Reggeon and pion contributions in semi-exclusive diffractive processes at HERA

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Abstract

A detailed analysis of semi-exclusive diffractive processes in $e\rho$ DIS at HERA, with the diffractive final states in the forward direction is presented. The contributions of the subleading $f_2$, $\omega$, $a_2$, $\rho$ reggeons and the pion exchanges to the diffractive structure function with the forward proton or neutron are estimated. It is found that the $(a_2, \rho)$ reggeons are entirely responsible for the forward neutron production at $x_F < 10^{-3}$. The $\pi N$ production in the forward region is estimated using the Deck mechanism. The significance of this reaction for the processes measured at HERA, especially with the leading neutron, is discussed.
The diffractive processes in deep inelastic scattering observed recently at the \( ep \) collider HERA at DESY by the H1 and ZEUS collaborations \([1, 2]\), were interpreted in terms of the exchange of the leading Regge trajectory corresponding to the ”soft” pomeron \([3, 4, 5, 6]\) (for alternative explanations see \([7, 8]\)). In this approach, first proposed by Ingelman and Schlein\([9]\), the diffractive interaction is treated as a two-step process: an emission of the pomeron from a proton and subsequent hard scattering of a virtual photon on partons in the pomeron. The idea that the pomeron has partonic structure was experimentally supported by the hadron collider experiments \([10]\). In \( ep \) scattering this idea is expressed through the factorization of the diffractive structure function

\[
\frac{dF_D^2}{dx_{\mathbf{p}}dt}(x, Q^2, x_{\mathbf{p}}, t) = f^{\mathbf{p}}(x_{\mathbf{p}}, t) F_2^{\mathbf{p}}(\beta, Q^2),
\]

where \( f^{\mathbf{p}}(x_{\mathbf{p}}, t) \) is the pomeron flux in the proton and \( F_2^{\mathbf{p}}(\beta, Q^2) \) its DIS structure function. The kinematical variables are defined as follows

\[
Q^2 = -q^2, \quad t = (p - p')^2, \quad x = \frac{Q^2}{2pq}, \quad \beta = \frac{Q^2}{2q(p - p')}, \quad x_{\mathbf{p}} = \frac{x}{\beta}.
\]

and \( q = p_e - p'_e \), where \( p_e, p'_e, p \) and \( p' \) are the momenta of the initial and final electron, initial, and recoiled proton respectively.

The pomeron structure function \( F_2^{\mathbf{p}}(\beta, Q^2) \) is related to the parton distributions in the pomeron in a full analogy to the nucleon case. Because the pomeron carries the vacuum quantum numbers, the number of independent distributions is smaller than for the proton. Recently the partonic structure was estimated \([3, 4, 5]\), and independently fitted to the diffractive HERA data \([1, 2]\). Contrary to the nucleon case a large gluon component of the pomeron was found at \( \beta \to 1 \), \([11]\).

1 Reggeons and pions in inclusive hard diffraction

The new data shown by the H1 collaboration at Warsaw conference \([12]\) indicate breaking of the factorization \([1]\). In order to describe this effect it was recently proposed to include the contributions of subleading reggeons \([12, 13, 14]\). In this generalized approach the diffractive structure function can be written as:

\[
\frac{dF_D^2}{dx_{\mathbf{p}}dt}(x, Q^2, x_{\mathbf{p}}, t) = f^{\mathbf{p}}(x_{\mathbf{p}}, t) F_2^{\mathbf{p}}(\beta, Q^2) + \sum_R f^R(x_{\mathbf{p}}, t) F_2^R(\beta, Q^2),
\]

where \( f^R \) and \( F_2^R \) are reggeon flux and structure function respectively. \( ^1 \)

In the present paper we take the pomeron flux factor of the form given in \([4, 15]\)

\[
f^{\mathbf{p}}(x_{\mathbf{p}}, t) = \frac{N}{16\pi} x_{\mathbf{p}}^{1-2\alpha_p(t)} B_{\mathbf{p}}^2(t),
\]

