RENORMALIZED DIFFRACTIVE CROSS SECTIONS AT HERA
AND THE STRUCTURE OF THE POMERON

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ABSTRACT

A phenomenological renormalization scheme for hadronic diffraction is proposed, which achieves unitarization without the need for “screening corrections”. Predictions for diffractive photoproduction cross sections at HERA are presented and compared with experimental results. A new interpretation of hard and deep inelastic diffractive data emerges, in which the momentum sum rule is obeyed by the constituents of a pomeron described as a mixture of quark and gluon color singlets in a ratio dictated by asymptopia.

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1 Introduction

The early success of the concept of the pomeron in describing elastic, diffractive, and total cross sections in a simple Regge-pole model [1, 2] was tempered by the measurements of $p\bar{p}$ single diffraction (SD) dissociation cross sections at the SppS Collider [3] and at the Tevatron [1, 4]. These measurements showed that the rise of the SD cross section with energy is too slow relative to that predicted by the theory. Such a result was, of course, not unexpected, since it was well known that the SD cross section in Regge theory with a pomeron trajectory intercept $\alpha(0) > 1$ rises faster than the total cross section, and if this rise continued it would lead to violation of unitarity at the TeV energy scale. However, the need for unitarizing the simple Regge-pole description of cross sections was elevated to a crisis by the high energy SD measurements, and several schemes, e.g. [6, 7, 8], were proposed to implement unitarization. In this paper, we first discuss briefly a proposal [9] for a phenomenological unitarization procedure of hadronic diffraction that gives the observed energy dependence for the $pp/p\bar{p}$ single diffractive cross section, and then we use this procedure to calculate photoproduction cross sections at HERA energies. Furthermore, by applying it to hard and deep inelastic diffractive data, we obtain a picture in which the pomeron consists of an asymptotic mixture of quark and gluon color singlets in a ratio dictated by the quark counting rules for the asymptotic regime.

2 Renormalization of hadronic diffraction

The cross section for single diffraction dissociation in Regge theory has the form

$$\frac{d^2\sigma_{sd}^{ij}}{dtd\xi} = \frac{1}{16\pi} \frac{\beta^2(t)}{\xi^{2\alpha(t)-1}} \left[ \beta_j P(0) g(t) \left( \frac{s'}{s'_0} \right)^{\alpha(0)-1} \right] = f_{P/i}(\xi, t) \sigma_{T}^{Pj}(s', t)$$

(1)

where $P$ stands for pomeron, $s'$ is the $s$-value in the $P-j$ reference frame, $s'_0$ is a constant, $\xi = s'/s$ is the Feynman-$x$ of the pomeron in hadron-$i$, and $\alpha(t)$ the pomeron trajectory given by $\alpha(t) = \alpha(0) + \alpha't = 1 + \epsilon + \alpha't$. The term in the square brackets is interpreted

![Figure 1: The triple-pomeron amplitude for single diffraction dissociation.](image)

as being the pomeron-$j$ total cross section, $\sigma_{T}^{Pj}(s', t)$, where $g(t)$ is the “triple-pomeron
coupling constant”. This interpretation leads naturally to viewing single diffraction as being due to a flux of pomerons, \( f_{P/i}(\xi, t) \), emitted by hadron-\( i \) and interacting with hadron-\( j \) (see Fig. 1).

The term \( \beta^2_{P}(t) \) in the pomeron flux factor can be expressed in terms of the total cross section \( \sigma^{ii}_T(s) \) and the elastic form factor \( F^i(t) \) (obtained from \( d\sigma^{ii}_{el}/dt \)):

\[
\beta^2_{P}(t) = \beta^2_{P}(0) [F^i(t)]^2 = \frac{s}{s_0}^{-\alpha(0)-1} [F^i(t)]^2
\]

The same expression can be used to write \( \beta_{jP}(0) \) in terms of \( \sigma^{jj}_T(s) \) and \( s_0 \), using \( F^j(0) = 1 \).

