GENERALIZED VECTOR DOMINANCE AND LOW-\(x\) PROTON STRUCTURE

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ABSTRACT

The low-\(x\) HERA data on inelastic lepton-proton scattering are interpreted in terms of Generalized Vector Dominance.

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Looking back with great pleasure to my participation at the VIIIth Rencontres de Moriond which took place in Méribel-les-Allues in 1973, the subtitle “Generalized Vector Dominance, 25 years later” seems most appropriate for my present talk.

There are two basic motivations for returning to the subject, an experimental one (i) and a theoretical one (ii):

(i) At HERA two interesting experimental results at low $x$ were established since HERA started operating in 1992: first of all, the proton structure function $F_2(x,Q^2)$ rises steeply with decreasing $x \lesssim 10^{-2}$ and shows a considerable amount of scaling violations. Second, when analysing the final hadronic state, the H1 and ZEUS collaborations found an appreciable fraction of final states (approximately 10% of the total) of typically diffractive nature (“large rapidity gap events”) with invariant masses of the diffractively produced hadronic state up to about 30 GeV.

(ii) With respect to DIS at small $x$, a long-standing theoretical question concerns the role of the variables $x$ and $Q^2$. This question has been most succinctly posed and discussed by Sakurai and Bjorken, as recorded in the Proceedings of the ’71 Electron–Photon Symposium’ at Cornell University. It concerns the transition to the hadron-like behaviour of photoproduction, more generally, whether concepts similar to the ones used in photoproduction are relevant in the limit of $Q^2 \to 0$ only, or rather in the limit of $x \to 0$ at arbitrarily large fixed values of $Q^2$. Within the framework of QCD there is no unique answer to this question so far. We may hope that the HERA low- $x$ data in conjunction with theoretical analyses will resolve this important issue.

In a recent paper and in the present talk, I take the point of view that indeed $x$ is the relevant variable, in the sense that $x \lesssim 10^{-2}$ defines the region in which those features of the virtual photoproduction cross-section, $\sigma_{\gamma^*p}$, that show a close similarity to real photoproduction and hadron-induced processes (Generalized Vector Dominance) become important. Work along these lines, accordingly, is to be considered as an attempt to quantitatively and directly combine the above-mentioned two experimental observations at HERA (low- $x$ rise of $F_2$ and diffractive production) within a coherent picture.

Qualitatively, the conceptual basis of Generalized Vector Dominance (GVD) is strongly supported by:

(i) The very existence of diffractive production at low values of the scaling variable, $(x \lesssim 10^{-2})$, and large $Q^2$, established at HERA and constituting a “conditio sine qua non” for the GVD picture: in GVD, the role of the low-lying vector mesons, $\rho^0, \omega, \phi$ in photoproduction, at low $x$ and large $Q^2$, is conjectured to be taken over by the continuum of more massive vector states seen in $e^+e^-$ annihilation, which accordingly ought to be produced diffractively in lepton-proton scattering.

(ii) The strong similarity in shape between a diffractively produced state of mass $M_x$ and the state produced in $e^+e^-$ annihilation at the energy $\sqrt{s_{e^+e^-}} = M_x$. Compare the thrust and sphericity distributions shown in Fig. 1 (from Ref.) for diffractive production and $e^+e^-$ annihilation. In other words, just as the $\rho^0$ meson produced in photon-proton interactions looks the same, in good approximation, as the one seen in $e^+e^-$ annihilation, also the heavy-mass continuum diffractively produced at HERA looks much the same as the one seen in $e^+e^-$ annihilation.

(iii) Last, not least, the persistence of shadowing in electron (muon) scattering from complex nuclei at small $x$ and large $Q^2$. Diffractive production of high-mass states with photon quantum numbers, the essential ingredient of GVD, is essential for the destructive interference responsible for the persistence of shadowing at large values of $Q^2$. 
Quantitatively, GVD starts from a mass dispersion relation which in general involves off-diagonal transitions in mass and, for the transverse part of the photon absorption cross-section, takes the form

$$\sigma_T(W^2, Q^2) = \int dm^2 \int dm'^2 \frac{\tilde{\rho}_T(W^2, m^2, m'^2)m^2m'^2}{(m^2 + Q^2)(m'^2 + Q^2)}$$