\( ^1 \)To be precise the term ”diffractive processes” applies only to processes described by the pomeron exchange. For simplicity we shall use the same terminology for the non-pomeron reggeon exchanges including processes with the forward neutron in the final state which correspond to \( I = 1 \) exchange.
where $\alpha_{\gamma}(t) = 1.08 + (0.25 \text{ GeV}^{-2})t$ is the "soft" pomeron trajectory, $B_{\gamma}(t)$ describes the pomeron-proton coupling and $N = 2/\pi$, following the discussion in [13]. In analogy to the pomeron the subleading reggeon flux factors are parametrized as

$$f^R(x_{\gamma}, t) = \frac{N}{16\pi} x_{\gamma}^{1-2\alpha_R(t)} B^2_R(t) |\eta_R(t)|^2,$$

where $\alpha_R(t) = \alpha_R(0) + \alpha'_R t$ is the reggeon trajectory, $B_R(t)$ describes the coupling of the reggeon to the proton and is assumed to have the form $B_R(t) = B_R(0) \exp \left( \frac{t}{2\Lambda_R} \right)$ with $\Lambda_R = 0.65 \text{ GeV}$, as known from the reggeon phenomenology in hadronic reactions [16]. The function $\eta_R(t)$ is a signature factor [17]; $|\eta_R(t)|^2 = 4 \cos^2(\pi \alpha_R(t)/2)$ and $|\eta_R(t)|^2 = 4 \sin^2(\pi \alpha_R(t)/2)$ for even and odd signature reggeons respectively.

The analysis done in [13] for the isoscalar reggeons ($f_2, \omega$) shows that this contribution to the diffractive structure function becomes important for $x_{\gamma} > 0.01$. In the present paper we extend this analysis by including the isovector subleading reggeons ($a_2, \rho$). Although the isovector reggeons contribution to the total diffractive structure function is small, it becomes important for the processes with leading neutron in the final state. We will show that for small values of $x_{\gamma}$ this is the dominant contribution. In addition, we add to our analysis the one-pion exchange contribution which is expected to be important at large $x_{\gamma}$ values. The pionic contribution to deep inelastic lepton-proton scattering (Sullivan process) was found to provide a parameter-free description of the experimentally observed $\bar{u} - \bar{d}$ asymmetry in the proton [18].

In the past several phenomenological methods were used to determine the contribution of subleading reggeons in hadronic reactions. Inspired by the success of a recent parametrization of the total hadronic cross sections (see for instance [19]) by Donnachie and Landshoff [20] we parametrize total cross sections as:

$$
\sigma_{tot}^{pp}(s) = \sigma_P(s) + \sigma_{f_2}(s) + \sigma_\omega(s) + \sigma_{a_2}(s) + \sigma_{\rho}(s), \\
\sigma_{tot}^{pn}(s) = \sigma_P(s) + \sigma_{f_2}(s) - \sigma_\omega(s) + \sigma_{a_2}(s) - \sigma_{\rho}(s), \\
\sigma_{tot}^{nn}(s) = \sigma_P(s) + \sigma_{f_2}(s) + \sigma_\omega(s) - \sigma_{a_2}(s) - \sigma_{\rho}(s), \\
\sigma_{tot}^{nn}(s) = \sigma_P(s) + \sigma_{f_2}(s) - \sigma_\omega(s) - \sigma_{a_2}(s) + \sigma_{\rho}(s).
$$

Assuming the Regge-like energy dependence of each contribution

$$\sigma_R(s) = \sigma_R(s_0) \left( \frac{s}{s_0} \right)^{1-\alpha_R(0)}$$

and the same intercept for each reggeon, one finds: $\alpha_R(0) = 0.5475$, $B_{f_2}^2(0) = 75.49 \text{ mb}$, $B_{\omega}^2(0) = 20.06 \text{ mb}$, $B_{a_2}^2(0) = 1.75 \text{ mb}$ and $B_{\rho}^2(0) = 1.09 \text{ mb}$. One clearly sees the following ordering

$$B_{f_2}^2(0) > B_{\omega}^2(0) \gg B_{a_2}^2(0) \sim B_{\rho}^2(0),$$

which implies dominance of isoscalar reggeons over isovector ones. One should remember, however, that the contributions of the latter will be enhanced by the appropriate isospin Clebsch-Gordan factor of 3, when going to deep-inelastic $ep$ scattering and including both forward proton and neutron in the final state.
In Fig. 1 we show the $f_2$, $\omega$, $a_2^0$ and $\rho^0$ reggeon flux factors as a function of $x_{IP}$ integrated over $t$ up to the kinematical limit $t_{\text{max}}(x_{IP}) = -\frac{m^2_{IP}}{1 - x_{IP}}$. The flux factors reflect the ordering of the normalization constants (8) and a small difference in shapes at large values of $x_{IP}$ is caused by the fact that the signature factors are different for the positive and negative signature reggeons. A more complicated structure at larger $x_{IP} > 0.1$ (not shown in Fig. 1) comes from the integration limits $t_{\text{max}}(x_{IP})$. One should remember, however, that the Regge (high-energy) approximation applies exclusively to small $x_{IP}$ values, definitively smaller than 0.1. For comparison we also present in Fig. 1 the pomeron (solid line) and pion (dashed line) flux factors.

