DIFFRACTIVE DISSOCIATION IN DEEP INELASTIC SCATTERING AT HERA

by

A. Capella, A. Kaidalov, C. Merino and J. Tran Thanh Van

Laboratoire de Physique Théorique et Hautes Energies*
Bâtiment 211, Université de Paris-Sud, 91405 Orsay cedex, France

Abstract

The diffraction dissociation of virtual photons is considered in the framework of conventional Regge theory. It is shown that the recent HERA data on large rapidity gap events can be successfully described in terms of the Pomeron structure function. Using Regge factorization, the latter can be related to the deuteron structure function. The parameters which relate these two structure functions are determined from soft hadronic diffraction data. The size of the shadowing corrections at low $x$ and large $Q^2$ is also obtained.

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Experiments at HERA provide new possibilities to study diffractive processes and the properties of the Pomeron. Recently, spectacular large rapidity gap events in deep inelastic scattering at very small $x$ have been observed by Zeus$^{[1]}$ and H1$^{[2]}$ collaborations at HERA. On the other hand, diffractive production has been studied for many years in high energy hadronic interactions and a large amount of information on these reactions has been obtained (see for example reviews$^{[3−5]}$). A new unexplored region of diffraction production by highly virtual photons is now accessible at HERA.

Here we shall consider the process of diffractive dissociation of highly virtual photons in the framework of Reggeon theory, which is the basis for the description of diffractive processes in hadronic interactions. We shall demonstrate that the characteristic features of the data on large rapidity gaps events can be understood using the Regge based description of structure functions, introduced in a previous work$^{[6]}$, together with our knowledge of diffractive production in high-energy soft hadronic collisions.

The amplitude of the single diffractive production of a hadronic state $X$ is described by the Pomeron exchange diagram shown in Fig. 1. The initial particle $i$ in this figure can be either a hadron or a photon (real or virtual). This diagram corresponds to single diffractive production without dissociation of the initial proton, while double diffraction corresponds to dissociation of both projectile and target. At high energies $s >> m^2$, when the total rapidity interval $\xi = \ell n \frac{s}{m^2}$ is large, these diagrams describe kinematical configurations of final particles in which large rapidity gaps ($\Delta y$) are present.

Consider first the single diffraction dissociation of a real particle $i$ (Fig. 1). In the pole approximation for Pomeron exchange the cross section of this process is given by (see e.g.$^{[3]}$)

$$s_1 \frac{d\sigma_D}{dt ds_1} = \frac{1}{16\pi} \left( g_{pp}(t) \right)^2 \exp \left[ 2 (\alpha_P(t) - 1) \xi' \right] \sigma_{iP}^{\text{tot}}(s_1, t)$$

where $s_1 \equiv M^2$ is the square of the invariant mass of the hadronic system $X$, $t = (p' - p)^2$
is the invariant momentum transfer to the final proton and $g_{PP}^{P}(t)$ is the vertex describing the Pomeron coupling to a proton. The Feynman-$x$ of the Pomeron is defined by $x_P = \frac{s_1}{s}$, and $\xi' = \ell n \ s/s_1 \approx \Delta y$. The last term in eq. (1) is the total Pomeron-particle cross-section\[^{[7]}\]. It is obtained by summation over all final states $X$ and over their phase space. Note that this quantity, contrary to the cross section of usual particles, is just defined by eq. (1), but cannot be interpreted as a physical observable on its own. At large $s_1 >> m_i^2$ this cross section is determined by the Pomeron and Regge exchanges and has the form (see Fig. 2):

$$
\sigma_{iP}^{tot}(s_1, t) = \sum_k g_{ii}^k(0) r_{PP}^k(t) \left(\frac{s_1}{s_0}\right)^{\alpha_k(0)-1},
$$

with $s_0 = 1 \text{ GeV}^2$. Here $\alpha_k$ denotes the trajectory of any reggeon $k$ contributing to the $i-P$ elastic amplitude, and $g_{ii}^k(0)$ and $r_{PP}^k(t)$ are the couplings of the reggeon $r$ to particle $i$ and to the Pomeron, respectively (see Fig. 2). The only reggeons $k$ that contribute to eq. (2) are the Pomeron itself and the $f$-trajectory. Note that in the first factor of eq. (1) we have only considered the Pomeron contribution. The contribution of secondary reggeons such as the $f$-trajectory is important only for $x_P > 0.05$ to 0.1.

