Generalized parton distributions, the hunt for quark orbital momenta

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Abstract. The Generalized Parton Distributions (GPDs) are the appropriate framework for a universal description of the partonic structure of the nucleon. They characterize the dynamics of quarks and gluons inside the nucleon and consequently contain information about the spin of the nucleon. The current experimental knowledge about GPDs is reviewed with the emphasis on the determination of $E_q(Q^2, x, \xi, t)$, the least known and constrained GPD, of particular importance in the nucleon spin puzzle. The perspectives of this experimental program are also addressed.

Keywords: Nucleon spin; Generalized parton distributions; Deep exclusive scattering.

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INTRODUCTION

After several decades of intensive experimental efforts, the origins of the nucleon spin still keep a lot of secrets. While the recent measurements at CERN, DESY, JLab and SLAC have clearly established the quark helicity contributions to the nucleon spin [1], little is known about the gluon polarization contribution [2], and the quark and gluon orbital momenta contributions are essentially unknown. On the theoretical front, it is only recently that a comprehensive picture of the nucleon spin sum rules, enlightening the importance of the transversity distributions, was proposed [3]. Intuitively, these different distributions are the expression of a single unique reality, the dynamics of quarks and gluons constituting the nucleon, which should rely on more fundamental quantities. Generalized Parton Distributions (GPDs) [4, 5] provide a universal and powerful framework which unifies in the same formalism electromagnetic form factors, parton distributions, and the spin of the nucleon. GPDs encode the correlations between quarks, anti-quarks and gluons, and can be interpreted as the transverse distribution of partons carrying a certain longitudinal momentum fraction of the nucleon [6, 7], providing then a natural link with the transverse degrees of freedom. The GPD framework and its experimental knowledge is hereafter presented, particularly in the context of the nucleon spin puzzle.

GENERALIZED PARTON DISTRIBUTIONS

GPDs are universal non-perturbative objects entering the description of hard scattering processes. They are defined for each quark flavor and gluon, and correspond to the amplitude for removing a parton of longitudinal momentum fraction $x + \xi$ and restoring
it with momentum fraction $x - \xi$ (fig. 1). In this process, the nucleon receives a four-momentum transfer $t = \Delta^2$ whose transverse component $\Delta_\perp$ is Fourier conjugate to the transverse position of partons. At the leading twist, the partonic structure of the nucleon \[8, 9\] is described by four quark helicity conserving and chiral even GPDs ($H^q, \tilde{H}^q, E^q, \tilde{E}^q$) and four quark helicity flipping and chiral odd GPDs ($H^q_T, \tilde{H}^q_T, E^q_T, \tilde{E}^q_T$), together with eight similar gluon GPDs. In the forward limit ($t \to 0, \xi \to 0$), the optical theorem links the $H$ GPDs to the usual density, helicity, and tranversity distributions measured in deep inelastic scattering (DIS). The $E$ GPDs, which involve a flip of the nucleon spin, do not have any DIS equivalent and consequently constitute a new piece of information about the nucleon structure. The first Mellin moments relate chiral even GPDs to form factors, as \[E^q\] with the Pauli electromagnetic form factor
\[
\int_{-1}^{+1} dx \ E^q(Q^2, x, \xi, t) = F_2^q(t),
\]
and the second Mellin moments relate GPDs to the nucleon dynamics, particularly the total angular momentum carried by the partons, following Ji’s sum rule \[10\]
\[
J^q = \frac{1}{2} \Delta \Sigma + L^q = \frac{1}{2} \int_{-1}^{+1} dx \ x \left[ H^q(Q^2, x, \xi, 0) + E^q(Q^2, x, \xi, 0) \right].
\]
\[\Delta \Sigma\] being known from DIS, GPD measurements allow to access the contribution of the orbital momentum to the nucleon spin. In this prospect, \[E(Q^2, x, \xi, t)\] is of particular interest since it is not constrained by any DIS limit and remains essentially unknown. Similar relations have been proposed which relate chiral odd GPDs to the transverse spin-flavor dipole moment and the correlation between quark spin and angular momentum in an unpolarized nucleon \[11\].