The constants \( s_0 \) and \( s'_0 \), which represent energy scales in the pomeron propagator, are not specified by the theory, and experiment shows \([1]\) that \( g(t) \) is independent of \( t \), i.e. \( g(t) = g(0) \). For a universal pomeron the energy scale should be process independent and hence \( s'_0 = s_0 \). Thus, there are two free parameters in formula (1) for single diffraction, \( s_0 \) and \( g(0) \). Since \( s_0 \) appears both in the flux factor and in the \( Pj \) cross section, and since from the SD cross section as given in (1) one can determine only the product \( [s_0^{\alpha(0)-1}]^{1/2} g(0) \), the normalization of the pomeron flux cannot be determined uniquely by the SD data in the standard Regge theory. However, in the pomeron flux renormalization scheme that we propose, the constants \( s_0 \) and \( g(0) \) can be determined independently from SD data, resulting in a uniquely normalized pomeron flux.

As mentioned in the introduction, in the standard theory the \( pp \) single diffractive cross section rises much faster than that observed, reaching the total cross section and therefore violating unitarity at the TeV energy scale (dashed line in Fig. 2). The renormalization scheme that we propose treats the pomeron flux as a probability density whose integral over \( \xi \) and \( t \) is not allowed to exceed unity. The renormalized flux is given by

\[
f_N(\xi, t) = \frac{f_{P/i}(\xi, t)}{N(\xi_{min})}; \quad N(\xi_{min}) = \left\{ \begin{array}{l}
A(\xi_{min}) \equiv \int_{\xi_{min}}^{\xi_{max}} d\xi \int_{t=0}^{t_{max}} f_{P/i}(\xi, t) \, dt \\
1, \quad \text{if } A(\xi_{min}) < 1
\end{array} \right.
\]

where \( \xi_{min} = (1.5 \text{ GeV}^2/s) \) for \( pp \) soft SD. The solid line in Fig. 2 shows an ‘eyeball’ fit to the data using this flux (the obvious systematics in the data do not permit a proper \( \chi^2 \)-fit). The position of the ‘knee’ in this curve occurs at the \( \sqrt{s} \)-value at which the flux integral becomes unity, which depends on the parameter \( s_0 \). Therefore, \( s_0 \) is determined from the position of this ‘knee’ in the data. In Fig. 2, the ‘knee’ occurs at \( \sqrt{s} = 22 \text{ GeV} \) for \( s_0 = 1 \text{ GeV}^2 \).
Figure 2: SD cross section data $2\sigma_T^{p(p')-p}$ for $\xi < 0.05$ compared with predictions using the standard pomeron flux (dashed line) and the renormalized flux (solid line).

3 Proton-(anti)proton diffractive cross sections

The total, elastic, and renormalized single diffractive, double diffractive and double pomeron exchange cross sections are evaluated and compared with data in Ref. [9].

The following parameters were used in Eq. (1) to produce the solid curve in Fig. 4:

$$
\begin{align*}
\epsilon &= 0.115 \\
\alpha' &= 0.26 \text{ GeV}^2 \\
\beta_{pP}(0) &= 6.06 \text{ GeV}^{-1} \\
F^p(t) &= \epsilon^{2.3t} \\
g(t) &= g(0) \\
\sigma_{0}^{pp} &= 2.6 \text{ mb} \\
s_0' &= s_0 = 1 \text{ GeV}^2
\end{align*}
$$

These parameters were determined from data including the recent CDF measurements. The proton form factor, $F^p(t)$, is valid for $|t| < \approx 0.1 \text{ GeV}^2$; to incorporate larger $t$-values, one may set $F^p(t) = F_1(t)$, the isoscalar form factor measured in electron-nucleon scattering:

$$
F_1(t) = \frac{4m^2 - 2.8t}{4m^2 - t} \left[ \frac{1}{1 - t/0.7} \right]^2
$$

(4)