In the case when particle $i$ is a virtual photon (with virtuality $q^2 = -Q^2$), $\sigma_{\gamma^*P}^{tot}$ and $g_{ii}^k$ in eqs. (1) and (2) depend on $Q^2$. For large values of $Q^2$, it is convenient to introduce the structure function of the Pomeron\[^{[8-10]}\], $F_P$, related to the total cross-section of a virtual photon $\sigma_{\gamma^*P}^{tot}$ in the same way as the total cross section of a virtual photon on a proton is related to the proton structure function $F_2$:

$$
\sigma_{\gamma^*P}^{tot}(s_1, Q^2, t) = \frac{4\pi^2\alpha_{em}}{Q^2} F_P(s_1, Q^2, t).
$$

Note that in the present case there is an extra variable $t$ (the virtuality of the Pomeron). It is natural to assume\[^{[8-10]}\] (and calculations of the simplest QCD diagrams
confirm it\cite{10-15}) that at large $Q^2$ the function $F_P$ obeys approximate Bjorken scaling (up to a logarithmic dependence on $Q^2$, given by QCD-evolution), i.e. depends essentially on the variable

$$x_1 = \frac{Q^2}{2(p_p \cdot p_i)} \simeq \frac{Q^2}{s_1 + Q^2} . \quad (4)$$

It follows from eq. (4) that the characteristic masses in the diffractive production by highly virtual photon are $s_1 \sim Q^2$. For fixed values of $x_1$ the $Q^2$-dependence of the diffraction production process is the same ($1/Q^2$) as for the total cross section of the virtual photon on the proton, i.e. it is a main twist effect. On the other hand the diffractive production of a state with fixed mass (e.g. $\rho, \omega, \phi, \ldots$) decreases faster with $Q^2$.

In the case of virtual photons we also have the Bjorken variable

$$x = \frac{Q^2}{2(p_p \cdot p_i)} \simeq \frac{Q^2}{s + Q^2} .$$

The longitudinal momentum fraction taken by the Pomeron is $x_P = x/x_1$, and, consequently, the variable $\xi'$ in eq. (1) is now given by $\xi' = \ln x_1/x$.

The crucial point of the present work is the following: using the reggeon factorization property in eq. (2) it is possible to relate the Pomeron structure function $F_P$ to the proton structure function $F_2^p$ (or more precisely to that of the deuteron $F_2^d$, since the isospin of the Pomeron is equal to zero). Furthermore, the parameters in $F_P$ are entirely given in terms of those in $F_2^d$, plus a few reggeon couplings which can be obtained from soft hadronic diffraction in the framework of conventional Regge theory.

**The model.** In a previous paper\cite{6}, we have introduced the following parametrization of the proton (and deuteron) structure function $F_2^p(F_2^d)$ at moderate values of $Q^2$, based on Regge theory:
\[ F_2(x, Q^2) = A \ x^{-\Delta(Q^2)} (1 - x)^{n(Q^2)+4} \left( \frac{Q^2}{Q^2 + a} \right)^{1+\Delta(Q^2)} + B \ x^{1-\alpha_R} (1 - x)^{n(Q^2)} \left( \frac{Q^2}{Q^2 + b} \right)^{\alpha_R} \]

with

\[ \Delta(Q^2) = \Delta_0 \left( 1 + \frac{2Q^2}{Q^2 + d} \right), \quad n(Q^2) = \frac{3}{2} \left( 1 + \frac{Q^2}{Q^2 + c} \right) \]

