STUDY OF GENERALIZED PARTON DISTRIBUTIONS
WITH CLAS AT JEFFERSON LAB

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The program to study the Generalized Parton Distributions in deeply exclusive processes with CLAS at Jefferson Lab is discussed.

1 Introduction

In the past nearly five decades of electron scattering, experiments have focused either on the measurements of form factors using exclusive processes or on measurements of inclusive processes to extract deep inelastic structure functions. Elastic processes measure the momentum transfer dependence of form factors, while the latter ones probe the quark’s longitudinal momentum and helicity distributions in the infinite momentum frame. Form factors and deep inelastic structure functions measure two different one-dimensional slices of the proton structure. While it is clear that the two pictures must be connected, a common framework for the interpretation of these data has only been discovered recently with the Generalized Parton Distribution (GPD) functions. The GPDs are two-parton correlation functions that encode both the transverse spatial dependence and the longitudinal momentum dependence. At the twist-2 level, for each quark species there are two spin-dependent GPDs, \( \tilde{E}(x, \xi, t) \) and \( \tilde{H}(x, \xi, t) \), and two spin-independent GPDs, \( E(x, \xi, t) \) and \( H(x, \xi, t) \). The first moments of GPDs in \( x \) link them to the proton’s form factors, while at \( t=0 \), the GPDs \( H \) and \( \tilde{H} \) reduce to the quark longitudinal momentum \( q(x) \) and the helicity distributions \( \Delta q(x) \) respectively. Mapping out the GPDs will allow, for the first time, to construct “tomographic” images of the nucleon’s charge and quark helicity distributions in transverse impact parameter space.

The joint probability distribution, represented by the GPDs, contains much more of the physics of partons than forward parton distributions and form factors. For example, the spin sum rule makes a direct connection between GPDs and the total quark contribution to the nucleon spin:

\[
J^q = \frac{1}{2} \int_{-1}^{1} x dx [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)]
\]

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The quark helicity in $J^q$ has been measured for the past decade through polarized deep-inelastic scattering. Therefore, an experimental determination of $J^q$ allows a measurement of the quark orbital angular momentum.

2 Probing GPDs at Jefferson Lab

The basis for getting access to GPDs is the “handbag” mechanism for deeply virtual exclusive process shown in Fig.1. The process must be controlled by the pQCD evolution to probe the nucleon dynamics. Hard production of high energy photons (Deeply Virtual Compton Scattering, DVCS) is likely to enter the Bjorken regime at relatively low photon virtuality, $Q^2$. At the energies currently available at JLab, the DVCS process is masked by the more copious production of photons from the Bethe-Heitler (BH) process. However, using polarized electron beams allows to isolate the DVCS/BH interference term, which is related to the GPDs as:

$$\Delta\sigma \sim \sin\phi [F_1 H(\xi, \xi, t) + k_1 (F_1 + F_2) \tilde{H}(\xi, \xi, t) + k_2 F_2 E(\xi, \xi, t)],$$

where $F_1$, $F_2$ are the Dirac and Pauli form factors of the nucleon, $k_1$, $k_2$ are kinematical quantities, and $\phi$ is the angle between the $\gamma^*\gamma$ plane and the electron scattering plane.

The well known BH term is used here to “boost” the much smaller DVCS terms which depends on the unknown GPDs. The asymmetry, which is due to the interference, has recently been measured\textsuperscript{[9,10]} The polarization asymmetry is shown in Figure 2 compared to various GPD predictions\textsuperscript{[11,12]}. The CLAS data have been predicted within the GPD framework using cross section data from HERA\textsuperscript{[13,14]} measured at very small $x_B$ values as input\textsuperscript{[15]}. 

Figure 1. Handbag diagrams for deeply virtual Compton scattering a), and deeply virtual meson production b).
Figure 2. Beam spin asymmetry measured with CLAS. The shaded band shows the systematic uncertainties. The curves represent early predictions within the GPD framework.

The measured asymmetry is in excellent agreement with the prediction in LO. Other channels are currently under investigation with CLAS, e.g. $\gamma^*_L p \rightarrow p \rho^0$. For meson production the longitudinal component of the photon is of interest. L/T separated cross section data taken at $Q^2 = 1.5 - 2.3$ GeV$^2$ have been analysed, and are approximately described within the GDP formalism, together with data from HERMES and Fermilab using a “frozen” $\alpha_s$ value. The results on both DVCS and deeply virtual $\rho$ production allow us to make a rough estimate of the $Q^2$ range where the handbag diagram may give the dominant contribution to the reaction, to $Q^2 > 1 - 2$ GeV$^2$ for DVCS/BH, and $Q^2 > 2 - 5$ GeV$^2$ for vector meson production.