Noting that $s' = M^2 = s\xi$, the renormalized total SD cross section is given by

$$
\sigma_{sd,N}(\xi_{min} < \xi < \xi_{max}) = \sigma_{0}^{pp} \left( \frac{s}{s_0} \right)^\epsilon \int_{\xi_{min}}^{\xi_{max}} \int_0^{\infty} \xi^\epsilon f_N(\xi, t) d\xi dt = \sigma_{0}^{pp} \left( \frac{s}{s_0} \right)^\epsilon \langle \xi^\epsilon \rangle
$$

(5)
where $\xi_{\text{min}} = (1.5 \text{ GeV}^2)/s$. Since $\xi_{\text{min}}$ decreases with increasing $s$, $\langle \xi^e \rangle$ also decreases and therefore $\sigma_{\text{sd,N}}$ increases at a rate slower than $s^e$, i.e. slower than the pomeron exchange component of the $p\bar{p}$ total cross section given by $\sigma_{T}^{p\bar{p}}(s) = \beta_{pP}(0) (s/s_0)^e$, which dominates at high energies. Thus, as required by unitarity, the renormalized SD cross section remains safely below the total cross section at all energies.

Above $\sqrt{s} = 22 \text{ GeV}$, where the pomeron flux factor integral becomes unity, the total renormalized SD cross section, calculated from Eq. 5 and multiplied by 2, has an approximately logarithmic $s$-dependence given by

$$\sigma_{p\bar{p}}^{sd}(s)_{\xi<0.05} = 4.3 + 0.3 \ln s \quad [\text{s in GeV}^2]$$

The double diffraction (DD) dissociation cross section for $p\bar{p} \rightarrow X_1X_2$ depends on $s$, $M_1$ and $M_2$. Numerical values for renormalized DD cross sections are presented in Ref.[9]. In the region $30 < \sqrt{s} < 1800 \text{ GeV}$, the total DD cross section for $M_1^2, M_2^2 > 1.5 \text{ GeV}^2$ and $M_1^2M_2^2 < 0.1(s/s_0)$, which represents the coherence condition for DD, can be approximated by

$$\sigma_{dd}^{p\bar{p}}(s) \left( \frac{M_1^2M_2^2}{s/s_0} < 0.1 \right) \approx 4.3 - 0.2 \ln s \quad [30 < \sqrt{s} < 1800 \text{ GeV}]$$

Finally, the renormalized total double pomeron exchange cross section for $p\bar{p} \rightarrow p\bar{p}X$ within $1 \text{ GeV}^2 < M^2 < 0.01s$ is approximately constant at the level of $\sim 50 - 70 \text{ }\mu\text{b}$[9] in the energy range from ISR to LHC.

## 4 Photoproduction cross sections at HERA

At HERA, where $\sim 28 \text{ GeV}$ electrons are brought into collision with $\sim 800 \text{ GeV}$ protons ($\sqrt{s} \approx 300 \text{ GeV}$), photoproduction cross sections have been measured at $\gamma p$ c.m. energies $W \sim 200 \text{ GeV}$ using low-$Q^2$ photons whose energy is tagged by measuring the energy of the outgoing electron in $e+p \rightarrow (e+\gamma)+p \rightarrow e+X$. In this section, we calculate the total, the SD and the DD photoproduction cross sections at HERA from the corresponding $p\bar{p}$ cross sections by simply replacing in the Regge formulas for $p\bar{p}$ the proton-pomeron coupling constant, $\beta_{pP}(0)$, by $\beta_{\gamma P}(0)$. The latter is obtained from the cross section for $\gamma p \rightarrow Xp$ at $\sqrt{s} \sim 14 \text{ GeV}$ measured in a fixed target experiment[11]. The calculated cross sections are compared with H1[12, 13] and ZEUS[14] measurements at HERA.
4.1 Pomeron-photon coupling constant