where \( 1 + \Delta(Q^2) \) is the Pomeron intercept and \( \alpha_R \) that of the secondary reggeon. The only secondary trajectory that contributes to \( F_2^d \) is the \( f \) one. By comparing the Pomeron structure function (Fig. 2) with that of the nucleon (Fig. 3), and using factorization, we see that the Pomeron structure function \( F_P \) is identical to \( F_2^d \), given by eq. (5), except for the following changes in its parameters

\[ F_P(x_1, Q^2, t) = F_2^d \left( x_1, Q^2; A \rightarrow eA, B \rightarrow fB, n(Q^2) \rightarrow n(Q^2) - 2 \right) \]

and where

\[ e = \frac{r_{PP}^P(t)}{g_{pp}^P(0)}, \quad f = \frac{r_{PP}^f(t)}{g_{pp}^f(0)}. \]

Note that the \( t \)-dependence of \( F_P \) is entirely due to that of the triple reggeon couplings \( r(t) \). Comparison with experiment shows that the \( t \)-dependence of \( r_{PP}^P \) and \( r_{PP}^f \) is practically the same and very weak. We have incorporated it in the \( t \)-dependence of \( g_{pp}^P(t) = g_{pp}^P(0) \ exp \ (Ct) \), with \( C = 2.2 \ \text{GeV}^{-2}[3] \). In this way \( e, f \) and \( F_P \) become independent of \( t \). All the parameters in \( F_2^d \) are given in ref. [6]. In particular \( B = B_u + B_d = 1.2 \).

The parameters \( e \) and \( f \) in \( F_P \) are obtained from conventional triple reggeon fits to high mass single diffraction dissociation for soft hadronic processes. The most important
point in relating soft and hard diffraction dissociation is the following. As discussed in ref. [6], absorptive (or shadowing) corrections due to rescattering are very small at large $Q^2$ but may be quite large at $Q^2 = 0$. This is particularly true for diffractive processes. Indeed, it has been shown in ref. [16] [17] that absorption corrections to the proton diffractive cross-section are quite large: they reduce the value of the unabsorbed cross-section by a factor of 3 to 4. (In the case of pions and photons, vector mesons, the effect is somewhat smaller). Since absorptive corrections decrease very rapidly when $Q^2$ increases, it is clear that, in the above considerations, valid at moderate and large values of $Q^2$, we deal with unabsorbed cross-sections. The values obtained[17] in this way are: $e = 3f = 0.1$. It should be stressed, however, that, while the value of $e$ is rather well determined, there are uncertainties in the determination of $f$. In conventional triple reggeon fits[3] with the Pomeron intercept equal to 1, one obtains for the values of $e$ and $f$ in the absorbed diffractive cross-sections $e \approx f$. With a Pomeron intercept above 1 (as the one in the present paper), the value of $e$ is practically unchanged while the value of $f$ decreases by a factor of 2 to 3. Precise data from HERA should allow a good determination of the parameter $f$.

The Pomeron trajectory in the second factor of eq. (1) is parametrized as $\alpha_P(t) = 1 + \bar{\Delta} + \alpha't$ with $\alpha' = 0.25$ GeV$^{-2}$. Here we use the value of the intercept at $Q^2 \leq 1$ GeV$^2$. This is due to the fact that the high virtuality of the photon does not “penetrate” into the lower part of the diagram of Fig. 3. Following refs. [16] and [17] we use $\bar{\Delta} = 0.13$, which corresponds to the effective Pomeron intercept obtained without eikonal absorptive corrections. (In view of the smallness of the triple reggeon coupling $r$, the eikonal absorptive corrections in the lower part of the diagram are expected to be small).

The only remaining parameter is the proton-Pomeron coupling $g^p_{pp}(0)$ for which we use the value $(g^p_{pp}(0))^2 = 23$ mb[16][17][18].