(1)

with appropriate generalization to the longitudinal part $\sigma_L(W^2, Q^2)$ of the total photon absorption cross-section $\sigma_{\gamma p}(W^2, Q^2)$. While the existence of off-diagonal terms can hardly be disputed from our experimental knowledge of diffraction dissociation in hadron reactions, and off-diagonal model calculations have indeed been put forward, and recently reconsidered, in applications of GVD, one frequently approximates (1) by an effective representation of diagonal form,

$$\sigma_T(W^2, Q^2) = \int_{m^2_0} dm^2 \frac{\rho_T(W^2, m^2)m^4}{(m^2 + Q^2)^2},$$

(2)

where the threshold mass, $m_0$, is to be identified with the energy at which the cross-section for the process $e^+e^- \rightarrow$ hadrons starts to become appreciable. The spectral weight function, $\rho_T(W^2, m^2)$, in (2) is proportional to the product of i) the transition strength of a time-like photon to the hadronic state of mass $m$, as observed in $e^+e^-$ annihilation at the energy $\sqrt{s_{e^+e^-}} = m$, and ii) the imaginary part of the forward scattering amplitude of this state of mass $m$ on the nucleon.

For comments on the ansatz for $\sigma_L(W^2, Q^2)$ in the diagonal approximation,

$$\sigma_L(W^2, Q^2) = \int_{m^2_0} dm^2 \frac{\rho_T(W^2, m^2)m^4}{(m^2 + Q^2)^2} \xi Q^2 m^2,$$

(3)

we refer to Refs. The parameter $\xi$ denotes the ratio of the longitudinal to the transverse (imaginary) forward-scattering amplitude for vector states of mass $m$. 

Figure 1: Thrust $< T >$ and sphericity $< S >$ in diffractive production (ZEUS-LPS data) and $e^+e^-$ annihilation (from Ref. 7).
When confronting GVD predictions with experimental data, I will discriminate between an analysis in the region of very small \( Q^2 \), i.e. \( Q^2 \lesssim 1 \text{ GeV}^2 \), and an analysis taking into account the full set of HERA data at low \( x \) and values of \( Q^2 \) up to the order of \( Q^2 \simeq 100 \text{ GeV}^2 \).

At small values of \( Q^2 \lesssim 1 \text{ GeV}^2 \), the dominant contributions to the integrals in (2) and (3) stem from low masses, \( m^2 \), of the order of \( Q^2 \). In this mass range, the energy dependence for the contributing hadronic processes may be assumed to be approximately independent of mass \( m \), in generalization of what is known from photoproduction of the low-lying vector mesons, \( \rho^0, \omega \) and \( \phi \). Accordingly, from (2) and (3), upon integration, one obtains an expression in which \( W^2 \) dependence and \( Q^2 \)-dependence factorize, the \( Q^2 \) dependence being contained in a single pole in \( Q^2 \),

\[
\sigma_T(W^2, Q^2)_{\gamma^*p} = \frac{m_0^2}{Q^2 + m_0^2} \sigma_{\gamma p}(W^2),
\]

\[
\sigma_L(W^2, Q^2)_{\gamma^*p} = \xi \left[ \frac{m_0^2}{Q^2} \log \left( 1 + \frac{Q^2}{m_0^2} \right) - \frac{m_0^4}{Q^2 (Q^2 + m_0^2)} \right] \sigma_{\gamma p}(W^2). \quad (4)
\]

The comparison of (4) with the ZEUS-BPC experimental data is shown in Fig. 2.\[\]

Figure 2: HERA data at low \( Q^2 \) compared with GVD predictions (from Ref. 1).