DEEPLY VIRTUAL EXCLUSIVE SCATTERING

Deeply Virtual Compton Scattering (DVCS), corresponding to the absorption of a virtual photon by a quark followed quasi-instantaneously by the emission of a real photon, is the simplest reaction to access GPDs. In the Bjorken regime, $-t \ll Q^2$ and $Q^2$ much larger than the quark confinement scale, the leading contribution to the reaction amplitude is represented by the so-called handbag diagram (fig. 1) which figures the convolution of a known $\gamma^* q \to \gamma q$ hard scattering kernel with an unknown soft matrix element describing the partonic structure of the nucleon parametrized by GPDs \[12, 13\]. Consequently, GPDs ($E^q$) enter the reaction cross section through a Compton form factor ($\mathcal{E}$) which involves an integral over the intermediate quark propagators
\[
\mathcal{E} = \sum_q e_q^2 \mathcal{P} \int_{-1}^{+1} dx \left( \frac{1}{x - \xi} + \frac{1}{x + \xi} \right) E^q(Q^2, x, \xi, t)
\]
\[-i\pi \sum_q e_q^2 \left[ E^q(Q^2, \xi, \xi, t) - E^q(Q^2, -\xi, \xi, t) \right]
\]
eq$ being the quark electric charge in units of the elementary charge. In addition to the DVCS amplitude, the cross section for electroproduction of photons gets contributions
from the Bethe-Heitler (BH) process where the real photon is emitted by the initial or final lepton, leading to

\[ \frac{d^5 \sigma}{dQ^2 dx_B dt d\phi_e d\phi} = \mathcal{T}_{BH}^2 + |\mathcal{T}_{DVCS}|^2 + 2 \mathcal{T}_{BH} \Re \{ \mathcal{T}_{DVCS} \} \]

with \( \phi_e \) the scattered electron azimuthal angle, and \( \phi \) the out-of-plane angle between the leptonic and hadronic planes; the \(+\)(−) sign of the interference amplitude stands for negative(positive) leptons. Though undistinguishable from DVCS, the BH amplitude is known and exactly calculable from the electromagnetic form factors. Beam charge and beam and/or target polarization observables can be advantageously used to select different contributions to the cross section. For instance, the polarized cross section difference for opposite beam helicities allows to isolate the imaginary part of the DVCS amplitude

\[ \frac{d^5 \Delta \sigma}{dQ^2 dx_B dt d\phi_e d\phi} = \frac{1}{2} \left[ \frac{d^5 \bar{\sigma}}{dQ^2 dx_B dt d\phi_e d\phi} - \frac{d^5 \bar{\sigma}}{dQ^2 dx_B dt d\phi_e d\phi} \right] \]

where \( \Im \{ \mathcal{T}_{DVCS} \} \) appears now linearly and magnified by the BH amplitude. In practice, the measurements of the cross section and a selected set of single and double spin polarization observables allows to extract the real and imaginary parts of the Compton form factors, from which the GPDs can be deconvoluted [14].

Deeply Virtual Meson Production (DVMP), where the real photon is replaced by a meson, is another channel to access GPDs which provides in addition an elegant flavor decomposition. In this case, the factorization of the cross section applies only to longitudinal virtual photons and the GPDs entering the Compton form factors (eq. 3) are further convoluted with a meson distribution amplitude. The measurement of the angular distribution of the decay products of the vector mesons allows to extract the longitudinal part of the cross section and the longitudinal polarization of the vector mesons, assuming the \( s \)-channel helicity conservation. Other reaction mechanisms, like the 2-gluon exchange from a \( q\bar{q} \) fluctuation of the virtual photon, may contribute to the production process. Similarly to DVCS, polarization observables help to single-out the pure handbag contributions.
EXPERIMENTAL STATUS