Apart from the change in the parameters resulting from Regge factorization, the Pomeron and proton (or deuteron) structure functions also differ in the $x \to 1$ behaviour.
The Dual Parton Model arguments relevant for $Q^2 = 0$ lead\cite{19} to $n(0) = -1/2$ (as compared to $3/2$ for the proton), and dimensional counting rules relevant for $Q^2 \neq 0$ lead\cite{20} to $n = 1$ (as compared to $3$ for the proton). This provides the justification for the change in $n(Q^2)$ introduced in eq. (6).

As discussed in our previous paper\cite{6}, the parametrization in eqs. (5) and (6) has to be used at moderate $Q^2$ (up to $Q^2 \sim 5 \div 10 \text{ GeV}^2$). At larger values of $Q^2$, we use eq. (6) as an initial condition for QCD evolution, proceeding as in ref. \cite{6}. In doing so we determine $F_P$ at all values of $Q^2$. Note that in order to perform the QCD evolution we have to know the gluon distribution function. In the proton case, the normalization of this distribution was obtained\cite{6} using the energy-momentum conservation sum rule. In the Pomeron case, $\sigma^{tot}_{\gamma^* P}$ is not an ordinary cross-section (see the discussion following eq. (1)), and therefore this sum rule cannot be applied. Fortunately, the normalization of the gluon structure function can be obtained in this case using Regge factorization, i.e. multiplying the gluon distribution in the proton, given in \cite{6}, by the factor $e = 0.1$. However, one expects that the gluon distribution in the Pomeron is harder than the one in the nucleon. In this case, the QCD evolution would be modified and this would produce some changes in our predictions (see below).

**Numerical results.** In order to compare our predictions with preliminary HERA data we first compute the contribution to $F_2$ of the diffractive events. This is obtained from eq. (6) upon integration in $x_1$ and $t$. Using eqs. (1) to (3) we have

$$F_{2DD}(x,Q^2) = \frac{1.3}{16\pi} \int \frac{ds_1}{s_1} \int dt \left( g^{PP}_P(t) \right)^2 \exp \left[ 2 (\alpha_p(t) - 1) \xi' \right] F_P(x_1,Q^2,t) . \quad (7)$$

The integral $s_1$ runs from $0.4 \text{ GeV}^2$ to $(x_P^{max}/x - 1)Q^2$. The dependence on the Bjorken-$x$ variable is due to the dependence of $\xi'$ on $x$ and to the upper limit of the integration on $s_1$. This value is determined using the cut $x_P \leq 0.01$ present in the HERA data. Note also
that HERA data contain both single and double diffraction. The latter is estimated to be \( \approx 30\% \) of the former. This accounts for the factor 1.3 in eq. (7). Our results are presented in Fig. 4 for the \( x \) dependence at fixed value of \( Q^2 \), and in Fig. 5 for the \( Q^2 \) dependence at fixed value of \( x \), and compared with preliminary data from the H1 collaboration. The agreement both in shape and absolute value is satisfactory.

In Fig. 6, we show the theoretical \( x_P \) dependence of \( F_{2DD}(x_1, x_P, Q^2) \) for different bins of \( Q^2 \) and \( x_1 \). It has to be noticed that in eq. (1) the \( x_P \) dependence is basically contained in the factor \( x_P^{-2\Delta} \), the Pomeron structure function of eq. (6) being independent of it. This explains why the \( x_P \) dependence of \( F_{2DD}(x_1, x_P, Q^2) \) appears to be the same for all bins when only one Pomeron is exchanged.

We also present in Fig. 7 our prediction for the Pomeron structure function obtained from eq. (6) at different values of \( Q^2 \). It will be important to check at HERA whether there is an approximate Bjorken scaling for the Pomeron structure function and to study effects of scaling violation due to QCD-evolution. As it was emphasized above these effects are sensitive to the behaviour of the gluon distribution in the Pomeron for \( x_1 \sim 1 \). This point deserves further study.