Using factorization, the ratio of the pomeron-photon to pomeron-proton couplings, $\beta_{\gamma/p}$, is equal to the ratio of the cross sections for $\gamma p \rightarrow X p$ and $pp \rightarrow X p$:

$$\beta_{\gamma/p} \equiv \frac{\beta_{\gamma p}(0)}{\beta_{p p}(0)} = \frac{\sigma_{\gamma \rightarrow X p}^{\gamma p}}{\sigma_{pp \rightarrow X p}^{pp}} = \frac{(6.59 \pm 0.32 \pm 0.86) \mu b}{0.5 \times 4.3 \text{ mb}} = (3.06 \pm 0.15 \pm 0.4) \times 10^{-3}$$ (8)

The SD cross sections here are for $\sqrt{s} = 14$ GeV in the region $M^2 > 1.5$ GeV$^2$ and $\xi < 0.05$. The value of $\sigma_{\gamma p \rightarrow X p}^{\gamma p}$ was obtained by integrating the first term in Eq. (9) of Ref.[11] using the parameters provided in Table 1 of Ref.[11] (the second error is due to the quoted $\pm 13\%$ normalization uncertainty). The value of $\sigma_{pp \rightarrow X p}^{pp}$ was obtained from Fig. 2. Below, we use $\beta_{\gamma/p}$ to predict photoproduction cross sections for HERA.

4.2 Total photoproduction cross section

At $W \sim 200$ GeV, the total $\gamma p$ cross section is completely dominated by pomeron exchange[2] and therefore is expected to be given by

$$\sigma_T^\gamma(W) = \beta_{\gamma/p} \sigma_{T,p}^{pp}(s = W^2) = (3.06 \pm 0.15 \pm 0.4) \times 10^{-3} \left[ \beta_{p p}^2(0) \left( \frac{W}{W_0} \right)^{2c} \right]$$ (9)

where $\sigma_{T,p}^{pp}$ is the portion of $\sigma_T^{pp}$ attributed to pomeron exchange[3] and $W_0 = 1$ GeV. Cross sections calculated using this formula are compared below with data from H1[12, 13] and ZEUS[14]:

| $W$ (GeV) | $\sigma_T^\gamma$ (predicted) | $\sigma_T^\gamma$ (measured) |
|----------|-------------------------------|-------------------------------|
| 197      | 147.5 $\pm$ 7.2 $\pm$ 19 $\mu b$ | 156 $\pm$ 2 $\pm$ 18 $\mu b$ (H1, Ref.[12]) |
| 200      | 148.0 $\pm$ 7.2 $\pm$ 19 $\mu b$ | 165 $\pm$ 2 $\pm$ 11 $\mu b$ (H1, Ref.[13]) |
| 180      | 144.5 $\pm$ 7.1 $\pm$ 19 $\mu b$ | 143 $\pm$ 4 $\pm$ 17 $\mu b$ (ZEUS) |

Within the experimental errors, there is good agreement between the predicted and measured total cross section values.

4.3 Diffractive photoproduction cross sections

The photoproduction cross sections for $\gamma p \rightarrow X p$ and $\gamma p \rightarrow X_1 X_2$ can be obtained by multiplying the corresponding $pp$ cross sections by $\beta_{\gamma/p}$. For $M^2_1, M^2_2 > 1.5$ GeV$^2$,

$$\sigma_{\gamma \rightarrow X p}^{\gamma p}(W)|_{\xi < 0.05} = \beta_{\gamma/p} \left[ \frac{1}{2} \sigma_{sd}^{pp}(s = W^2)|_{\xi < 0.05} = (3.06 \times 10^{-3}) \frac{1}{2}(4.3 + 0.3 \ln W^2) \text{ mb} \right]$$ (10)
\[ \sigma^{\gamma p \rightarrow X_1 X_2}(W) \left( \frac{M_1^2 M_2^2}{W^2 W_0^2} < 0.1 \right) = \beta_{\gamma/p} \sigma_{\mathrm{dd}}^{\gamma p}(s = W^2) \approx (3.06 \times 10^{-3}) (4.3 - 0.2 \ln W^2) \text{ mb} \]