The pioneering studies of the electro-production of photons at DESY \[15, 16\] and JLab \[17\] did prove the existence of the DVCS mechanism by measuring sizeable beam spin asymmetries (BSA from the ratio of eq. 5 and eq. 4) in the valence region and significant cross sections in the gluon sector. Other limited studies showed the importance of the beam charge \[18\] and the target polarization observables \[19\]. The recent remarkable results of the starting dedicated DVCS experimental program of JLab is the strong indication for scaling in the valence region at $Q^2$ as low as 2 GeV$^2$, and the observation of an unexpected DVCS amplitude magnitude at JLab energies \[20\]. This early scaling is also supported by the $\phi$ angular dependence of the BSA measured at JLab with an unprecedented accuracy over a wide kinematic range \[21\]. In general, GPD based calculations provide a reasonable but unsatisfactory agreement with these data which turn out to be fairly reproduced by a more conventional Regge approach \[22\]. The significance of this duality has not yet been resolved.

In the meson sector, the experimental status with respect to GPDs remains controversial. Sizeable BSAs have been reported for exclusive neutral pion electro-production at JLab energies \[23\], which suggest that both longitudinal and transverse amplitudes contribute to the process. On the one hand, this forbids a direct GPD based interpretation of the data, and on the other hand, a Regge based approach fails to reproduce them. The longitudinal cross section for the electro-production of longitudinally polarized neutral rho was recently measured at JLab \[24\]. Standard GPD calculations, particularly successful at high energies, do not reproduce data in the valence region, while calculations based on hadronic degrees of freedom are in very good agreement over the complete energy range scanned by the world data. The observation that strongly modified GPDs allow for a partonic interpretation of these measurements raises the question whether current GPD parametrizations must be revisited or the existence of strong higher twist corrections precludes a GPD wise interpretation of DVMP in the valence region.

PERSPECTIVES

Transversely polarized proton targets are of primary importance for the determination of the quark orbital momenta, since they provide a direct access to the GPD $E_q$ which is essentially parametrized in terms of the quark angular momenta \[25\]. In this respect, DVCS and DVMP transverse target asymmetries (TSA) are key observables. The first experimental indication of this sensitivity was reported by HERMES from DVCS TSA measurements off a proton target \[26\]. Within a simple twist-2 approach, the TSA data may be interpreted as a measurement of the GPDs combination $t[F_2H - F_1E]/4M^2$. Relying on a given GPD model, the most probable parameters $J_u$ and $J_d$, representing the $u$ and $d$ quarks angular momenta, can be extracted from the comparison between data and calculations, leading to the vertical band in fig. 2.

Another important observable connected to $E_q$ is the DVCS polarized cross section difference (eq. 5) off a neutron target. Taking advantage of the smallness of the neutron Dirac electromagnetic form factor and of the cancellation between the $u$ and $d$ quarks in the GPD $\tilde{H}$ at small $t$, this observable is, at leading twist, a measurement of the
FIGURE 2. Model dependent experimental constraint on $J_u$ and $J_d$ quark angular momenta from the HERMES $p$-DVCS [26] and the JLab $n$-DVCS [27] experiments. Different model calculations [28, 29, 30, 31, 32] are compared to an extrapolation of experimental data within the VGGG double distribution description of GPDs [33].

The first data on this observable were obtained by the JLab $n$-DVCS experiment [27]. Similarly to TSA, the comparison with calculations for the same GPD model leads to the horizontal band in fig. 2.

In the present status of GPD models, the main message of this appealing picture is the experimental demonstration of the complementarity between transversely polarized proton and neutron targets in the search for quark orbital momenta. This fundamental feature is a direct consequence of isospin symmetry. Experimental advances in this quest are depending on the progress in the developments of high luminosity transversely polarized targets [34] and on the next generation of $n$-DVCS experiments for which transversely polarized targets may provide an interesting observable to extract $E$ at very small $t$ [35].

CONCLUSIONS

The exciting exploration of the GPDs world is progressing. A larger set of experimental data are expected from JLab 6 GeV and the HERMES device supplemented by a recoil detector. In a near future, the energy upgrade of JLab and the completion of a DVCS program at COMPASS will considerably enlarge the kinematic range of GPDs knowledge. Together with the evolution of lattice QCD calculations capabilities, one may reasonably expect to get a comprehensive and quantitative understanding of the nucleon structure, including the contribution of the quark orbital momenta to the nucleon spin, by the end of the next decade.
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