Generalized Parton Distributions and Generalized Distribution Amplitudes: New Tools for Hadronic Physics\footnote{Talk given at the International Conference on Theoretical Physics, TH2002, Paris, July 2002.}

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Abstract

The generalized parton distributions and the generalized distribution amplitudes give access to a deeper understanding of the quark and gluon content of hadrons. In this short review, we select some new developments of their interesting connections with the physics information that one can extract from exclusive reactions at medium and high energies.

1 Generalized Parton Distributions

A considerable amount of theoretical and experimental work is currently being devoted to the study of generalized parton distributions, which are defined as Fourier transforms of matrix elements between different hadron states, such as:

$$\int d\lambda e^{i\lambda x(p+p')} \langle N'(p',s')|\bar{\psi}(-\lambda n)\gamma.n\psi(\lambda n)|N(p,s)\rangle$$

Their measurements are expected to yield important contributions to our understanding of how quarks and gluons assemble themselves into hadrons\footnote{Talk given at the International Conference on Theoretical Physics, TH2002, Paris, July 2002.}. The simplest and cleanest exclusive processes where these distributions occur are deeply virtual Compton scattering (DVCS), i.e., $\gamma^*N \rightarrow \gamma N'$ and meson electroproduction i.e., $\gamma^*N \rightarrow MN'$ in kinematics where the $\gamma^*$ has large spacelike virtuality $Q^2$ while the invariant momentum transfer $t$ to the proton is small (for recent reviews, see\footnote{Unité mixte C7644 du CNRS.} ). Their “inverse” processes, $\gamma N \rightarrow \gamma^*N'$ and $\pi N \rightarrow \gamma^*N'$ at small $t$ and large timelike virtuality of the final state photon\footnote{Talk given at the International Conference on Theoretical Physics, TH2002, Paris, July 2002.} are quite similar.

DVCS combines features of the inelastic processes with those of an elastic process. A relativistic charged lepton is scattered from a target nucleon or nucleus. A real photon of
4-momentum $q'_\mu$ is also observed in the final state. With $e(k)$, $e'(k')$ denoting the initial and final electrons of momenta $k$, $k'$ respectively, and $p$, $p'$ denoting the momentum of the target, the process is

$$e(k) + N(p) \to e'(k') + N'(p') + \gamma(q').$$

The net momentum transfer $\Delta$ to the target is obtained by momentum conservation,

$$\Delta^\mu = k^\mu - k'^\mu - q'^\mu.$$ 

The real photon may be emitted by the lepton beam, in which case a virtual photon of momentum $Q^\mu_{BH} = \Delta^\mu$ strikes the target. This is the Bethe-Heitler amplitude which is perfectly under control since the nucleon form factors at small $t$ are known. A second possibility is that the target absorbs a virtual photon of momentum $Q^\mu_{VCS} = p'^\mu - p^\mu + q'^\mu$ and emits the real photon. This is the genuine DVCS amplitude.

It is straightforward to select events where all components of $\Delta^\mu$ are small compared to $\sqrt{Q^2}$, with $Q^2 = -Q^\mu_{VCS}Q_{VCS,\mu} > \text{GeV}^2$. These conditions have recently been realized in experiments\cite{4} at HERMES at DESY and CEBAF at JLab.

The physical interpretation is that the target is resolved by the virtual photon on a spatial scale small compared to the target size. A photon of high virtuality $Q^2$ selects a short-distance region of the target: the spatial resolution is of order $\Delta b_T \sim \hbar/\sqrt{Q^2}$. Perturbative QCD (pQCD) can be applied to DVCS at large $Q^2$, exploiting the short-distance resolution of the virtual photon, despite the presence of a real photon in the reaction\cite{1}.

Extracting the GPD’s from the scattering amplitudes require to study a number of observables in different reactions\cite{2}; electroproduction of mesons and photons is the main source of information, but for the chiral-odd GPD’s which need a quite different process\cite{5}. GPD’s may also be studied for the deuteron\cite{6} and other nuclei.