(11)

At \( W = 200 \text{ GeV} \), \( \sigma^{\gamma p \rightarrow X} = (11.44 \pm 0.56 \pm 1.49) \mu\text{b} \) and \( \sigma^{\gamma p \rightarrow X_1 X_2} = (6.7 \pm 0.33 \pm 0.87) \mu\text{b} \). Similar results have been obtained by calculating the “screening corrections” in an eikonal model\[15\]. We emphasize that the above cross sections are for a minimum diffractive mass limit of \( M_{\min}^2 = 1.5 \text{ GeV}^2 \). In order to compare our calculated SD cross section with the recent measurement of \( 26 \pm 5 \mu\text{b} \) reported by H1 \[13\], we must extend the low mass limit down to \( M_{\min}^2 = m_\rho^2 + 0.2 = 0.79 \text{ GeV}^2 \) and the upper mass limit to \( M_{\max}^2 = 0.1 W^2 \). This extension of the mass limits increases our SD cross sections by a factor of 1.2, yielding \( 7.9 \pm 0.4 \pm 1.0 \mu\text{b} \) for the experimental value at \( W = 14 \text{ GeV} \) and \( 13.7 \pm 0.7 \pm 1.8 \mu\text{b} \) for the calculated value at \( W = 200 \text{ GeV} \). The latter is about half the cross section reported by H1. Comparing now directly the experimental results of H1 and Ref.\[11\], we note that the H1 single diffraction cross section at 200 GeV is 3.3 times larger than the cross section at \( W = 14 \text{ GeV} \), i.e. it scales as \( (W^2)^{\epsilon} \), where \( \epsilon = 0.115 \). Within the Regge framework, such an increase of the cross section with energy would occur only if “screening corrections” were altogether absent, contrary to theoretical expectations for substantial (factor of \( \sim 2 \)) screening corrections \[15, 16\].

5 The structure of the pomeron

The structure of the pomeron has been investigated in \( pp \) colliders by UA8\[17\], which observed diffractive dijets at \( \sqrt{s} = 630 \text{ GeV} \) and \( |t| \sim 1.5 \text{ GeV}^2 \), and by CDF\[18\], which searched for and placed upper limits for diffractive dijet and W production at \( \sqrt{s} = 1800 \text{ GeV} \) and \( |t| \sim 0 \). At HERA, the quark content of the pomeron has been probed directly with virtual high-\( Q^2 \) photons in \( e^-p \) deep inelastic scattering. Both the H1 \[19\] and ZEUS \[20\] Collaborations have reported measurements of the diffractive structure function \( F_2^D(Q^2, \xi, \beta) \) (integrated over \( t \), which is not measured), where \( \beta \) is the fraction of the pomeron’s momentum carried by the quark being struck. The experiments find that the \( \xi \)-dependence factorizes out and has the form \( 1/\xi^{1+2\epsilon} \), which is the same as the expression in the pomeron flux factor (see Eq.\[1\]). Moreover, the fits yield \( \epsilon \approx 0.1 \), which is in agreement with the value measured in soft collisions.