The pomeron and reggeon structure functions, $F_{2P}^{IP}$ and $F_{2R}^{IP}$ in relation (3), are related to the parton distributions in the pomeron and reggeons in a conventional way, and can be estimated using the "soft" pomeron interaction properties and "triple-Regge" phenomenology [3, 4, 13]. They can also be constrained by the fit to diffractive DIS data from HERA [11, 12]. In the method presented in [4, 13] the small $\beta$ behaviour is the same for both the pomeron and reggeon structure functions:

$$F_{2R}^{IP}(\beta) = A_R \beta^{-0.08}.$$  \hspace{1cm} (10)

The coefficients $A_P$ for the pomeron and $A_R$ for the reggeon are related to the "triple-Regge" $IP/IP/IP$ and $RR/IP$ couplings respectively, and their ratio

$$C_{\text{enh}} = \frac{A_R}{A_P},$$  \hspace{1cm} (11)

is varied in the interval $1 < C_{\text{enh}} < 10$, as suggested by the "triple-Regge" analysis of inclusive processes in hadronic reactions [22]. We extrapolate parametrization (11) to the region of large $\beta$ multiplying the r.h.s. of Eq. (10) by $(1 - \beta)$.

In contrast to the reggeon case the structure function of the pion at large $\beta$ is fairly well known from the analysis of the pion-nucleus Drell-Yan data. The region of small $\beta$, however, cannot be constrained by the available experimental data. In our calculations
we shall take the pion structure function as parametrized in [24], which in the region of $\beta > 0.1$ properly describes the pion-nucleus Drell-Yan data.

Having fixed all ingredients we calculate the contributions of different reggeons to the diffractive structure function integrated over $t$

$$F_2^{D(3)}(x, Q^2, x_{IP}) = f^{p}(x_{IP}) F_2^{p}(\beta, Q^2)$$

$$+ \sum_R f_R(x_{IP}) F_2^{R}(\beta, Q^2) + \sum_{\pi} f_{\pi N}(x_{IP}) F_2^{\pi}(\beta, Q^2) . \quad (12)$$

In Fig. 2 we show the function $x_{IP} F_2^{D(3)}(x_{IP})$ at $Q^2 = 4$ GeV$^2$, for two extreme values of $\beta = 0.01$ and 0.7 and two values of the parameter $C_{\text{enh}} = 2$ and 10, calculated with the quark distribution functions in the pomeron from [4]. The evident rise of the $F_2^{D(3)}$ structure function at $x_{IP} > 0.02$ is an effect of the subleading reggeons and pions; the reggeon contribution being considerably bigger for $C_{\text{enh}} = 10$, whereas for $C_{\text{enh}} = 2$ the pion contribution being equally important (compare dashed and dash-dotted lines). We expect that a future HERA data will allow to fix the presently unknown parameter $C_{\text{enh}}$. It should be noted, however, that the rise of the structure function is not far from the region where the Regge parametrization is not expected to be valid, therefore some caution is required in the analysis of experimental data.

2 Fast forward neutron production

The recent discovery of large rapidity gap events at HERA is based on the inclusive analysis of rapidity spectra of particles which entered the main calorimeter. It is expected that these events are associated with the production of a fast baryon, the proton being probably the dominant case. The installation of the leading proton spectrometer and forward neutron calorimeter opens up a possibility to analyze the diffractive events more exclusively. In particular these experimental efforts will allow to answer the question what fraction of diffractive deep inelastic events is associated with the emission of fast forward proton and neutron.

The model presented above allows to separate the diffractive structure function (12) into two distinct contributions

$$F_2^{D(3)}(\beta, x_{IP}, Q^2) = \Delta^{(p)}(\beta, x_{IP}, Q^2) + \Delta^{(n)}(\beta, x_{IP}, Q^2) , \quad (13)$$

where the upper indices $p$ and $n$ denote the leading proton or neutron observed in the final state respectively. In order to calculate the functions $\Delta^{(p)}$ and $\Delta^{(n)}$ we make use of the isospin symmetry for the flux factors of the corresponding reggeons:

$$f^{p+}_{\rho}(x_{IP}) = 2 f^{p}_{\rho}(x_{IP}) \quad , \quad f^{\Delta^+}_{a_2}(x_{IP}) = 2 f^{\Delta}_{a_2}(x_{IP}) . \quad (14)$$

In Fig 3, we show the proton and neutron contributions to the diffractive structure function (13), marked by the solid lines. As expected the proton contribution dominates
over the neutron one almost in the whole range of $x_F$ because of the dominance of the pomeron contribution in $\Delta^{(p)}$, absent in $\Delta^{(n)}$. The ratio $\Delta^{(n)}/\Delta^{(p)}$ becomes significant ($\sim 0.1$) only for $x_F \approx 0.1$, where the pomeron exchange is suppressed. In this case the reggeon and pion contributions come into play. However, as we have stressed before, this region needs a careful treatment since it might already be unsuitable for the Regge analysis.

