21].

GPDs are related to PDFs, FFs and transverse momentum distributions (TMDs) through the integration over variables or through specific limits that are considered. Through Fourier transformations these distributions can turned into the corresponding charge or spin densities. Figure 2 gives an instructive overview of the connections between the different distributions.

3. The 3D Structure of the Proton
A complete description of the nucleon in terms of GPDs, once it were available, would allow the determination of the distribution of partons inside the proton in three dimensions - one dimension of longitudinal momentum fraction \(x\) and two dimensions of impact parameter space \(b_\perp\) [23]:

Figure 2. Relationships between Generalised Transverse Momentum Distributions (GTMD), Wigner Distributions (WD), Transverse Momentum Distributions (TMD), Generalised Parton Distributions (GPD), Form Factors (FF), Parton Distribution Functions (PDF), spin and charge densities [22].
Figure 3 visualises this 3D picture of the proton: for any given longitudinal momentum fraction $x$ a two-dimensional distribution partons inside the proton can be obtained, which e.g. makes it possible to ‘see’ the pion cloud.

4. HERMES Recoil Detector
For the 2006/7 data taking the Hermes experiment was upgraded with a Recoil Detector[25], a small spectrometer surrounding the target cell, designed to detector the recoiling proton in DVCS scattering events. The Recoil Detector consisted of a silicon strip detector inside the beam vacuum of the HERA electron/positron ring, a scintillating fibre tracker and a photon detector inside a 1 Tesla superconducting solenoid (cf. Fig.4).

The analysis of the Recoil Detector data using a kinematic fitting technique made it possible to select elastic DVCS events with high efficiency ($\sim 84\%$) and to suppress the background from associated processes, e.g. intermediate $\Delta$-production, and semi-inclusive processes to a negligible level ($\sim 0.1\%$).

5. Recent DVCS Results from HERMES with the Recoil Detector
This paper presents results on the beam spin asymmetry on an unpolarised hydrogen target, obtained from the 2005/6 Hermes data taken with the recoil detector:

$$A_{LU}(\phi) \equiv \frac{(d\sigma(\phi)^- - d\sigma(\phi)^+)}{(d\sigma(\phi)^- + d\sigma(\phi)^+)}$$

where $d\sigma(\phi)^-$ and $d\sigma(\phi)^+$ refer to cross sections taken with beam spin parallel (anti-parallel) to the beam momentum. More precisely, it presents the Fourier coefficients of the $\sin \phi$- and $\sin 2\phi$-terms of the beam spin asymmetry.

Thanks to the Recoil Detector and the kinematic fitting technique used in the analysis it was possible to create a data set that is essentially background-free. Figure 5 shows the fractions of elastic and associated events for the three considered data samples: without Recoil Detector, without Recoil Detector but in the Recoil Detector acceptance and with Recoil Detector.
Figure 4. CAD drawing of the Hermes Recoil Detector, superconducting solenoid not shown.

Figure 5. Fractions of elastic and associated events for different event samples: without Recoil Detector, without Recoil Detector but in the Recoil Detector acceptance and with Recoil Detector.
Figure 6. DVCS beam spin asymmetry for different event samples: without Recoil Detector, without Recoil Detector but in the Recoil Detector acceptance and with Recoil Detector.

In some kinematic bins the associated fraction is as large as 20-30%. With Recoil Detector it becomes essentially zero. Figure 6 shows the experimental results for the first two Fourier coefficients of the beam spin asymmetry for the three different samples.

There is no large difference between previously published results and the result of the reference sample in the acceptance of the Recoil Detector. However, for the sample using the Recoil Detector, i.e. the pure elastic sample here is an indication that the elastic amplitude is larger in magnitude. Before physics conclusions can be drawn, the asymmetry of the associated process, which presumably is causing this change, must be investigated in detail. The analysis of the Recoil Detector data also makes it possible to select a data sample that most consists of events from associated processes and this is still the subject of an ongoing dedicated analysis.

6. Future Experiments in DVCS

The Hermes experiment has played a pioneering role in Deeply Virtual Compton Scattering and has measured many asymmetries for the first time. With the analysis of the Recoil Detector data, Hermes has now also provided the first background-free, and therefore truly exclusive, measurement of the beam spin asymmetry. The field of DVCS, or more generally, hard exclusive reactions, is now entering a new phase of high statistics measurements, in particular at the upgraded accelerator at Jeffersonlab with both the Hall A and CLAS12 experiments, but also with the new measurement programme at COMPASS at CERN. The introduction of the Recoil Detector at HERMES influenced the design of both experimental programmes, as both CLAS12 and COMPASS will feature similar detectors in the future.

The CLAS12 experiment will include a target spectrometer that will serve the same function
as the Recoil Detector at HERMES and also enable truly exclusive measurements. At the same
time, the statistics at CLAS12 are expected to be about three orders of magnitude higher, which
will allow a multidimensional mapping of the asymmetries in the different kinematic variables.

In the future at COMPASS a 2.5 m long liquid hydrogen target will be surrounded by a 4
m long scintillator-based Recoil Proton Detector (RPD). Tests with a 1 m long prototype in
2009 have already conclusively demonstrated the detection of Bethe-Heitler and DVCS events.
COMPASS is expected to take data for its DVCS programme in 2013-15 and due to the
particularities of the muon beam COMPASS will extract a combined beam spin and charge
asymmetry.

For the longer term future several different designs for an electron-ion or electron-nucleon
collider are being considered. Jeffersonlab and BNL are planning ELIC and eRHIC as competing
designs within the Electron-Ion-Collider Collaboration, CERN is considering the combination
of LHC with an electron accelerator to form the Large Hadron-electron Collider (LHeC) and at
the new FAIR laboratory a possible extension of the HESR accelerator into an Electron-Nucleon
Collider (ENC) is being considered. The physics programmes for each one of these projects has
the structure of the nucleon at its heart, and with the exception of the LHeC, DVCS will be
playing the key part in it.

7. Summary

Generalised Parton Distributions provide a theoretical framework to describe the structure of
the nucleon. Once they have been determined experimentally sufficiently well, they will lead
to a picture of the nucleon that clearly shows the distribution of partons inside the nucleon
depending on the scale given by the longitudinal momentum fraction of the partons.

The investigation of nucleon structure through scattering processes was originally invented
by Rutherford when he was investigating the atom. Since then this method has been used to
investigate the structure of the nucleus and the nucleon and some of the largest accelerators ever
bult have been designed for it. There is a direct line from the first experiments one hundred
years ago to today’s scattering experiments and further into the future.

The HERMES experiment at DESY’s HERA accelerator has taken data for more than a decade,
from 1995 until 2007. During this time Hermes has measured a series of DVCS asymmetries for
the first time, including the very first measurement of a proton beam spin asymmetry in 2001.
This paper presents the first background-free DVCS beam spin asymmetry, and shows at the
same time that the absence of background leads to a significant change in the amplitude. The
Corresponding asymmetry for background, i.e. associated DVCS events, can be expected in the
near future.

The Jeffersonlab experiments Hall A and CLAS12, as well as COMPASS at CERN, will continue
to explore the nucleon structure using DVCS over the next decade. Plans for a future electron-ion
or electron-nucleon collider are already taking shape and we can look forward to many new
and exciting results in the coming decade and beyond.
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