Parton promenade into the nucleon

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Abstract. Generalized parton distributions (GPDs) offer a comprehensive picture of the nucleon structure and dynamics and provide a link between microscopic and macroscopic properties of the nucleon. These quantities, which can be interpreted as the transverse distribution of partons carrying a certain longitudinal momentum fraction of the nucleon, can be accessed in deep exclusive processes. This lecture reviews the main features of the nucleon structure as obtained from elastic and inelastic lepton scatterings and unified in the context of the GPDs framework. Particular emphasis is put on the experimental methods to access these distributions and the today experimental status.

1. Introduction
The nucleon, this most singular object of nuclear physics whose mass is quite larger than the mass of its constituents, did resist since several decades to theoretical and experimental investigations. It is only recently that a comprehensive picture of the nucleon structure started to develop within the framework of the generalized parton distributions (GPDs) [1, 2]. These distributions parametrize the partonic structure of the nucleon in terms of correlations between quarks, antiquarks and gluons, and therefore contain information about the dynamics of this system. The power of this framework for the problem of the nucleon structure is certainly within the Mellin moments of the GPDs [3] which provide a natural link between microscopic and macroscopic properties of the nucleon.

GPDs can be accessed in the Bjorken regime of deep exclusive processes [4, 5], that is when the resolution power of the probe is large enough to resolve partons and when the momentum transfer to the nucleon is small enough to insure the separation of perturbative and non-perturbative scales. Pioneer measurements at HERMES [6] and CLAS [7], and recent experiments at the Jefferson Laboratory [8, 9] have established the relevance of the deeply virtual Compton scattering (DVCS) process for this studies. The real and imaginary parts of the DVCS amplitude are the quantities of interest that can be separated via beam charge, or beam polarization, or target polarization observables.

This lecture reviews the main steps of the story of the nucleon structure and its modern expression within the GPDs framework. The experimental methods to access these distributions and the today experimental status are also discussed.

2. From nucleon to partons...
From an experimental point of view, the story of the nucleon structure started in the fifties when deviations from the Mott cross section were observed in elastic electron scattering [10],
meaning that the nucleon is not a pointlike object. The size of the nucleon is expressed by the so-called electromagnetic form factors which characterize the nucleon shape with respect to the electromagnetic interaction. This shape depends not only on the resolution of the probe, controlled by the momentum transfer $Q^2$ to the nucleon, but also on the nature of the probe, this last feature being an early indication of the complexity of the nucleon structure. Within a non-relativistic framework, the electric (magnetic) form factor is the Fourier transform of the charge(current) density. Relativistic corrections to this picture modify this simple relationship but preserve this intimate link [11]. As today, there exists a significant enough knowledge of these form factors to question the experimental disagreement between Rosenbluth and recoil polarization measurements [12], as well as the role and magnitude of the two photons exchange mechanism [13].

At the end of the sixties, the nucleon revealed an unexpected behaviour in deep inelastic electron scattering (DIS). For excitation energies well beyond the resonance region, the cross section was found to weakly depend on the momentum transfer as compared to elastic scattering, indicating an interaction off a structureless object [14]. This behaviour was later identified as the first evidence of the existence of partons. The cross section for these experiments depends on the variable $x_B$, the fraction of the nucleon longitudinal momentum carried by the partons, and can be expressed in terms of the probability to find in the nucleon a parton carrying a given longitudinal momentum. This feature led to extensive measurements of the momentum distributions of partons into nucleons, the so-called parton distributions whose satisfactory knowledge has now been obtained after thirty years of experimental efforts. The nucleon appears as a system of three valence quarks globally equally sharing the nucleon momentum, and lying in a sea of quark-antiquark pairs and gluons.

Soon after this discovery, it was realized that deep inelastic scattering of polarized leptons off polarized targets allows to experimentally access the spin of the nucleon. Helicity conservation at the $\gamma^*$-quark interaction vertex requires the $\gamma^*$ coupling with opposite helicity quarks. Therefore, changing the polarization of the nucleon allows to measure alternatively the population of quarks with spin parallel or anti-parallel to the nucleon. Within the naive parton model, the difference between these populations is a measurement of the nucleon spin. This picture turns out to be too rough when it was found that quarks carry about 20-30 % of the total spin of the nucleon [15, 16]. In a more realistic partonic picture, the nucleon spin gets orbital and spin contributions of each constituent in a scale dependent manner, and the dynamics of the system expresses differently in the longitudinal (helicity) and transverse (transversity) directions yielding two spin sum rules [17]. If a fair knowledge of quark helicity distributions has now been obtained, investigations of the gluon contribution and transversity distributions are only starting, and the orbital momentum contributions are essentially unknown. Overall, the spin of the nucleon remains by many respects a terra incognita.