We conclude that

(i) the \( Q^2 \) dependence of \( \sigma_{\gamma^*p}(W^2, Q^2) \) for \( Q^2 \neq 0 \) is well described by the GVD ansatz,

(ii) the extrapolation to \( Q^2 = 0 \) coincides with (unpublished) photoproduction results as indicated,

(iii) the fitted mass scale \( m_0 \) in (4),

\[
m_0^2 = 0.48 \pm 0.08 \text{ GeV}^2,
\]

is reasonable for the threshold energy of \( e^+e^- \) annihilation into hadrons, effectively described by a continuum starting at \( \sqrt{s_{e^+e^-}} = m_0 \). \[\]
Figure 2 also shows a plot of the structure function \( F_2(W^2, Q^2) \),

\[
F_2(W^2, Q^2) \simeq \frac{Q^2}{4\pi^2\alpha} \sigma_{\gamma^*p}(W^2, Q^2).
\]

(6)

It is amusing to compare this plot of the truly high-energy ZEUS data with a very similarly-looking plot from 1976 by Robin Devenish (at that time a theorist at DESY) and myself \(^{12}\) that is based on the “low-energy” data then available from the SLAC-MIT collaboration. The theoretical curves in Fig. 3 are based on \(^{12}\), using a fixed input for the threshold mass

\[
m_0^2 = 0.36 \text{ GeV}^2
\]

(7)

based on theoretical arguments within the off-diagonal ansatz\(^9\). The small difference between (5) and (7) should not be overinterpreted, but it is in the right direction, taking into account the fact that the energy of the SLAC-MIT experiment hardly reaches the charm-production threshold.

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Figure 3: SLAC-MIT data in comparison with GVD predictions (from Ref.\(^{12}\))

At large values of \( Q^2 \), the simple factorization of the \( Q^2 \)- and \( W^2 \)-dependence in \(^{12}\) breaks down. The results in Fig. 4, obtained by Spiesberger and myself \(^b\), are based on a simple logarithmic ansatz for the spectral weight functions in \(^{12}\) and \(^{b}\).

\(^b\)Compare also Ref.\(^{13}\) for an analysis of the data that is similar in spirit but different in detail.
which for the photoproduction limit implies a logarithmic rise with energy,

\[ \sigma_T(W^2, Q^2 \to 0) = \sigma_{\gamma p}(W^2) = N \left( \frac{W^2}{m_0^2} \right) \left( \log \frac{W^2}{m_0^2} - 1 \right) , \]

only valid in the truly high-energy HERA regime of \( W > \sim 50 \) GeV. For details, I refer to Ref. 5. Let me note, however, that in principle the magnitude and energy dependence of the photoproduction cross-section is sufficient to determine the parameters \( N \) and \( a \), once \( m_0^2 \) is fixed by the threshold for the effective \( e^+e^- \) continuum. From the fit to H1 and ZEUS data we obtained

\[ N = 5.13 \cdot 4\pi^2\alpha = 1.48 , \]
\[ a = 15.1 , \]

and for the parameter \( \xi \),

\[ \xi = 0.171 . \]

A brief comment concerns the threshold mass,

\[ m_0^2 = 0.89 \text{ GeV}^2 , \]

obtained in the fit. Taking into account the fact that the mass dispersion relations (2) and(3) contain a single threshold mass, \( m_0 \), for the effective \( e^+e^- \) annihilation continuum, rather than
an extra threshold, discriminating the charm, $c\bar{c}$, continuum from the rest, a value for $m_0^2$ larger than $m_{p}^2 = 0.59$ GeV$^2$, such as (12), is to be expected. In fact, restricting the data set being fitted to a value of $Q^2 \lesssim Q^2_{\text{max}}$ with $Q^2_{\text{max}} \lesssim 1$ GeV$^2$, thus suppressing the charm contribution, leads to values of $m_0^2$ consistent with (5), (7), while for any choice of $Q^2_{\text{max}} \gtrsim 10$ GeV$^2$ a stable value consistent with (12) is obtained. A more detailed analysis will obviously have to introduce a separate threshold mass for the charm, $c\bar{c}$, continuum in the mass dispersion relations.

In conclusion, Generalized Vector Dominance provides a unified representation of photoproduction and the low-$x$ proton structure in the kinematic range accessible to HERA. Various refinements remain to be worked out in the near future, such as a more precise treatment of the charm contribution, the incorporation of data at lower energies, and a theoretical analysis of the diffractively produced final state. While details are subject to improvement and change, the principal dynamical ansatz, relating $\sigma_{\gamma^{\ast}p}$ or, equivalently, $F_2$ at low values of $x$ to diffractive scattering (via unitarity) of the states produced in $e^+e^-$ annihilation, is likely to stand the test of time.

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