## 2 Femtophotography

Complementarily to ordinary parton distributions which measure the probability that a quark or gluon carry a fraction $x$ of the hadron momentum, GPD’s represent the interference of different wave functions, one where a parton carries momentum fraction $x + \xi$ and one where this fraction is $x - \xi$. $\xi$ is called the skewedness and is fixed in a DVCS experiment by external momenta. On the contrary, $x$ is an integration variable varying from $-1$ to $+1$. When $x < \xi$, the GPD’s should be interpreted as the interference of the hadron wave function with the wave function of the hadron accompanied by a $q\bar{q}$ pair. It is thus very reminiscent of the probability amplitude to extract a meson from a hadron.

Apart from longitudinal momentum fraction variables, GPD’s also depend on the momentum transfer $t$ between the initial and final hadrons. Fourier transforming this transverse momentum information leads to information on the transverse location of quarks and gluons in the hadron\cite{7}. Real-space images of the target can thus be obtained, which is completely new. Spatial resolution is determined by the virtuality of the incoming photon. Quantum photographs of the proton, nuclei, and other elementary particles with resolution on the scale of a fraction of a femtometer are thus feasible.
3 Generalized distribution amplitudes

The crossed version of GPD’s describe the exclusive hadronization of a $q\bar{q}$ or $gg$ pair in a pair of hadrons, a pair of $\pi$ mesons for instance. These generalized distribution amplitudes (GDA) [8], defined in the quark-antiquark case, as

$$\Phi_q^{\pi\pi}(z, \zeta, s) = \int \frac{dx}{2\pi} e^{-izP^+x^-} \langle \pi(p')\pi(p)|\bar{\psi}_q(x^-)\gamma^+\psi_q(0)|0\rangle$$

where $s$ is the squared energy of the $\pi\pi$ system, are the non perturbative part of the light cone dominated process [9] $\gamma^*\gamma \to \pi\pi$ which may be measured in electron positron colliders of high luminosity. This new QCD object allows to treat in a consistent way the final state interactions of the meson pair. Its phase is related to the the phase of $\pi\pi$ scattering amplitude, and thus contains information on the resonances which may decay in this channel. Results on the related reaction $\gamma^*\gamma \to \rho\rho$ may be expected from LEP 2.

4 Hunting for the Odderon

A nice application of the GDA’s concerns the search for the Odderon [10]. Pomeron and Odderon exchanges are the theoretically dominant contributions to hadronic cross sections at high energy. They appear on an equal footing in the QCD description of hadronic reactions, and in the lowest order approximation they correspond to colour singlet exchanges in the $t$-channel with two and three gluons, respectively. The Odderon remains a mistery from an experimental point of view. On the one hand, recent studies of the elastic $pp$ scattering show that one needs the Odderon contribution to understand the data in the dip region [11]. On the other hand, the studies of meson production processes which should select the odderon exchange didn’t show any clear signal of its importance [12, 13]. In these cases, the scattering amplitude describing Odderon exchange enters quadratically in the cross section.

A number of interesting features of the two pion diffractive electroproduction process allows to search for the QCD-Odderon at the amplitude level. Since the two pion state described by the GDA’s doesn’t have any definite charge parity, both Pomeron and Odderon exchanges contribute. The charge asymmetry is ideally suited to select the interference of the two amplitudes. As in open charm production [14], the Odderon amplitude enters linearly in the asymmetries and therefore one can hope that Odderon effects can show up more easily. Moreover factorization properties allow to perturbatively calculate the short-distance part of the scattering amplitude. The long distance part contains the product of the C-even and C-odd GDA’s, and shows a dramatic dependence in the two pion invariant mass.
In conclusion, let me acknowledge that I would not have been able to give this mini review without all the fruitful discussions I had during the last 6 years with all my collaborators and particularly Markus Diehl, Thierry Gousset, John Ralston, Lech Szymanowski and Oleg Teryaev.

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