The pomeron structure function was evaluated from the H1 results in Ref.\[21\] using the renormalized pomeron flux. H1 integrates the diffractive form factor \( F_2^D(Q^2, \xi, \beta) \) over \( \xi \) and provides values for the expression

\[ \tilde{F}_2^D(Q^2, \beta) = \int_{0.0003}^{0.05} F_2^D(Q^2, \xi, \beta) d\xi \]

(12)
The pomeron structure function is related to \( \tilde{F}_2^D(Q^2, \beta) \) by factorization:

\[
\tilde{F}_2^D(Q^2, \beta) = \left[ \int_{0.0003}^{0.005} \int_0^\infty \frac{\mathcal{F}_{\rho_p}(\xi, t) dt}{N(s, Q^2, \beta)} \right] F_2^P(Q^2, \beta)
\]  

(13)

The expression in the brackets is the normalized flux factor. For fixed \( Q^2 \) and \( \beta \), \( \xi_{\text{min}} = (Q^2/\beta s) \). Therefore, the flux integral, which to a good approximation varies as \( \xi_{\text{min}}^{-2\epsilon} \), is given by

\[
N(\xi_{\text{min}}) = N(s, Q^2, \beta) \approx \left( \frac{\beta s}{Q^2} \xi_0 \right)^{2\epsilon} = 3.8 \left( \frac{\beta}{Q^2} \right)^{0.23}
\]  

(14)

where \( \xi_0 \) is the value of \( \xi_{\text{min}} \) for which the flux integral is unity. For our numerical evaluations we use \( \sqrt{s} = 300 \, \text{GeV} \) and the flux factor of Ref. [9], in which \( \epsilon = 0.115 \). The value of \( \xi_0 \) turns out to be \( \xi_0 = 0.004 \).

Assuming now that the pomeron structure function receives contributions from the four lightest quarks, whose average charge squared is 5/18, the quark content of the pomeron is

\[
f^P_q(Q^2, \beta) = \frac{18}{5} F_2^P(Q^2, \beta)
\]  

(15)

The values of \( f^P_q(Q^2, \beta) \) obtained in this manner are shown in Fig. 3.

As seen, the renormalized points show no \( Q^2 \) dependence. We take this fact as an indication that the pomeron “lives” in the asymptotic regime and compare the data points with the asymptotic momentum fractions expected for any quark-gluon construct by leading-order perturbative QCD, which for \( n_f \) quark flavors are

\[
f_q = \frac{3n_f}{16 + 3n_f} \quad f_g = \frac{16}{16 + 3n_f}
\]  

(16)

For \( n_f = 4 \), \( f_q = 3/7 \) and \( f_g = 4/7 \). The quark and gluon components of the pomeron structure are taken to be \( f^P_{qg}(\beta) = f^P_{qq} [6\beta(1 - \beta)] \). The pomeron in this picture is a combination of valence quark and gluon color singlets and its complete structure function, which obeys the momentum sum rule, is given by

\[
f^P(\beta) = \frac{3}{7}[6\beta(1 - \beta)]_q + \frac{4}{7}[6\beta(1 - \beta)]_g
\]  

(17)

The data in Fig. 3 are in reasonably good agreement with the quark-fraction of the structure function given by \( f^P_q(\beta) = (3/7)[6\beta(1 - \beta)] \), except for a small excess at the low-\( \beta \) region. An excess at low-\( \beta \) is expected in this picture to arise from interactions of the photon with the gluonic part of the pomeron through gluon splitting into \( q\bar{q} \) pairs. Such interactions, which are suppressed by an order of \( \alpha_s \), result in an effective quark \( \beta \)-distribution of the form \( 3(1 - \beta)^2 \). We therefore compare in Fig. 3 the data with the distribution

\[
f_{q,\text{eff}}^P(\beta) = (3/7)[6\beta(1 - \beta)] + \alpha_s(4/7)[3(1 - \beta)^2]
\]  

(18)
Figure 3: The quark component of the pomeron seen in DIS is compared to the prediction (solid line) based on four quark flavors and a pomeron that obeys the momentum sum rule; the dashed line represents the direct quark contribution.

using $\alpha_s = 0.1$. Considering that this distribution involves no free parameters, the agreement with the data is remarkable! The UA8 and CDF results, and the recently reported value of (30-80)% for the hard-gluon content of the pomeron, are all consistent with this picture.

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