The lower curves in Fig.3 shows different contributions to the fast forward neutron production. For large values of $x_F$ the $\pi^+$ exchange process, marked by the dash-dotted line, is the dominant effect for the fast neutron production. The $a_2$ and $\rho$ isovector reggeon exchange contributions, shown by the dashed line, are by the order of magnitude smaller. The situation changes dramatically when $x_F$ is getting smaller. The reggeon exchanges are almost entirely responsible for the fast neutron production for $x_F < 10^{-3}$.

Is it possible to identify these contributions experimentally? In Fig.4 we present the cross section for the fast neutron production integrated over $x$, $Q^2$ and $t$ for $C_{enh} = 10$

$$\frac{d\sigma^{(n)}}{dx_F} = \int_0^{x_F} dx \int_{Q^2_{min}}^{Q^2_{max}(x)} dQ^2 \int_{t_{min}}^{t_{max}(x_R)} dt \frac{d\sigma(ep \rightarrow enX)}{dxdQ^2dx_Fdt}. \quad (15)$$

Here in order to be roughly consistent with the preliminary H1 data \[26\], we have fixed $Q^2_{min} = 2.5 \text{ GeV}^2$ and $t_{min} = -1 \text{ GeV}^2$. Although at $x_F \sim 0.1$ the charged pion exchange dominates, the $(a_2, \rho)$ reggeon exchanges take over at very small $x_F < 10^{-3}$. This is exactly the region of $x_F$ where unexplained by the existing Monte Carlo programs, enhanced strength has been observed \[28\].

### 3 The Deck mechanism

Up to now we have totally neglected the contribution of diffractively produced $\pi N$ and $\pi\pi N$ states. The latter one becomes important only for larger values of $x_F$. \[29\]. For small $x_F$ relevant here only the $\pi N$ contribution is of interest.

Let us try to estimate the contribution of diffractively produced $\pi N$ state in the forward region (with respect to the proton beam). In hadronic reactions the $\pi N$ component is known to be produced dominantly by the Deck mechanism (see for instance \[27\]). The Deck mechanism can be generalized to the case of lepton DIS. In analogy to the hadronic diffractive production there are three lowest order diagrams leading to the $\pi N$ final state (see fig.5.1 in \[27\]). In hadronic reactions for small masses of the pion-nucleon system there is almost exact cancellation of the "s-" and "u-" channel diagrams \[27\]. Both "s-" and "u-" channel diagrams are expected to have much smaller slope in $t$ distribution. Therefore at small $t$, relevant for the FNC measurements, the contribution of "u-" and "s-" channel diagrams is expected to be rather small. The same argument applies to the diffractive production of proton resonances. The decay of protonic resonances into neutron (proton) channel causes both broadening of the $t$-distribution and an effective

\[2\]Here "s-", "u-" and "t-" channel diagrams correspond to the diagrams with single particle exchanges in the "s-", "u-" and "t-" channels of the "process" $Fp \rightarrow \pi N$. 

5
shift towards larger $x_p$ values \[23\], making their identification by the present ZEUS and H1 detectors rather inefficient.

In the following we shall therefore limit to the calculation of the contribution of the "t-" channel diagram in which the pomeron couples to the virtual pion. In the simplest approximation the corresponding structure function with leading proton or neutron can be written as:

$$\frac{dF_2^D}{dx_p dt} = f_{\pi N}(x_\pi, t) \cdot F_{2}^{p/\pi}(\beta, Q^2), \quad (16)$$

where the flux factor here is exactly the same as the one for the Sullivan process (9) (with $x_\pi = x_p$). The effective structure function $F_{2}^{p/\pi}(\beta, Q^2)$ can be estimated as:

$$F_{2}^{p/\pi}(\beta, Q^2) = \int_{\beta}^{1} dx_p^{i} \int_{-\infty}^{t_{max}} dt' f_{p/\pi}(x_p^{i}, t') F_{2}^{p/\pi}(\tilde{\beta}, Q^2), \quad (17)$$

where $\tilde{\beta} \equiv \beta/x_p$. In order to calculate the $f_{p/\pi}$ flux factor we assume empirically established universality of the pomeron coupling to hadrons which involves extra factor 2/3 (two quarks for the pion versus three quarks for the nucleon).