GPDs procure the cement of the nucleon spin puzzle and more generally of the hadron structure.

3. ... And conversely

GPDs are universal non-perturbative objects entering the description of hard scattering processes 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 $\Delta_T$ is Fourier conjugate to the transverse position of partons. Consequently, GPDs can be interpreted as a distribution in the transverse plane of partons carrying a certain longitudinal momentum [18, 19, 20, 21], constituting a femto-tomography of the nucleon.

At the leading twist, the partonic structure of the nucleon [3, 22] is described by four quark helicity conserving and chiral even GPDs ($H^q, \bar{H}^q, E^q, \bar{E}^q$) and four quark helicity flipping and
chiral odd GPDs \((H_q^T, \bar{H}_q^T, E_q^T, \bar{E}_q^T)\), together with eight similar gluon GPDs. In the forward limit \((t \rightarrow 0, \xi \rightarrow 0)\), the optical theorem links the \(H\) GPDs to the usual density, helicity, and transversity distributions measured in DIS. However, the \(E\) GPDs, which involve a flip of the nucleon spin, do not have any DIS equivalent and then constitute a new piece of information about the nucleon structure. The first Mellin moments relate chiral even GPDs to form factors, as \(E_q^T\) with the Pauli electromagnetic form factor

\[
\int_{-1}^{+1} dx \ E^T(Q^2, x, \xi, t) = F_2^q(t),
\]

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 [23]

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

Here, \(E\) 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 [24].

4. Deep exclusive processes

\[
\sigma(ep \rightarrow ep\gamma) = \sigma_{BH} + \sigma_{DVCS} + P_l \bar{\sigma}_{DVCS} + e_l \sigma_{INT} + P_l e_l \bar{\sigma}_{INT}
\]
where the $\sigma(\tilde{\sigma})$’s are even(odd) function of the out-of-plane angle between the leptonic and hadronic planes; $P_l$ and $e_l$ are the lepton polarization and charge, respectively. Though undistinguishable from DVCS, the BH cross section is known and exactly calculable from the electromagnetic form factors. The pure DVCS and interference contributions contain the information of interest, particularly $\sigma_{INT}(\tilde{\sigma}_{INT})$ is proportional to the real(imaginary) part of the DVCS amplitude. From the above relation, it is obvious that four different measurements combining beam charge and/or polarization allow to extract the four unknown contributions involving different Compton form factor combinations. Polarized target observables add other combinations with different sensitivity to the GPDs. For instance, $E$ can be accessed from the difference between polarized cross section off the neutron for opposite lepton helicities, and from the target spin asymmetry for a transversely polarized proton.

Deeply Virtual Meson Production (DVMP), where the real photon is replaced by a meson, is another channel to access GPDs additionally providing 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 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 $s$-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, particularly the production of longitudinal $\rho^0$ off a transversely polarized proton target is an observable very sensitive to $E$ [26].

5. Experimental status

The pioneering studies of the electro-production of photons at DESY [6, 27] and JLab [7] did prove the existence of the DVCS mechanism by measuring sizeable beam spin asymmetries (BSA) in the valence region and significant cross sections in the gluon sector. Other limited studies showed the importance of the beam charge [28] and the target polarization observables [29]. A recent remarkable JLab result 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 [8]. This early scaling is also supported by the $\varphi$ angular dependence of the BSA measured at JLab with an unprecedented accuracy over a wide kinematic range [9]. 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 [30]. 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 $\pi^0$ electro-production at JLab energies [31], 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 $\rho^0$ was recently measured at JLab [32]. 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 percludes a GPD wise interpretation in the valence region.

Concerning the quest for the angular momentum, DVCS measurements off the neutron [33] and off a transversely polarized proton [34], as well as longitudinal $\rho^0$ production off a transversely polarized proton [35] were reported. The interpretation of these data in terms
of GPDs can lead to a constraint on the angular momentum of the $u$ and $d$ quarks [36]. This constraint is however highly model dependent. It is the goal of the future experimental programs to provide enough data to map out the GPDs and allow for a model independent determination of the angular momentum of the partons.

6. Conclusion
Since a decade, the study of the nucleon structure entered a new era with the advent of GPDs which unify within the same framework form factors, parton distributions, helicity and transversity distributions. DVCS appears as the golden channel to access GPDs, showing an early scaling behaviour supported by recent JLab experimental results. The lack of experimental data does not yet allow for a precise and model-independent extraction of these quantities from experimental observables. The future experimental programs at JLab 12 GeV and CERN are expected to overcome this situation, and hopefully provide a model independent determination of the contribution of the quark angular momentum to the spin of the nucleon.

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