NON-FACTORIZABLE CONTRIBUTIONS TO THE LARGE RAPIDITY GAP AT HERA *

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The large rapidity gap events from HERA are analyzed within a model containing a
pomeron and an f – reggeon contribution. The choice for the pomeron contribution
is based on the Donnachie-Landshoff model. The dependence of the “effective
intercept” of the pomeron on the momentum fraction β and on its Bjorken variable
ξ is calculated.

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The increasing precision of the HERA-measurements and the extension of
the kinematical domain where diffractive deep inelastic scattering (DIS) was
measured, necessitates the perfection of the relevant theoretical calculations
beyond the simple, single, factorizable pomeron exchange, as it was originally introduced in \(^1\) and was used in subsequent papers (for a partial list of recent papers on the subject see \(^2\). Although the role of other than a single pomeron contribution to the rapidity gap has been realized by the theorists long ago \(^3\), it was only recently \(^4\) that the effect was measured experimentally.

Studies of diffractive DIS beyond the simple pole exchange approximation have two, albeit interrelated aspects: one is rather technical and has to deal with various contributions that break factorization; the other one is conceptual, dealing with the nature and in particular the internal structure of the pomeron(s).

The pomeron itself appears to be a complicated object; according to the perturbative QCD calculations \(^5\), it corresponds to an infinite number of singularities in the complex angular momentum plane accumulating at the rightmost point, \(J = 1 + \delta, \delta \geq 0.3\).

Below we consider a simple model for the pomeron: that of Donnachie and Landshoff \(^6\), corresponding to a single "supercritical" Regge pole exchange. Other options are possible, for example the dipole pomeron (DP) model (see \(^6\)) with two terms - one constant and the other one rising with energy logarithmically. This DP model is close to that of D-L as to the numerical fits - both producing a moderate ("soft") energy dependence, but the latter one may be used also as a polygon for studying the effects coming from the pomeron non-factorizability. Here we will limit ourselves to consider the first choice.

Other possible contributions are those allowed in elastic hadron (e.g. \(pp\)) scattering: the odderon, \(f, \omega\), etc reggeons, daughter trajectories, \(\pi\) exchange etc. We confine our analysis by considering two major contributions, namely the pomeron (single and double poles) plus an effective reggeon, essentially dominated by \(f\). Other contributions are either negligibly small or they may be absorbed by the above ones (subtle details - like \(\pi\)-exchange - have not been settled in the literature even in the case of the much better known case of elastic scattering).

Explicitly, the spin-averaged differential cross-section for a diffractive DIS, ignoring spin and the proton mass, is (see Fig. 1 for kinematics and notations):

\[
d\sigma = \frac{(2\pi)^{-5}}{2pl} \frac{d^3p}{2p^0} \frac{d^3p'}{2p'^0} \sum_n \left( \frac{d^3k_n}{2k_n} \delta(p + l - l' - k_n - p') |T(p + l \to p' + l' + k_n)|^2 \right).
\]

We consider the scattering amplitude corresponding to two Regge exchanges \(R_i\) (\(R_i = P, f\)):

\[
T \equiv T(p + l \to p' + l' + k_n) = \sum_i T^{(i)} = \sum_i F(R_i + l \to l' + k_n) \Phi_i(\xi, t),
\]
where
\[ \Phi_i(\xi, t) = \left( e^{i\pi/2\xi} \right)^{-\alpha_i(t)} \beta_i(t), \]
and the slowly varying function \( \sin(\pi \alpha/2) \) has been absorbed by the residue.