In Reggeon theory\cite{21}, shadowing corrections to the proton structure function due to double-Pomeron exchange are equal in magnitude and opposite in sign to the diffractive cross-section. Thus, we can reliably calculate the amount of shadowing in deep inelastic scattering at very small \( x \), by using our model in the kinematical regions not yet covered by experiment. More precisely, we compute the ratio \( F_P(x, Q^2)/F_{2}^p(x, Q^2) \) where \( F_{2}^p \) is the proton structure function computed in ref. \cite{6} and \( F_P \) is given by eq. (7) with the value \( s_1^{max} \) obtained using \( x_P \leq 0.1 \), and we show the theoretical result in Fig. 8. In the region of large \( Q^2 \) and in the interval \( 10^{-4} < x < 10^{-3} \) the shadowing effects are rather small, (16% \( \div 18\% \) at \( Q^2 = 15 \text{ GeV}^2 \) and 12% \( \div 14\% \) at \( Q^2 = 30 \text{ GeV}^2 \), at \( x = 10^{-4} \)). Therefore, at HERA one does study the properties of the unabsorbed Pomeron.

Before concluding we would like to discuss the possibility of using the above formulae
to describe diffractive production with real photons \((Q^2 = 0)\). Although this is possible, there is, however, a subtility which is precisely related to the fact (already discussed above) that, for diffractive processes, absorptive or shadowing corrections due to rescattering are very small at large \(Q^2\) but are quite large at \(Q^2 = 0\). Thus, when we put in our formulae \(Q^2 = 0\), we obtain the unabsorbed values of diffractive cross-sections of real photons.

In order to compare with experiment, we have to correct the obtained cross-section for absorption (which amounts roughly to reduce by a factor of 2 to 3 the values resulting from the above formulae). In this way, the value of \(R\) for real photons turns out to be \(R \sim 0.30 \div 0.35\) - including the contribution of low mass vector mesons \((\rho, \omega, \phi)\).

In conclusion, using a parametrization of the structure functions\([6]\) based on Regge theory together with Reggeon factorization, we have been able to describe the properties of the large rapidity gap events observed at HERA in terms of Regge parameters determined from soft diffraction in hadronic processes.

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Figures Captions

Fig. 1 Diffractive dissociation of particle $i$ in an $i$-$p$ collision.

Fig. 2 Triple reggeon diagram obtained by squaring, in the sense of unitarity, the single diffraction dissociation diagram of Fig. 1.

Fig. 3 Reggeon diagram for elastic $i$-$p$ scattering. When $i$ is a virtual photon this diagram corresponds to the proton structure function.

Fig. 4 Diffractive contribution to $F_2(x, Q^2)$ versus $x$, at fixed $Q^2$. The curves are obtained from eq. (7) with $x_P^{max} = 0.01$. The preliminary data from the H1 collaboration, taken from the second item in ref. [2], have the same $x_P$ cut. The upper (lower) curves correspond to $e/f = 2$ ($e/f = 3$).

Fig. 5 The same as in Fig. 4 for $F_{2DD}(x, Q^2)$ versus $Q^2$, at fixed $x$. (a) $x=0.00042(*)^{125}$, (b) $x=0.00075(*)^{25}$, (c) $x=0.00133(*)^{5}$, (d) $x=0.00237(*)^{1}$.

Fig. 6 $F_{2DD}(x_1, x_P, Q^2)$ versus $x_P$ for different bins of $Q^2$ and $x_1$. The upper (lower) lines correspond to $e/f = 2$ ($e/f = 3$) in the case of single diffraction.

Fig. 7 The structure function of the Pomeron $F_P(x_1, Q^2)$ obtained from eq. (6). The curves in 1 (2) have been obtained by taking $e/f = 2$ ($e/f = 3$).

Fig. 8 Shadowing contribution versus $x$ for two different values of $Q^2$. Full (dashed) lines have been obtained with $e/f = 2$ ($e/f = 3$).
Figure 4
Figure 5

\[ F_{2}^{DD}(x, Q^2) \]
Figure 6
Figure 7

Figure 8