Since the same pion flux factor occurs in Eq.\((12)\) and Eq.\((17)\), it is sufficient to compare the pion structure function $F_{2}^{\pi}$ and the effective structure function $F_{2}^{p/\pi}$ to assess the importance of the Deck mechanism in the fast proton or neutron production. This is done in Fig. 5 where both functions are shown together with their ratio at $Q^2 = 4 \text{ GeV}^2$. It becomes clear that at large $\beta$ the Deck mechanism for production of $\pi N$ states can safely be neglected. The Deck contribution can also be neglected in the spectrum of neutrons as is shown by the dotted line in Fig. 3.

The situation at larger $x_p$ values is less clear if one imposes the large rapidity gap condition. While the Sullivan process does not lead to the large rapidity gap events \[23\], it may be not true for the Deck mechanism. Because of identical flux factors for the Sullivan and Deck mechanisms one expects very similar $x_p$ distributions.

An interesting and unique feature of the Deck mechanism is that it contributes to large rapidity gap events even at $x_L = 1 - x_p$ much smaller than unity. The preliminary ZEUS data \[29\] seem to confirm our approximation. An approximately constant in $x_L$ ratio of

$$\frac{\text{large rapidity gap events with leading neutron/proton}}{\text{total number of events with leading neutron/proton}} \quad (18)$$

in the region $0.65 < x_L < 0.85$. has been observed \[29\], consistent with our simple estimate. A detailed comparison with the experimental spectra will require the inclusion of all experimental cuts and efficiencies and goes beyond of the scope of the present paper.

4 Summary

We made a detailed analysis of semi-exclusive diffractive processes in $ep$ DIS at HERA, with the diffractive final states in the forward (with respect to the incoming proton)
direction. The contributions of the subleading $f_2$, $\omega$, $a_2$ and $\rho$ reggeons as well as the pion exchanges to the diffractive structure function with the forward proton or neutron were estimated. In addition the $\pi N$ production in the forward direction was computed using the Deck mechanism. Our main results are summarize as follows. The isoscalar reggeon exchanges together with the pion exchanges can describe the Regge factorization breaking in the inclusive DIS diffractive data observed by the H1 collaboration.

Their relative strength can be determined by the data. The $\pi^+$ exchange is the dominant mechanism for the fast forward neutron production at large $x_F$ values, while for $x_F < 10^{-3}$ the isovector $(a_2, \rho)$ exchanges play the dominant role. The later effect seems to explain an excess of neutrons produced in the region of small $x_F$ values. Finally, the contribution of the $\pi N$ production in the forward region, described by the Deck mechanism, is found to be rather small in the case of outgoing neutron ($N = n$) and even smaller in the case of outgoing proton ($N = p$). However this effect can be important for the forward neutron production in the region of large values of $x_F$ and/or small $\beta$ with an extra requirement of large rapidity gap. The approximately constant ratio (18), observed by the ZEUS collaboration can be explained by the Deck mechanism of the $\pi N$ production.

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Figure 1: The integrated over $t$ flux factors of $f_2$, $\omega$, $a_2$ and $\rho$ reggeons as a function of $x_P$. For comparison we present the pomeron (dotted) and pion (solid) flux factors.
Figure 2: The structure function $x_P F_{2}^{D(3)}(x_P, \beta, Q^2)$ as a function of $x_P$ at $Q^2 = 4 GeV^2$ for two values $\beta$ and $C_{enh}$. The pomeron ($P$), reggeon (R) and pion ($\pi$) contributions to the total structure function (solid lines) are shown as separate curves.
Figure 3: The $\Delta^{(p)}$ and $\Delta^{(n)}$ contributions to the diffractive structure function $F_{2D}^{(3)}$ as functions of $x_P$ for $Q^2 = 4 GeV^2$ and for two values $\beta$ and $C_{enh}$ (solid lines). The contributions from the $(a_2, \rho)$ (dashed lines) and pion (dot-dashed lines) exchanges to $\Delta^{(n)}$ are shown. The $\pi N$ contribution for neutron from the Deck model is marked by the dotted lines.
Figure 4: Dominant contributions to the charge exchange cross section $d\sigma^{(n)}/dx_p$ as a function of $x_p$. 
Figure 5: The functions $F_2^\pi(\beta, Q^2)$ and $F_2^{\pi/\pi}(\beta, Q^2)$ versus $\beta$ at $Q^2 = 4\text{GeV}^2$ and their ratio.