By denoting
\[ F(R_i + l \rightarrow l' + k_n) = \frac{e}{q^2} F(R_i + q \rightarrow k_n) = F_{R_i+l} \]
we get in the case of two Regge exchanges, \( P \) and \( f \),
\[ |T|^2 = |F_{P+t} \Phi_P(\xi, t)|^2 + |F_{f+t} \Phi_f(\xi, t)|^2 + 2 \Re[F_{f+t} F_{P+t}^\ast \Phi(\xi, t) \Phi_P^\ast(\xi, t)]. \tag{1} \]
The first two terms in Eq. (1) assume an immediate physical interpretation. Really, the cross section for \( R_i + l \rightarrow l' + X^n \) is
\[ d\sigma_{R_i+l} = \frac{1}{2r_l} \frac{d^3p}{2l^{1/2}} \sum_n \left( \frac{d^3k_n}{2k_n^0} g(t)(r + l - l' - k_n)|F_{R_i+t}|^2 \right). \]
Thus, for the \( p + l \rightarrow p' + l' + X^{(n)} \) differential cross section with the exchange
of a single reggeon $R_i$ one has

$$d\sigma^{(i)} = \frac{r}{pl} \frac{d^3 P'}{2p'0} |\Phi(\xi, t)|^2 d\sigma_{R_i+l} \simeq \frac{\pi}{2} d\xi dt |\Phi(\xi, t)|^2 d\sigma_{R_i+l},$$

where the relations $(rl)/(pl) \simeq (rq)/(pq) = \xi$ and $(d^3 P')/(2p'^0) \simeq 1/4d\phi'_0 d\xi dt,$ valid for small $\xi$, were used.

The last term in the r.h.s. of Eq. (1) is related to the imaginary part of the $f + l \to P + l'$ transition amplitude, and consequently, in $d\sigma$ a term proportional to

$$d^3 \vec{p}' \sum_n \frac{d^3 k_n}{2k_n^0} \delta^4(p + l - p' - l' - k_n) F_{f+l} F_{P+l}^*,$$

emerges, corresponding to an $f$ meson dissociating into a pomeron. Following an "educated guess" by N.N.Nikolaev, W.Schäfer and B.G.Zakharov, we ignore this contribution as being small compared to the elastic case.

As recently noticed by J.Ellis and G.G.Ross, the rapidity cuts commonly employed in diffractive DIS measurements require the struck parton in the pomeron be far off shell in a sizable region of parameter space. The H1 cuts correspond to very small $k^2_{min}$ that justify the treatment of the pomeron structure function.

Once the above-mentioned approximation has been accepted, one may write

$$d\sigma_{R_i+l} = d\beta G_{q/R_i}(\beta) dq^2 d\phi' \frac{d\hat{\sigma}}{dq^2 d\phi'} (k + l \to k' + l'),$$

in terms of the parton-lepton cross section $d\hat{\sigma}$, where $k = \beta r$ and $G_{q/R_i}$ is the structure function of the Reggeon $R_i$.

The above detailed presentation of the formalism was intended to fix the basic notions of diffractive DIS, to avoid further confusion and misunderstanding.

Now we proceed towards a quantitative analysis of the phenomenon by using explicit models for the reggeon fluxes and their structure functions, based on our experience in treating both elastic and inelastic scattering.

Let us write our basic formula (1) in terms of the commonly used notation for diffractive DIS structure functions:

$$F_2^{D(4)}(x, t; \beta, Q^2) = A[\Phi_{q/P}(\xi, t)G_P(\beta, Q^2) + a\Phi_{q/f}(\xi, t)G_f(\beta, Q^2)],$$

where, apart from the overall normalization factor $A$, $a$ is the only free parameter of the model.
The $f$-Reggeon flux is determined uniquely from standard fits to elastic hadron scattering (see e.g. [1]):

$$\Phi_f(\xi, t) = g_f^2(t)\xi \exp[(1 - 2\alpha_f(t))L],$$

where $g_f(t) = \exp[b_f\alpha_f(t)]$, $\alpha_f(t) = \alpha_f(0) + \alpha'_f t$ and $L \equiv \ln(1/\xi)$.

We use "world average" values for the above parameters [3]: $b_f = 5$, $\alpha_f(0) = 0.65$ and $\alpha'_f = 0.9 \text{ GeV}^{-2}$.