3 GPD Program at 6 GeV

Data at 5.75 GeV have been taken with CLAS to measure vector meson and pion production in the deep inelastic region and further explore the validity of the GPD framework for meson production. Also DVCS/BH asymmetries have been measured with an order of magnitude improved statistics over the first measurement at 4.3 GeV. Experiments are in preparation at JLab with CLAS and in Hall A to measure the DVCS/BH interference in a range $Q^2 = 1.5 - 3.5$ GeV$^2$ using a set of new detectors that will allow a complete
Figure 3. Expected uncertainties for the $t$-dependence in experiment E-01-113. Errors are shown for $Q^2 = 2 \text{GeV}^2$, $x_B = 0.35$, $\phi = 90^\circ$. The dashed and long-dashed lines are for the same kinematics but different GPD ingredients. The other lines correspond to different kinematics that will be measured simultaneously.

measurement of all final state particles ($e$, $\gamma$, $p$). The $Q^2$ dependence will be precisely measured, as will the $\xi$ and $t$-dependences, allowing to obtain a first detailed view at the kinematical dependences of DVCS, and to test GPD models. Figure 3 shows projected errors for some of the kinematics points that will be measured.

There will also be first results on DVCS/BH asymmetries using a longitudinally polarized hydrogen target. While beam spin asymmetries probe the GPD $H(\xi, \xi, t)$, longitudinal target asymmetries are sensitive to the GPD $\tilde{H}(\xi, \xi, t)$.

4 GPD with the CEBAF Upgrade to 12 GeV

At 11 GeV, the DVCS and BH cross section become comparable in size in a broader kinematics domain. Since the BH cross section is well known, this will allow direct extraction of the DVCS cross section. While beam asymmetries give access to the imaginary part of the DVCS amplitude, the DVCS cross section determines the $x$-integral, and contains other combinations of GPDs, therefore providing independent information.
The proposed energy upgrade of the JLab accelerator, in conjunction with the unprecedented luminosity that will be available, will allow a much broader kinematic coverage to be accessed in measurements of deeply virtual exclusive processes. Figure 4 shows the expected coverage in $Q^2$ and $x_B$. Although the energy is lower than for other experiments, the luminosity will be several orders of magnitudes greater for experiments at JLab. For the upgraded CLAS (CLAS++) an operating luminosity of $10^{35}$ cm$^{-2}$ s$^{-1}$ is anticipated. Figure 5 shows the projected coverage of the beam spin asymmetry measurement. These measurements will produce high precision DVCS data for $Q^2 = 1.0 - 7.5$ GeV$^2$, $x_B = 0.1 - 0.65$, and $-(t - t_{min}) < 1.5$ GeV$^2$.

5 From Observables to GPDs

Extracting GPD information from asymmetries and cross section measurements is not an easy task, and in general may not give unambiguous results. However, we can use constraints given by form factors as well as DIS experiments, and all deeply exclusive processes may be used in such an analysis. In addition, the GPDs are strongly constraint by certain polynomial conditions. Currently, at least three avenues are being investigated on how to obtain the most direct information on the GPDs from exclusive reactions.

(1) Approximations can be made for certain kinematics allowing to directly extract individual GPDs from asymmetry data. For example, the GPD
Figure 5. Left panel: Kinematics for DVCS beam asymmetry measurements at 11 GeV. Only the bins for lower t values are shown. All bins will be measured simultaneously with CLAS+++. Right panel: One of the bins from the left panel is shown with projected error bars. The curves represent two models for GPDs.

H may be extracted from the beam asymmetry measurements for \( x_B < 0.25 \) values. Similar approximations may be possible for the GPD \( \tilde{H} \) in target asymmetry measurements.

(2) Fits of GPD parametrizations to large sets of data may be employed, in which constraints from elastic form factors, meson distribution amplitudes, forward parton distributions, and polynomiality conditions are imposed

(3) A new technique, not unrelated to the focus of this workshop, has recently been proposed that make use of partial wave analysis techniques where the GPDs are expanded in infinite sums over t-channel exchanges. The convergence of such a procedure, however remains to be explored.

6 “Tomographic” Images of the Nucleon.

Recently it was found that knowledge of the \( x \) and \( t \) dependence of GPDs for specific quark flavors provides the basis for a visualization of the proton’s quark content in the transverse plane, in some analogy to the way images of macroscopic objects can be assembled in tomography. Using models for GPDs the quark density distribution and the quark spin distribution have been studied. A strong dependence of the quark density with increasing value
of the longitudinal momentum fraction $x$ is found. These studies also show a very strong spin-flavor polarization between $u$ quarks and $d$ quarks if the proton is polarized in the transverse plane. It is found that the $u$ and the $d$ quark spin distribution are spatially separated from each other especially at high $x$. This regime can be accessed in deeply exclusive processes at currently available energies, and will be fully accessible after the JLab Upgrade.

In summary, GPDs uniquely connect the charge and current distributions of the nucleon with the forward quark distributions measured in DIS. Recent results demonstrate the applicability of the GPD framework at currently achievable values of $Q^2$ for DVCS and possibly for vector meson production. There is a program underway at JLab to study the DVCS process at 6 GeV. A broad program of DVCS and DVMP has been proposed for the 12 GeV Upgrade. The results of such a program will provide new insights into the internal dynamics of the nucleon unimaginable just five years ago.

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