The pomeron flux

$$\Phi_{q/P}^{D_L}(\xi, t) = [\exp(b(\alpha - 1)\xi^{-\alpha})]^{2\xi}, \quad (5)$$

where $\alpha \equiv \alpha_P(t) = 1 + \delta + 0.25t$, $\delta = 0.08$, is integrated in $t$. (For an explicit treatment of the $t-$dependence see [2].)

We make standard choices for the structure functions. For the $f$-reggeon we choose the following parametrization by Glück, Reya and Vogt [11]:

$$\beta G_f(\beta, Q^2) = N\beta^a(1 + A\sqrt{\beta})(1 - \beta)^D \quad (6)$$

(Originally intended for pions). The values of the parameters $N, a, A$ and $D$, together with their explicit $Q^2$-dependence may be found in Ref. [11]. The parameter $N$ will be rescaled by our fitting procedure. Actually, we are not too much concerned with any $Q^2$ dependence since it is known [11] to be weak anyway.

A representative fit to the diffractive structure function $F_2^{D(3)}$ is shown in Fig. 2 for fixed $Q^2 = 12 \text{ GeV}^2$ and $\beta = 0.175, 0.375$.

The non-trivial dependence of the effective power $n(\beta/\xi) = \partial \ln F/\partial \ln \xi$, calculated from our model, is shown in Fig. 3 as a function of $\beta$ and $\xi$. Factorization breaking, that manifests itself in the $\beta$ dependence of the effective power $n$, is evident at larger $\xi$ values, where the $f$ contribution is no more negligible with respect to the pomeron one. Since we use in this analysis the published 1993 H1 data [4], differences in the $\beta$-dependence of $n(\beta)$ from the result of [6] are expected. A maximum of $n(\beta)$, around $\beta \approx 0.6$ at large $\xi$, seems to be a feature present also in the 1994 preliminary H1 data [7] where different selection cuts, e.g. in the $t$-dependence, are applied.

Note that the $f$-reggeon intercept as extracted from various fits to the data has a trend to increase progressively with the time. The "old-fashioned" value of $\alpha_f(0) = 0.5$ is incompatible with the data, while another extreme, 0.8 is claimed by some authors [5] to be compatible with the data. We (see e.g. [1]) consider $\alpha_f(0) = 0.65$ to be a reasonable value both in the scattering ($t < 0$) and resonance ($t > 0$) region. Due to the strong $P-f$ mixing, the pomeron and $f$-reggeons intercepts are strongly correlated.
Figure 2: A representative fit of \( F_2^{D(3)}(x, \beta, Q^2) \) to the published H1 data for fixed \( Q^2 = 12 \text{GeV}^2 \) and \( \beta = 0.175, 0.375 \).
Figure 3: $\xi$ and $\beta$ dependence of $n(\xi, \beta) = \partial \ln F/\partial \ln \xi$ with the parameters fitted to the data of Ref. [12]. The departure from factorization, manifest in the $\beta$-dependence of $n$, tends to increase with increasing $\xi$. 
To conclude, we have presented an explicit model for factorization-violating diffractive DIS. Some details of the model may still vary but two essential points remain invariant, namely: 1) the overwhelming contribution in the kinematical region of diffractive DIS as measured at HERA comes from the pomeron and the $f$-reggeon. The separation and identification of these objects is a complicated but at the same time interesting problem in doing phenomenology; 2) the pomeron emitted from the lower vertex in Fig.1 is the same as it appears in elastic hadron scattering. Therefore, one can rely on pomeron models fitted to high energy $pp$ and $\bar{p}p$ data. These fits unambiguously fix the energy dependence of the pomeron, which is "soft". In fitting Eq. (4) to the data, the rest of the parameters may be let free.

The pomeron, which is the central object of the present analysis, itself may be parametrized in various ways. Here, we have presented a typical model of the pomeron, other possibilities will be considered elsewhere. Notice that a different type of the pomeron (see and earlier references therein) gives rise to a strong rise of $n(\beta)$ at small $\beta$, that however may be compensated by various subleading contributions.

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For the sake of definiteness, we did not consider the case of double diffraction dissociation. Our results can be generalized to the case when the incident proton dissociates as well.
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